SmartBuildings: an AmI System for Energy Efficiency

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***Abstract*—Nowadays, the increasing global awareness of the importance of energy saving in everyday life acts as a stimulus to provide innovative ICT solutions for sustainability. In this scenario, the growing interest in *smart homes* has been driven both by socioeconomic and technological expectations. One of the key aspects of being *smart* is the efficiency of the urban apparatus, which includes, among others, energy, transportation and buildings. The present work describes SmartBuildings, a novel Ambient Intelligence system, which aims at reducing the energy consumption of "legacy" buildings by means of artificial intelligence techniques applied on heterogeneous sensor networks. A prototype has been realized addressing two different scenarios, i.e. the management of a campus and of a manufacturing facility. A complete description of the elements included in the case study is presented.**

I. Introduction

In recent years, the concept of *environmental friendliness* has become more and more popular due to the availability of new unobtrusive technologies which allow to support the citizens in their everyday life. Sustainability depends on different key factors including health care, water supply, recycling and, above all, energy efficiency.

Recent studies published by the European Commission [1] report that buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. In particular, older buildings (about 35% of the EU buildings are over 50 years old) consume 7 times more than newer ones. Thus, obtaining a reduction in the energy consumption of pre-existing buildings is of prime importance for improving both local economies and the citizens' quality of life. Such a challenging task can be addressed from many different perspectives, as is well documented in relevant research in the field of *smart homes* and *smart offices*.

This work presents SmartBuildings, a novel Ambient Intelligence (AmI) system designed to improve the energy efficiency of buildings by means of a pervasive monitoring infrastructure and artificial intelligence techniques. While being "smart" is nowadays traditionally stated as the request for an efficient implementation of building automation, the key idea of our proposal is instead to move a step forward. Namely, our aim is to exploit the availability of pervasive monitoring equipment in order to make the environment responsive to the users' needs, and at the same time respectful of the energy saving requirements.

In this perspective, SmartBuildings is based on a three-layer architecture, implementing a unifying approach to information management, ranging from acquiring unprocessed data from a pervasively distributed monitoring equipment up to performing centralized abstract reasoning. At the lowest level, a Sensor and Actuator Network (SAN) is used both to gather information about the environment and the users, and to act on the environment itself in order to satisfy users' needs. Sensory data is stored in the intermediate level and analyzed by some intelligent modules which are responsible for modelling the underlying environments and providing timely reactions if unexpected events occur. The intelligent core of the systems resides at the upmost level, where the actions needed to improve the energy efficiency of the whole building are defined.

The remainder of the paper is organized as follows: relevant work from literature is reported in Section II. The SmartBuildings architecture is presented in Section III. Section IV describes the system deployment in two different application scenarios. Conclusions are discussed in Section V.

II. Related Work

The challenge of providing intelligent solutions for the energy efficiency of buildings can be met in different ways. One of the simplest solution is probably to just stimulate the user awareness about energy consumption. The system presented in [2] achieves this objective by means of web-enabled power outlets which measure the energy consumption of the corresponding appliances, and make acquired data available through the Web.

This goal was also carried out by Smart Meter Texas (SMT), a website that allows customers with smart meters to track and review their electricity use. The system in [3] uses SMT data and users' locations, tracked by means of an Android app, to inform users if high power consumption occurred when they were not at home.

In [4] a centralized power management system for intelligent buildings, namely *iPower*, is presented. The iPower system uses WSNs to monitor environmental conditions and energy consumptions, whilst the control of the appliances is performed by means of X10-based devices. A multi-layer architecture is adopted to manage separately the end user interfaces (*user layer*), the rule-based reasoning engine (*service layer*), the profiles needed to manage both the users and the devices (profile layer), the sensors (*sensor layer*) and the actuators (*actuator layer*).

A home energy management system (HEMS) is presented in [5]. HEMS aims to monitor and control a set of networked devices, i.e., home appliances and personal computers, that use the Universal Plug-and-Play (UPnP) protocol. A mobile iOS-based application was also developed to enable users to

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remotely access the services provided by the platform. A three-levels (*physical*, *service*, *application*) OSGi-based architecture for controlling home appliances is also proposed in [6].

