TÉCNICO LISBOA

PerOMAS

Personal Office Management and Automation System

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Thesis to obtain the Master of Science Degree in

Telecommunications and Informatics Engineering

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October 2014

Abstract

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 are needed in order to reduce costs for companies or to avoid environmental destruction. In this scope, this thesis proposes a system to address the energy consumption problem and inadequate habits of people in office buildings. It's a highly flexible office management system that can scale from an individual node in an office to the whole building. The proposed system differs from traditional centralized Building Automation and Control Systems (BACS) by offering a distributed architecture with nodes deployed in every office. This provides a low granularity of control, enabling building-wide policies to be enforced while providing users with a local interface for controlling their comfort level. The goal is to reduce global building energy consumption without significantly affecting the users' comfort level.

This document surveys the current state-of-the-art in building automation, wireless communication and occupancy detection systems. Our proposal is presented in detail and validated in the context of an academic institution, more specifically at IST-Taguspark.

Keywords: Human Behavior, Energy Efficiency, BAS, Occupancy Detection, Wireless Mesh Networks, Sensors

Resumo

O problema de criar mais hábitos de consumos energéticos sustentáveis recentemente tem recebido muita atenção da comunidade investigadora. Sistemas capazes de reduzir o consumo energético são precisos para reduzir custos para as empresas ou para evitar destruição ambiental. É com este escopo que esta tese propõe um sistema que aborda o problema do consumo energético e hábitos de pessoas em prédios de escritórios. É um sistema de gestão de escritório altamente flexível que pode escalar de um nó individual em um escritório para todo o edifício. O sistema proposto difere do tradicional BACS centralizado, oferecendo uma arquitetura distribuída com nós instalados em cada escritório. Isso proporciona uma baixa granularidade de controlo, permitindo que as políticas sejam aplicadas em todo o prédio, proporcionando aos utilizadores uma interface local para controlar o seu nível de conforto. O objetivo é reduzir o consumo global de energia do edifício, sem afetar significativamente o nível de conforto dos usuários.

Este documento analisa o estado-da-arte atual em automação de prédios, sistemas de comunicação sem fios e taxa de ocupação. A nossa proposta é apresentada em detalhe e avaliada no contexto de uma instituição académica, mais especificamente no IST - Taguspark.

Palavras-chave: Comportamento Humano, Eficiência Energética, BAS, Taxa de Ocupação, Redes Sem Fios em Malha, Sensores

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AC	Alternating Current
ACR	Algorithmic Change Reporting
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
AI	Artificial Intelligence
ANSI	American National Standards Institute
AODV	Ad-Hoc On-Demand Distance Vector
AP	Access Point
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BA	Building Automation
BAC	Building Automation and Control
BACnet	Building Automation and Control Networking Protocol
BACS	Building Automation and Control Systems
BAS	Building Automation System
B.A.T.M.A.N	Better Approach to Mobile Ad-Hoc Networking
BCUs	Bus Coupling Units
BIBB	BACnet Interoperability Building Block
BLE	Bluetooth Low Energy
BMS	Building Management System
BPSK	Binary Phase-Shift Keying
BSS	Basic Service Set
BT	Bluetooth
BVLL	BACnet Virtual Link Layer
CEN	European Committee for Standardization
CH	Central Heating

COV	Change of Value
CSMA/CA	CSMA with Collision Avoidance
CSMA	Carrier Sense Multiple Access
CSMA/CD	CSMA with Collision Detection
CSRF	Cross-site Request Forgery
DHCP	Dynamic Host Configuration Protocol
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
DTO	Data Transfer Object
EC	European Commission
ECI	Energy Cost Indicator
EDCA	Enhanced Distributed Channel Access
EHS	European Home System
EIA	Electronic Industries Alliance
EIBA	EIB Associations
EIB	European Installation Bus
EIRP	Equivalent Isotropically Radiated Power
ESS	Extended Service Set
ETS	Engineering Tool Software
EU	European Union
FFD	Full-Function Device
FHSS	Frequency-Hopping Spread Spectrum
FO	Fiber Optics
FS	File System
GPIO	General Purpose Input/Output
HTML	Hyper Text Markup Language
HVAC	Heating, Ventilation and Air-Conditioning
I2C	Inter-Integrated Circuit

IBSS	Independent Basic Service Set
IC	Integrated Circuit
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
I/O	Input/Output
IP	Internet Protocol
IrDA	Infrared Data Association
IR	Infrared
ISM	Industrial, Scientific and Medical
IST	Instituto Superior Técnico
LAN	Local Area Network
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LNS	LonWorks Network Services
LoS	Line-of-Sight
M2M	Machine-to-Machine
MAC	Media Access Control
MANET	Mobile Ad-Hoc Network
MP	Mesh Point
MQTT	Message Queue Telemetry Transport
MS/TP	Master-Slave/Token-Passing
NIST	National Institute of Standards and Technology
NoSQL	Not Only SQL
O-QPSK	Orthogonal Quadrature Phase-Shift Keying
OSI	Open Systems Interconnection
OS	Operating System
PBKDF2	Password-Based Key Derivation Function 2

PEI	Pin External Interface
PGA	Programmable-Gain Amplifier
PHY	Physical
PICS	Protocol Implementation Conformance Statement
PIR	Passive Infrared
PL	Power-Line
PTP	Point-to-Point
RADIUS	Remote Authentication Dial In User Service
RDBMS	Relational Database Management System
RFD	Reduced-Function Device
RFID	Radio Frequency Identification
RF	Radio Frequency
RSS	Received Signal Strength
RTS/CTS	Request to Send / Clear to Send
SBC	Single Board Computer
SLP	Service Location Protocol
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SNVT	Standard Network Variable Types
SPDT	Single Pole Double Throw
SPI	Serial Peripheral Interface
SQL	Structured Query Language
STA	Station
TFT	Thin-film Transistor
TLS	Transport Layer Security
TP	Twisted-Pair
UART	Universal Asynchronous Receiver/Transmitter
UDP	User Datagram Protocol

UI	User Interface
URL	Uniform Resource Locator
USB	Universal Serial Bus
VLAN	Virtual LAN
WEB	World Wide Web
WEP	Wired Equivalent Privacy
Wi-Fi	Wireless fidelity
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WPA2	Wi-Fi Protected Access II
WPAN	Wireless Personal Area Network
WPA	Wi-Fi Protected Access
WSGI	Web Server Gateway Interface
WS	Web Services

Chapter 1

Introduction

There is a wide range of factors that motivate the rapid creation of more sustainable energy consumption patterns. These include the current financial and economic crisis, environmental pressures including the global warming concerns and the safety of the energy supply.

In 2009 Guerra Santin [1] reported that 41% of the total final energy consumption in the European Union (EU) comes from buildings. To explore potential cost-effective energy savings, the European Commission (EC) adopted an Action Plan for Energy Efficiency aiming at 20% reduction in energy consumption by 2020 [2]. As a result, a number of standards have been created. One way to contribute to this objective is the use of BACS in new buildings to enhance their efficiency. Unfortunately, not all buildings are equipped with such system. Furthermore, some BACS offer limited functionality and only to the building managers.

Due to various factors such as bad user habits, lack of knowledge and miss-configurations regarding Heating, Ventilation and Air-Conditioning (HVAC) and other systems [3], the potential energy gains are not achieved. In the majority of cases, the occupants are not capable of calibrating the system to provide the best user comfort in the most energy-efficient manner possible. Also, the lack of occupancy detection systems in buildings can lead to high energy loses, especially in the form of illumination or heating by operating when unoccupied. When user detection systems are used, lighting, shading, and HVAC needs can be better determined and adjusted, therefore increasing energy savings.

Buildings have been improving in energy efficiency. Even though, in the past decades, materials with better thermal properties and more efficient systems have lowered overall energy consumption, significant differences are still observable between similar buildings with occupants with different habits. The energy consumption in this situation can vary up to three fold [1]. This is why user behavior could strongly influence the energy consumption of a building.

1.1 Motivation

It is very difficult to adjust a Building Automation System (BAS) to provide comfort for every occupant and, at the same time, assure its energy efficient operation. It is also difficult to motivate people to save energy, especially in large buildings where the occupants are usually not billed for the energy consumption. For these reasons, occupants are likely to neglect the use of this kind of systems which heavily impacts energy consumption.

A specific example of these problems occurs at Instituto Superior Técnico (IST) - Taguspark, a university campus with nearly two thousand students, teachers and researchers working on several research and development labs, classrooms and common areas. This university is equipped with a basic BAS that has a scheduler based control which is unaware of the building occupancy or user location. The scheduler is programmed to maximize energy savings, i.e. the distributed heating system starts working at 8 AM and remains operational until 9 PM, the centralized cooling system works from 8 AM to 6 PM and the corridor lighting is turned on from 5 PM until 7 AM. Some lights are on all the time. It is easily noted that this solution does not provide the best results in terms of energy efficiency regarding lighting and HVAC. For example during exam periods and projects deadlines the occupants of the university tend to stay up until very late hours. In such situations 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. This situation is more noticeable during winter and summer, when the HVAC system are constantly required. Also, during vacation periods, the system operates as if the building is being fully used.

There are also occupant related problems which frequently happen due to negligence, such as :

- Setting higher values on the thermostat than actually necessary
- Forgetting to turn off the HVAC system upon leaving
- Leaving the door open when heating/cooling is active
- Leaving the lights on needlessly or forget to turn them off
- Leaving the lights on when daylight illumination is sufficient

These are some examples of user behaviors that cause significant energy waste and can be solved through user feedback analysis and detection based automation. However, in order to detect these behaviors, sensors that can measure energy consumption and perform user detection must be present in every room. At the moment, buildings with rooms equipped as such are almost non-existent.

1.2 Problem Statement

The major goal of this thesis is to reduce the overall energy use of a building without impacting its users' comfort. In order to achieve this, a list of problems must be analyzed and resolved:

- **User Behavior and Neglect** - These are the main variables responsible for the different energy consumption patterns in buildings. It is difficult to change user habits, and the amount of information they have available or are willing to use in their decision making process is limited.

- **Limited Flexibility** - Currently installed BACS are not open source and require specialized personnel for installation and configuration. Because of that, they are limited to pre-installed functions and have the risk of easily becoming outdated.
- **Limited Efficiency** - Current solutions are unable to predict the future demand on a specific system or service. Thus, their duty cycle is approximated which could lead to big energy loses or user comfort. E.g. a chiller may operate all night to store a large amount of thermal energy, when the building will be mostly vacant during the next day.
- **Limited Customization** - Since existing BAS are operated centrally by building managers, they don't cater to the particular needs of every user which are also dependent of his localization in the building. For example, users with windows in their rooms will have different luminous and thermal requirements than of those who don't.
- **Expensive installation** - Another problem with BAS is the cost of devices and their installation or upgrade. Since bus networks are usually used, the cost of wiring and dedicated conduits becomes significant in large buildings. Hence, the number of sensors and actuators is usually limited to the automation of building zones rather than offices.

1.3 Proposed Solution

This thesis presents a solution for the lack of affordable personalized office management and automation systems designed to enhance the occupants' comfort and minimize energy footprint at the building scale. We designed a system capable of controlling the building's main energy demanding equipment such as lighting, cooling and heating systems. In order to achieve maximum energy efficiency, the load of these systems will be adjusted according to the occupancy level and the users' needs.

With the constant growth of the computational power of embedded systems, it is now affordable to build a network of devices that can deal with these problems. All the benefits of a BAS can be integrated into a cheap small device that can be installed in every room and personalized for the present occupant or group of people, even in the presence of conflicting personal preferences.

In large buildings, these devices can be interconnected to form a network. They can work as a distributed platform that manages every room independently to increase the comfort of every user and work cooperatively to increase the building's energy efficiency levels, e.g. by turning off a boiler that serves a floor when none of the offices there is occupied.

The system will be composed of devices placed at strategic locations and in every office. The strategic locations will correspond to specific location of systems/services and their bifurcation in the building in order to control a subset of rooms or building zones. Devices will be built from low-cost off-the-shelf hardware. They will run on a free and easy to develop software platform with support to high level programming languages.

The devices will function as an interface between the system and services of every room and the user. They will feature sensors for occupancy awareness and ambient sensing used to automatically adjust the room environment to each user, based on their feedback, ambient and weather conditions and historical data. The device will also keep track of the users preferences, enable him to specify automation rules and at the same time enforce general energy efficient rules. The below listed examples represent some actions that are neglected by the users and cause unnecessary energy consumption which could be avoided with our system:

- Automatically turn off artificial lighting when user presence is not detected
- Automatically turn off artificial lighting when natural lighting is sufficient
- Automatically turn off HVAC when user presence is not detected
- Automatically turn on or off any other system/service depending on occupancy levels in rooms, building zone or building

The system will also include the option to support and test multiple calibration and management algorithms which could provide better results in terms of energy efficiency and/or user comfort. Based on the collected information from sensors, energy consumption, user presence and their actions, statistic charts may be created for easy interpretation of this data to users and building managers.

The devices will be arranged in a hierarchical architecture where the root device will aggregate information regarding the entire building that could be used to determine the building's total heating, cooling and energy needs. The intermediate devices will gather information regarding a part of the building such as floor levels or building zones. Finally, the devices in every room represent the leaves of the tree that generate information used by the upper levels. This solution will help adjust the load of every intermediate system/service to that required by the occupants in the distinct parts of the building, thus improving energy efficiency.

For example if system X is responsible for serving a number of rooms and only one room is using that service, then system X can be configured to fulfill the actual demand. Depending on the system, the actual energy savings can vary and can even reach the 100% mark when the system in not being used in any room.

1.4 Thesis Contribution

The following list presents the main contributions of this thesis.

- **Hardware Architecture** - Design of a prototype node capable of integrating multiple sensors (ambient, energy consumption, occupancy, localization) and inputs as well as network interfaces for communication.
- **Software Architecture** - Design of an application to run on the target hardware that offers the user the control of the local HVAC and lighting services while recording ambient and power usage data.
- **Network Architecture** - Design of scalable easy-to-install network architecture with independent nodes and collaborative goals.

- **User Interface** - Development of two user interfaces for easy control of the system: a primary web based interface for user registration, remote system control and detailed information display and a secondary interface for the device's Liquid Crystal Display (LCD) touch-screen for easy feedback input and important data display.
- **Automation and Management Algorithm** - Development of an algorithm capable of dealing with conflicting comfort preferences of multiple users and enforcement of energy efficient rules.
- **Functional Prototype** - Deployment of the system in a group of four nodes and one gateway. Each node will serve an office and the gateway will control an service common to the four nodes (corridor lighting).
- **System Evaluation and Performance** - Evaluation of the user comfort and system energy efficiency improvements.
- **Paper Submission** - A paper was submitted and accepted for publication in The 5th International Conference on Ambient Systems, Networks and Technologies (ANT-2014).

1.5 Outline

The rest of this document is organized as follows.

- Chapter 2 describes the previous work in the field.
- Chapter 3 describes the system requirements and the architecture of PerOMAS.
- The implementation of PerOMAS and the description of the technologies chosen are provided in chapter 4.
- Chapter 5 describes the evaluation tests performed and the corresponding results.
- Chapter 6 summarizes the developed work and future work.

Chapter 2

Related Work

In the next subsections we will explore the main related work used by this thesis.

Section 2.1 starts by examining the main Building Automation (BA) systems. Following in the Section 2.2 we explain the most used wireless communication technologies and their functionality. Next, Section 2.3 presents some tools and techniques used for occupancy detection. Finally, Section 2.4 describes the influence of human behavior in buildings energy efficiency.

2.1 Building Automation (BA) Systems

Building Automation Systems is a distributed control system composed of an intelligent network of electronic devices that are used to monitor and control the building's electronics, lighting, shading, heating, ventilation, and air-conditioning (HVAC) systems (Figure 2.1 represents a typical BAS network). Its most important targets are to maintain the building's climate within a comfortable range, provide lighting based on an occupancy schedule, monitor device failures and energy consumptions. This kind of systems reduces building maintenance and energy costs. Improvement in energy efficiency will also contribute to environmental protection. For this reason policies and regulations sometimes mandate the use of this kind of systems.

Intelligent buildings require integration of a variety of Building Automation and Control (BAC) systems components that are usually made by different manufacturers. The exchange of information among these devices is critical in order to obtain a successful operation of the building systems. Historically, competitive pressures and lack of standards forced manufacturers of building automation equipment to develop unique, proprietary communication protocols.

Even within a single building automation function, such as the control of an HVAC system can cause trouble. If there is a need to expand or upgrade the control system, the building owner has been forced to either return to the same vendor who installed the existing system, replace the entire system, or install a separate independent system because the communication protocols with the other products are incompatible. And in some cases new products can even be incompatible with older products from the same vendor.

Proprietary approaches to providing these communications have created big challenges for systems integrators and restricted the development of intelligent building technology. Even though digital automation and control technology has been widely available for a long time, intelligent buildings with integrated building services are still more of a promise than a reality.

2.1.1 BACnet

The Building Automation and Control Networking Protocol (BACnet) [4, 5, 6, 7, 8] was especially developed to address the needs of all kinds of BAC systems. Key features needed for BA applications were built into BACnet from the beginning. In 2003 BACnet has adopted as a national standard by the 28 member countries of EU.

While BACnet messages can theoretically be transported over any network, just a few relevant networks types were standardized. They are Ethernet, ARCNET, Master-Slave/Token-Passing (MS/TP), LonTalk and Point-to-Point (PTP). Each of them is a local area network standard except MS/TP and PTP. MS/TP is used for connectivity over Twisted-Pair (TP) using EIA-458[6] signaling while the PTP protocol accesses the communication medium through an EIA-232[6] interface. A typical application would be to connect to a modem for dial-up access to a remote building automation system. The LonTalk protocol is limited to transporting BACnet messages over a LonTalk network.

The Internet Protocol (IP) was included into BACnet in early 1999, creating ”BACnet/IP”. Due to this, IP networks are natively supported, which allows BACnet devices to communicate directly using IP, instead of using tunneling routers.

A BACnet network topology is composed of *segments* which are physical runs of cable, that can be connected using *repeaters* and *bridges*. BACnet networks, which also can be of different media types, are connected by *routers* to form a BACnet *internetwork*. A BACnet network address is represented by a 2-byte network number and a local address of up to 255 bytes. The local address depends on the link layer medium which can be an IP address for BACnet/IP or a Media Access Control (MAC) address in case of a Local Area Network (LAN). The BACnet routers which connect the individual networks route the packets based on the network numbers.

BACnet uses *objects* to represent the functionalities and capabilities of a node. All BACnet objects have a collection of properties. For example, an analog input object that reports room temperature will have a ”current value” property (which is associated with last read value from the physical input).

Any device on the BACnet network can have many objects of any type but must have at least one object, the ”Device” object. This object is used to control and report various characteristics of the device. The object model present in BACnet can be easily extended to include new objects or properties.

While objects give an abstract representation of a BA device, BACnet *services* provides commands for accessing and manipulating this information to automate tasks. BACnet defines 40 services which are grouped into five categories: Object Access, File Access, Alarm and Event, Remote Device Management and Virtual Terminal.

Who-Is/I-Am and Who-has/I-Have are remote device management services that are used for dynam-

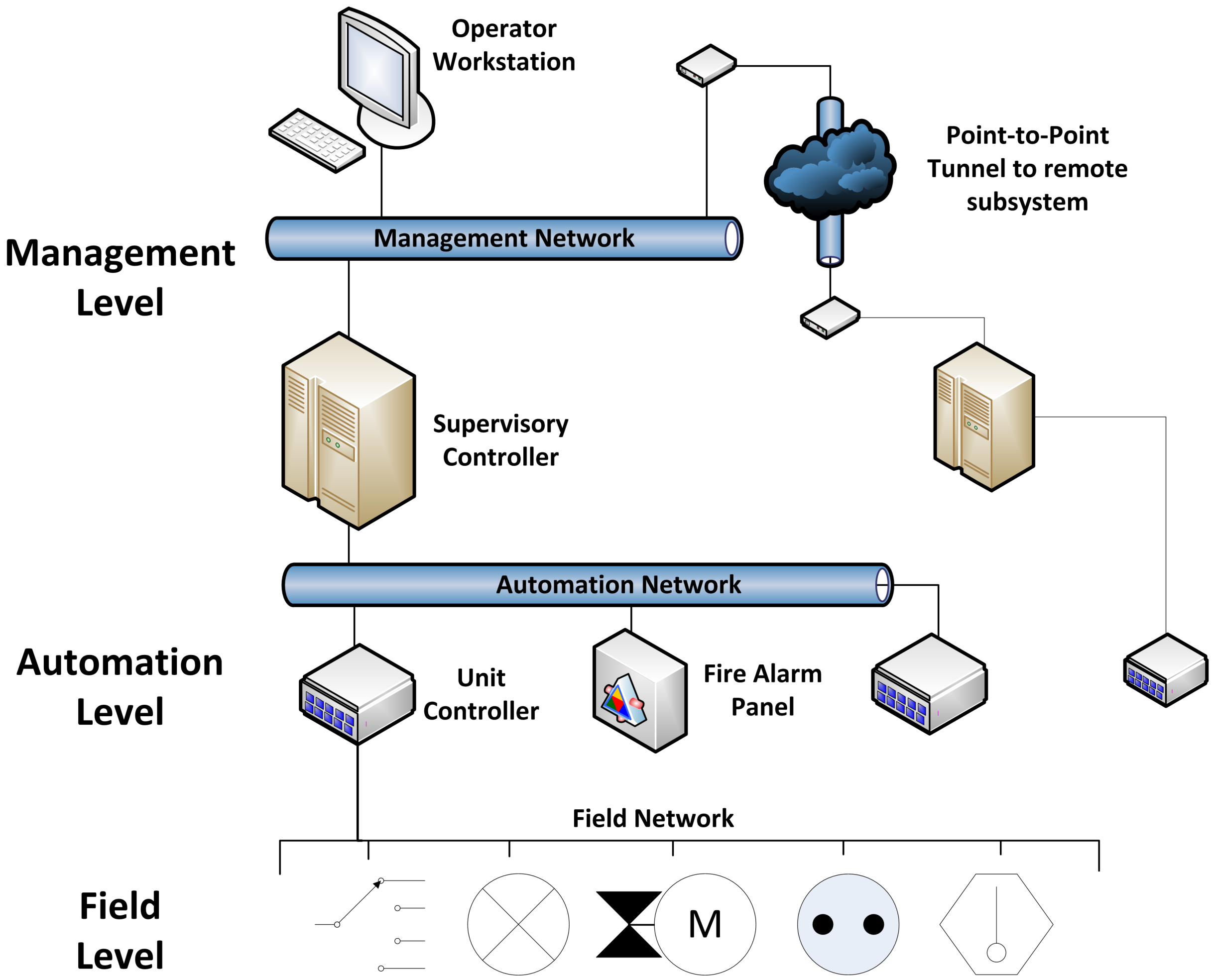


Figure 2.1: Example of an BAS system

ically discovering devices and specific objects using their object name or identifier. Other such services are used in the BACnet network for time synchronization and device reinitialization.

