Interoperable and Intelligent Architecture for Smart Buildings

Pedro Gonzalez-Gil
Department of Information and Communications Engineering
University of Murcia
Murcia, Spain
0000-0001-6338-1603

Rafael Marin-Perez
Odin Solutions S.L.
Murcia, Spain
0000-0002-8521-1864

Aurora González-Vidal
Department of Information and Communications Engineering
University of Murcia
Murcia, Spain
0000-0002-4398-0243

Alfonso P. Ramallo-González
Department of Information and Communications Engineering
University of Murcia
Murcia, Spain
0000-0001-7021-0634

Antonio F. Skarmeta
Department of Information and Communications Engineering
University of Murcia
Murcia, Spain
0000-0002-5525-1259

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***Abstract*—Smart Building is essential to advance towards more comfortable and sustainable cities. However, existing Building Management Systems (BMS) are proprietary non-interoperable solutions based on automatic operations configured by the users. These BMS can not control intelligently current and future buildings with highly heterogeneous legacy appliances and equipment including renewable energy generation, storage, e-vehicles charging points among others. In order to achieve it, this paper proposes an interoperable and intelligent architecture based on recent ICT technologies such as Internet of Things, Artificial Intelligence and Cybersecurity Protocols. This architecture provides five main innovations such as adapt-&-play hardware integration, standardised multi-systems interoperability, building/human behaviours prediction, security/privacy protection and smart services provision for increasing building energy-efficiency, occupants' well-being and grid flexibility. To evaluate the proposed architecture, five diverse European pilots have been proposed. Specifically, this paper presents the Spanish pilot with multiple heterogeneous equipment and systems that will be employed to demonstrate the impact of the proposed architecture.**

***Index Terms*—Internet of Things, Artificial Intelligence, Smart Buildings**

I. INTRODUCTION

Smart Building [1] has emerged as one of the most relevant innovation to tackle the energy consumption and pollution associated to the growth of urban population and cities. The building sector is deemed to account for around 40% of final energy consumption in developed countries and for 36% of greenhouse gas emissions in Europe [2]. It is therefore, important to give a particular emphasis to improving energy performance of buildings. At present, about 45% of the EU's buildings are over 50 years old and almost 75% of the building stock can be considered as energy inefficient [3]. This issue is even more worrying in the light that 75–90% of the existing buildings are expected to be standing by 2050. At the same time, only 0.4-1.2% (depending on the country) of the building stock is renovated each year [4]. Refurbishment of existing buildings could lead to significant energy savings and play a key role transitioning to clean energy, as it could reduce EU's total energy consumption by 5-6% and lower CO2 emissions by about 5%. Therefore, stricter and newer international regulations for reducing the power consumption and pollution in buildings, are currently being developed [7]. Concretely, EU has committed to reduce by at least 40% greenhouse gas emission by 2030. To do so, a new framework called "Clean energy for all Europeans package" has defined new regulations, which set the necessary legal framework and financial infrastructure to achieve this ambitious goal. In particular, the new Energy Performance Building Directive (EPBD) aims to promote energy efficiency, renewable energy production, grid flexibility and user interaction. In this context, Smart Building technologies are essential for achieving more energy-efficient, comfortable, sustainable and clean cities.

Nowadays, most of current Building Management Systems (BMS) focus on the improvement of the energy efficiency [9]. These BMS provide limited energy saving by means of automatic operations configured manually by building administrators. Nevertheless, these BMS based on energy-driven automated operation have created human-related problems such as health issues, uncomfortable workplaces, overall dissatisfaction with automation, etc. For this reason, new user-

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centric BMS need to be created to meet the necessities of building occupants. Moreover, an essential part of new BMS solutions is the changing role of buildings from consuming energy to actively controlling and optimising the indoor comfort while contributing to energy system flexibility by ensuring distributed energy generation from renewable energy sources, energy storage, facilitation of e-vehicles charging. To achieve that, grid flexibility (e.g. demand response) has been researched for many years, however, their application in cooperation with BMS systems has been limited. Thus, more intelligent BMS systems considering the needs of occupants and grid have to be developed.

On the other hand, current and future buildings tend to include heterogeneous legacy appliances and equipment such as renewable energy generation, storage and e-vehicles charging points among others [8]. In that sense, the development of Smart Building technology is a complex domain due to the high variety of legacy equipment (i.e. domestic appliances such as refrigerators, dryer, HVAC, lighting, etc), smart devices (i.e. metering) and local systems employing many different technologies for communications, sensing, and data processing. The available equipment and systems in buildings have to be integrated and upgraded in order to provide new services that will benefit both building users and the grid. To facilitate the digital transformation of buildings equipped with legacy appliances and systems, towards smart environments, it is required to combine innovative ICT technologies such as Internet of Things - IoT, Artificial Intelligence - AI, and Cloud Computing among others.