The *GreenBuilding* system [7] consists of two main components. The former is the *monitoring* subsystem, that is responsible for measuring the energy consumptions of the appliances and the environmental conditions in which they are running. The latter is the *control subsystem*, which aims to control the behavior of each appliance by meeting the energy consumption constraints defined by the user.

A low cost multilayered architecture for wireless communication in smart cities is presented in [8]. In particular, the authors addressed the issue of reducing the cost and the complexity needed for the integration of different devices. The first of the four levels they designed, namely the *sensing layer*, consists of heterogeneous sensor nodes to collect environmental data; the communication between different types of nodes and technologies is supported by the *access network layer*, whilst the *Internet/Cloud layer* makes data available to the users and to the services of the upmost layer, i.e., the *application layer*.

A three-tier architecture similar to the one we adopted is presented in [9]. The intermediate level consists of different building blocks to implement a number of services, whilst the lowest and the highest layers are responsible for capturing and analyzing data respectively. This system also provides an abstraction mechanism to manage heterogenous sensory devices in a common way.

A method for managing the energy consumption of household appliances was proposed by the AIM consortium [10]. Such system is based on a two-level architecture, where a *gateway* coordinate a set of *Energy Management Devices* (EMDs) which are responsible for managing different appliances. Each EMD provide both the power monitoring and power control functionalities, whilst the energy management task (e.g., appliances control and user profiling) are demanded to the gateway. This solution allows for extensive scalability and can be considered close to the ideal reference Building Management System.

A comprehensive survey of intelligent management systems for energy efficiency in buildings is proposed in [11], also including the Reference Building Management Architecture on which SmartBuildings is based.

III. SMARTBUILDINGS ARCHITECTURE

SmartBuildings is based on a multilayered software architecture [12], as shown in Fig. 1.

The lowest level, the **physical layer**, consists of actuator devices and cheap sensor nodes capable of measuring different data by means of specific expansion modules (e.g., barometers, thermometers, hygrometers, accelerometers, instruments to measure noise and light levels, RFId readers). Sensor and actuator networks (SANs), typically using different protocols, are managed by several connection units, called *Collectors*, which implement a two-way communication between the nodes and the AmI components. In particular, each Collector interacts both with the upper levels, making captured data available to AmI algorithms, and with the SAN, by translating and delivering to the nodes the commands coming from the intelligent modules.

The **middleware layer** provides a standard interface between physical sensors and AmI algorithms. The core of this intermediate layer is the *BuildingAgent*, which contains both the modules responsible for modeling the environments of a single building, and the controllers needed to make prompt decisions to unexpected situations (e.g., network faults, malfunctioning actuators, conflicting decisions).

A further level, called **application layer**, is needed to manage the underlying entities. This level includes the *AmIBox*, which represents the intelligent core of the system and allows to perform the monitoring and controlling tasks with respect of the overall energy consumption constraints.

In the remainder of this section, we provide a more detailed description of the three physical units which implement the functionalities discussed so far.

A. Collector

AmI systems usually collect information from different sources, so it is necessary to interface these systems with different types of networks, each with its own characteristics. The Collector addresses this task by means of a novel, flexible and scalable architecture adaptable to different types of networks. Scalability is guaranteed by using a hierarchical network model where different Collectors are responsible for managing one or more subnets. The number of collectors is limited only by the higher levels' capacity to manage these devices, whilst the number of subnets managed by a Collector depends on the processing capacity of the Collector itself.

From a logical point of view, the Collector includes a *Management and Coordination Module* which translates the commands received from the AmI components, and manages the various networks connected to the Collector. Moreover, this module implements the centralized functionalities of the Network Management System (NMS) for each subnet, i.e., sensor registration, command dispatch, event/fault management and data delivery.

A SAN interface was designed to connect the Collector with different SANs by means of an abstraction mechanism that allows to separate physical networks from higher level components. In particular, a *data centric* communication paradigm was used to isolate the application layer from issues related to the network management, whilst a unique communication interface to higher levels was defined in order to make them independent from the peculiarities of each network. Thus, the SAN interface allows to translate requests from the management module to the SAN, and to forward information received from the sensor networks to the management and coordination module. Three different data delivery modes are provided: *continuous*, in which information is transmitted at regular time intervals; *event-triggered*, with information being transmitted only when a particular event occurrs; and *query-triggered*, in which information is transmitted on request.

