A Reference Architecture for Smart and Software-defined Buildings

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Abstract—The vision encompassing Smart and Software-defined Buildings (SSDB) is becoming more and more popular and its implementation is now more accessible due to the widespread adoption of the IoT infrastructure. Some of the most important applications sustaining this vision are energy management, environmental comfort, safety and surveillance. This paper surveys IoT and SSDB technologies and their cooperation towards the realization of Smart Spaces. We propose a four-layer reference architecture and we organize related concepts around it. This conceptual frame is useful to identify the current literature on the topic and to connect the dots into a coherent vision of the future of residential and commercial buildings.

Index Terms—Smart Cities, IoT, Building Operating Systems, Software Defined Systems

I. INTRODUCTION

Smart and Software-defined Buildings (SSDB) represent the introduction of hardware, software and sensing into the places where we live, in the same way as electronics has been introduced into cars and vehicles over the last twenty years. It is therefore the new frontier for what concerns housing solutions [3]. Advanced technology was introduced in cars in 80s initially in expensive models for then becoming the normality for small-size cars, and eventually legal frameworks adjusted in order to make formally mandatory the presence of certain sensing and acting functions [6]. In the same way, technology will possibly enter the market starting from high-end housing and public places to then move to more popular solutions. This paper surveys IoT and SSDB technologies and their cooperation towards the realization of Smart Cities and Smart Environments. We propose a four-layer reference architecture for SSDB and we organize related concepts around it. This conceptual frame is useful to identify the current literature on the topic and to connect the dots into a coherent vision of the future of residential and commercial buildings.

The manuscript is organized as follows: after this introduction of the domain in Section I, we first define Smart and Software Defined Buildings (Section II) and discuss the hardware infrastructure (Section III) and the communication networks and protocols (Section IV) that are necessary for their realization. We then overview the SSDB management in Section V, their applications and services in Section VI and crosscutting concerns in Section VII. Finally, in Section VIII we present our conclusion.

II. SMART AND SOFTWARE DEFINED BUILDINGS

Smart buildings (SB) are structures that use automated processes to control operations such as heating, ventilation, air conditioning, lighting, and security, and allowing sophisticated monitoring and control over their functions [23]. One of the major set of functionalities that can be managed is the one concerning the environment and users’ comfort. This includes temperature, light, and humidity. More complex functions can also be performed such as presence monitoring, identity recognition and detection of users' emotional states [29], under concomitant legal and ethical considerations. SB also represent an important element in a Smart City ecosystem, and are therefore often considered as drivers for the urban smartization process.

A Software Defined Building (SDB) [18], is a “programmable” building abstracting and virtualizing [11] the underlying (ICT) physical infrastructure to make it available (through specific API) for third party applications and services. SDB provide a Building Service Layer to implement an interoperable and programmable environment for their management and to control applications and services, following a software defined approach also adopted in Smart Cities [29]. Smart and Software Defined Building are two related concepts, even if not strictly dependent on each other. An SB can be either based on an SDB or not, and an SDB does not necessarily imply an SB. In the former case of an SB established on top of an SDB, specific SB services and applications for the building management are deployed on the SDB infrastructure by injecting their codes on the SDB programmable devices and nodes. An SDB-powered SB inherits the benefits of programmability from SDB, allowing to reuse and share existing physical resources and infrastructure through different services and applications. This allows that existing applications and services can be easily evolved and/or maintained or even extended with new ones, always exploiting the same SDB infrastructure.

In the SSDB domain we can identify at least three different concepts that can be related to SB: smart home, smart office...
and smart shop. Their interactions and overlapping are shown in Fig. 1. The overall idea lying behind all these concepts is the one of smart space, i.e. a technology-equipped environment (residential, commercial or governmental) that facilitates life and operations of the people who are living it. Domotics and Automation are essential parts of smart spaces, as well as data management and Analytics.