To cope with this gap, this work proposes an interoperable and intelligent architecture based on recent ICT technologies such as IoT, AI and Cloud for increasing building energy-efficiency, occupants' well-being and grid flexibility. The proposed architecture tackles the main challenges identified to develop future smart buildings with highly heterogeneous legacy equipment and systems, including renewable energy production, storage and grid interactions. To achieve this ambitious goal, the architecture provides five main innovations such as adapt-&-play IoT hardware integration, standardised multi-systems interoperability, building/human behaviours prediction based on AI toolbox, security/privacy by-design protection and smart services provision to both building occupants and energy utilities. For demonstrating the real impact and replicability of this architecture, five diverse pilots have been proposed at European level (i.e. Ireland, Greece, Sweden and Spain). This work describes the Spanish pilot with multiple heterogeneous equipment and systems that will be used to evaluate the performance results of the technological architecture.

The rest of the paper is organised as follows. Section II, describes the background in Smart Building domain and their main challenges. Section III explains the proposed architecture including five main innovations. Section IV indicates the 5 different pilots at European level and details the real-world Spanish pilot for demonstration and impact evaluation. Finally, Section V provides the conclusions and future work.

II. BACKGROUND IN SMART BUILDINGS

The digital transformation of the existing European building stock requires a solution based on ICT technologies such as Internet of Things (IoT), Artificial Intelligence (AI), Data Analytics and Cloud Computing, that also takes care of the business exploitation of the innovations created in the process.

The installed equipment in buildings needs to be either integrated or upgraded, to provide new services that will benefit both users and the grid. In particular, multiple Plug-&-Play IoT gateways, sensors, actuators and communication systems can be deployed to monitor and control the operation of the building. All data gathered by these different sources needs to be analysed by means of AI algorithms that can support decision-making of individuals (occupants, managers, energy utilities agents) and automatise the operation of systems and appliances which means, in general, provide intelligence to the building. State-of-the art AI approaches include the prediction of energy consumption [10], that serves in the optimisation of the grid, predictive control of HVAC and natural ventilation [11] and occupancy and window-opening behaviour analysis [12]. Data and communication systems face potential security and privacy risks, which may result in a significantly reduction of end-user's confidence. In the literature, we see that blockchains can be used for providing a secure data transfer between surfaces in buildings [13].

When automation technologies exist in buildings, they mostly focus on the improvement of the energy efficiency neglecting possible human-related problems such as uncomfortable spaces [16] and health issues. Therefore, new user-centric services need to be created, to meet the necessities of people. Services for grid flexibility (e.g. demand response [14]) have been studied for many years, but their application has been limited. Thus, new flexible services for the grid need to be developed. Finally, the exploitation of all technological innovations and new services oriented to building users and grid stakeholders is key so that projects can have an impact in society. An example of IoT business model for smart buildings management is found in [15].

To facilitate buildings' transformation, international organisations have come forth to establish homogeneous guidelines and standards. The Industrial Internet Consortium (IIC) defined the Industrial Internet Reference Architecture (IIRA) including multiple layers (business, functional, information, communication, integration and asset). A very similar structure was proposed by FIWARE and IDSA (International Data Space Association) too, which addresses interoperability with many heterogeneous equipment and ICT systems.

A. Main challenges for upgrading the smartness of existing buildings

Given such background, we have identified the following main challenges for upgrading the smartness of existing buildings:

1) **Allow seamless integration of domestic appliances, legacy equipment and building systems.** The proliferation of smart devices, provides the opportunity for a

close control of the energy flows within buildings, with the added potential of reducing wastage and increasing efficiency. Different families of connected devices are already present; from envelope adaptation such as shading, window control, mechanical ventilation or heat recovery; to small appliances, devices and entertainment kits. In this scenario, creating solutions capable of automatically controlling building equipment to take advantage of synergies and strategies of operation that minimise the energy use and maximise the comfort and security in the building is key.