Finally, the description of the networks is based on *SensorML* (OpenGIS Sensor Model Language Encoding Standard) which provides a standard model and an XML encoding of the measurement process.

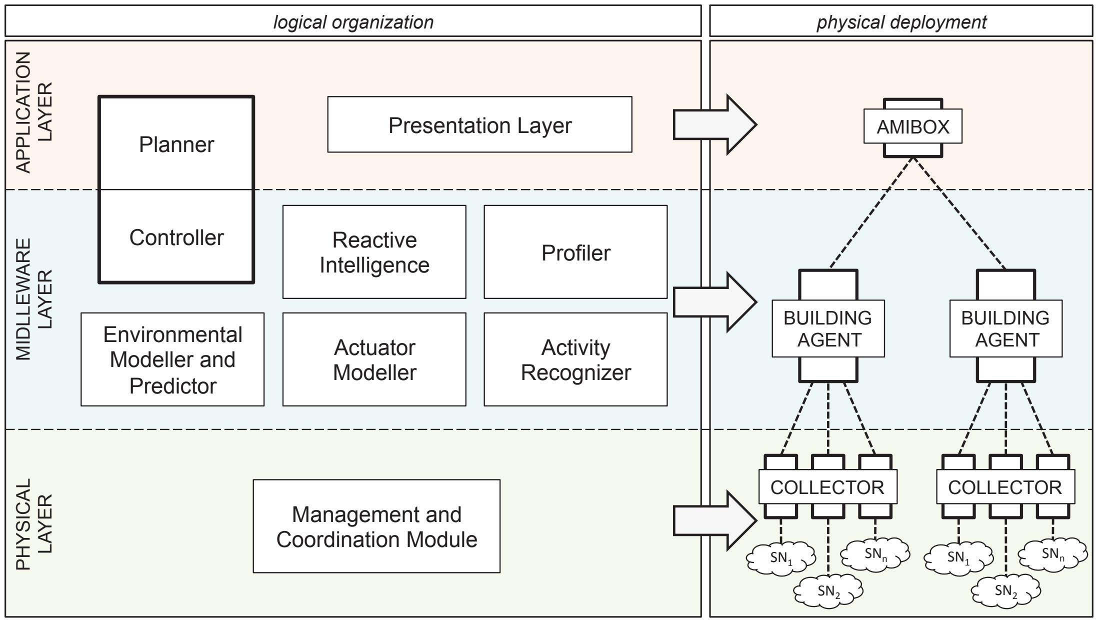

Fig. 1: System architecture. SmartBuildings is organized into three logical layers and consists of three main physical units: the AmIBox, the BuildingAgent and the Collector. A typical deployment consists of a single AmIBox, to manage multiple buildings, and several Collectors per building managed by different BuildingAgents.

B. BuildingAgent

Moving from the physical to the middleware layer, data gathered by several Collectors is analyzed in order to build the models of the monitored environments. This task is accomplished by one or more BuildingAgents depending on the dimensions and the structure of the buildings.

BuildingAgents functionalities are provided by different modules (see Fig. 1).

The *Activity Recognizer* is responsible for analyzing heterogenous sensor data in order to detect and recognize the activities performed by the users. In our architecture, the sensing layer is implemented through both wired and wireless sensor nodes that are able to monitor quantities as temperature, humidity, ambient light exposure and noise level. However, in order to achieve challenging goals such as effectively understanding what the user is doing at a given time, more complex sensors capable of capturing the interactions between the user and the environment are required.

More specifically, software sensors have been installed in users' workstations to measure the idle time, whilst scheduled events are stored on a free time-management web application, i.e., Google Calendar.