Several BACnet device profiles have been defined, in order to simplify the vendors work. Each of the profiles is a collection of BACnet Interoperability Building Blocks (BIBBs) that are intended to be implemented in the most common BA equipment such as : smart actuators, smart sensors, building controllers, operator workstations and application specific controllers.

BACnet/WS is the most recent addiction to BACnet which describes the use of XML[1] and Web Services (WS) for the integration of BACS with other enterprise systems. BACnet/WS is protocol neutral, thus can be also applied to non-BACnet systems (although a logic mapping between BACnet and BACnet/WS is included in the standard).

2.1.2 LonWorks

The LonWorks system is a networking platform created to address the needs of control applications. It consists of the LonTalk communication protocol (created by Echelon Corp), a controller (the Neuron Chip [8]) and a network management tool [9, 5]. The communication protocol LonTalk is a flexible field bus protocol which in 1999 was approved as an Electronic Industries Alliance (EIA) international communication standard (ANSI/EIA-709.1) [9].

The LonTalk standard was designed as a generic control network, thus it supports many communication media and wiring topologies. A number of communication *channel* profiles were defined over different media types such as : TP, Fiber Optics (FO), Coax, Infrared (IR), Power-Line (PL) and Radio Frequency (RF). From all of these the most used in BA is the free topology TP profile FT-10 (78.1 kb/s), which allows physical segments with a maximum of 500 m. Normally the TP-1250 (1.25 Mb/s) profile is used in bus topology for the backbone of the network. More recently, there is a tendency to use IP tunneling mechanisms (LonWorks/IP) instead of the traditional TP-1250 backbone. Both tunneling routers and fully IP-based LonWorks/IP nodes can be used. Over the TP medium LonTalk uses the *predictive* p-persistent Carrier Sense Multiple Access (CSMA) protocol [10, 11].

All the addressable space of a LonTalk network is referred as the *domain*. The domains are identified by an ID that can be up to 48 bit long. The domain can hold up to 255 subnets with a maximum of 127 nodes each, which results in 32385 addressable nodes in the same domain. Usually each physical channel is represented as a subnet, but it is also possible for multiple physical channels to be linked into a subnet through bridges and repeaters. On the other hand, many subnets can co-exist in the same physical segment. Therefore, routing is only performed between different subnets, which usually are arranged in a tree hierarchy. In case of domain routing, a proxy node is needed in order to transfer the information at the application layer.

In every domain there can be up to 256 multicast groups. Broadcasts messages can be addressed to the entire domain or to a specific subnet. If needed, a reliable transmission mode with end-to-end acknowledgments can be used for unicast and multicast messages. In addition to *unacknowledged*

[1] `http://www.w3.org/TR/REC-xml/`

mode, the *unacknowledged-repeated* mode can be used, which automatically repeats the transmission a programmed number of times.

The LonTalk application layer offers a particular support for the manipulation of network variables. Management and diagnostic services include querying the content of these variables, node status, reading and writing memory, device identification and router configurations.

Normally the nodes are based on a chip from the Neuron series by Echelon[2], but there are also other embedded controller solutions such as from Loytec[3]. These controllers execute the seven Open Systems Interconnection (OSI) Layers including the application program itself, which accesses the sensors and actuators connected through the Input/Output (I/O) interface. The controllers are programmed using ANSI C whereas the Neuron chips are programmed using the Neuron C programming language [5] which is based on ANSI C.

There are entirely non-open systems which are build using LonTalk technology. Moreover, the LonMark International founded in 1994 defines guidelines in order to ensure interoperability between devices from different manufacturers. They include LonTalk channel profiles, Standard Network Variable Types (SNVT) and functional profiles. Many functional profiles have been published, many of them related to BA such as: ”Constant Light Controller”, ”Scheduler”, ”Occupancy Sensor” and others that are freely available, but are not a part of any formal standard.

2.1.3 EIB/KNX

The European Installation Bus (EIB) [12, 7] is a fieldbus protocol that was designed for decentralized monitoring, control and management of buildings and homes[12, 7, 13]. In 2002, EIB was merged with Batibus and European Home System (EHS) creating the new KNX[4] standard with the objective of creating a single European standard for BA.

The most used KNX medium is the TP cabling variant known as TP1. It carries the signal at a rate of 9600 b/s as well as 29 V DC link power. The medium access on TP1 is controlled using CSMA with Collision Avoidance (CSMA/CA), and provides up to four priority levels. TP1 allows a free topology wiring composed of physical segments of up to 1000 m. Using bridges, a maximum of four segments can be concatenated in order to form a line, which can hold up to 254 devices. Lines then are connected via routers (named line couplers) to form a zone. Zones can be coupled by a backbone line or IP tunnels. A fully populated network can support roughly 57600 devices.

The KNX RF medium uses the frequency band reserved for short-range devices (telecommand, telemetry, alarms) which is in the 868 MHz range. The communication is done in a peer-to-peer manner. In addition to devices which support bidirectional communication, transmit-only devices can also be used (such as simple sensors and switches) in order to extend battery life and reduce their costs.

EIBnet/IP [14] currently defines two service protocols, Tunneling and Routing: EIBnet/IP Tunneling provides easy remote maintenance access to the EIB/KNX network but is limited to PTP communication.

[2] http://www.echelon.com/
[3] http://www.loytec.com/
[4] http://www.knx.org/

EIBnet/IP Routing on the other hand, is used as an IP backbone for interconnecting multiple EIB/KNX networks.

Every device in the EIB/KNX network gets an unique address, which corresponds to the device position within the topological structure of the network (zone/line/device). This address is used for client-server communication for initialization, programming and diagnostic operations. They also get a group address which is used for multicast communication between EIB/KNX devices.

EIB/KNX uses a shared variable model to represent the capabilities of each node. The variables which are shared with the network are referred to as *"group objects"*, which can be readable, writable or both. Group membership is defined individually for each *"group object"* of a node, which can belong to multiple groups. The EIB/KNX makes use of the publisher-subscriber model in order to disseminate changes of values in a group.

The specifications also defines a set of standard system components such as Bus Coupling Units (BCUs). BCUs are devices that implement the full network stack and the application environment. They are used as a base for simple user applications and can provide a set of group objects. The 10-Pin External Interface (PEI) on the BCUs can be configured to connect simple application modules such as sensors, switches, digital I/O or a Analog-to-Digital Converter (ADC). More complex user applications which require more processing power than the simple microcomputer used in the BCUs can use the so-called TP-UART Integrated Circuit (IC). The IC implements the Physical (PHY) and data link layers of the OSI model and offers an Universal Asynchronous Receiver/Transmitter (UART) interface to the Host controller that can be personalized for specific uses [13, 15].

2.1.4 Summary

In the above examined BAS, we observed that all the above platforms were designed for limited resource devices and low energy consumption in mind. These factors limits the possibilities and capabilities of every node. The reason is that the automation control platform is usually on a centralized server, commonly specified to as the Gateway, which does all the processing. These devices are normally composed of proprietary hardware, designed with a single purpose and therefore are limited to certain specialized tasks. Almost all of them require personalized software and/or hardware to be configured. Sometimes even specialized professionals are need in order to perform simple configuration tasks. Some of them promise easy system integration with other platforms but in the end failed to do so for the complex tasks, which typically forces the buyers to stay with a single vendor. Another important aspect is the very high cost that these solutions could reach and are not properly explained by the cost of their individual electronic parts.

2.2 Wireless Communication

In the past decade, wireless sensors and actuators networks have gained momentum, receiving a lot of attention from the BA industry and standards development organizations. The use of wireless communications allows flexible addition and removal of devices to and from the network. But more importantly, it reduces installation costs since wired solutions require cable trays or conduits. However, this medium has its own challenges and limitations due to the nature of radio propagation. Some of these technologies have had commercial success despite of these limitations.

2.2.1 Infrared (IR)

IR wireless is used for short and medium-range communication and control where devices communicate through IR radiation [16]. Some systems only work in *Line-of-Sight (LoS) mode* that require unobstructed straight path between the transmitter and the receiver. Others support *diffuse or scatter mode*[17] where the signal can bounce off the surfaces and still be received, even without LoS. But unlike RF links, IR cannot pass through walls. This can be seen as a problem, but in other scenarios it may be seen as a security feature. Some IR systems offer a level of security comparable to that of hard-wired systems. For example it is harder to physically eavesdrop on a LoS IR laser communication link than a Wireless fidelity (Wi-Fi) connection.

IR technology is used in a variety of peripherals such as remote control units, intrusion detectors, cordless microphones and handsets. It is also used in LoS Laser communications which can offer high speed data rates [18].

Infrared Data Association (IrDA)[5] is an industry driven interest group that provides a complete set of protocols for wireless IR communication that permit data communication up to 1 Gbit/s (standardized as Giga-IR) [19].

2.2.2 Bluetooth (BT)

BT, also known as Institute of Electrical and Electronics Engineers (IEEE) 802.15.1 standard [20, 21] is a wireless technology designed for short-range communication of fixed and mobile devices, also known as Wireless Personal Area Network (WPAN) [22]. BT operates in the 2.4 Ghz short-range Industrial, Scientific and Medical (ISM) band and uses a radio technology called Frequency-Hopping Spread Spectrum (FHSS) where every packet is transmitted on one of the 79 designated BT channels and offers data rates of up to 3 Mbit/s.

BT uses a master-slave communication model where one master device can communicate with a maximum of seven other devices in a piconet. A piconet is an ad-hoc computer network using BT technology where all devices are synchronized using the clock of the master. Slaves communicate only with their master that controls the communication. Besides having an active mode, a slave device can be in the standby or parked mode to reduce power consumption [22]. Two or more piconets can be connected to create a scatternet[23], in which certain devices simultaneous can play the role of master in one piconet and the slave in another. A BT device may participate in several piconets at the same time, thus allowing for information to flow beyond the coverage area of a single piconet.

[5] `http://www.irda.org/`

BT was primarily designed as low power wire-replacement. Its effective range depends on the Class of the device. Table 2.1 shows the three possible Classes of devices found in the market, their maximum Equivalent Isotropically Radiated Power (EIRP) and respective range. Usually Class 2 devices are used with a range of around 10 meters. However, some Class 1 devices[6] allow open field ranges of up to 1 km without exceeding legal emission limits.

Bluetooth Low Energy (BLE) is a subset of the BT Core Specification v4.0 (also called BT Smart) adopted in June 2010 [21]. As an alternative to BT standard (BT v1.0 to v3.0) it is aimed at very low power applications running off coin cell. It features a lightweight Link Layer providing ultra-low power consumption when in idle mode operation and reliable point-to-multipoint data transfer with advanced power-save and secure encrypted connections at the lowest possible cost per device.

2.2.3 Wireless fidelity (Wi-Fi)

Wi-Fi is a brand name for the IEEE 802.11 standard [24, 25, 22], which is a set of MAC and PHY layer specifications for Wireless Local Area Networks (WLANs). It operates in the 2.4 and 5 Ghz frequency bands and uses CSMA/CA to control the medium access and offers data rates of up to 1.3 Gbp/s with the new IEEE 802.11ac revision [26]. It can also use the optional Request to Send / Clear to Send (RTS/CTS) mechanism to reduce frame collisions between nodes that cannot sense each other but cause collisions at the receiver [27]. Enhanced Distributed Channel Access (EDCA) is used to provide differentiated and distributed traffic prioritization, with eight different priority levels.

The most basic entity of IEEE 802.11 WLAN is a STA which represents a device with Wi-Fi capabilities such as a Smart-phone or Laptop. An AP is a STA with extended capabilities that is the central device of a WLAN, which is usually connected to a wired network. STAs associate and authenticate with the AP to get access to the network, forming a star topology. This topology is called an infrastructure Basic Service Set (BSS). STAs could also connect between themselves using the ad-hoc mode to form an Independent Basic Service Set (IBSS) (Figure 2.2).

As depicted in the Figure 2.2, because of the EIRP limits imposed by the EU (100 mW) and attenuation caused by the radio propagation the range of a single AP is limited. Furthermore, multiple BSSs could be interconnected using a Distribution System (DS) to form a Extended Service Set (ESS) network of arbitrary size and complexity. The IEEE 802.11 standard can also be used to create multi-hop networks.

[6] http://www.bluegiga.com/en-US/products/bluetooth-classic-modules/wt41-long-range-bluetooth--module/

Class	Maximum permitted power		Typical range
	(mW)	(dBm)	(m)
Class 1	100	20	100
Class 2	2.5	4	10
Class 3	1	0	1

Table 2.1: Possible types of BT devices

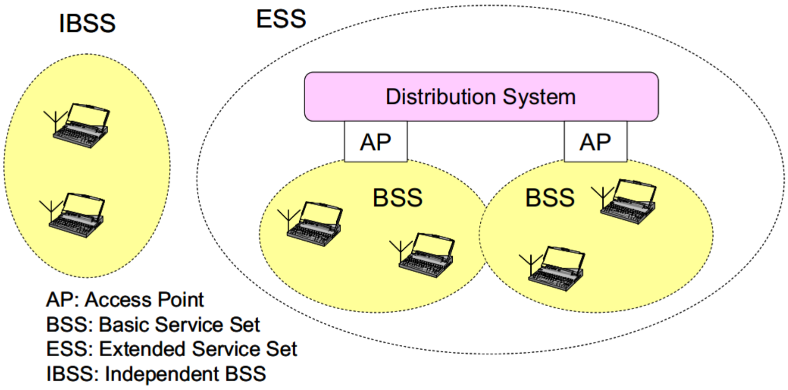


Figure 2.2: IBSS and ESS configurations of 802.11 networks [22]

IEEE 802.11s is an IEEE 802.11 amendment that describe the necessary functions to form a Wireless Mesh Network (WMN)[25, 28]. The basic element in 802.11s is the Mesh Point (MP), which is different from any other 802.11 entity. MPs can exchange messages with other MPs that can be multiple wireless hops away. This is possible because a MP has relaying capabilities similar to an AP which allows it to forward messages for communications that it is not involved in. The IEEE 802.11s also uses strong security mechanisms and power saving techniques that have their own challenges due to the distributed nature of the network.

Batman-adv or Better Approach to Mobile Ad-Hoc Networking (B.A.T.M.A.N) advanced is an open source multi-hop routing protocol based on the ad-hoc mode of the IEEE 802.11 standard [29, 30]. It is classified as simple and robust proactive routing protocol for establishing multi-hop routes in ad-hoc networks. B.A.T.M.A.N does not maintain the full route to the destination, instead each node maintains only the information about the best next link to be used as a gateway, which saves resources and processing power. Contrary to IEEE 802.11s, B.A.T.M.A.N allows node mobility and can be implemented as routing protocol for Mobile Ad-Hoc Networks (MANETs).

2.2.4 IEEE 802.15.4

IEEE 802.15.4 standard specifies the PHY layer and MAC for low-rate WPANs which focus on low-power, low-cost and short distance communication between devices [31, 32].

It operates in the 868 MHz band in Europe, 915 MHz band in North America and 2.4 GHz ISM band worldwide with data rates of 20 kb/s, 40 kb/s and 250 kb/s respectively. In conjunction with Direct Sequence Spread Spectrum (DSSS), Binary Phase-Shift Keying (BPSK) modulation is used in the first two bands with Orthogonal Quadrature Phase-Shift Keying (O-QPSK) in the 2.4 GHz ISM band.

For channel access in IEEE 802.15.4 two methods were defined: beacon-enabled and beaconless [33]. In the beaconless mode, the devices use the CSMA/CA scheme. In beacon-enabled mode, the devices assumes that there is a node acting as a coordinator, which broadcasts beacons that synchronize the network. The time between coordinator beacons is divided into three periods. First a contention access period is used with CSMA/CA where the nodes compete for the medium. Secondly a contention-free period where a node can transmit in an allocated guaranteed time slot. And finally an inactive period, in which the nodes may remain in sleep mode.

ZigBee and 6LoWPAN, explained in the next sections, are two of the best known open standards based on the IEEE 802.15.4 MAC and PHY layer.

6LoWPAN or IPv6 over Low power Wireless Personal Area Networks is a developing standard from the Internet Engineering Task Force (IETF) 6LoWPAN Working Group and defines how to use IPv6 over low power, low data rate radio networks as specified by IEEE 802.15.4 standard [32, 33]. The concept originated from the question: "Why invent a new protocol when we already have IP?" [34] and that low-power devices with limited resources should be able to participate in the *Internet of Things*. Because the underling protocols are IP based, it can make use of all the exiting standards and tools to speed up the development, such as Simple Network Management Protocol (SNMP) for node management, Service Location Protocol (SLP) for service discovery and so on. There are also many standardized higher level services such as Load Balancing, Firewalling and Mobility that could also be easily integrated. Configuration servers also could be eliminated using the ZeroConf and Neighbor Discovery capabilities of IPv6.

6LoWPAN also has an alternative when faced with routing. Rather than routing the messages using the IEEE 802.15.4 standard (layer 2 mesh or *mesh under*) under the IP layer, it is possible to build the mesh network on top of IP using standard protocols (layer 3 routing or *route over*).

ZigBee is a wireless networking technology developed by the Zigbee Alliance. The Zigbee protocol is composed of four main layers: the PHY and MAC layer from the IEEE 802.15.4 standard and the network and application defined by the Zigbee specification [33, 35]. It provides self-organized multi-hop and reliable mesh networking which is created on demand and maintained using the Ad-Hoc On-Demand Distance Vector (AODV) routing protocol. Zigbee defines three device roles: the coordinator, the router and the Zigbee end device. It also defines two different type of devices: a Full-Function Device (FFD) and an Reduced-Function Device (RFD) [36]. The FFDs can have any of the defined roles, but RFDs can only be end devices that communicate only with FFDs. A FFDs is used for very simple applications such as light switch or a passive IR sensor, thus they can be built using minimal resources and at a very low cost. There are two Zigbee application profiles that can be used to develop ZigBee application objects (the program itself) [33]. The first one is the Zigbee Home Automation Public Application Profile for residential or light commercial complexes usually used for light, HVAC and security. The second one is the Zigbee Smart Energy Profile, that is used for load management and response to energy demand.

2.2.5 Summary

In conclusion to the examined open standards for wireless communication solutions, we observed that multi-hop is one of the key functions that can be used to overcome some limitations of wireless communication such as range, fault tolerance and network extensibility. We have seen that protocols based on the IEEE 802.15.4 such as Zigbee are the most energy efficient. They were especially designed for BACS applications and can function years on a single battery. On the other hand, their data rate is very restrict and cannot be used for more bandwidth demanding applications. The Wi-Fi standard offers data rates up to 1.3 Gbp/s with the new 802.11ac release but has the disadvantage of high energy consumption. It has support for mesh networks using the IEEE 802.11s standard or the Batman-adv routing protocols making Wi-Fi usable for BA when the devices are not battery dependent. As shown by the 6LoWPAN developing standard, a big part of tools and services needed for BA can be adopted from the IP protocol, which demonstrates the potential of connecting these devices directly to the Internet.

2.3 Occupancy Detection

Occupancy detection techniques are used nowadays to reduce energy consumption in buildings by supplying lighting, HVAC and other building systems with occupancy information. Based on it, these systems could adjust their configuration and achieve potential energy savings of up to 50% for lighting and 20% for HVAC systems [37].