2) **Create building knowledge with innovative techniques to upgrade the smartness of existing buildings.** The introduction of the Smart Readiness Indicator (SRI) in the new EPBD, marks the compromise of the European Commission with energy reduction and improved experience in buildings. This indicator aims at identifying the level of smartness that a building is able to achieve. In the same way as the building performance certificate, making the SRI a visible feature of the building will be regarded as an added value of the property. It is expected to motivate an even bigger proliferation of artificial intelligence and data analytic tools. Despite these technologies, we are still lacking means to increase the smartness of buildings. Leveraging the connected nature of this devices, we can take advantage of it to develop intelligent services designed for each building to achieve the potential benefits in efficiency and comfort.
3) **Enable real-time communication with energy stakeholders to optimise the grid operation.** The potential smartness of buildings will convert them into active agents of the energy system. The future energy system must enable the creation of an energy data economy based on the interoperability with building management systems. To achieve that, it needs to facilitate the grid interactions and develop new services that will allow energy companies to take advantage of novel revenue streams based on mitigating inefficiencies in the system.
4) **Provide cost-effective services for building end-users to maximise the energy efficiency and the overall performance.** A number of studies relate internal conditions of the building with health and productivity, showing that indoor conditions have a substantial impact in humans. Extreme events, such as heat waves, linked to increasing morbidity among the most vulnerable citizen groups, have seen an increase due to climate change. Smart control and sensing offer an opportunity for improving this situation. Building sensors capable of recognising the thermal response of a building, can help under a thermal extreme event, even helping to identify buildings in energy poverty, requiring help from the councils, or those with inadequate conditions, falling into health risks. To ensure that the new paradigm of smart buildings helps on the improvement of the living conditions, specially those at a health risk, it is crucial that user-friendly services and techniques must be created, so building users can easily interact with the building systems and also the human behaviour can be analysed and applied to provide automated well-being operations.
5) **Allow security and privacy of building data regarding the revised EPBD and the GDPR law.** Secure data exchange within the building stock is currently limited due to the heterogeneity of the data sources and the lack of interoperable standards, the different requirements of the different parts and the lack of a common data exchange model considering security and privacy aspects. Having such model is the first step for wide scale deployment of solutions aiming at absorbing the data and being exchanged for optimising energy use. A standard for secure data exchange will be capable of establishing a common language for the variety of agents that will coexist in the future building stock of smart buildings. A secure reference architecture also needs to be in place to integrate existing systems, and to offer data services for current and future actors in the energy domain.

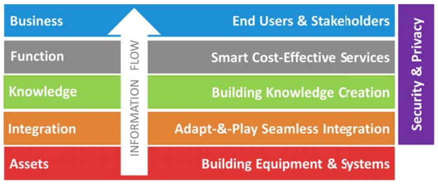

Fig. 1. PHOENIX Conceptual Architecture for Smart Buildings

III. PROPOSED ARCHITECTURE BASED ON 5 MAIN INNOVATIONS

To cope with the mentioned challenges and following previously referenced architectures (i.e. International Data Spaces -IDS- and FIWARE), we propose the PHOENIX architecture, divided into five horizontal layers and a vertical security layer, in order to develop, integrate and deploy a secure interoperable and intelligent ecosystem for enabling energy-efficient smart buildings as well as the interactions with non-technical end-users and stakeholders. This architecture is depicted in Figure 1 using a conceptual design, based in the flow of generating data, information and knowledge extraction from building assets and provision of business and services data analysis through the following layers:

1) **Business layer** represents the point of views and the interactions with end-users (e.g. building owners) and stakeholders (e.g. Energy Aggregators).
2) **Function layer** includes multiple smart cost-effective services offered to end users, to optimise energy savings, occupants' satisfaction, the overall performance of the buildings and grid operations.
3) **Knowledge layer** enables modular tools for creating building knowledge, based on homogenised data through data processing and analytic.
4) **Integration layer** provides the mechanisms for remote control and data monitoring from different build-

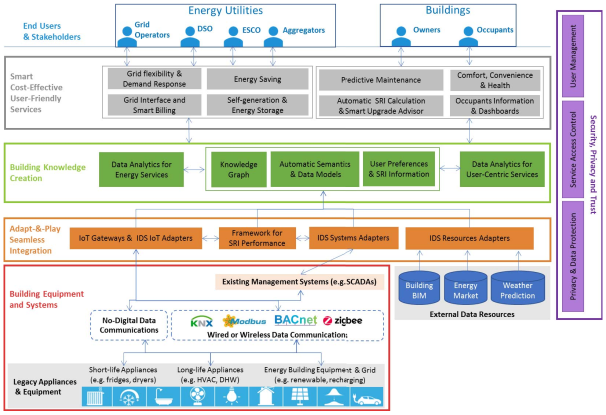

Fig. 2. PHOENIX Architecture for Smart Buildings

ing equipment, systems and external data sources (i.e. weather predictions) with heterogeneous protocols.