Real-time activity recognition is demanded to a probabilistic framework [13], [14] which analyzes 3D data captured by Microsoft Kinect devices placed in the users' office rooms. Firstly, the human body is modeled as a set of *joints*; then, three different machine learning techniques are combined to detect the most significative postures involved while performing an activity (K-means), classify them (Support Vector Machines), and model each activity as a spatio-temporal evolution of known postures (Hidden Markov Models).

The output of the Kinect-based framework and information provided by software sensors represent the input of a more general activity recognition module [15], [16] which uses a probabilistic approach to infer what activity the user is performing, e.g., working on computer, talking on phone, having a meeting. Such information is also used by the *Profiler* to find the correspondences between activities and environmental conditions preferred by the user; that is to associate an activity (e.g, reading) with the context in which it is performed (e.g., table lamp on).

The Kinect is also used as a controller for the actuators [17]. To this end, a fuzzy classifier was trained for analyzing Kinect data and recognizing some simple gestures (i.e., open/closed hands) in order to produce a set of commands, (e.g., turn on/off the light, turn on/off HVAC).

The *Environmental Modeller and Predictor* is mainly responsible of creating the mathematical models which describe how the observed physical quantities (i.e., temperature, humidity) change over time.

Being all these measures somehow related to their historical trend, a reliable representation of the environment should be built on the basis of a certain number of past observations.

The algorithm we developed is based on the approach described in [18], where a predictive controller is trained using both past and forecast information from an external weather forecast service. In particular, a rough 24-hour prediction of the external temperature is generated according to data captured in the past 24 hours; then, as new data is available (every 20 minutes), the prediction is updated by making a linear correction over the next 6 hours. Experimental results showed that the standard deviation from the correct temperature values is about 2.5 degrees for one to three-day predictions.

The same approach is used to predict the indoor temperature and humidity. The first depends on indoor and external temperature captured in the past 24 hours, whilst the latter is dependent both on the humidity values measured in the past 24 hours and on the predicted indoor temperature. The recurrence relations for external temperature T_e, internal temperature T_i and humidity H_i are shown in (1), (2) and (3) respectively.

$$T_e(t) = \alpha_t T_e(t-1) + \beta_t \tag{1}$$

$$\begin{aligned} T_i(t) = {} & \alpha_t T_i(t-1) + \beta_t T_i(t-2) \\ & + \gamma_t T_e(t-1) + \varphi_t T_e(t-2) + \mu_t \end{aligned} \tag{2}$$

$$H_i(t) = \alpha_t H_i(t-1) + \beta_t T_i(t) + \mu_t \tag{3}$$

The parameters (α, β, γ, φ) are used to weight the importance of the factors involved in each prediction. They are initialized so as to minimize the error between actual and predicted values for the past 24 hours; then, for each new measurement taken at time t, the whole set of parameters is updated to minimize the overall prediction error.

The *Reactive Intelligence* module provides some functionalities for the management of unexpected events. In particular, it is responsible for maintaining the observed physical quantities (e.g., temperature) within the range of admissible values chosen by the user. If the safety thresholds are exceeded, the reactive intelligence module decides the actions to perform (e.g., the commands to send to the actuators) in order to bring the system back to a safe state.

When choosing among a set of possible actions, the *Actuator Modeller* is queried to select the best solution according to the specific energy consumptions of the actuators (e.g., in a dark environment to open the curtains is usually preferable to turn on the light).

C. AmIBox

The main task performed by the AmIBox is to make plans to meet the overall energy requirements and users' preferences.

The *Planner* is the core of the AmI system and is responsible for finding a set of actions which, once executed, allows the system to achieve a specific objective. Such an objective, e.g., reducing the energy consumption for heating, can be defined either by the user or, as intermediate goal, by the AmI system itself.

The planning is performed according to data which depend on a specific building and its environment, namely the predictions made by the environmental modeler, the output of the activity recognition module and the users' preferences. From a logical point of view, the Planner includes two distinct components. The former, the deliberative one, is located within the AmIBox and uses a Tabu Search approach to find an optimal set of fuzzy rules that corresponds to the best actions to perform for meeting both the users' preferences and the objective function. The second component, called *Controller*, resides within the BuildingAgent and translates the fuzzy rules selected by the planner into commands to the actuators.