In the next sections we will describe the main technologies used for occupancy detection and user identification.

2.3.1 RFID

Radio Frequency Identification (RFID) technology is now widely used in buildings to detect and track occupants or products [38]. It is a wireless communication technology for data exchange between a reader and a tag. An RFID system is composed of two basic components: RFID readers and RFID tags [39]. The RFID reader can read the data emitted from the RFID tags. There are two types of RFID tags: passive tags and active tags. Passive RFID tags operate without a battery and are very cheap to make but have very limited communication range. They reflect the RF signal receive from the reader and add information by modulating the reflected signal. They basically allow an ID to be read.

On the other hand active tags contain a battery to power an incorporated transceiver and because of that can achieve much higher ranges. However, besides the limited battery life that can last for several years, the active tags are very expensive.

The main use of this technology is the identification and tracking of objects such as commercial products in large stores, but the same principle can be used for users. The use of passive RFID tags can be a very cheap way of user identification that can be installed at the main entrances. A disadvantage of using RFID technology is the requirement of people having to carry RFID tags to be located and the privacy issues that need to be taken into consideration due to the tag being readable by anyone with a reader.

On the other hand, schools and universities and other entities already integrate RFID tags inside their Identification (ID) cards, which is also the case of IST-Taguspark.

2.3.2 PIR

Current buildings usually use Passive Infrared (PIR) technology for occupancy detection [39]. It is composed of IR sensors and works by detecting the electromagnetic radiation emitted by the person when they pass by.

But it has some major disadvantages for the purpose of occupancy detection: (1) IR sensors are sensitive to sunshine radiation, (2) static persons cannot be detected, (3) the IR radiation can be easily blocked by ordinary glass or plastic, and (4) detection fails when multiple persons pass through the sensor at the same time. These factors cause miss-readings by the system. Also, there is no mechanism for user identification.

On the other hand there is no need for the use of any specific device for people to be detected.

2.3.3 Vision-based

Occupancy detection can also be done using the video surveillance now widely used in buildings. By analyzing the captured images it is possible to deduce people's shapes and movement. A number of approaches have been developed which are divided into three main categories: motion analysis, feature-based detection and mapping-based methods [39]. Motion detection and tracking focus on extracting object silhouettes from consecutive frames using motion analysis. Feature-based detection are more appropriate for accurate human detection in static images such as faces or parts of the body using machine learning algorithms. Mapping-based methods are used for statistical mapping between the number of person on the scene and the moving pixels in the images [40].

Most buildings already have surveillance cameras which can reduce the cost of their deployment. On the other hand, video processing is computationally very demanding, that can increase the cost of this type of technology. Another problem is the difficult calibration and the infrastructure needed to connect to this kind of systems which can also be expensive.

2.3.4 Wi-Fi

Nowadays the Wi-Fi technology (also known as IEEE 802.11 standard) is widely used (especially in office buildings) and can be found in almost all modern devices (such as laptops, smart-phones and even printers). Occupancy detection using the Wi-Fi infrastructure is easy to implement and can be economical, because it does not require the installation of additional equipment.

There are two ways that can be used to identify user occupancy and position using Wi-Fi technology. Either using cell based positioning or using the Received Signal Strength (RSS). In some cases, triangulation based on RSS of at least three APs can be used to infer the physical location of a STA [41]. When this method is used indoors, reflection and multipath problems arise and can heavily impact accuracy.

Figure 2.3 represents an example of cell based positioning implemented by the author of this document at IST-Taguspark. The data from the APs and from the Remote Authentication Dial In User Service (RADIUS) server can be merged in order to identify the occupants of a certain area. Due to the big coverage area of a single cell the accuracy can be fairly low but is enough to determine if a user is in a certain zone of the building.

2.3.5 Bluetooth

BT is a low-cost technology that is currently built-in in most of the mobile phones [21]. This fact can be exploited to use the technology for localization proposes. There are two main used methods for device localization using BT: connection-based and inquiry-based [42].

Connection-based systems use the RSS of the established connection between the master and the slave. This mode has the disadvantage of having to configure the device. Authorization between the two devices is needed using a PIN code, which makes the devices connectible even when in *hidden* mode. This mode also has limited scalability because of the BT limitation of only seven connections.

Inquiry-based makes use of the device discovery protocol for allowing a device to find a neighbor before establishing a piconet. This method also returns the RSS of the inquired device. The main disadvantage of this method is that the devices need to be in *visible* mode in order to be detected.

A study showed that both of the methods are suitable for tracking room level proximity between BT devices with a range of 5 m [43], which is a smaller coverage area than that of Wi-Fi but much more precise.

2.3.6 Summary

In conclusion to the examined technologies of occupancy detection, the main characteristics were summarized in Table 2.2. PIR detections systems didn't have any mechanisms for user identification, which is very important when taking into consideration a multi-user system with different preferences.

Vision-based detection can be used for user identification, but for that we need a database to control the readings too, which is again user intrusive and a resource demanding process.

On the other hand, RFID Passive tags showed to be very cost effective and used in many commercial

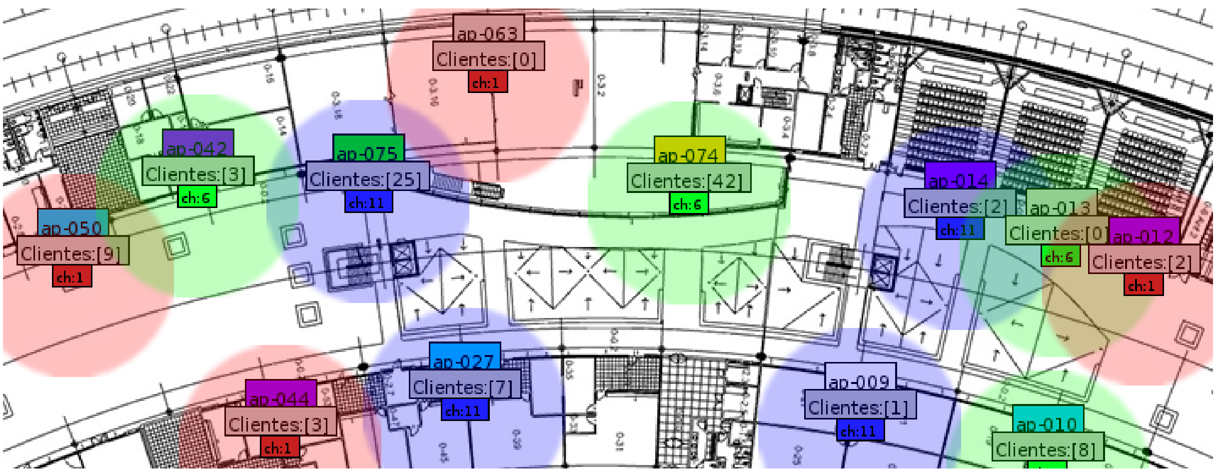


Figure 2.3: Blueprint of the library area at IST-Taguspark with the position of some APs and the number of STAs connected to each of them.

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.

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 could be cheaply modified to support occupancy detection as demonstrated in Figure 2.3. But has the problem of having low accuracy. Thus, BT technology could be used inside the offices, which, again, paired with a smart-phone could provide the needed accuracy. The combination of these two technologies could be a solution for accurate user identification and localization in dense office buildings.

2.4 Human Behavior

The human behavior is composed of habits which are often described as :

"Learned sequences of acts that have become automatic responses to specific cues and are functional in obtaining certain goals or end-states." [44]

These habits occur automatically and sub-consciously. They are beneficial to humans because they free up resources for other activities that can be carried out simultaneously [3]. Many routines that are related to energy consumption such as switching off lights, are presumed to be under habitual control. Thus habits can be further studied in order to better understand their impact on energy consumption.

Studies have shown that the human behavior in fact causes big variations in energy consumption [45, 1, 46, 47, 48]. 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 [3]. This 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. However, just a few behavioral actions have been identified to impact the energy use, leaving a large consumption variance unexplained.

One factor that is thought to have great influence is human motivation. In [49] was studied the effect of motivation in relation to climate change taking into account socio-economic differences. The study concluded that there are energy variations that are not explained by occupant characteristics such as age distribution, level of education or the household size. However, the only significant variation they found based on user characteristics was that 4% more energy was used by families that were least motivated to save energy.

A monetary reward system were studied that may serve as a motivator to conserve energy [50]. The

	RFID (Passive)	**PIR**	**Vision-based**	**Wi-Fi**	**Bluetooth**
Occupant Identification	Yes	No	No	Yes	Yes
Occupant Localization	Yes	No	Yes	Yes	Yes
System Scalability	Medium	Low	Low	High	High
Overall Cost	Very Low	Medium	High	Low	Low
Detection Range	Medium	Small	Big	Big	Small

Table 2.2: Most important characteristics of the occupancy detection technologies

results were very encouraging. All participating households reduced electricity consumption, and in the best case resulted in 12% of reduction in electricity use. This indicates that money could be seen as a strong motivator for reducing energy use [3]. However, the savings decreased as the experiment period progressed, suggesting a short-term effect of rewards. The low effectiveness of measures in reducing energy consumption could be explained by the presence of strong habits [3].

Another experiment based on feedback was used [50], which is often applied to promote energy conservation. Feedback consists of giving occupants information about the building 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 ECI [51] that displayed the electricity use in cents per hour. On average, the group of occupants which had a monitor installed used 12% less electricity than the control group.

This kind of monitors are very common nowadays, usually installed in intelligent houses. For example Cloggy is a Portuguese ECI solutions from ISA Energy[7]. Figure 2.4 represents an example of the user interface of this kind of systems.

A recent field experiment aimed to determine if social influence played a role in the energy consumption behavior of users based on eco-feedback [47]. Eco-feedback is a technology that provides feedback on individual or group behaviors with the goal of reducing environmental impact [52]. In this case the study objective was to maximize the spread of information about conservation measures that users could explore in order to reduce energy consumption across everyone in the system. The idea is that social integration could substantially increase the efficacy of eco-feedback systems, leading to long-term sustained reductions in energy consumptions. The study concluded that social influence in fact impacted the energy consumption behavior of users and also indicated that users were influenced towards reducing their consumption rather than increasing it.

In conclusion to a survey done to UK habitants [3] it was discovered that habit emerges as the most important barrier to changing behavior. Data indicated a relation between the occupant's behavior, their energy consumption and motivation in engaging in energy-saving actions. This link shows the

[7] http://www.isasensing.com/

Figure 2.4: Interface of a ECI used by Cloggy

importance of breaking habits in order to change energy consumptions patterns. Habits are normally difficult to change. Because of this, when energy-efficient incentives are unsuccessful, a better approach that could change the occupant habits is to change the situation [3]. When a context change disturbs an individual's habits, new behavior is more likely to be consciously considered and consequently changed. For example moving house or work place could be considered such a change in context, giving landlords or real estate agencies the opportunity to help the new occupants to engage in energy-savings habits, e.g. by doing a tour of the building discussing its HVAC operation and maintenance.

Studies about building energy conservation often overestimate potential energy savings, because the impact of consumer behavior is not taken into account [45].

For example [1] found that the use of a thermostat for temperature control increased energy use. The study determined a correlation between the presence of a thermostat and the temperature setting during the night. This behavior could be explained by the fact that in buildings equipped with a thermostat occupants are more aware of the interior temperature and therefore tend to turn it on more often than those without a thermostat.

Another study [53] found that for households living in dwellings where the energy bill is paid collectively, the average indoor temperature was higher by 2 $^{\circ}C$, which also indicates a strong correlation to human behavior.

Consumer behavior as we have seen may significantly influence the level of energy demand by means of choosing the temperature levels, ventilation rates, thermostat settings and others. These facts lead to the conclusion that energy savings achieved in practice due to energy conservation measures will be lower that those calculated in engineering conservation studies [45].

[1, 45] found that building regulations on energy use have been very important in reducing energy consumptions in new buildings. Because of this total energy use associated with buildings proprieties is decreasing, making the role of the occupant even more important.

[46] takes a step further and includes human behavior as a variable in building performance simulations. The study showed that user behavior was one of the most important parameters to influence the end results of the building performance simulation. The author concludes that the simple approach used nowadays for designing buildings using simulation, are inadequate for buildings that have known close interaction of the user with the building. As a result, classification of the user behavior was done in order categorize and optimize the overall building performance in the simulation scenario.

Chapter 3

Architecture

This chapter describes the architecture of PerOMAS, a platform for personal office management and automation designed to offer comfort to every user and reduce the overall building energy use with minimum intervention. The platform will also be used by the academic community to develop and validate alternative algorithms that maximize user comfort and/or building energy efficiency.

This chapter is divided in four sections: Section 3.1 starts by defining the requirements of the system that will lead the design of our architecture. In Section 3.2 the architecture of the system is described in depth. Finally, section 3.3 and 3.4 present a brief overview of the hardware and software architectures.

3.1 System Requirements

Our system targets buildings with an increased number of individual offices which is the case of the research departments at IST campus Taguspark. Subsections 3.1.1 and 3.1.2 describe and analyze a survey done to a subset of occupants at this location. This helped to characterize them and establish a baseline of their behavior and comfort needs.

In order to choose the appropriate architecture in terms of performance, functionality, extensibility and comfort, the system must satisfy the following set of requirements:

- **Scalable** - Using IST - Taguspark as an example building we are looking at roughly 700 equipped offices. With such a large number of offices, the system must be very scalable and offer rapid deployment of new nodes. Cable wiring introduce costs and as a consequence it must be kept to a minimum.

- **Isolation** - The control and automation of the offices must be independent and work regardless the state of the rest of the system.

- **User-aware** - It must be possible to identify the user location with medium/low precision inside the building and with high certainty if the occupant is in the office.

- **Load-aware** - The system must be able to adjust subsystems/services such as HVAC and lighting in an energy efficient manner that satisfies the needed capacity at the office, department and building levels.

- **Multiuser** - It must be capable of finding and maintaining multiple user preferences based on their interaction with the system, which also needs to be minimal. In case multiple occupants with conflicting preferences find themselves in the same office, the system must be capable in adjusting the ambient settings in order to minimize their discomfort.
- **Evolving** - The system must also be auto-adjustable to weather change and behavioral changes.
- **User-friendly** - The system must allow individual remote configuration of each of the components of the system via an easily available tool such as a web browser, that could even be used from a smart-phone. It must also support user configurable actions to be triggered by a scheduler or sensor values.
- **Flexible** - It must also be easily programmed to enforce multiple energy efficiency algorithms.

3.1.1 Survey Description

A survey was organized to characterize the comfort preferences of the users at IST-Taguspark. The initial data was collected from December 25th 2013 until January 5th 2014 via a Web-based form. The main distribution vector for the link to the form was via email to teachers, staff and students of the IST-Taguspark building. Distribution was also done via social networks but only to restricted groups of users that are present at IST-Taguspark.

The form contained 20 items with multiple response formats. The questionnaire started with a characterization of the user and then assessed behavioral intentions and practices relating to energy consumption at IST-Taguspark. Other questions were related to user comfort in situations where multiple users share an office. There was also questions regarding the number of mobile devices per user and how many of them were equipped with Wi-Fi and/or BT technology. The complete survey, in Portuguese, is available in appendix A.

3.1.2 Survey Analysis

All data were based on the replies from 69 users. The survey showed that all the users have at least one mobile equipment with an average of 2.1 devices/person, 98% of which were equipped with Wi-Fi and 96% with BT technology. Of all the users, 47% have access to an office and 51% of those share the office with at least one other person and an average of 3.87 other occupants. Also 37% of the users who share a office with other users stated to have conflicted preferences for HVAC settings that cause them discomfort. Regarding energy related user habits, 72% of all users reported to only shutting down the HVAC system sometimes, when leaving the office. Likewise 43% said the same about the lighting in the office. When asked about the preferred temperature, in spite of big variations, the average temperatures were $22.4\,^{\circ}\mathrm{C}$ during winter and $19.9\,^{\circ}\mathrm{C}$ during the summer. These values could be used as a starting point for the user preferences calibration.

These values also show that the users don't know what they want. Usually, during summer the occupants use less clothes and as a result they withstand higher temperatures. During winter, the occupants tend to use lower temperatures because of the extra clothes they wear.

3.2 Architecture Overview

To ensure the scalability of the system, a hierarchical architecture, shown in Figure 3.1, was developed that better adapts to the required application. It follows a centralized hierarchical architecture because of the way the building services are installed, such as the HVAC system or electricity. In a building, these services always merge at a single point where they can be measured and controlled, and as such, our model will follow the same principle.

The proposed system consists of three main components: the assistant, the gateway and the core. The assistant is responsible for the room automation systems and to collect user data via sensors and user inputs. The gateway is responsible for collecting data from the assistants and to take actions based on the collected data or to relay it to gateways higher up in the hierarchy. 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 will perform tasks relevant to the entire building(s).

As represented in Figure 3.1, every assistant has two modes: either it connects to a single gateway or it works without the presence of any gateway. The same way, a gateway can connect to one or more assistants and can also connect to a higher level gateway. The model enables an adaptable number of hierarchical levels in a tree like format.

In the next sections we will detail the three main components of the system and briefly explain the proposed instantiation for the IST-Taguspark campus.

3.2.1 The Assistant

The assistant, which will be present in every office, is the most important component of the system. It will be responsible for collecting data from the attached sensors and for controlling the HVAC and electrical systems of the office. It will feature an user interface for easy configuration of the assistant, important data display and user feedback input. Relevant data will be relayed to a gateway using the publish-subscribe model. Using this model, the gateway can announce its interest in particular data

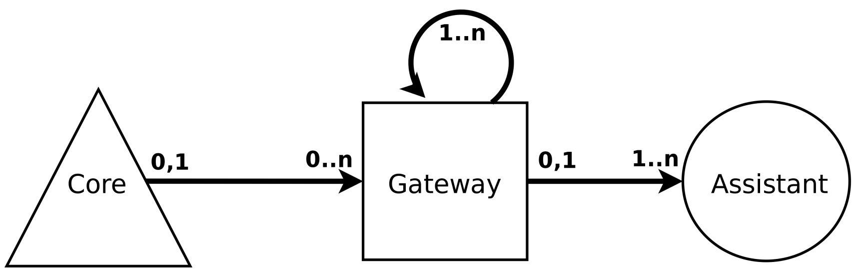


Figure 3.1: Architecture of the system

to the assistants. Then, when any of this information changes, the assistant will immediately send the updated state to the gateway.

Assistant communication with the gateway will be based on a wireless mesh network. This approach speeds up the deployment of new nodes and also assures the modular scalability of the network. This also avoids the need to install dedicated communication wiring between the assistants and, as a consequence, lowers the installation cost. As an example, Figure 3.2 shows an approximation of the offices' layout in a department and a possible routing path created between the nodes. Using a mesh network means that in the case where no direct communication with the gateway is possible, messages can still be relayed by another node. For example, in Figure 3.2 it is possible to note that node *A7* is not in range of the gateway (*G11*), but it can still forward messages through any other node in its communication radius, thus reaching its destination.

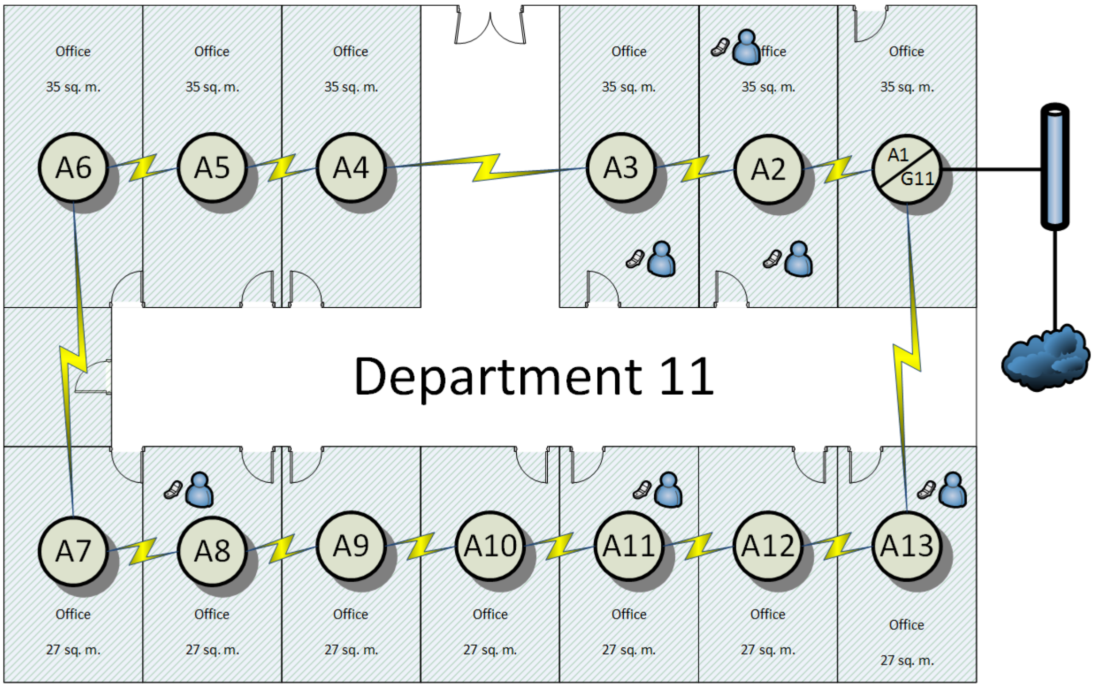


Figure 3.2: An example of RF communication paths within a department

3.2.2 The Gateway

The gateway module is responsible for collecting relevant information in strategical zones that can be mainly used to trigger energy efficiency inducing actions. For example adjusting the duty cycle of any system/service such as an energy demanding equipment. The triggered actions could be as simple as turning on a Light-Emitting Diode (LED) or as complex as calling the nearest fire department with accurate information of the building and office on fire.