SSDB Reference architecture

One of the contributions of this paper is the identification of a conceptual frame useful to organize concepts around the idea of SSDB. We propose a four-layer reference architecture shown in Fig. 2. At the bottom of the stack, the Hardware layer deals with all aspects related to the SSDB ICT infrastructure, ranging from devices, sensors, actuators and IoT smart objects to network, storage and processing hardware facilities deployed in the building for automation and smart management purposes. Such SSDB nodes, devices, objects and things have to be properly interconnected, exploiting mechanisms and solutions provided by the Network layer. On top of the latter, the Management layer implements facilities for managing Smart Buildings ICT resources and data, dealing with interoperability issues arising from heterogeneous devices, as well as data management issues. Such mechanisms, technologies and solutions allow to implement proper applications and services for a smart building such as those related to smart energy, surveillance, billing, and so on, which are grouped in the Application & Service layer. Finally, Crosscutting Concerns and issues such as security, privacy, AAA, quality of service and similar, spanning the full stack of this Smart Building ICT architecture, are grouped altogether in the corresponding vertical layer. All such layers and modules are detailed in following sections.

The reference architecture of Fig. 2 covers both SDB and SB, highlighting their relationship. An SDB can mainly provide to an SB the ICT infrastructure, thus including the 3 bottom layers and the corresponding crosscutting concerns, while an SB also implements applications and services thus including the corresponding layer. As stated above, SB can even be deployed on SDB, by mainly injecting specific application codes on the programmable building infrastructure. Anyway, the SDB management level is usually more complex than the one of non SDB-powered SB, since it includes specific mechanisms for hardware abstraction through softwarization (API), and control mechanisms on top of this to manage, deploy and orchestrate tasks into pooled resources. This is often implemented through specific Building Operating Systems. In the remaining of the paper we will describe in details each layer above introduced.

III. Hardware

The hardware components that allow the management of the SSDB environment and the data collection are usually referred as Internet of Things (IoT). The advantages of the introduction of this technology seem to overcome the disadvantages and its application becomes easier every year since the price of hardware components is decreasing fast and the power of microprocessors is growing [34]. IoT kept growing for several years now [4]. It has been defined in multiple ways [36], but IoT is now usually used to refer to a set of objects that are connected to the internet and can possibly communicate with each other via different protocols. These objects are sensors, actuators and, more generally, embedded systems. Latest statistics state that there are around 22 billion of IoT devices in the world [5] and enable the creation of a vast range of scenarios where devices communicate and cooperate [26]. These different scenarios regard many fields of our life, for example home automation, health, transportation and logistics. With regard to smart buildings, IoT sensing and actuation components can be categorized as follows:

**Occupancy Detectors**: these are specialized circuits that are placed in light bulbs, doors, and parking lots. They have dedicated motion sensors for sensing if there are individuals in the vicinity. If they detect motion, then the room is activated, which means switching on light bulbs, opening doors, and marking the parking slot as busy.

**Positioning and Tracking**: these sensors are placed on the person of individuals or are placed at different parts of a room to track the position of a person. They are typically used to track the movements of geriatric patients. We can have specialized activity detectors that detect if a patient is falling down, or has suddenly become immobile.

**Ambient Control**: Building automation is typically used in controlling the environment such as the air conditioning systems, heaters, humidity controllers, and for measuring the pollution, and ambient noise. They can be used to optimize
the air conditioning cooling/heating only those parts of build-
ing that are populated. Most buildings with centralized air
conditioning waste a lot of power because they assume that the
total building is populate at all times.

Measurement of Usage: home automation systems are
being extensively used as of today to measure the consumption
of electricity, gas, and water. The power bill or the water bill
based on analyses of usage patterns.

Security: starting from early burglar alarm systems security
has been an important user of home automation technologies.
Modern smart homes have an array of sensors at important
entry points, and integrate this information with the motion
detected from CCTV cameras.

This wide variety of sensors, actuators and devices, is
complemented by networking, storage and processing infras-
structure facilities such as local switches, routers, NATs, and
firewalls for networking, NAS and/or storage servers for stor-
age as well as servers for processing. Of course, storage and
processing servers could even be virtual or remote, provided
by Cloud services.

IV. NETWORKING

From a technical point of view, communication between
devices is an important aspect in building automation systems
[35], which can operate at different levels of abstraction. At the
same time, a fully distributed system can be implemented in
the building, in which the smart nodes interact only with each
other to accomplish the task together. Given that the energy
for communication is expensive, such peer-to-peer interactions
are not preferable. Instead, the standard model is that the IoT
nodes send their data to a centralized controller that collates
all the data, performs some analysis, and then communicates
with other upstream gateways.