Action	Actuator	Network
Air Conditioning Setting	IguanaWorks IR Transceiver	Wired
Curtain Up/Down	Curtain Motor	Wired
Rolling shutter Up/Down	Rolling Shutter Motor	Wired
Light On/Off	Relay	Wired
Door Open	Electric lock	Wired

TABLE I: List of the actuators used in the deployed case study.

IV. Case Study

SmartBuildings is a prototypal system designed by the NDS (Networking and Distributed Systems) Lab of the University of Palermo and some industrial partners.

In this section we provide a detailed description of the system deployment in two different application scenarios: first is the management of some offices in a Campus, where the main challenge regards dealing with many users with different needs; the second is the monitoring of a Manufacturing Facility while focusing both on the safety of the staff and the energy efficiency of the work environments.

In the Campus scenario we considered private offices and communal areas (e.g., meeting or lecture rooms, hallways, laboratories). The sensor and actuator network is composed of two parts. The wireless one is responsible for monitoring certain important environmental parameters, including temperature, humidity, lighting conditions, CO_2, noise level and HVAC settings. The devices we used are the Crossbow IRIS sensor nodes equipped both with commercial (MTS300 and MTS400) and ad-hoc sensor boards, i.e., one to monitor the level of CO_2 and one to intercept the commands sent to the HVAC.

The wired network is responsible for monitoring the energy consumption and the status of given ad-hoc actuators. In the scenario under consideration, we focused on the monitoring of the energy consumption of both the office as a whole and of certain devices such as lights, HVAC and electrical sockets. The measurements are performed by means of RS-485 digital transducers managed by a master node equipped with a programmed micro-controller. The master node also handles the motion and reads the state of the rolling shutters and the office curtains. Moreover, it controls the relay switch for lighting management and door opening.

In order to simplify network management, sets of nodes are organized into *groups* so that a message can be sent directly to a *group*. Such organization makes it possible to optimize the number of messages forwarded to the network and improve the energy efficiency of the nodes. The network functionalities include setting the data rate for each physical quantity to be acquired, the group membership of a node, the rate for transferring network configuration data, querying the nodes to capture individual physical quantities or to check their status, setting the data collection mode (on event or periodic) and activating/deactivating a single node or a group.

Most sensors deployed in the Campus are also suitable for monitoring industrial environments. However, in this scenario the same amount of care must be devoted to the users as to the machinery.For this reason, the sensor infrastructure has been