The gateway will also be responsible for storing a permanent record of the collected data. Analysis of this information could 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 the centralized cooling system.

Some cooling systems use a coolant that is refrigerated 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 usage patterns.

Depending on the building complexity, different number of hierarchical levels could be projected, following a strategical distribution such as zones, building levels or other energy demanding resources. Every gateway will also aggregate the data and only pass summary information to upper level gateways lowering data traffic. This filtering is very useful in high density buildings as it decreases the load on upper gateways.

3.2.3 The Core

The Core component will have all the functionalities of the gateway with a single difference, it does not need to relay data to gateways in upper hierarchy layers. With this in mind, this node will be responsible for services that are common to the whole building.

It is also possible to use this architecture in small buildings such as residential houses that have a limited number of systems/services. In this case the intermediate gateway nodes could be unnecessary and the system could operate on a single level, i.e. the core being directly connected to the assistants without the need for relaying gateways. Moreover, in this case all the architecture could run on top of the same hardware, performing all the functions.

3.3 Hardware Architecture

The hardware for the construction of the nodes must follow a set of guidelines in order to assure extensibility, easy installation and enforce the open standards of the project. This will help to keep the devices updated and allows for a modular architecture since the peripherals needed for each type of node may be different. For example, each Assistant will feature sensors for gathering ambient and energy consumption data which might not be necessary by the Gateway nodes. Instead, a Gateway may need more actuators or other type of peripheral. Figure 3.3 represents the modularity of a Node and the main communication protocols that could be used between the main board and its peripherals.

3.3.1 Communication Protocols

Normally, off-the-shelf electronic parts such as sensors and actuators are controlled using popular communication protocols such as serial, Inter-Integrated Circuit (I2C) [54], Serial Peripheral Interface (SPI) [55] or simply by using the General Purpose Input/Output (GPIO) pins. In some cases, sensors with analog output, like current sensors, may need an ADCs. I2C and SPI are master/slave protocols and because of that, a single interface could be used to connect to hundreds of other devices. On the other hand, we may need to have multiple GPIO pins for connecting simple devices such as buttons and actuators. Via the I2C or SPI buses, GPIO expanders, shown in Figure 3.3, may provide the needed extra pins to the main board.

3.3.2 Connectivity

Depending on the type of node, the device must also have a wired and/or wireless interfaces. An Assistant node may only have a wireless interface for connecting to the Gateways, but the least one Assistant must have both because it also acts as a bridge between the two media. Wireless standards with mesh capabilities are preferred because they permit each node to act as an relay and expand the total network range, lowering the deployment cost. Nowadays, a wide range of 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 3.3

3.3.3 Information Input and Data Feedback

When the device is fully configured, the user may not need to interact with it. But sometimes a system override may be needed, e.g. in case the user forgot the ID token or for the configuration of a new user. For this purpose, the device will need to have an input and feedback interface.

Section 2.4 shows the positive effect of feedback from an ECI on the user energy consumption behavior. The interface of the device will also function as an ECI in order to observe similar results.

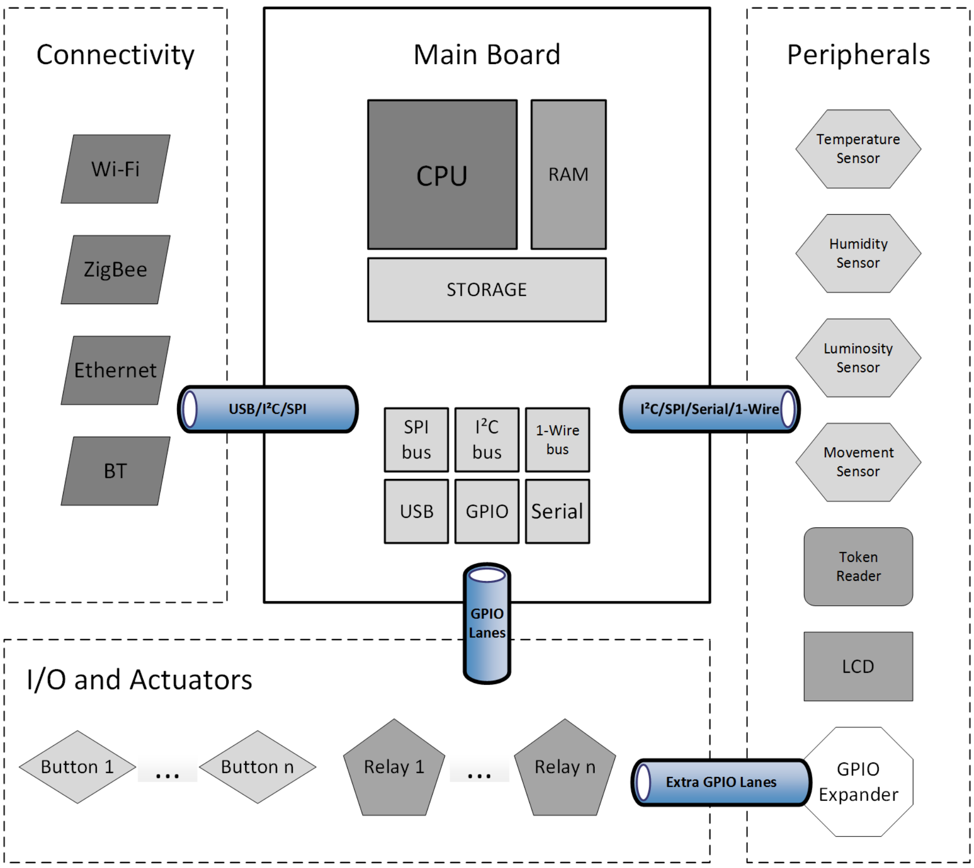


Figure 3.3: The main communication protocols used between the main board and the peripherals

3.4 Software Architecture

In order to support the modularity of the hardware, the configuration of the software and the application design must also be modular. With this in mind, the software will follow a layered architecture which will accommodate the use of multi-vendor peripherals. Figure 3.4 presents the main components of the software architecture and categorizes them in a set of sub-layers.

The presented architecture is designed to run on all types of nodes, would it be an Assistant, a Gateway or the Core. The main difference between an Assistant and a Gateway would be the connected sensors and actuators. A node could even function as both: as an Assistant and Gateway at the same time by running two instances of the application in different modes.

The following subsections explain in detail each of the layers presented in Figure 3.4.

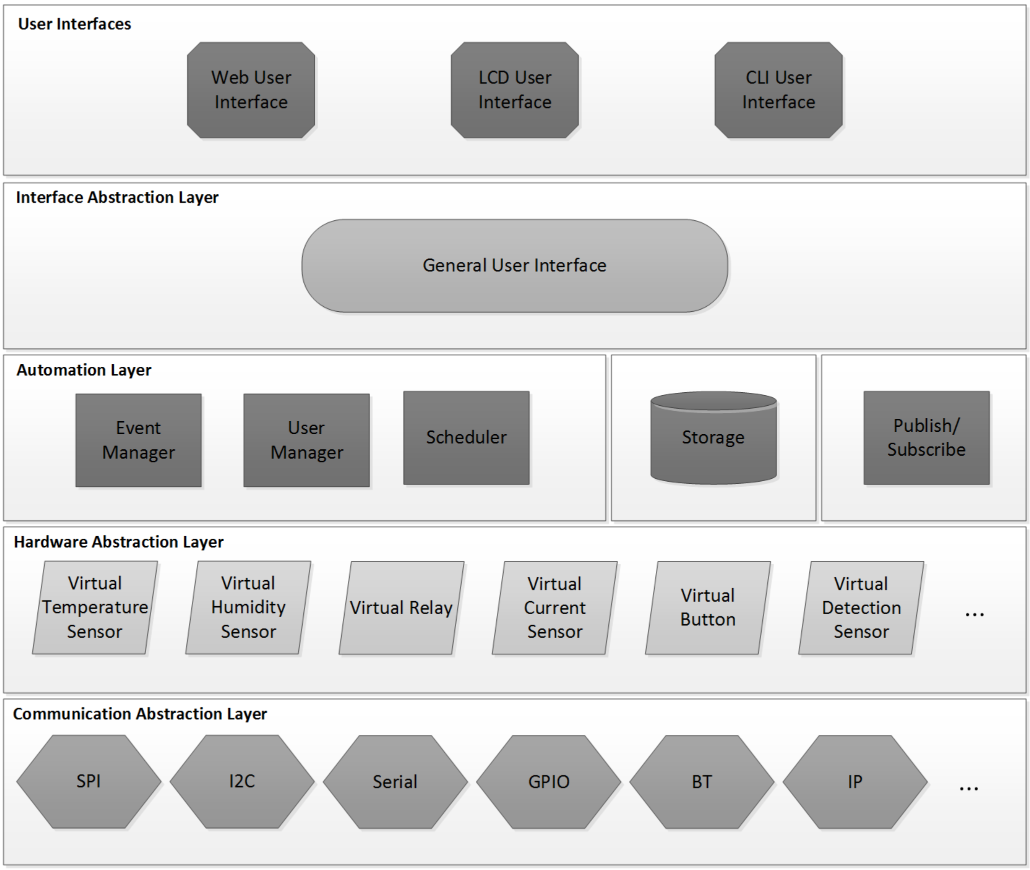


Figure 3.4: Abstraction Layers of the Application

3.4.1 Communication abstraction layer

This layer includes a set of libraries that abstracts the communication protocols from the rest of the application. They will offer simple primitives similar to *Read* and *Write*, abstracting the complexity of each protocol such as sessions, communication errors and retries. These could be hardware specific protocols such as I2C and SPI or tunnels to remote systems based on IP. An example could be an HVAC system managed by a remote BACnet or LonWorks system that receives Application Programming

Interface (API) specific commands over IP.

3.4.2 Hardware abstraction layer

The Hardware abstraction layer will abstract 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 and can be a *ReadOnly* device or a *Readable* and *Writable* device.

The virtual device knows what communication library it should use in order to communicate with the hardware. The internal state is updated using a polling mechanism to read the new values. This assures that the upper layers will instantly access updated values without having to wait for the communication to occur, at a cost of slightly outdated values. The polling interval will mostly depend on the time it takes to read the values and the available bandwidth and resources. For example a minimum of one sample per second for the energy consumption measurements and one sample every fives second for the ambient sensors will suffice. In case of the sensors with high refresh rate, such as the example of the current sensor which makes 120 measurements per second, the average of these 120 measurements will be used.

Writable virtual devices such as actuators will also update the state of the physical devices upon request from the upper layers. The change will then be verified using a read command to ensure the change of the state.

3.4.3 Automation layer

The automation layer is composed from a set of modules each responsible for distinct tasks:

The Storage module is used as a persistent database to store information such as:

- System configuration and parameters
- Sensor data readings in chronological order
- Registered users and their preferences
- System-wide and User defined rules, events and actions
- Logs of: triggered events, user actions, debug information

The Event Manager module is responsible for adjusting the system state depending on the occurring events. Every events are composed of set of rules and a set of actions. In order to trigger the actions all the rules must be satisfied. A rule could be as simple as comparing a sensor value to a constant but may also be sophisticated. For example, a rule may contain complex algorithms to determine if the actual temperature satisfies all the present users of the office, based on historical readings of sensor values and the behavior of the occupants.

There are system-wide events and user defined events. The system-wide events are configured by the system administrators to enforce energy efficiency and user comfort at the building scale. User define events are configured by the occupants for their offices, offering them a high level of automation and independence.

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 may also enforce access restrictions to certain features that only users with administrator privileges have access to.

The Publish/Subscribe modules are used to communicate between nodes. Normally the Assistants only use the publish module to send information to separate communication channels for each sensor value, event or other important information. On the other hand the Gateways has both, the subscribe module and the publisher module. The subscribe module is used for listening on the different channels and combing the received values that after processing could be sent to higher level Gateways using the publisher module.

The Scheduler is responsible for executing repetitive tasks at regular time intervals or at fixed moments in time. It is used to trigger pre-programmed external tasks such as turning on the heating system at eight in the morning. It is also used to trigger regular task, internal to the program itself, such as logging data from each sensor at variable time intervals for posterior analysis or sending it to a Gateway.

3.4.4 Interface abstraction layer

Since the system will support more than one user interface, a synchronized state across all the interfaces is needed. A interface abstraction layer will be used to deal with this problem. It will contain a collection of functions common to all User Interfaces (UIs) and let them only focus on the presentation of the information avoiding conflicts between interfaces.

3.4.5 User interfaces

The WEB interface is the main UI for the control of the nodes. In case of the Assistant node it will offer:

- Real-time ambient sensors readings and their evolution over time in form of graphical charts.
- Manual control of the HVAC and lighting systems.
- User registration, ID token association and ambient preference configuration.
- Creation of user automation rules, actions and events.

Every Gateway and the Core node will also present the above information but in relation to the building zone they are responsible for, combining the values from the assistants. Their automation rules and events will be triggered by the information from their assistants or other gateways and applied to the service/s they are bound to.

The LCD interface mainly serves as an ECI for the occupants. Using this UI, they also have the ability to manually override the system. They would be capable to perform the normal tasks of the devices that the new hardware replaced such as the lighting switches and the thermostat control. More complex tasks would also be possible. For example when a user is not in possession of the ID token and willing to trigger the automation process.

The interface will have multi-user support, used to distinguish between occupants. This is useful when giving personal feedback to the system using this UI.

The CLI interface is used for administrative purposes. It will offer low-level access to the internals of the main application. It will allow executing all the possible commands offered by the other UIs in a command line interface.

3.5 Deployment at IST-Taguspark

In order to ensure the scalability of the system at IST - Taguspark, the hierarchical model from Section 3.2 was applied to the main building obtaining the system architecture shown in Figure 3.5.

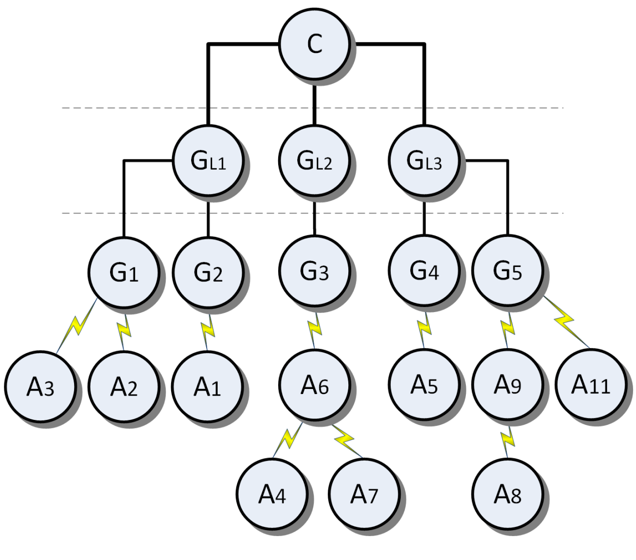


Figure 3.5: Proposed architecture for IST-Taguspark

The HVAC system at IST-Taguspark is composed of eighteen heating units distributed between the departments and a central cooling unit which serves the entire building. Thus, the energy demand for cooling could be calculated and controlled by taking into account all the data of the building, further increasing energy efficiency. The same process could be applied to the heating units, by mapping the departments to a certain heating unit. The control of these devices is very important because they contribute significantly to the energy use of a building.

Observing the architecture presented in Figure 3.5, it is possible to observe that there is a Core node, denominated *C*, a series of top level Gateways represented as G_{L1}, G_{L2}, G_{L3}, a series of lower level Gateways represented as *Gx* and a series of Assistants (*Ax*) connected to these gateways.

The Core node collects information relevant to the entire campus, such as building occupancy, energy consumption, heating and/or cooling demands. It will also store a permanent record of these measurements for further analysis of the values that could demonstrate usage patterns. This is useful for systems that have big inertia, which is the case of the cooling system.

On the other hand, the inertia of the heating system is much lower and can be adjusted within one hour. As such a prediction model is not as necessary, only the department's occupancy and heating demand is needed in order to adjust them.

Each node represented as *Gx* will be responsible for collecting the statistics of the departments and passing them up the management chain. Apart from that, they will also perform actions within the department such as controlling the department's corridor lighting. For example the corridor lighting will be managed interacting with the existing LonWorks installation of the campus, using the presence of people in the department as an indicator.

Finally, the nodes *Ax* will gather information about their individual office, and perform actions predefined in the occupants profile, such as ambient preferences, lights configurations and power socket configuration.

3.6 Summary

In this chapter the solution to the hardware and software architectures of the system were presented and detailed. PerOMAS was designed to cope with a set of requirements that were defined in Section 3.1.

These set of requirements conditioned the design choices of the hardware architecture, creating a distributed scalable system composed of three kinds of nodes: Assistants, Gateways and the Core. A layered software architecture was also defined. It will allow the creation a software application with modular support of hardware and intelligent automation algorithms.

This chapter ends with a definition of a possible structure for a large deployment at IST's Taguspark campus.

In Chapter 4, the implementation of the hardware and software architecture is detailed in depth.

Chapter 4

Implementation

This chapter addresses the main decisions taken in order to implement the hardware and software architectures presented in Chapter 3.

This chapter is divided in three main sections. In Section 4.1 the detailed hardware architecture is described. Each of its subsection shows the decisions taken in the selection of the components.

Section 4.2 describes the implementation of the software architecture. This section is composed of several subsections that detail the software configuration and explains the developed code.

Finally, Section 3.5 details the deployment of the system in a set of offices at IST - Taguspark.

4.1 Hardware Architecture

4.1.1 Single Board Computer

Following the guidelines of Section 3.3, a small controller board capable of supporting a range of protocols must be chosen to be used as the base for the development of the nodes.

Multiple boards were taken into consideration with special attention to the connectivity ports, price and computational speed. These factors are very important since they will define the modularity and flexibility of the nodes.

Table 4.1 shows the main differences between the most popular Single Board Computers (SBCs) and micro-controllers existent on the market that are relevant for our purpose.

The Arduino Uno Single-board Micro-controller is a very popular device but does not fit our needs since it is very limited in terms of storage and processing power which complicates the development of the software architecture described in Section 3.4.

Every board supports a variety of different Operating Systems (OSs). This plays a major role since it will define the base for the software development and the tools available in each platform.

As described in Section 3.3 the board has to have a collection of I/O ports that include GPIO, I2C, SPI and USB support. The Pandaboard ES SBC, other than the high cost, lacks support of the SPI protocol that is used in a variety of sensors and peripherals. This leaves: the Raspberry Pi [1], the Cubieboard

[1] http://www.raspberrypi.org/

and the Beaglebone Black eligible to be used for the construction of the boards. From the three, the Raspberry Pi Model B SBC is the smallest, the cheapest, has two USB ports and it is available in large quantities at local stores. It also has great support from sensor and peripheral vendors in term of device drivers which aids the development of the software. Because of these aspects, the Raspberry PI Model B shown in Figure 4.1 will be used.

Name	Raspberry Pi Model B	Beaglebone Black	Pandaboard ES	Cubieboard	Arduino Uno
Type	Single-board Computer	Single-board Computer	Single-board Computer	Single-board Computer	Single-board Microcontroller
CPU	ARM11	ARM Cortex-A8	ARM Cortex-A9 DualCore	ARM Cortex-A8	ATmega328
CPU Speed	700 MHz	1 GHz	1.2 GHz	1 GHz	16 MHz
RAM	512 MB	512 MB	1 GB	1 GB	2 KB
Flash	(SD Card)	2 GB	(SD Card)	4 GB	32 KB
GPIO	26	65	56	96	14
ADC	-	7 (12-bit)	-	-	6 (10-bit)
USB	2	1	3	2	-
Ethernet	10/100	10/100	10/100	10/100	-
I2C	Yes	Yes	Yes	Yes	Yes
SPI	Yes	Yes	No	Yes	Yes
OS Support	Various Linux, BSD, RISC OS	Various Linux, BSD, Symbian, Windows CE	Linux/Ubuntu	Various Linux	-
Size (mm)	86 x 54	87 x 54	114.3 x 101.6	100 x 60	68.6 x 53.3
Cost	$35	$45	$162	$49	$27

Table 4.1: The main differences between the most popular SBCs and single-board micro-controllers

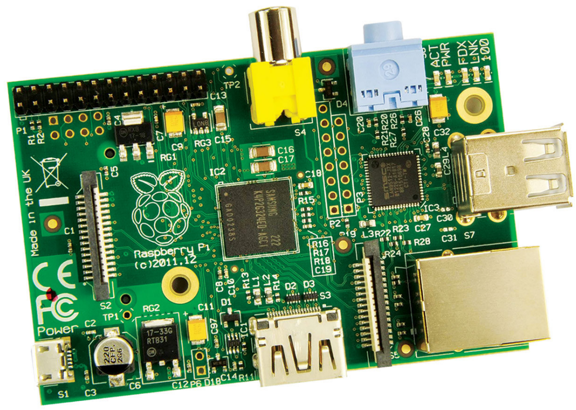


Figure 4.1: Raspberry Pi Model B

4.1.2 Wireless and Wired Communication

As stated previously in Section 3.3.2, a wired and/or wireless module must be used for communication between nodes. In order to adapt the system to a bigger area and ensure its extendibility, a mesh network was used to interconnect the assistants and the gateway nodes. The gateways and the core node will also require an Ethernet connection which the Raspberry Pi Model B SBC already has included.