Network protocols for Smart Buildings solutions are di-
vided into smart device networks and traditional networks
designed for high-speed data transfer. It is reasonable that
the protocols of smart home networks will use the protocols
already established in wireless sensor networks (WSN) and
machine-to-machine communications (M2M). Since adding
advanced features to a protocol increases the cost and re-
duces usability, developing an attractive protocol is not a
trivial task and usually represents a trade-off between cost
and performance. In terms of the topology used, the mesh
network is the most suitable choice of network topology for
wireless communication due to the presence of obstacles in
the house, such as walls, furniture, etc. [39]. Double mesh,
which means that the network is both wired and wireless,
providing a suitable solution for buildings in which a wired
home automation system was previously installed. There are
many communication networks and protocols designed for
exchanging information with multiple devices, components,
and sensors. Such communication protocols are created by
various organizations, consortia or associations, or can be
developed privately when a protocol is applied only by specific
manufacturer(s) who must first obtain a license to use it. Com-
monly used protocols for communication in smart buildings
via wireless or wired levels are described below [9],[25]:

InfraRed Data Association (IrDA): simple protocol, usu-
ally offering one-way communication. It has a limited range
and requires direct visibility of a pair of receiver-transmitter.

Ethernet: Fast and robust wired communication with a
range of up to 100m, enabling high noise immunity and the
ability to power supply via cable for low power nodes.

UWB: an indoor short-range high-speed wireless communi-
cation (up to 10 m) with the bandwidth of over 110 Mbps (up
to 480 Mbps), which can satisfy most multimedia applications,
such as audio and video delivery in home networks.

WiFi: Fast and reliable wireless IPv6 with a transmission
distance of about 25m. Its main feature is the existing broad
support: almost every new electronic device comes with WiFi
technology installed. As a rule, this is a upper level protocol,
where IP is the most predominant protocol that allows commu-
nications over the Internet without using a protocol translator.

WLAN: Wireless local area network (WLAN), also known
as Wireless Ethernet, is capable to provide reliable communi-
cation with low latency for both point-to-point and point-to-
multi-point transmissions up to 250m. WLAN applies spread
spectrum technology, so users can occupy the same frequency
bands with minimal interference to each other.

Bluetooth: a short-range wireless protocol (up to 10 m),
the main characteristics of which are low power consump-
tion (especially Bluetooth low energy - BLE) and fast data
exchange, as well as widespread availability. Its adaptive
frequency hopping system detects existing signals, such as
WiFi, and coordinates the channel map for Bluetooth devices
to minimize interference. It also implements node discovery
services.

6LoWPAN: the IPv6 low power adaptation for devices
with limited resources, combining the advantages of both IP
and Bluetooth and enabling mesh networks for energy-saving
applications in smart buildings with a distance up to 200m.

Thread: the IPv6-based, low-power technology for IoT
networks designed to provide security and meet future require-
ments. The specification of the Thread protocol is available
free of charge, however, this requires consent and permanent
adherence to the license agreement. Thread exploits 6LoWP-
AN, which is based on the use of a connecting router,
called an edge router. This means that 6LoWPAN does not
know about application protocols and changes that reduces
the load on the computing power at the edge routers. Thread
is designed to exchange data between devices, even when the
WiFi network is turned off.

Zigbee: a wireless mesh network that has proven its effi-
ciency and cost-effectiveness when strengthening and expand-
ing the network, having a transmission distance of 10-75m.
ZigBee offers low data rates for personal area networks (PAN).
It can be widely used in device control, reliable messaging,
building automation, consumer electronics, remote monitoring,
healthcare, and many other areas.

Z-Wave: a mesh network protocol standard designed for
remote control applications in residential and business areas,
whose bandwidth is about 6 times lower than for Zigbee. This, however, requires less energy to cover the same range as Zigbee. The main advantages of this technology come from a simple command structure, freedom from domestic interference, a low frequency bandwidth control environment and IP support. Z-Wave has typically 30m indoor range, which extends up to 100 m outdoors.

**KNX:** one of the most popular open protocols for automation. It operates on several physical levels, such as twisted pair, network power line, infrared, Ethernet and RF channel. Subscribers (devices) connected to the bus (network) can exchange information through a common transmission channel (bus). In this case, the information to be transmitted is packed in a telegram and transmitted via cable from a sensor to actuators. Upon successful transmission and reception, each receiving device confirms the receipt of the telegram, otherwise the transmission is repeated only two more times. If there is no confirmation, the transmission process ends. That is why the KNX protocol is not used in the critical industrial applications. In the decentralized topology, the system does not work from the central unit, which means that each individual unit is connected to the most intelligent device of the KNX ecosystem and does not depend on the functioning of other parts. Therefore, if one unit fails, others may continue to work.