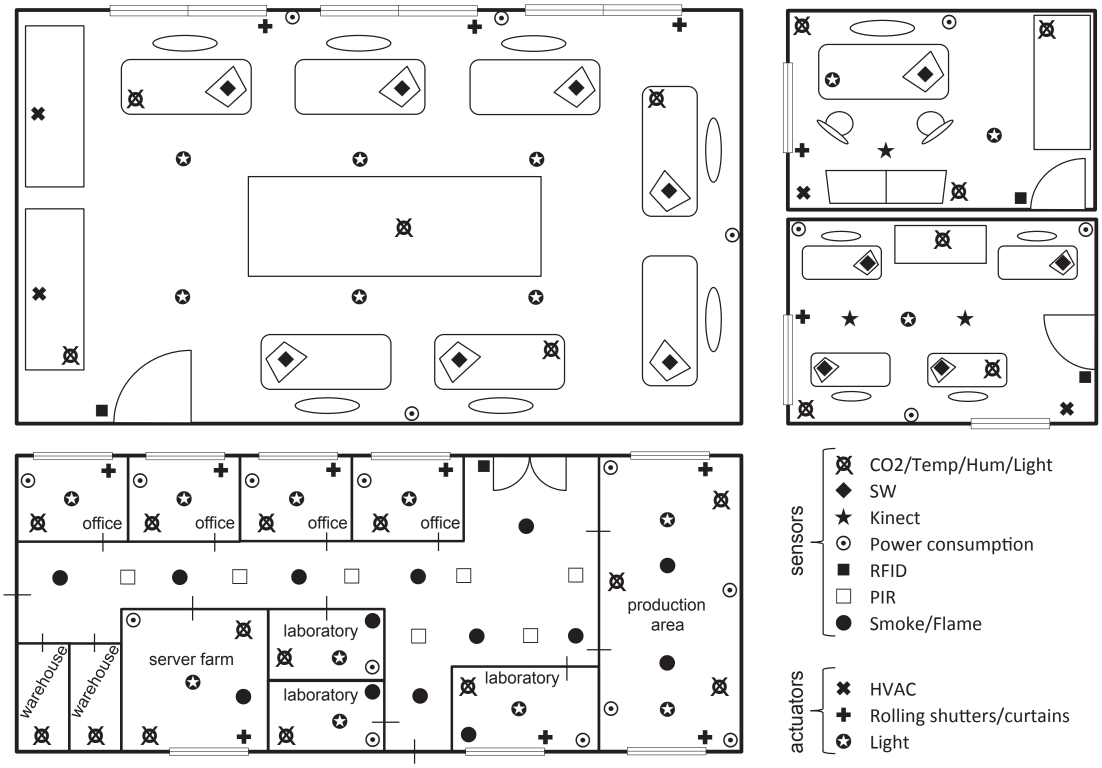

Fig. 2: Deployment of different types of sensors and actuators in the two scenarios we addressed. The top row shows the floor plan of three environments within the Campus (i.e., a laboratory, a private office and a room shared by four people), the bottom row shows the devices deployed in the Manufacturing Facility scenario.

extended to include specific devices such as optical smoke and flame detectors, CO gas sensors, passive infrared (PIR) sensors for motion detection on complex environments, current sensors for monitoring power usage and a weather station for real-time meteorological observations.

The main characteristics of the actuators and sensors deployed in the case study are summarized in Table I and Table II respectively. The floor plans of four environments managed by SmartBuildings are shown in Fig. 2.

Three different hardware solutions were selected to host the components described in Section III. The most appropriate hardware platform for the Collector was chosen by achieving a trade-off between energy consumption and processing capacity. To be specific, we opted for a miniature fanless PC based on an Intel Atom processor that guarantees a power consumption of only 8 Watts.

The BuildingAgent is based on a 2.20GHz Intel Xeon E5 processor which allows to achieve timely analysis of relevant data (e.g., those processed by the reactive intelligence module) and good performance in producing the models of the monitored environments.

The AmIBox requires a greater computational speed to support the continuous planning activity over the entire building. For this reason a multi-core server equipped with 4 Intel Xeon at 2.00 GHz processors was chosen.

The use of energy-consuming servers to provide AmI services for energy efficiency may seem quite contradictory.

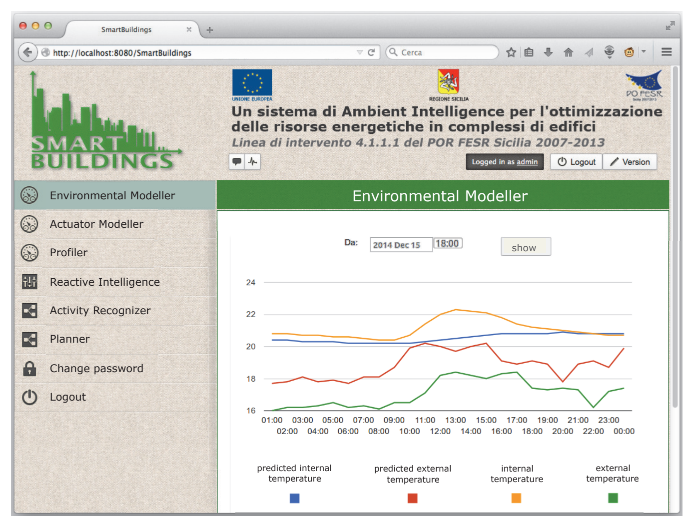

Fig. 3: A screenshot of the Presentation Layer showing the predicted values of internal/external temperature compared to the actual values measured in the past 24 hours.

However, smaller-scale systems are not suitable to perform real-time analysis of huge amount of data. Moreover, focusing on the management of a medium-size building, the energy consumption of the AmI units are negligible since a typical deployment consists of a single AmIBox and several Collectors managed by a single, or just a few, BuildingAgents.