The Ethernet interface is necessary because the gateways may be located far away from each other or in locations where wireless propagation is poor.

For the mesh network to be created, a range of radio modules exist, but since the IEEE 802.15.4 (ZigBee) has a maximum data rate of 250 kbit/s it makes it unusable for transmitting data rich web content as intended for the WEB UI described in Section 3.4. This leaves the IEEE 802.11 (Wi-Fi) interface to be used in conjunction with B.A.T.M.A.N or IEEE 802.11s to form a WMN.

The used wireless card, shown in Figure 4.2, is an SMC EZ Connect^{TM}N 150 Mbps N Wireless USB Adapter Model: SMCWUSBS-N3. This card was chosen because of its Ralink RT2870 chipset, as it has great driver support for the creation of WMN using the B.A.T.M.A.N open source multi-hop routing protocol.

Figure 4.2: SMC Wireless Card Model: SMCUSBS-N3

4.1.3 Sensors

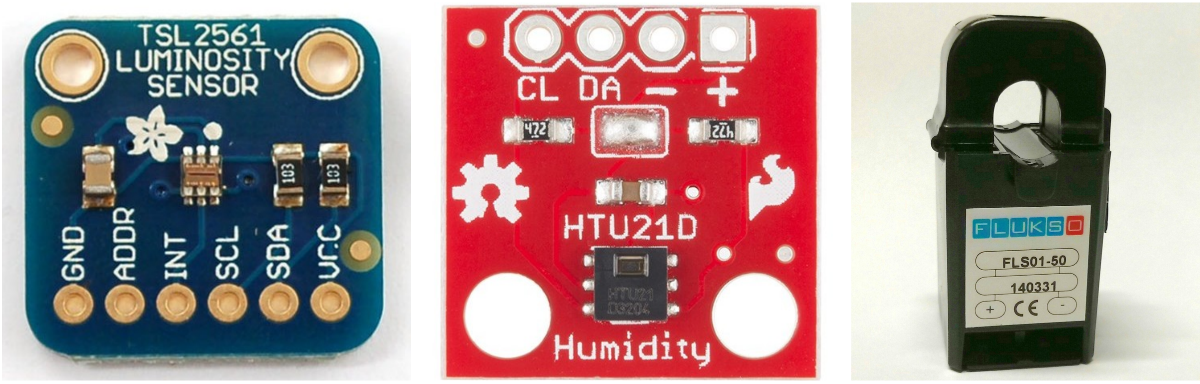
Our system will feature sensors capable of measuring the office ambient characteristics such as temperature, humidity, luminous intensity and energy consumption. Analog sensors were avoided because they need calibration and don't always have the best precision, also they require an ADC for the reading of the values. Unfortunately, we couldn't find an digital current sensor and had to use an ADC for the reading of the energy consumption values.

Table 4.2 and Figure 4.3 show the specific models used and how they connect to the main board.

<table>
<tr><th>Sensor Type</th><th>Vendor</th><th>Model</th><th>Connected via</th></tr>
<tr><td>Luminosity</td><td>Adafruit</td><td>TSL2561</td><td>I2C</td></tr>
<tr><td>Temperature</td><td rowspan="2">Sparkfun</td><td rowspan="2">HTU21D</td><td rowspan="2">I2C</td></tr>
<tr><td>Humidity</td></tr>
<tr><td>Current</td><td>Flukso</td><td>FLS01-50</td><td>ADC</td></tr>
</table>

Table 4.2: Details of the sensors used

TSL2561 is a very popular inexpensive light sensor with very good device driver support. Contrary to photo-resistors and photo-diodes, it incorporates both infrared and visible light sensors to better approximate the response of the human eye. It has dynamic range sensitivity that ranges from 0.1 to 40.000 Lux and connects to the main board via the I2C bus. The sensor has an operating temperature range



(a) TSL2561: Luminosity sensor (b) HTU21D: Temperature/Humidity sensor (c) FLS01-50: Current sensor

Figure 4.3: Sensors used for measuring ambient characteristics and energy consumption

from $-30°C$ to $-80°C$. It will help to provide information about the abundance of light in every room which later will be used to control the lighting configuration in the room.

HTU21D is a low-cost, low-power, highly accurate, digital relative humidity and temperature sensor that uses the I2C bus. The temperature sensor has a typical accuracy of $\pm 0.3°C$ with a resolution of 14-bits and an operating range from $-40°C$ to $+125°C$. It also contains a humidity sensor with a typical accuracy of $\pm$ 2%, resolution of 12-bits and an operating range from 0% to 100%. These sensors will provide information about the thermal comfort in every room, which is the main reference for the control of the HVAC system.

FLS01-50 is split core current clamp for current measurement that functions on the principle of induction. Depending on the number of coils in the clamp, it will produce an analog voltage output which an ADC will translate into digital values. This model has a maximum rated measurement current of 50 amps which is sufficient for residential or office loads. For measurement of greater loads, such as buildings zones, models for up to 500 amps are available. It will be mainly used to build an ECI, as described in Section 2.4, to provide energy consumption feedback to the users.

Since the Raspberry Pi doesn't have an ADC, a separate breakout board, the ADS1115 shown in Figure 4.4, will be used.

ADS1115 is a high precision quad-channel 16-bit ADC with an integrated Programmable-Gain Amplifier (PGA) produced by Adafruit [2]. The ASD1115 can be configured as four single-ended input channels, or two differential channels. It has a very low current consumption of only 150μA, provides up to 860 samples/seconds and uses the I2C protocol.

[2] http://www.adafruit.com/

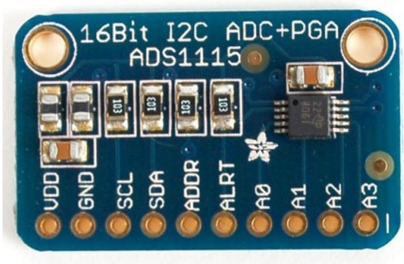
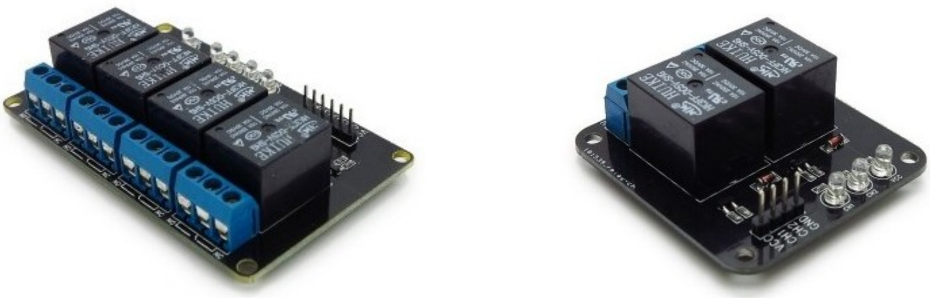


Figure 4.4: ADS1115: A 16-bit ADC with PGA

4.1.4 Actuators

Relays are used to control the main energy demanding devices such as lights, Alternating Current (AC) power sockets and the HVAC system. The HVAC system, previously controlled by a thermostat, besides the Heating/Cooling functionality, has the particularity of having three levels of ventilation. Thus, it will need to be controlled with at least four Single Pole Double Throw (SPDT) relays. Two additional relays will be used to control the two light zones in every office, which adds up to a set of six SPDT relays that are controlled via the GPIO interface. Figure 4.5 shows the two relays modules that were used. In order not to damage the GPIO circuitry, each module contains a number of transistors to drive the coils, which prevents current from surpassing the recommended 3mA from the GPIO pins. Each relay works from 5VDC and is rated for up to 10 amps at 250 VAC. The first module (4 relay) is used to control the HVAC and the second module controls the lighting zones.



(a) A four relay module

(b) A two relay module

Figure 4.5: Relays used to control the HVAC and lighting

4.1.5 User Detection

In the Office

In order to increase the energy efficiency in every office, the automation system will trigger rules based on the occupancy of the office. The detection and identification of users will be performed based on their cellphone BT presence in the office, since the survey done beforehand in Section 3.1.2 showed that 96% of the occupants already had a BT capable device. This decision significantly lowers the cost of the system since the cellphones are used as an identification token and are usually always close to the user. For the users that don't possess a BT device, a Bluetooth Low Energy (BLE) Token could be used instead. An example of such device is the Qualcomm's Gimbal proximity sensor Series 10 [3] shown in Figure 4.6(a). These 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 a BT 4.0 capable USB dongle, shown in Figure 4.6(b), either of the beacons can be captured and an approximate distance of the emitter determined, based on beacon's Signal-to-Noise Ratio (SNR).

(a) Qualcomm's Gimbal Proxmity Beacon

(b) Bluetooth 4.0 Adapter

Figure 4.6: Bluetooth Low Energy capable emitter and detector

Figure 4.6(b) shows the used LM506 BT 4.0 Dual-Mode SMART-Ready (BLE) USB Adapter. Since it is backwards compatible, it is capable to communicate with both traditional BT Classic 2.0, 2.1 and 3.0 standards along with the new BLE standard. It is a Class 1 adapter that can reach a maximum distance of 110 meters in open space, which is more than enough for the intended application.

In the Building

In order to detect the user presence in the building, the Wi-Fi DS of the building is used. Using cell based positioning, we can determine, without the need of any additional equipment, an approximate position of a device associated to an AP. This information is extracted using SNMP calls to the APs.

4.1.6 Data Input and Feedback

As described in Section 3.3.3, a system override may be needed in some situations. For example: when the occupant forgot the ID token, when registering a new user or simply to control the lighting and give important information to the user as an ECI.

For this purpose besides the WEB UI a second, physical, UI is needed.

Two types of displays with different input methods were tested: first a RGB 16×2 Character LCD with five push-down buttons connected via the I2C bus, shown in Figure 4.7(a), and secondly a 2.8 inch color Thin-film Transistor (TFT) LCD with resistive touch-screen surface connected through the SPI bus.

Table 4.3 presents the main differences between the two peripherals. In spite of the PITFT having a more complex configuration, being more expensive than the 16×2 LCD and requiring more work to design the UI, it will simplify the user interaction with the system by means of using a more user-friendly graphical UI design, thus lowering the interaction time.

[3] http://www.gimbal.com/

(a) RGB 16x2 LCD with Keypad

(b) PiTFT: 2.8” TFT with Touchscreen

Figure 4.7: The two types of displays with different input methods were tested

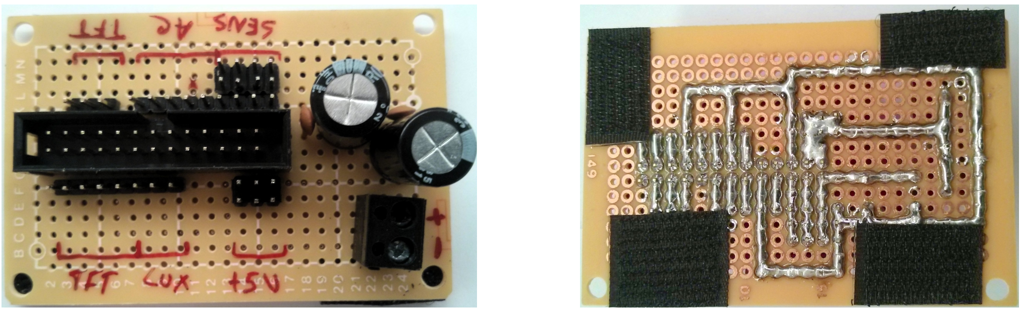
Model	Vendor	Type	Resolution	Input Method	Connected via	Cost
16x2 RGB Positive LCD	Adafruit	LCD	16x2 Characters	Push-Buttons	I2C	$24.95
PiTFT		TFT LCD	320x240 Pixels	Touch-Screen	SPI	$34.95

Table 4.3: Main differences between the PITFT and the 16x2 RGB LCD

4.1.7 Major Problems and their Solution

A major problem with hardware is that hardware fails and this thesis was no exception. The biggest problems are the ones that take time to occur and because of that hard to replicate and fix. Sometimes lower cost hardware cause more problems than expected, one of such cases was the popular temperature and humidity sensor used in the first prototype, the DHT22. The problem with the DHT22 was that it didn’t use the official Dallas one-wire protocol and some workaround was needed to make it work on the Raspberry Pi. But the code was not stable which caused the sensor to freeze after a random number of hours. The sensor caused too much trouble and was replaced by the before-mentioned HTU21D that uses the I2C protocol.

Some problems only occur during the system integration and field testing. One thing is to test the components individually, which behave normally, another is to see them interfere causing energy consumption spikes, which in our case was the fault of the coil based relays and their high energy demand. For this purpose and in order to ease the installation of the sensors, a power distribution board, showed in Figure 4.8, was developed. The Raspbery Pi has a 1.1 A polyfuse on the microUSB input port, making it responsible for many of the components being under-powered. The board surpasses this power delivery limitation by bypassing this fuse entirely. Instead of powering the components through the Raspberry Pi, they are directly powered through the power board. A 26-pin ribbon cable provides the connection between the power board and the Raspberry Pi, it supplies power to the main board and bridges the connectivity pins to the power board where the rest of the components are connected, except the USB dongles which are directly connected to the Raspberry Pi. The board also has a 3300 μF and a 100 nF capacitors for each of the 5 Volt and the 3.3 Volt rails to smooth the power delivery and diminish ripple.



(a) Front (b) Back

Figure 4.8: Developed connection and power board

4.1.8 Summary

The final iteration of the hardware architecture is resumed in Figure 4.9 which shows the connection protocols between the Raspberry Pi SBC and the sensors, actuators and peripherals.

Figure 4.10 shows a close-up preview of the internals of an Assistant node installed in one of the offices. Since this is a prototype node, it's size is quite big for the intended application but could be much smaller if integrated in a single SBC. Every node is worth around 150 € in parts. Its mass production would lower the production costs, making it more affordable and cost effective.

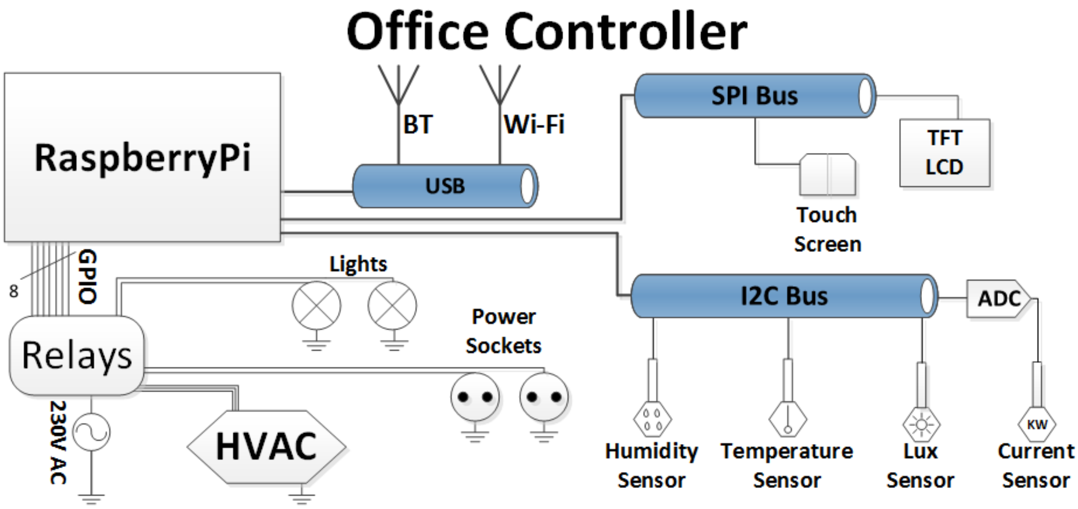


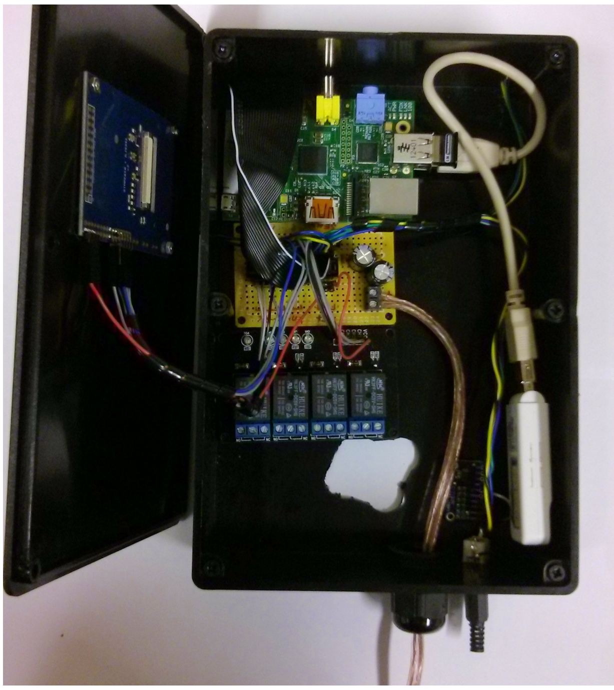
Figure 4.9: Electrical wiring of the sensors, actuators and peripherals

4.2 Software Architecture

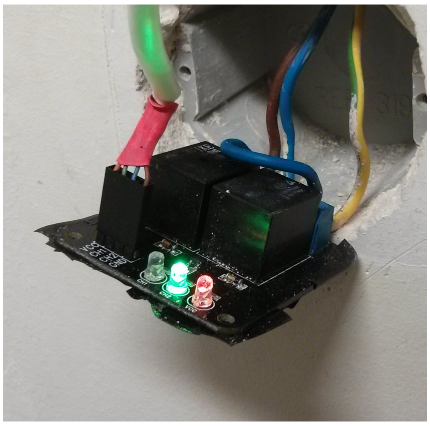
4.2.1 OS

As mentioned in Section 4.1.1 when the main board was being elected, the OS plays a major role in the selection process of the SBC. It is as important as the hardware itself because it defines the platform used to access the hardware. If the OS is not powerful enough it may cause significant delays in the

(a) The front of an installed Assistant node



(b) The interior of a non mounted Assistant node



(c) Relay connected to the Assistant

Figure 4.10: Assistant node

development phase and limit the potential of the hardware.

The chosen OS is a flavor of the Debian [4] Linux distribution, Raspbian [5]. Raspbian is very stable and especially optimized to run on the Raspberry Pi SBC. It has repositories with pre-compiled software for easy installation on the Raspberry Pi that speeds up the time needed to start developing on the platform. Because it is a widely used platform, it has great support from the community.

4.2.2 Programming Languages

The Python [6] programming language was chosen for the development of the main application. It is a fast, powerful, cross-platform and widely used programming language supported by a vast majority of

[4]https://www.debian.org/
[5]http://www.raspbian.org/
[6]https://www.python.org/

OSs and it is capable of preforming well in resource constrained systems. In particular, version 2.7 of the Python language was selected because it is the most widely used by the community and has a large quantity of open-source libraries. It is very popular because it offers multiple programming paradigms and also because the development of new application is very fast, the produced code is very easy to read and understand. On the other hand some sensors from Adafruit mentioned in Section 4.1.3 already supplied example code written in Python.

The main application also makes use of other languages such as Hyper Text Markup Language (HTML) and JavaScript for the creation of World Wide Web (WEB) pages templates. Structured Query Language (SQL) is used for accessing and storing application variables and configurations in a local MySQL [7] database instance. Bash [8] start-up scripts are also used for the configuration of the mesh network and auto-installation of packages before the execution of the main application.

4.2.3 Auxiliary Programs and Libraries

In order to ease the development of the application, a set of auxiliary programs and libraries were used.

For distributing the messages between nodes, the open source Mosquitto[9] message broker was used. It uses the lightweight Message Queue Telemetry Transport (MQTT) protocol which is designed for Machine-to-Machine (M2M) communications in a publish/subscribe model. A Mosquitto broker will be installed per building zone, in every Gateway and Core nodes. Instead of having one single broker running on the Core node, this approach will decentralize the system. The Assistant's main application will then use a python binder to connect to the zone broker in order to post messages.

For the development of the LCD UI the *pygame* [10] Python library was used. It is a set of modules that allow easy creation of games and multimedia programs which supports the frame-buffer driver used to display pictures on the PiTFT.

As mentioned before, the MySQL open source Relational Database Management System (RDBMS) will be used for storing the main application's data. It was mainly selected because it is a widely used, fast, multi-user and multi-threaded database used for application development.