**V. Management**

The Smart Building Management layer is in charge of managing the ICT infrastructure. Management functionalities form two groups: resource management and data management.

**A. Resource Management**

Smart buildings are melting pots of different, heterogeneous technologies, especially concerning sensing and actuation devices. To deal with such heterogeneity issues in Smart buildings, specific solution have been developed, mostly in form of operating systems. A first attempt in this direction is implemented by building management system (BMS) or building automation system (BAS) [9], providing an automation solution for controlling heating, ventilation and air conditioning (HVAC), security, fire, power, water supply and elevator systems of a building in a coordinated way. Extending the scope beyond automation, some attempts in defining more general building operating systems (BOS) have been performed, most of them reported and compared in [21], which also proposes a quite advanced BOS solution named XBOS. However, among them, one of the most relevant is the Building Operating System Services (BOSS) [17], since it defined a new approach to deal with smart buildings: through programmable buildings. This way, the idea of SDB is slowly affirming the smart building context, even if its potential is still untapped and should be further investigated and implemented. Even the concept of virtualization and virtualized buildings have been recently defined in [11], but there is still room for Building Function Virtualization (BFV) and new Virtual Building Functions (VBF).

The basic design philosophy of a building operating system is the plurality of possibly unrelated applications, high requirements of fault tolerance, and a very flexible specification for interacting with a plethora of applications. Some of the major issues to address by a BOS are related to interoperability, scheduling, placement, pooling and orchestration.

**B. Data Management**

The storage and analysis of Smart Building data is challenging in several ways. First, due to the diversity of systems [31] and technologies, the building automation technique faces a long relation with interoperability, leading to data integration concerns [23]. Secondly, for a better perception and control of instruments, the density of sensors, promptly increases, generating a vast amount of data. Bashir et al [14] propose a big data analytic framework for smart buildings. Let us divide a typically data processing architecture into several layers.

**Sensor layer:** This layer consists of sensors that generate data, and record ambient parameters.

**Data storage:** This information is communicated to routing nodes that collect the data and store it. Bashir et al. propose a TCP based protocol for communicating data and storing it in a cloud based database. Often no-SQL databases are used to store such streaming data such as Apache Flume, and HDFS.

**Analytics:** Some of the common engines that are used on such platforms are based on the classic Spark toolkit such as PySpark. PySpark can be used to set alerts and thresholds such as: once the level of oxygen dips in a room, oxygen pumps can be automatically started.

**Rule Engine:** This is an engine that has a set of pre-written rules. Every rule has a set of pre-conditions, and a set of actions. If the conditions for firing a rule exist, then the rule is fired, and appropriate action is taken.

**Visualization:** The last component, where users can visualize all the elements in the SSDB, the data that are generated, and the actions that are being performed.

**VI. Applications, Services and Ambient Intelligence**

From an end-user/application perspective, the idea of SB belongs to a wider concept: Ambient Intelligence (AmI) [33]. According to AmI vision, the environment is able to anticipate the needs of its inhabitants therefore responding in a timely and user-friendly way. Implementing the vision of AmI is highly ambitious, however to reach this objective it is necessary to realize at least a basic set of services that should be part of normal Smart Buildings’ behavior. In this section, we will discuss the main application and services that Smart Building should offer towards this vision. We identify three major areas where benefits may soon appear: Energy Management, Environmental Comfort and Safety and Surveillance

**A. Energy Management**

Given rising energy costs, energy management in modern buildings is vitally important. Almost all new constructions
need be green buildings. The reasons are that modern houses and buildings consume a lot of energy, which can be reduced by efficient management. Consumption in residential buildings accounts for about 40% of the total energy consumption in the world. In comparison, commercial and business buildings (offices, shops, shopping malls, hotels...) and spaces with public functions (schools, hospitals...) use approximately 30% of energy resources [1]. In recent years there has been a growing number of energy regulations and certifications, so the necessity to reduce energy consumption has become more urgent. At the same time, rising energy costs have made efficient energy management a matter of survival.