Sensor Type	Model	Network	Main Characteristics
Temperature and Relative Humidity	Sensirion SHT11	WSN	Temperature range: -40 ąC to +123.8 ąC Temp. accuracy: +/- 0.5 ąC @ 25 ąC Humidity range: 0 to 100% RH Absolute RH accuracy: +/- 3.0% RH Low power consumption
Temperature and Pressure	Intersema MS5534AM	WSN	Temperature range: -10 ąC to +60 ąC Temp. accuracy: +/- 0.8 ąC @ 25 ąC Pres. range: 400 to 1100 mBar Pres. Accuracy: +/- 1,5% at 25ąC Low power consumption
Temperature	Panasonic ERT-J1VR103J	WSN	Range: -40ąC to +125ąC Accuracy: +/- 2%
Light	TAOS TSL2550D	WSN	Range: 0 to 1847 lux Spectral responsivity: 400-1000 nm
Air Conditioning sniffer	IR receiver based on chip IR38DM	WSN	Developed ad hoc
CO_2	SenseAir K33LP	WSN	CO_2 range: 0 to 5000 ppm CO_2 accuracy: +/- 30 ppm Low power consumption
Voltage, current, power factor, active power, reactive power, active energy, reactive energy	CE-AJ12-34BS3-1.0	Wired	Accuracy: 0.5%
Curtain sensor Rolling shutter sensor Light On/Off	Developed ad hoc	Wired	-
RFID Reader	LabID KITNLO	Wired	Supported Protocols: ISO 15693, ISO 14443 A, ISO 14443 B - ST SRI family
Proximity reader ISO	LabID RFID Reader RWBLUE	Wired	Supported Protocols: ISO 15693, ISO 14443 A, ISO 14443 B - ST SRI family

TABLE II: List of the sensors used in the deployed case study.

The software architecture of SmartBuildings is based on REST (REpresentational State Transfer) in order to optimize data exchange between software components (services) which reside in different layers of the system. In particular, information need to be transmitted across all the levels of the system, from the sensory nodes to the AmIBox or vice versa, and then accessed by the user through the *presentation layer* (see Fig. 1), which provides all the graphical interfaces needed to manage the AmI system. By means of this layer, the user (e.g., the facility manager) can access both realtime and historical data, define the energy saving policies, supervise the behavior of the modeling and prediction modules and, more generally, be aware of the effectiveness of the system.

A screenshot of the presentation layer showing some results of the Environmental Modeller is shown in Fig. 3.

V. Conclusion

In this work we addressed the issue of improving the energy efficiency of pre-existing buildings by means of an intelligent system, i.e., SmartBuildings, designed to monitor different environments and make decisions according to some overall energy saving strategies.

Compared with well-established building automation solutions, the key idea of SmartBuildings is to exploit the availability of pervasive monitoring devices in order to make the environment responsive to the users' preferences and respectful of the energy saving requirements.

The sensory part of the system is based on a heterogeneous sensor and actuator network managed by coordination units, called Collectors, which include the interfaces needed to implement a two-way communication between the sensors and the high-level components. Collectors are usually responsible for small areas of the buildings, whilst the management of the whole building is demanded to the BuildingAgents. Here resides some intelligent modules responsible for modelling the environments monitored by the system, profiling the users and recognizing the activities they perform, and provide timely reactions (i.e., commands to the actuators) if unexpected events occur. At the upmost level of the architecture we presented, the AmIBox supervise the underlying components by planning the actions which ensure to meet the energy saving requirements defined by the user.

The deployment of a real prototype which addresses two different scenarios, i.e., a Campus and a Manufacturing Facility, allowed for exhaustive testing of the proposed AmI systems in accordance with the practical needs of the occupants the monitored environments.

Even though all the parts of SmartBuildings have been individually tested, an overall evaluation of the AmI system is still missing due both to the complexity of the system itself, and the number of the users involved in the experiments. A comprehensive assessment of the system is still in progress and results will be presented in future work.

Acknowledgment

This work is partially supported by the PO FESR 2007/2013 grant G73F11000130004 funding the SmartBuildings project.

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