4.2.4 Network Configuration

In order to configure the node to connect to the multi-hop ad-hoc network, a Bash script was developed. The script configures the parameters of the wireless interface and associates it to the mesh network. Then it requests an IP address from the Dynamic Host Configuration Protocol (DHCP) server which matches the node MAC to and IP. As shown in Figure 4.11 every Gateway also makes a bridge between its two interfaces in order to allow the Assistants to access the Internet.

In order to secure communication between the nodes, the Wired Equivalent Privacy (WEP) security algorithm was used to cipher the data. It was used because the ad-hoc mode, used by B.A.T.M.A.N,

[7] http://www.mysql.com/
[8] https://www.gnu.org/software/bash/
[9] http://mosquitto.org/
[10] http://pygame.org

doesn't yet support the Wi-Fi Protected Access II (WPA2) standard and the used wireless interface doesn't have support for the Wi-Fi Protected Access (WPA) standard in ad-hoc mode. A solution would be to cipher the payload of every packet in software. But since data security is not the main target of this thesis, the WEP algorithm is sufficient to difficult eavesdropping and tampering of messages. In the future, B.A.T.M.A.N is expected to support WPA2 or a different wireless interface card, with support for WPA, may be used.

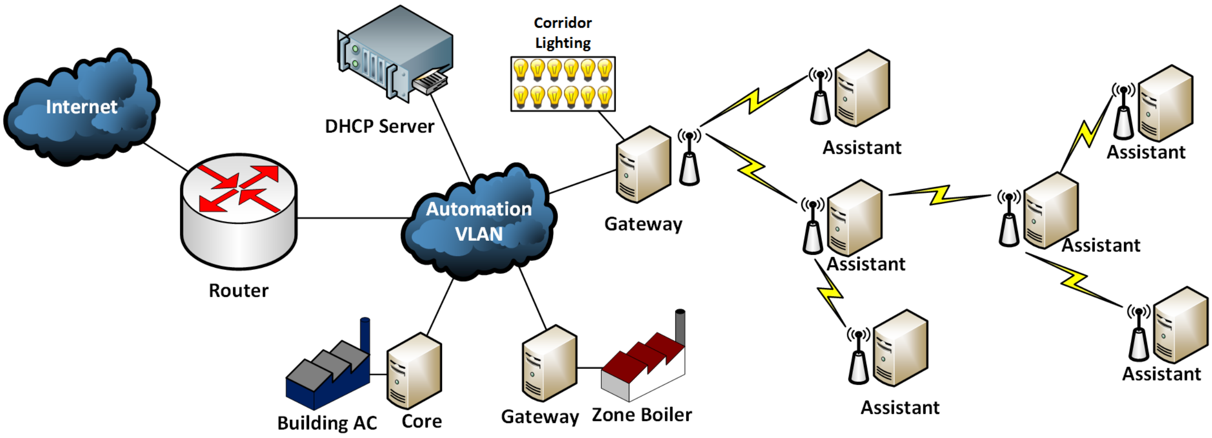


Figure 4.11: The topology of the network

4.2.5 Software Architecture Implementation

As described in Section 3.4, the main application was developed using a layered architecture. In order to rapidly accommodate the use of new multi-vendor peripherals and remote systems, the communication and hardware abstraction layers were created. Afterwards, when an easy control of the virtual devices was achieved, the main components of the automation layer were developed. Finally, the Interface abstraction layer and UIs were programmed.

Communication and Hardware abstraction layers

Section 3.4 described that the control of the physical devices is abstracted using virtual devices. In order to simplify and standardize the interaction with the virtual devices, an abstract class was created that is implemented by every virtual device. The abstract class is defined as a stateful object that reflects the present state of the physical device. It can be treated as a *ReadOnly* object or a *Readable* and *Writable* object. The abstract class also defines a set of abstract function that are used to normalize the interactions with the virtual devices. Every virtual sensor and actuator then extends this class to implement their specific parameters, communication libraries and data manipulation functions.

Each virtual sensor runs in a separate execution thread that is constantly updating its internal state. This allows a parallel inquiry of the sensors and better use of the system resources. As shown in Table 4.4 the polling interval depends mostly on type of sensor. The polling interval was adjusted in function of the relevance of the information obtained by every update. But these values may be also limited by the hardware itself, which is the case of the BT Office Presence sensor that takes around ten seconds to make a full scan. The sensor readings are returned using Data Transfer Objects (DTOs), this ensures that every reading is processed and stored according to its type which is specified by the DTO.

Virtual devices such as the HVAC and lighting, which are controlled by relays, don't have to be constantly updated, they only reflect the state of the hardware and contrary to the sensors, that are *ReadOnly* devices, also offer state changing functions that are applied to the physical actuators for the device.

Virtual Device	Type	Measurements/second
Temperature	ReadOnly	1/2
Humidity	ReadOnly	1/2
Current	ReadOnly	60
Luminosity	ReadOnly	1
Office Presence	ReadOnly	1/10
Building Presence	ReadOnly	1/10
HVAC	Readable/Writable	-
Lights	Readable/Writable	-

Table 4.4: Type and pooling interval of the virtual devices

Automation layer

The automation layer is composed of a set of modules with distinct functions. Their development and decisions option are described in detail in the next sections.

The Storage module is used to perform low level functions on the MySQL RDBMS. It provides an API for persistent storage to the rest of the application and serves as an abstraction layer for the query language. During the first stages of the application development, the SQLite [11] RDBMS was used. Since the main application was developed in a threaded environment the use of the SQLite database resulted in slow performance because it locks the database during writes, limitation parallel insertions and degrading performance. The migration to MySQL removed this limitation and allowed for truly multi-threaded access to the database.

The use of a relational database allows us to preform complex query's that return only the needed values at a cost of computational power. As a result, when dealing with data retrieval from large tables, which is the case of displaying sensor logs, the performance on the Raspberry Pi SBC shows its limitations in form of delay which negatively impacts the responsiveness of the user interfaces. A solution would be to perform tests with Not Only SQL (NoSQL) databases in order to verify possible performance gains. But since this was not the main purpose of this thesis, it was classified as an enhancement and proposed as future work.

The Publish/Subscribe module is responsible for assuring that the information is passed from the Assistants to the Gateways and from the Gateways to higher level Gateways. As mentioned before, the

[11] http://www.sqlite.org/

Mosquitto broker, which uses the MQTT protocol, was installed in every Gateway. The Publish/Subscribe module then uses the python binder to connect to the broker in order to publish or receive messages.

A concept of message queues or channels is used to differentiate the messages. A Gateway responsible for a building zone will subscribe to each of the channels in which it shows interest, listening for Assistant message publications. As presented in Figure 4.12, our implementation also divides the messages in three priority categories that are published and processed, when received, in a strict order. This assures that important messages will be quickly sent and processed.

The MQTT protocol has three levels of quality of service for message delivery: ”at most once” (best effort, message loss can occur), ”at least once” (messages are always delivered but duplicates may occur) and ”exactly once” (assures that the messages arrive exactly once). In our scenario, the messages are sent assuring that messages arrive ”exactly once” at the destination. This approach simplifies the message processing on the receiving end without having to deal with message deduplication. In case of network failure, when the messages cannot be sent, the messages are locally stored in three queues, one per priority level, then sent in the same order using strict priority when connectivity is restored.

It is possible to configure the Mosquitto broker to encrypt all the traffic using Transport Layer Security (TLS), but this feature would require much processing power from the Raspberry Pi, since it doesn’t support Advanced Encryption Standard (AES) hardware encoding and decoding. Assuming the wired network is secure and the wireless network interface already provides enough security this option wasn’t further investigated.

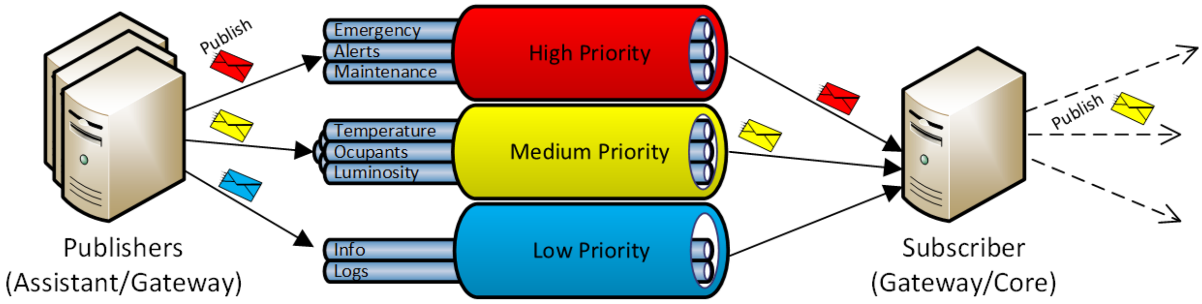


Figure 4.12: Message publishing with different priorities

The User Manager is the module responsible for creating and managing users. It also ensures the security of the users, their uniqueness in the database, loads the users from the database at start-up and stores them whenever a modification is done to the profile.

The process of creation of a new user requires the specification of a password. In order to secure the users’ passwords, they are first salted, with a unique salt for every user, then hashed using the Password-Based Key Derivation Function 2 (PBKDF2) [12] hashing function. This is the way that National Institute of Standards and Technology (NIST) recommends storing passwords [56], which protects against lookup tables, reverse lookup tables and rainbow tables attacks to the database.

There are two types of accounts: the *Normal* account and the *Administrator* account. The *Normal*

[12]http://tools.ietf.org/html/rfc2898

accounts are user accounts that are created through the registration process. They only have access to the control of the Assistant node of the office in which they are registered. On the other hand, the *Administrator* account comes pre-installed in all the nodes and has total access to all the nodes. It is used to program global energy efficiency events and system-wide configurations.

The Scheduler module is used for triggering tasks at a specific point in time or at repetitive intervals. Our implementation adds the possibility to define a maximum number of times a task can be executed. This is useful for one-time routine tasks that must be executed once and then forgotten.

The Scheduler module is also run by a separate execution thread. In order to reduce its complexity, the scheduler maintains a pool of executable tasks that it validates for possible execution in a round-robin model. When a task is validated for execution the Scheduler runs it. Each task contains all the necessary information for its execution, including variables and pointers to callable functions.

A list of internal tasks are always in execution. Since not all sensor readings need to be stored, there are tasks dedicated to store intermediary readings ever few minutes depending on the type of sensor and their inertia. This data is later used for historic analysis of the sensors readings. Another use of the Scheduler module is to periodically send sensor data to the Gateway. This is done at a much higher rate in order to archive better reaction times of the Gateway to the sent data.

Tasks could also be added to the pool at any time by users or administrators.

The Event Manager module is used to adjust the system state based on a set of pre-programmed triggers. Its functionality is similar to the Schedulers but differs in terms of what causes a specific event to be executed.

Every event is composed of Rules and Actions. In order to trigger the actions, all the rules must be satisfied. Algorithm 1 presents a simplified version of the main loop of the Event manager execution thread.

```
for Event in EventsPool do
    executeEvent ⟵ TRUE ;
    for Rule in Event do
        if Rule is Invalid then
            executeEvent ⟵ FALSE ;
            break;
        end
    end
    if executeEvent then
        for Action in Event do
            executeAction(Action);
        end
    end
end
```

Algorithm 1: The algorithm for the main loop of the Event manager execution thread

The event manager executes system-wide events and user defined events. The system-wide events have priority over user defined events and are configured by the system administrators to enforce energy efficiency. User defined events are configured by the occupants of every office.

Complex events could be programmed by the Administrators taking into account historical data of sensor readings. But for the purpose of this thesis, only a set of simple events were developed in order to show the potential of the system:

- the HVAC system is turned off when no users are present in the office
- automatically turn on the HVAC system when a occupant enters the office
- when more than one user is present in the office the target temperature is set to the average preferred temperature of present group of people

A user defined event could be programmed using the WEB UI. For example they could automate the process of turning on the lighting when the user walks into the office and the time is between 7PM and 8AM. Then turn them off again when they leave the office.

Interface abstraction layer and User Interfaces

The General User Interface is an API developed in order to reduce code repetition in every type of UI. It contains a set of function for manual control of the office systems, user creation and preferences modification. But, since only two UIs were developed, the shared functions are minimal. This also happens because the two interfaces complement each other in terms of functionality, which is described in the next sections.

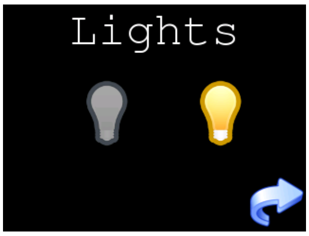
The LCD UI is an instinctive UI used for quick override of the system. The UI was developed in Python using the *pygame* library, which was mentioned before in section 4.2.3. It runs on a separate execution thread because it has to deal with touchscreen input events in a responsive manner. The *pybutton* library was also used, which helped to create and quickly identify the pushed buttons.

As shown in Figure 4.13, the UI is composed by a succession of menus that offer manual control of the lighting and HVAC systems and also displays useful information to the occupants.

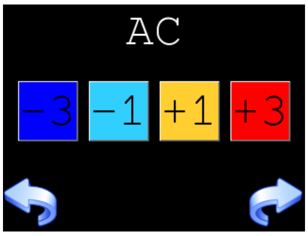
Figures 4.13(b) and 4.13(c) offer an alternative way to control the HVAC system. The first menu defines a score system for adjusting the personal target temperature and the second helps to identify the user. In order to rapidly identify the user, in Figure 4.13(c) the system only shows the occupants present in the office at that moment. The scoring system is used in order to conceal the present temperature and during the system use derive their own personal ambient comfort without knowing the actual temperature. The scoring system is used because as mentioned in Section 3.1.2, the users don't know what they want. This system lets them choose a higher or lower value in contrast to the actual temperature in the office.

Since the recommended 30 frames per second re-draw of the screen consumes a lot of processing power another alternative had to be found. The UI was designed in such a way that the screen is only updated when a change occurs in any element shown on the screen or a change of menu has occurred.

Figure 4.13(f) shows the Uniform Resource Locator (URL) used to access the WEB UI of the node and also shows the API key used to register new users. The key is a security measure that prevents users exterior to the offices from creating an account on the node of that office. It is composed of a sequence of six random alphanumeric characters that changes every 45 seconds.

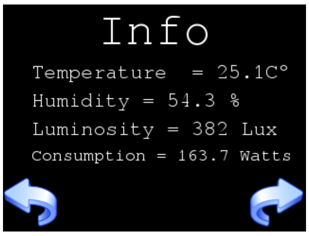


(a) Lights control



(b) HVAC control

(c) User identification



(d) Auxiliary Information

(e) Temperature Dash

(f) API Key

Figure 4.13: Menu sequence of the LCD UI

The WEB UI is the main UI used to control the system. Its development was based on the Tornado [13] Web Server Gateway Interface (WSGI) container and the Flask [14] lightweight WEB application framework written in Python, which is based on the Jinja2 [15] template engine. This allowed for the use of a fast Python based WEB server that generates template based dynamic web pages.

In addition to Flask, some of its extensions such as *sessions, cache and loginManager*, were also used. For field definition and value verification the WTForms [16] Python library was used, which can be seen working in Figure 4.14. We also enabled its Cross-site Request Forgery (CSRF) protection mechanism in the Flask framework.

For the design of the pages we used the Bootstrap [17] mobile front-end framework which composes the base design of the web pages.

Before using the interface the user must be registered, using the registration Form shown in Figure 4.14. The registration form uses intelligent fields provided by the WTForms that reports any errors in the fields and displays them in red. The last field is the registration key which is an always changing key provided by the LCD menu, shown in Figure 4.13(f).

When logged out, the system only shows the ambient sensors readings (Figure 4.15), asking for the log-in credentials if trying to access any other menu.

After logging in, the control of the lighting and HVAC systems is revealed in the main menu. The access to the configuration menu and graphs is also unlocked. Figure 4.16 shows the dashboard and

[13] http://www.tornadoweb.org
[14] http://flask.pocoo.org
[15] http://jinja.pocoo.org/
[16] http://wtforms.simplecodes.com/
[17] http://getbootstrap.com/

the simple controls used for managing the lighting and HVAC systems of the office as well as sensor data information. When the manual control of the HVAC system is selected, its manual controls shows up on the automation menu (Figure 4.17).

The graph representation of sensor data presented in Figure 4.18 was achieved using the Dygraph [18] JavaScript library. It offers a responsive and precise visualization of historic data with zoom and aliasing functions to the plotted values.

Figure 4.19 shows the menu used for selecting the ID token which is used to detect the user presence. Still, in Figure 4.19, we can observe the interface for manipulation of the user defined events. On the bottom of the figure, the triggered actions can be created from a list of pre-selected actions with optional user arguments. The middle menu is used to define triggers such as time intervals and the user presence in the office. Finally, the menu below the token ID selection is used to associate triggers to actions. In order for the action to be executed all the triggers must be valid.

The rest of the menus are used for debugging of the WEB UI.