It is not surprising that in such a growing market the major IT corporations have realized the importance of home and building automation, in particular the aspects that concern energy management. Intel, for example, provides an IoT platform with analytics to offer building operators and managers the possibility of keeping systems functional and cost-effective [7]. The Nokia smart building energy management application has been designed to monitor and control critical building systems and ensure efficient operation. Reporting and alerts help managers in determining the areas where there is high energy consumption, and the energy use can be optimized [5]. Academic research has also focused on the topic of identifying open issues and possible solutions [32] and characterizing energy management systems (EMS) [37]. An energy management system is defined as a computer-aided tool used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system. Some researchers have gone beyond the identification of issues and have proposed approaches and technology stacks, and in fact designed functioning energy management systems for smart homes [38].

A Home/Building Energy Management System (H/BEMS) is a system that incorporates sensors in household appliances through a home/building network to optimize energy consumption. Most of the academic and industrial solutions are defined according to a general architecture for H/BEMS. This is composed of a Home/Building Area Network (H/BAN), a local residential network interconnecting devices (sensors, smart plugs, intelligent thermostats, cameras). It could be a wireless wired network. Then, Monitoring and Control Devices are responsible for monitoring and controlling the energy consumption of appliances and devices. Processors are in charge of concentration, storage and management of the information. The server and the database are in this central module. Gateways ensure connection between the H/BEMS and the outside to allow remote access.

B. Environmental Comfort

The basic function of Smart Building is to regulate environment parameters such temperature, humidity, lightning to maximize comfort. This problem has been considered in literature in non-trivial way. For example, in [30] a dynamic thermal model of occupants has been proposed. The model is based on the heat balance equation of human body and thermal characteristics of the occupants. In the context of Smart Offices, occupant satisfaction with indoor environmental conditions has been studied in [13]. This application area is broader than just regulating temperature and similar parameter. While some of the results of environmental regulation have to be immediate and promptly perceivable, sometime well-being of space inhabitants may depend on factor that require deeper attention. In [16] the authors introduce a real system deployed in the offices of four Microsoft campuses in China in order to monitor indoor air quality enabling employees to enquire the air quality of a place by using a mobile phone or checking a website and then make informed decisions.

C. Safety and Surveillance

Maximal safety conditions are guaranteed by Smart Buildings through surveillance operated by IoT technology. Cameras are just one of the basic instruments of surveillance, but it is certainly not the only one. Access authorization can be performed via biometric parameter and face recognition can be used for security reason. It is important to emphasize that, although the device infrastructure is an important element to ensure safety, it is the software playing a major role here. In [12] the authors realized that information provided by single sensor and surveillance technology may not be sufficient to understand the whole context of the monitored environment, and therefore propose the Smart Building Suite, where independent and different technologies are developed in order to realize a multimodal surveillance system.

VII. CROSSCUTTING CONCERNS

Crosscutting Concerns are issues spanning the full stack of our reference architecture. Each of these would require a separate investigation. Given the limited space we will here scratch the surface and identify two of these concerns:

Security: The more a building is connected the more security threats it is subject to. Given the experiences with automotive or other devices, building owner may be aware of it [2], [20]. The problem has to be addressed from two different point of view: technical and communication.

Adaptability: Information internally and externally gathered from a range of sources can be used to prepare buildings for a particular event before that event actually happens [15]. This is a radical shift from the idea of reactive building to the one of proactive. Smart Buildings should be adaptive. For example a building can adapt to different times of year and different people’s perceptions of comfort.

VIII. CONCLUSIONS

In this paper we surveyed SSDB and related technologies, and looked into the major solutions proposed by industry and academia. We would like here to emphasize the major concerns for the widespread adoption of such technologies:

Skilled Operators: people do not know the existence of the described frameworks. In general, operators have no experience and skills in managing Smart Buildings and analyzing large amounts of performance data. Even adopting
the technology, it will take a significant training effort before operating buildings in the optimal way [10].

Costs of startup and maintenance: installing such technologies and maintaining them is at the moment expensive and we are not aware of tax incentives in most of the countries. Without some kind of incentives it will be hard to convince building owners that the investment is worth the cost, especially for small- and medium-sized buildings [2].

Interoperability: as mentioned before in this paper, not all smart devices are interoperable with each other and making things work could be a challenge. Standard protocols to connect all devices do not exist at the moment [23]. There are several aspects that we did not cover here, but that would deserve a separate discussion. First, Autonomous Cars and Smart Buildings are two emerging technologies that are destined to cooperate [22], [40]. Second, the use of cryptocurrencies for payments and financial interactions between smart entities will soon emerge as a consuetude, and most likely Blockchain may be the enabling backbone [24].

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