[18] http://dygraphs.com/

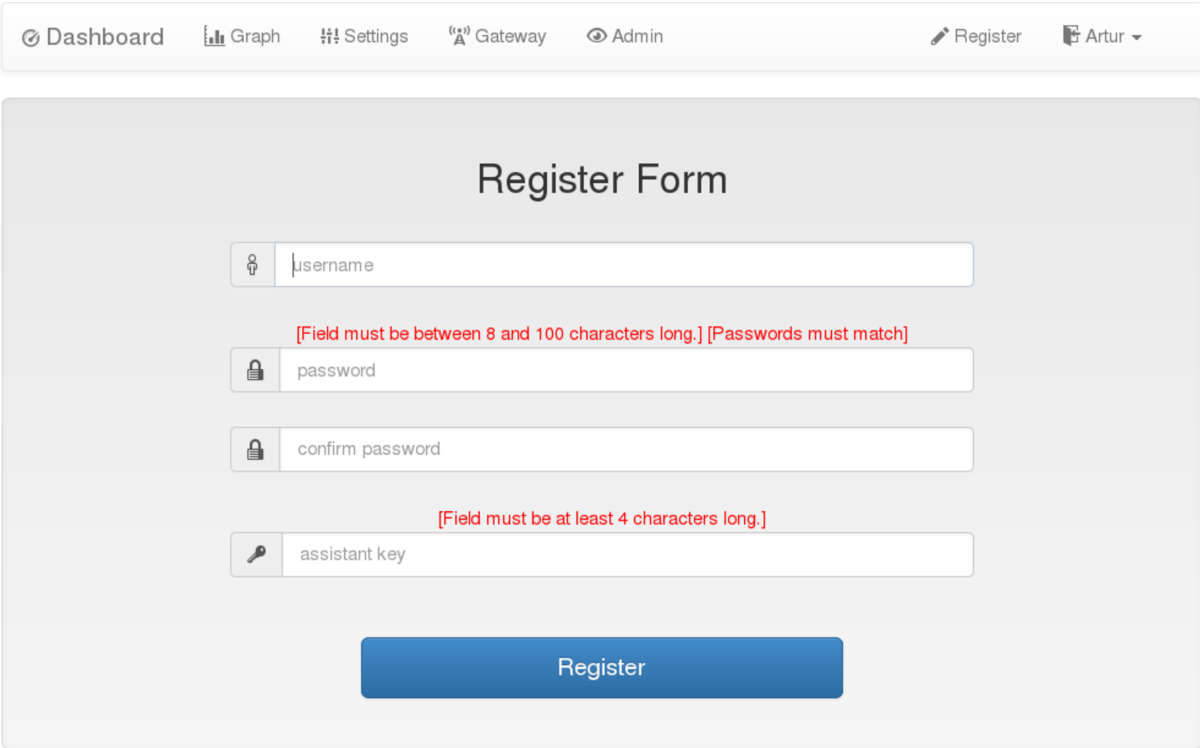


Figure 4.14: Registration Menu

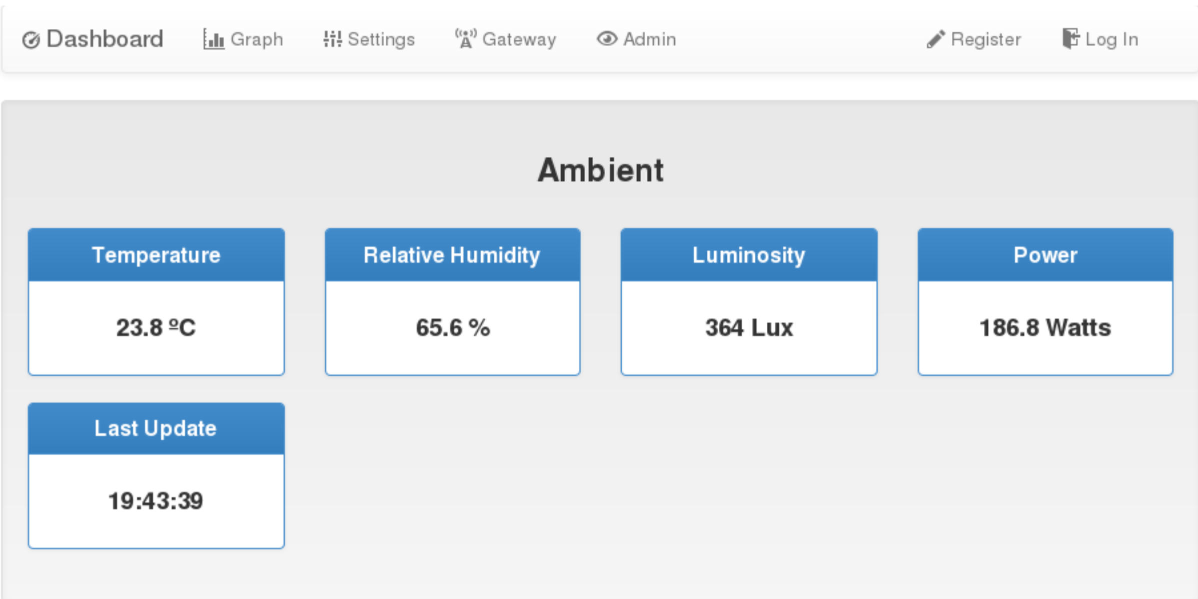


Figure 4.15: Automation Menu when logged off

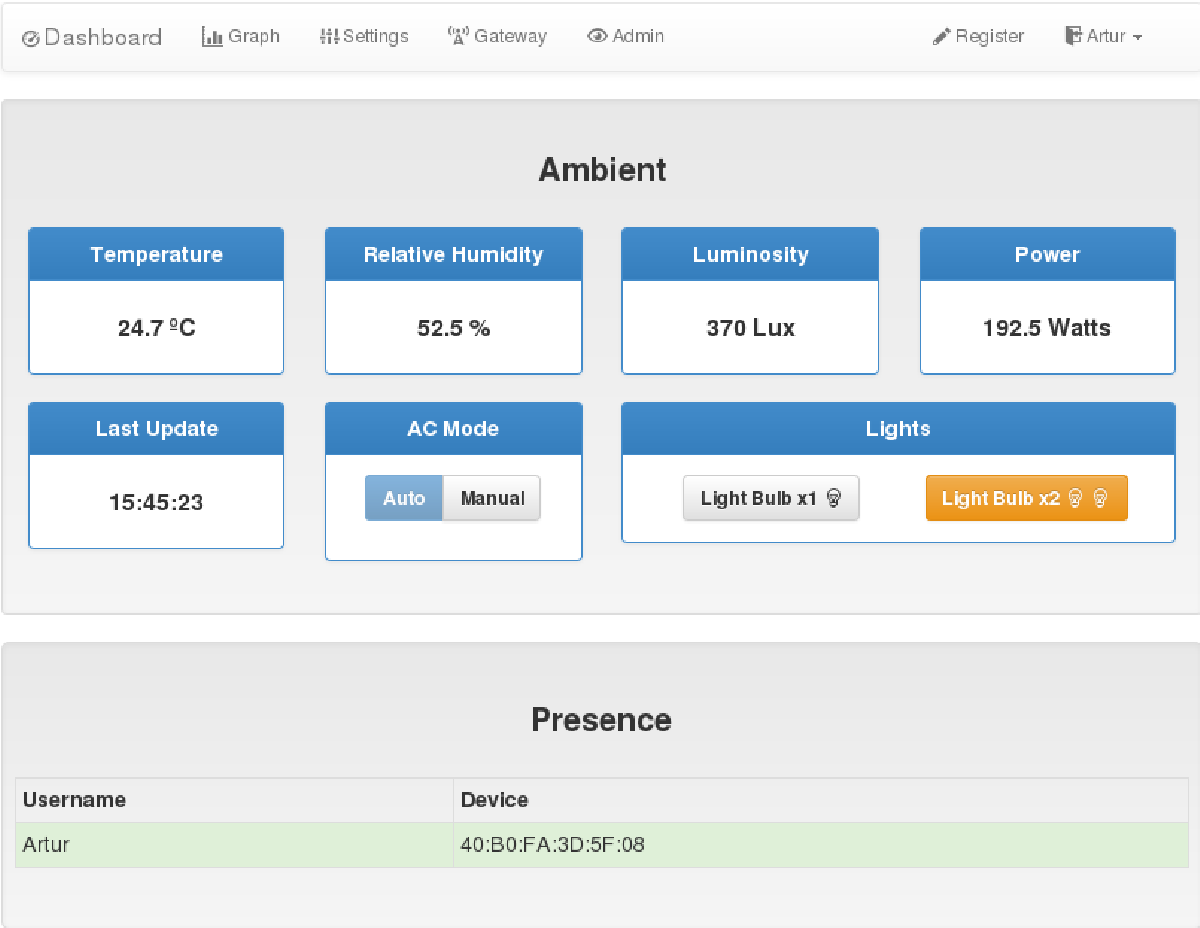


Figure 4.16: Automation Menu

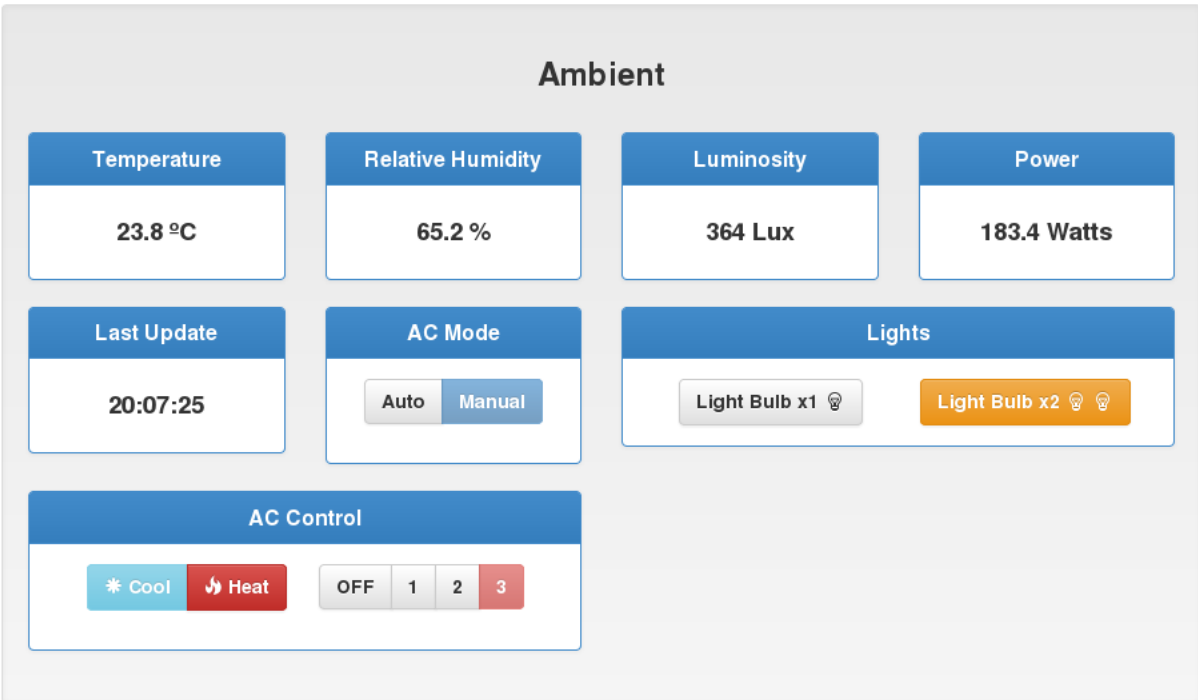


Figure 4.17: HVAC Controls

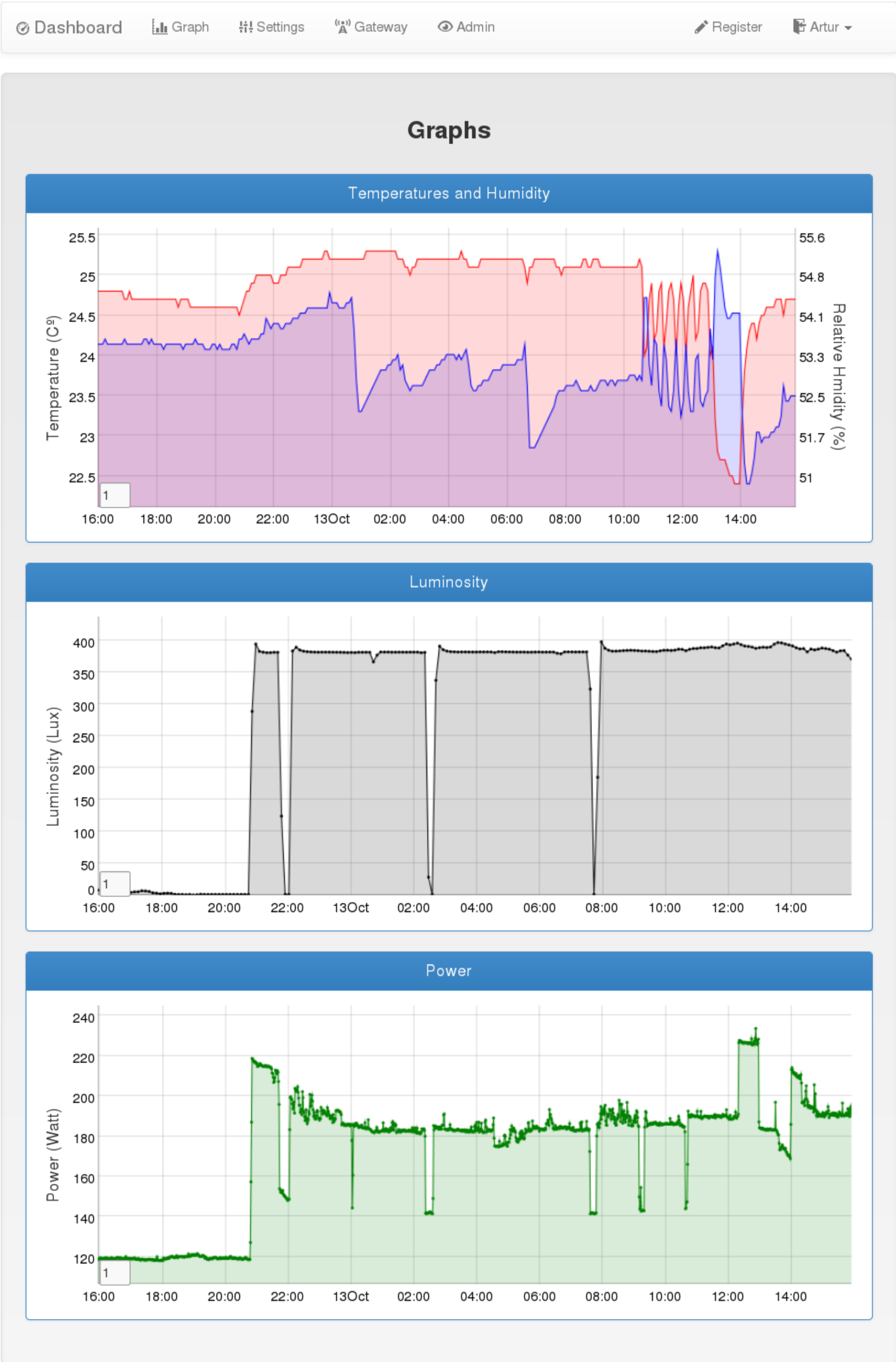


Figure 4.18: Graph Menu

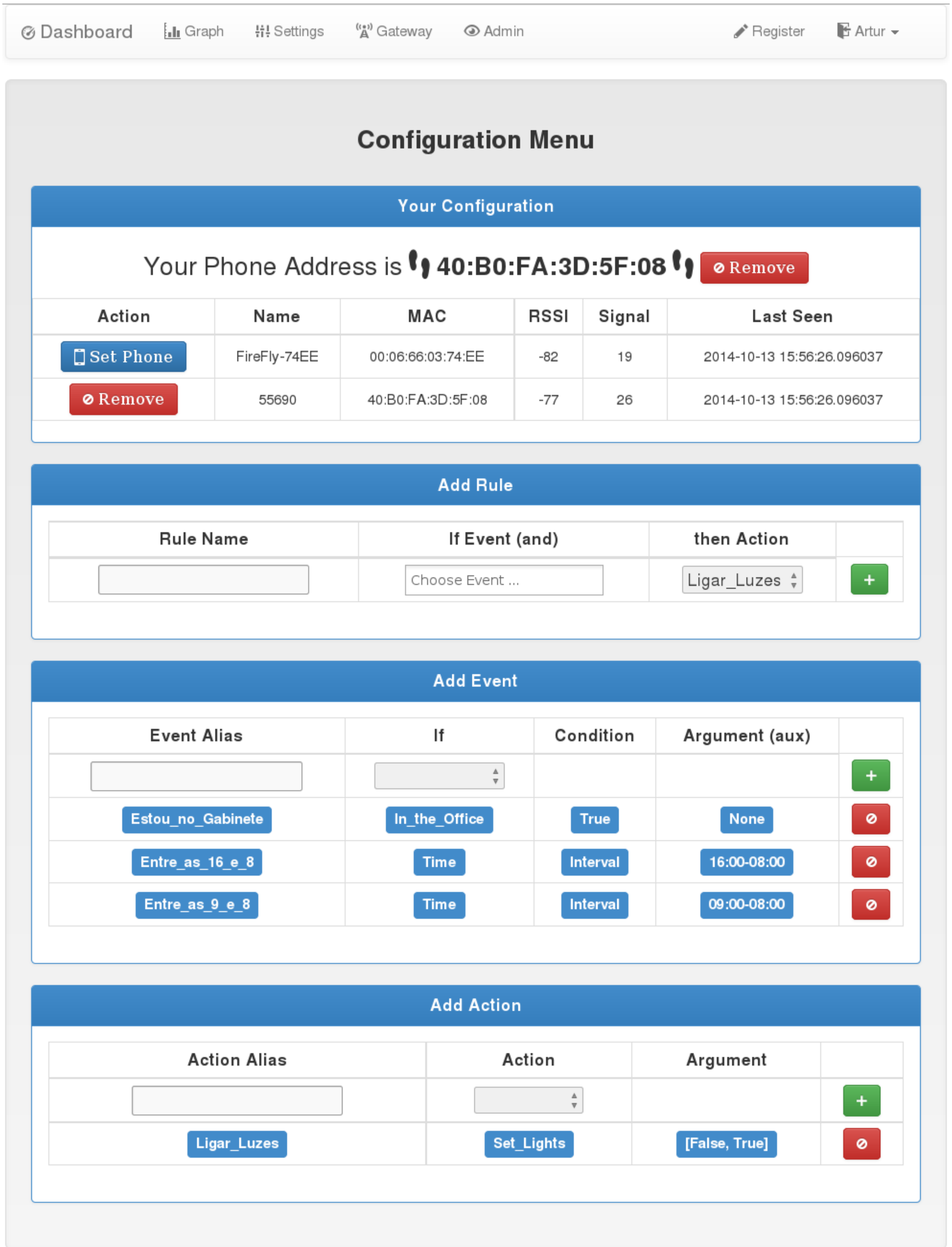


Figure 4.19: Configuration Menu

4.3 Deployment at IST-Taguspark

From the planned architecture for IST - Taguspark only a small part was deployed. The initial plan was to deploy the system in an entire building zone, but due to hardware acquisition constraints, the pilot was deployed on a much smaller scale.

Six nodes were prepared but the current installed system is only composed of three nodes: two Assistants and one Gateway/Assistant distributed in a building zone as shown in Figure 5.1. The testing scenario is further detailed in Section 5.1.

4.4 Summary

In this chapter the implementation choices were described. The chapter starts with a detailed description of the hardware architecture, first the SBC then the rest of the sensors end peripherals.

Then the implemented software architecture is described in detail, starting from the platform and tools used and ending with a detailed explanation of each layer and modules of the main application.

At the end of this chapter a working implementation of the system is presented. In the next chapter this solution is validated using a series of tests.

Chapter 5

Evaluation

In order to evaluate the developed system, several tests were performed. Section 5.1 starts by describing the test scenario. Next, in Section 5.2 the detailed description of each test is presented. Finally, Section 5.3 presents the results of the tests.

5.1 Tests Scenario

All the tests were conducted in real scenarios inside a building zone of the IST - Taguspark campus. They were executed using three fully functional Assistant nodes, composed with the hardware described in Section 4.1, one of which was also functioning as a Gateway as explained in Section 3.4. Figure 5.1 shows their approximate location in the building zone and the probable communication paths within the wireless mesh network. The Gateway node also worked as a bridge between the Assistants and the automation Virtual LAN (VLAN) to which it was connected using an Ethernet connection. All the nodes were powered using 5 V 2100 mA switching power supply connected to the nearest power plugs. User detection and identification was performed using BT capable mobile phones.

5.2 Tests Description

5.2.1 Energy Consumption

In order to test the accuracy of the current sensor it was tested against two electric devices: a heater rated at 2000W and a heat gun rated at 1500W. These devices were chosen because, contrary to computers which have switching power supplies, they offer a constant power consumption over time and their power consumption is much higher than the load created by other electronic devices in the office such as monitors and computers. The test consists in observing the energy consumption variation by using the current sensor which is attached to the input of the electrical cable that delivers power to the office's power plugs. The test must run for at least five minutes in order to determine the power consumption of the devices and filter the background noise created by other equipment.

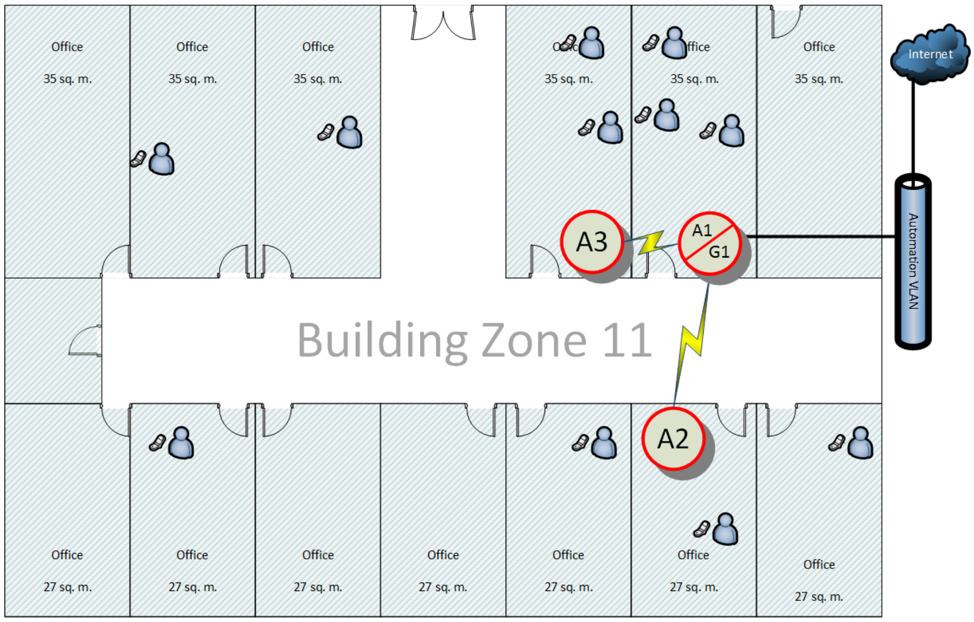


Figure 5.1: Test Location

5.2.2 User Detection

In order to test the reaction time of detection of user presence in the office, a series of measurements were performed. The test consists in observing the time the Assistant takes to detect the user's presence, with the user being identified by its BT capable mobile devices. The measurements will be performed with the BT mobile device near the Assistant in order to increase the SNR of the signal and avoid miss readings. The device used will be a LG Nexus 4 with BT support up to version 4.0 .

Due to the rapid reaction of the detection system, a chronometer will be used to determine the reaction time. The test will result in at least a set of 25 measurements in order to determine a meaningful average of the reaction time of the system.

5.2.3 Temperature, Humidity and Luminosity

To test the Temperature, Humidity and Luminosity sensors and their capabilities, a series of measurements will be executed. The tests will be performed using the sensors described in Section 4.1.3 which are installed on an Assistant node. The Assistants will store sensor readings as well as log files of user actions and interactions with the system during a time span of one week.

They test will consist in observing the sensor readings behavior in function of user interaction with the system and their presence in the office.

5.2.4 Conflicted Preferences

In order to test the operation of the automatic conflict resolution protocol described in Section 4.2.5, a series of measurements will be used to determine the effect of the algorithm. The measurements will help to determine if the applied setting provide all the members of an office with different ambient preferences. The test will make use of the sensor readings of the Assistant node and log all the sensor readings for posterior analysis.

The test will consist in determining the effect of multiple users with different preferences in the same office and in the same time interval. First during the day, when the HVAC system is functioning, one user with predefined preferences will be present in the office. After some time, another user with different thermal preferences must enter the office. Finally, the first user must leave the office, leaving the second user alone.

5.3 Test Results

5.3.1 Energy Consumption Results

As mentioned before, two devices with 2000W and 1500W ratings were tested for a period of at least five minutes. As shown in Figure 5.2, the first spike that begins at around 5:53 AM jumped from a value of 184.6W to 2171.7W which results in a jump of 1987.1W at the moment when the 2000W rated heater was turned on. The device then maintained a constant power draw until it was switched off at 6:53 AM, which caused a drop in power consumption reading from 2157.0W to 190.2W, representing a drop of 1966.8W.

Also, shown in Figure 5.2 is the second test that took place from 10:15 AM until 10:20 AM using the 1500W rated heat gun. The heat gun caused an energy consumption spike from 183.9W to 1631.1W when turned on and then a decrease from 1633.0W to 183.7W when turned off, resulting in a difference of 1447.2W and 1449.3W respectively.

The real energy consumption of the devices were measured beforehand using a multimeter and are presented on the third column of Table 5.1.

Columns four and five show the average measured values by the Assistant and the induced error compared to the real energy consumption values. The introduced error in the readings is acceptable taking into account the background noise generated by other equipment and quantization error introduced by the 16-bit resolution of the ADC. This also shows that the consumption readings are very accurate and are suitable for the intended application of an ECI discussed in Section 3.3.3.

Electrical Equipment	**Power Rating**	**Real Energy Consumption**	**Observed Average Energy Consumption**	**Error**
Heater	2000W	1947.83W	1976.95W	1.495 %
Heat Gun	1500W	1433.13W	1448.25W	1.055 %

Table 5.1: Reading Error caused by the Current Sensor

5.3.2 User Detection Results

A set of measurements were performed in order to determine the responsiveness of the detection system. The test resulted in a set of 25 measurements with an average response time of 7.01 seconds and a standard deviation of 2.48 seconds. The cumulative distribution function of the readings can be

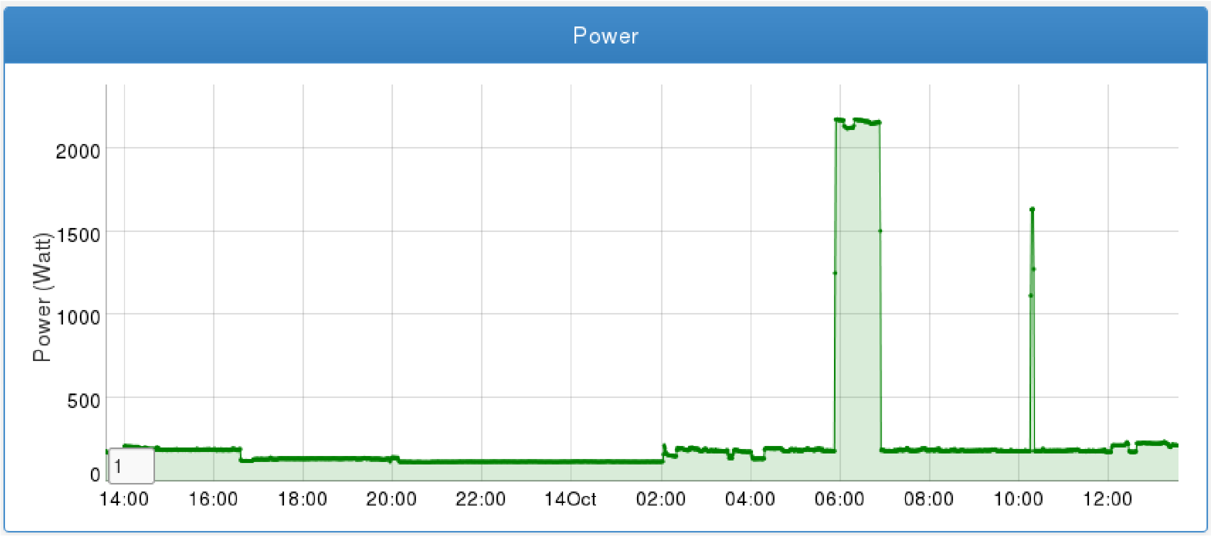


Figure 5.2: Energy consumption spikes created by a 2000W and a 1500W rated heating devices

observed in Figure 5.3. These results show that the system is fast in detecting a single or multiple users. The detection of multiple users was not performed because of process that the sensor uses to detect users would have produced the same conclusion regardless of the number of users. Very large numbers of users would have impacted the RF medium with noise, causing miss-readings and as a consequence detection delays.

One fact to be noted is that, excluding the signal attenuation caused by the walls, the system can detect the users at a distance of ten meters. In the majority of the cases, whenever the users have reached the door of the office the system already detected and identified the user, without causing any perceivable delay from their point of view.

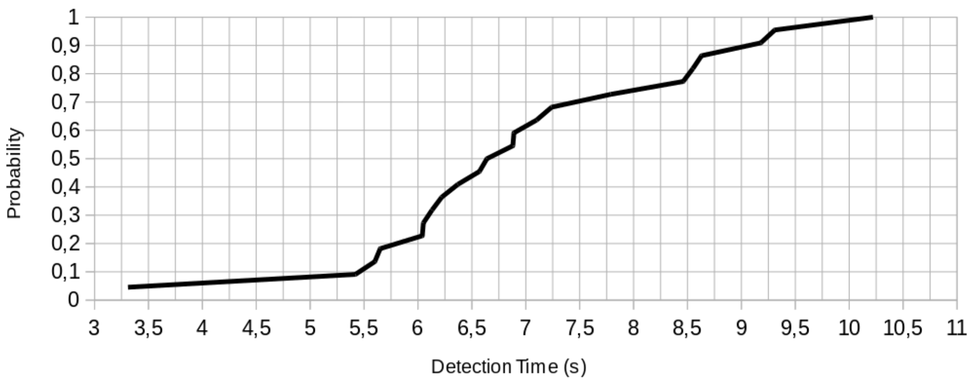


Figure 5.3: Cumulative distribution function of the time it takes to detect a user

5.3.3 Temperature, Humidity and Luminosity Results

In order to test the functionality of the temperature, humidity and luminosity sensors in the Assistants, these were used to collect ambient data. A day was selected were the presence of the occupants in the office would affect the readings. Figures 5.4, 5.5, 5.6 show the readings of the sensors during October

9^{th} 2014. In the figures, the line painted in green represents the presence of occupants inside the building.

Figures 5.4 shows the temperature of the office. We need to take into account that during the night the HVAC system is not functional and as a result from 1 AM to around 3 AM the office is warm even though occupants are present. Later, at around 10 AM, the HVAC system is turned on and the temperature is reduced. The values then vary with the presence of the users in the office until around 8 PM when the HVAC is turned off again. As expected, the presence of the occupants highly impacts the ambient characteristics of the office as the system detects their presence and operates the HVAC.

The oscillation of the temperature when the occupants are present is due to the mechanism implemented to manage the HVAC. Instead of constantly turning on and off the HVAC system, the temperature in the office must overcome a certain threshold in order to trigger the heating or cooling of the office which causes the oscillating effect.

The humidity graph shown in Figure 5.5 has an inverse effect when comparing with the temperature graph. Every time an occupant enters the office there is a certain build up of humidity, but afterwards the humidity decreases showing the effect of the HVAC system operation.

Finally, Figure 5.6 shows the level of luminosity in the office during the day. Since the lights in the office have a much higher incidence over the sensor, it can be noted by the readings when the office lights are on or off. During the day it registers small values which seem to be sufficient for the occupants of the office. During the night, whenever the occupants are present we can observe an expressive amount of luminosity, demonstrating that the lights are on.

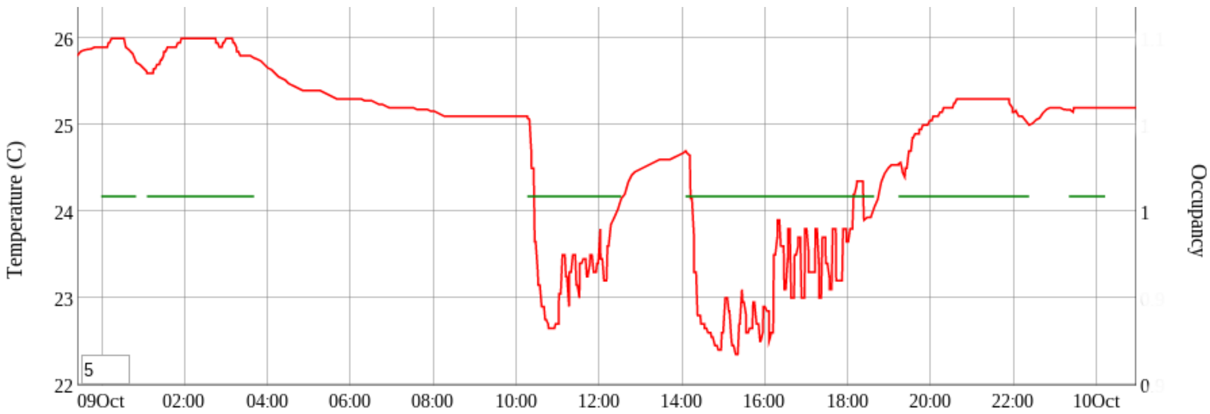


Figure 5.4: Temperature Readings

5.3.4 Conflicted Preferences Results

In order to test the operation of the automatic conflict resolution protocol mentioned before, a specific set of actions must be executed in order. Figure 5.7 shows the temperature variation in the office during a period of 24 hours. The red line represents the temperature and the green line shows the time intervals when the office is occupied. The green line also shows a sequence of markers which represent the following set of events:

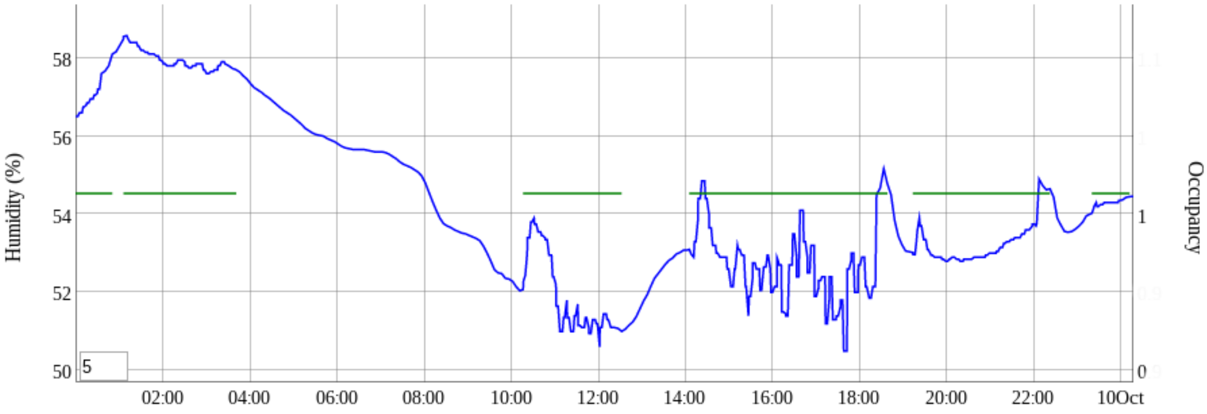


Figure 5.5: Humidity Readings

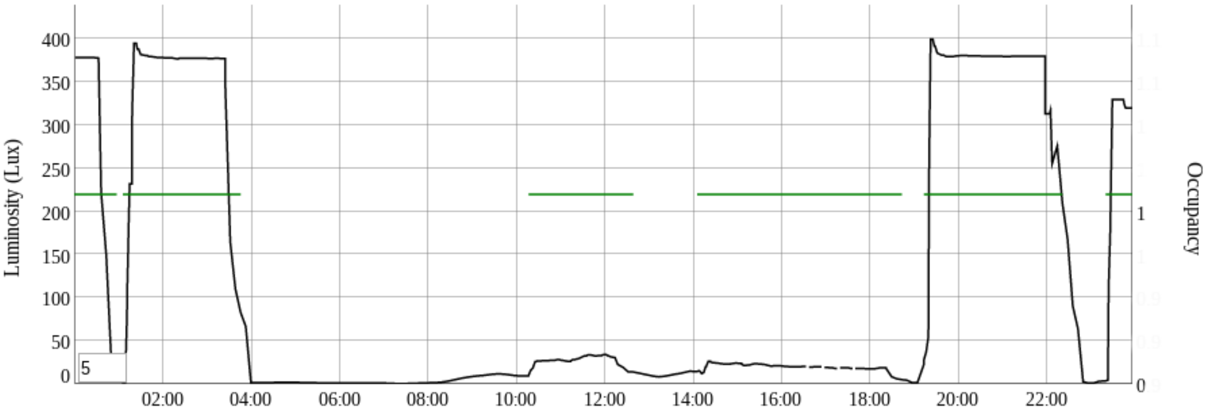


Figure 5.6: Luminosity Readings

- **Mark 1:** User 1 enters the office
- **Mark 2:** User 2 enters the office
- **Mark 3:** User 1 leaves the office

Some aspects to take into account are the users' thermal preferences. User 1 had a thermal preference of $22.7\,^{\circ}\mathrm{C}$ and User 2 of $24.1\,^{\circ}\mathrm{C}$.

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 $22.5\,^{\circ}\mathrm{C}$ value. The oscillation of the temperature was explained before and has the objective of only enabling the HVAC system when the temperature surpasses a certain margin, which in our case is $\pm 0.3\,^{\circ}\mathrm{C}$. When User 2 entered the office, at around 4 PM, the temperature of the office starts to rise and stabilizes at around $23.5\,^{\circ}\mathrm{C}$, 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 its thermal preferences of around $24.1\,^{\circ}\mathrm{C}$.

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 this time, resulting in a slow increase in temperature.

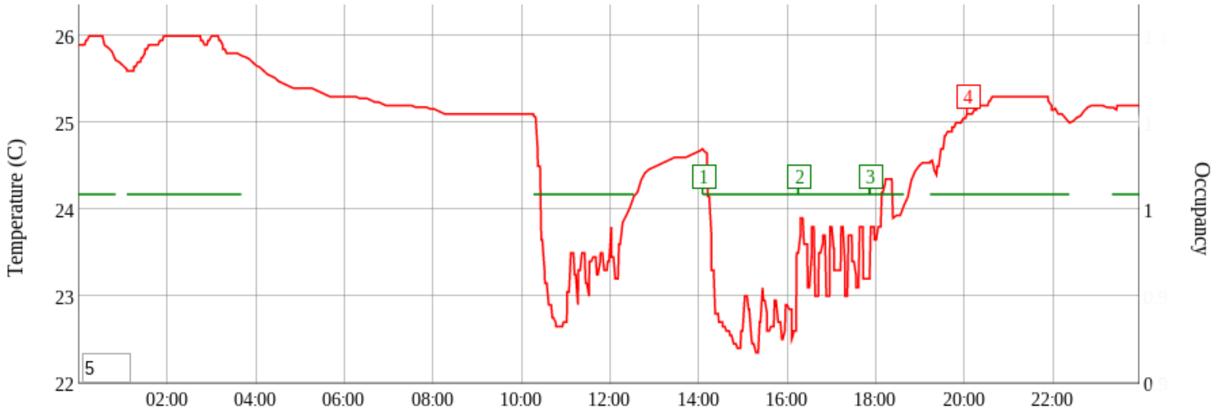


Figure 5.7: Adjustable temperature to the present occupant

5.4 Summary

In this chapter the tests done to assure the system's behavior were detailed. It was concluded that the system operation followed the predicted guidelines and performed well. The user detection and identification was proven to work without faults and was successfully used for the automation inside the office. The tested sensors showed good accuracy and provided useful information to the user.

Chapter 6

Conclusions

6.1 Summary

In this document, we present a system that has the objective of offering better comfort to the users of offices, as well as the minimization of the overall energy consumption of the building.

In order to develop the solution for the problem, we started by analyzing Building Automation standards available on the market. Then we explored the wireless communication systems to see if we can reduce costs and make the system easily deployable using off-the-shelf materials. A list of problems were identified regarding the user behavior in buildings and how they impacted its energy efficiency. The limited flexibility, customization and efficiency of the current solutions were identified and used as a base during the development of the PerOMAS architecture. For a full automation of the system, user detection and identifications techniques were tested using BT technology.

The architecture of the system was designed taking into account the possible future expansion of the IST-Taguspark campus. Some problems related to user behavior and neglect were mitigated by configuring the system to react to the user presence in the office.

Finally, the solution was tested in real scenarios at IST - Taguspark.

6.2 Achievements

Some of the main achievements of PerOMAS are the definition of flexible and expansible network, hardware and software architectures. Another contribution of PerOMAS is the offering of two intuitive user interfaces that ease the control and configuration of automation events. The proposed hardware, network and software architectures were instantiated in a fully functioning prototype. A simple conflict resolving algorithm that manages the office comfort depending on the preferences of the present users was demonstrated.

A deployment of the system in a group of three Assistants and one Gateway was used to validate its operation.

A paper was submitted and accepted for publication in The 5th International Conference on Ambient

Systems, Networks and Technologies (ANT-2014). Another paper was accepted for publication and presented in Energy at IST Conference, Iniciativa Energia (Energy@IST2014).

6.3 Future Work

Even though most the developed prototype is fully operational and the goals set in the beginning were fully achieved, this is a very active research area and many ideas may be pursued. 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. The same may be said for a way of defining global policies.

Many issues were found during the development of this thesis. But many have not been further explored. An important future work for this thesis would be to complete the initial planing of the system and have a building zone installed with Assistant nodes that would offer a complete control of the building zone.

During the development of our prototype, some hardware related issues were found. The touch screen panel have stoped responding in some occasions, which was found to be caused by the high energy demand from the coil based relays. These will to be replaced with solid state relays that use much less energy and will not cause voltage drops. We have also experienced File System corruptions caused by occasional power cuts at IST's Taguspark building. A battery backup power would prevent this from happening.

NoSQL databases may be tested to investigate the performance improvement in historic data analysis and information retrieval.

Solutions to share user preferences between the nodes may be studied in order to ease user migration between offices.

Appendix A

The survey

A.1 Survey

PerOMAS - Personal Office Management and Automation System

Por forma a recolher o máximo de informação, com o objectivo de tornar este sistema o mais útil possível para eventuais utilizadores, pedimos que responda a este questionário. Os dados recolhidos serão apenas usados para os fins de optimização do sistema de climatização e iluminação do IST-Taguspark, estando garantida a sua confidencialidade. Obrigado pela sua colaboração.

1. Sexo? ( ) Feminino ( ) Masculino

2. Idade? ( ) menos de 11 ( ) 11 - 19 ( ) 20 - 30 ( ) 31 - 50 ( ) mais de 51

3. Indique a sua função no IST-Taguspark ( ) Aluno ( ) Docente ( ) Funcionario ( ) Outro:

4. Possui dispositivos móveis? (ex: smarthphones, tablet's, computadores) ( ) Sim ( ) Não

4.1 Quantos? (Se respondeu "Não" à questão 4, ignore esta questão)

4.2 Quantos desses dispositivos possuem tecnologia Bluetooth? (Se respondeu "Não" à questão 4, ignore esta questão)

4.3 Quantos desses dispositivos possuem tecnologia Wi-Fi? (Se respondeu "Não" à questão 4, ignore esta questão)

5. Possui gabinete no IST-Taguspark? ( ) Sim ( ) Não

5.1 Partilha o gabinete com outros colegas? (Se respondeu "Não" à questão 5, ignore esta questão) ( ) Sim ( ) Não

5.2 Com quantas pessoas partilha o gabinete? (Se respondeu "Não" à questão 5.1, ignore esta questão)

5.3 As suas preferências quanto ao sistema de climatização costumam entrar em conflito com as dos seus colegas de gabinete? (Se respondeu "Não" à questão 5.2, ignore esta questão) ( ) Sim ( ) Não

5.4 Esse conflicto causa-lhe desconforto? (Se respondeu "Não" à questão 5.3, ignore esta questão) ( ) Sim ( ) Não

6. Com que frequência costuma desligar as luzes quando sai de um gabinete ou sala? (considerando que a sala ou gabinete irá ficar sem nenhum ocupante) ( ) Nunca ( ) Raramente ( ) Frequentemente ( ) Sempre

7. Com que frequência costumar desligar o sistema de climatização quando sai de um gabinete ou sala? (considerando que a sala ou gabinete irá ficar sem nenhum ocupante) ( ) Nunca ( ) Raramente ( ) Frequentemente ( ) Sempre

8.Quantas vezes por dia costuma regular o sistema de climatização?

9. De inverno, qual a temperatura ambiente que costuma usar no sistema de climatização? (indique o valor em graus Celsius)(caso seja a temperatura máxima ou a mínima indique MAX ou MIN respectivamente)

10. De verão, qual a temperatura ambiente que costuma usar no sistema de climatização? (indique o valor em graus Celsius)(caso seja a temperatura máxima ou a mínima indique MAX ou MIN respectivamente)

11. Costuma trabalhar durante a noite nas instalações do IST-Taguspark? (considerando que a partir das 20 h é noite) ( ) Sim ( ) Não

11.1 Durante a noite como classifica o sistema de climatização? (Se respondeu ”Não” à questão 11, ignore esta questão) ( ) Muito Mau ( ) Mau ( ) Razoável ( ) Bom ( ) Muito Bom ( ) Excelente ( ) Outro:

12. Durante o dia como classifica o sistema de climatização? ( ) Muito Mau ( ) Mau ( ) Razoável ( ) Bom ( ) Muito Bom ( ) Excelente ( ) Outro:

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