5) **Asset layer** consists of heterogeneous legacy equipment and systems already deployed in buildings that must be integrated and managed intelligently.
6) **Vertical protection layer** provides techniques and protocols to ensure the security, privacy and trust of the data exchange in the horizontal layers.

The PHOENIX architecture is based on open & secure Application Programming Interfaces (APIs) to enable deep integration of existing building systems, the incorporation of new mechanisms or tools by third-parties as well as the development of new services and business opportunities between multiple actors. The interoperable and intelligent architecture provides advanced capacity to integrate and process all kinds of building data and knowledge to improve the smartness of services offered to end-users and stakeholders. The architecture offers user-friendly services for inexpert users (i.e. building owners and occupants) to facilitate the easy use as well as to maximise the occupants comfort. Such services will be implemented following a cost-effective principle to minimise the costs of installation and maintenance as well as to maximise the energy savings.

A. Detailed Layers and Components of Proposed Architecture

The layers and main components of the proposed architecture as well as their relations and interactions are shown in Figure 2 and described below.

Asset Layer: Legacy Equipment and Building Systems. This layer consists of the following heterogeneous equipment and existing building management systems:

- Short-life appliances (e.g. fridges, ovens, microwaves, etc).
- Long-life appliances (e.g. HVAC, boilers, radiators, DHW (domestic hot water), ventilation, lighting, etc.)
- Energy building equipment (e.g. renewable sources, energy storage, e-vehicle recharging points, energy demanding points, smart meters, etc).
- Building management systems (BMS) already deployed in existing buildings to monitor and control legacy equipment.

These building equipments can be grouped in two categories according to their capacities to communicate within the PHOENIX architecture. First, digital equipment (e.g. HVAC, smart appliances) with wired or wireless communication for monitoring and control based on technologies such as Modbus, Zigbee, etc. Then non-digital devices (e.g. ovens, microwaves) that do not have the capacity for data communications.

Integration Layer: Adapt-&-Play Seamless Integration. To integrate building equipment, this layer provides multiples IoT Gateways and Smart Controllers to turn on/off and measure the consumption of non-digital devices as well as translating legacy protocols (e.g. Modbus, Zigbee, etc) of digital equipment, to standardised Internet protocols (e.g. IP, REST) in order to monitor and control their operations. Moreover, this layer allows the integration of existing BMS as well as external data sources offering building information, energy tariffs, weather predictions among others. To achieve a high interoperability, this layer follows the standard IDS approach that proposes multiple Agents to support the communication with different Internet protocols (i.e. COAP, REST, MQTT, HTTP, etc.) and heterogeneous data formats (i.e. XML, JSON, JSON-LD etc.) for the seamless interactions with IoT gateways, BMS and external data sources. This interoperable layer homogenises the communication protocols and data formats to enable an easy link between the physical assets and the next layer of knowledge creation.

Knowledge Layer: Building Knowledge Creation To create building knowledge, this layer follows standardised semantic representation and data models such as Smart Appliances REFerence (SAREF) and ETSI NGSI Data Model, among others which will be composed and extended. In this layer, we incorporate knowledge techniques and annotations to automatically assign semantic annotations to legacy building data, by using artificial intelligence (AI) methods, such as clustering and classification in order to build a Building Knowledge Graph (BKG). Our algorithms also enable self-learning capacities and automatic decisions in univariate and multivariate scenarios to improve energy savings and the overall performance of buildings. Moreover, these data algorithms generate valuable knowledge to feed the upper layer of smart services for building users and grid interactions.

Function Layer: Smart Cost-Effective User-Friendly Services. This layer provides two groups of smart services with user-friendly interfaces oriented on non-technical end-users (e.g. building owners) and technical stakeholders (e.g. energy aggregators). Such smart services will optimise the following key aspects: energy saving, grid flexibility, self-generation, comfort, convenience, health, maintenance and occupants' information. To achieve that, this layer offers decision support dashboards and grid communication interfaces to allow the smart building operations according to the needs of end-users and grid, respectively.

Business Layer: Building End-Users & Stakeholders.

This layer provides non-technical and business aspects for the digital transformation and smartness improvement of buildings sector to create holistic links among different business models based on hardware and software as services.

Protection Layer: Security, Privacy and Trust. Due to the interoperable and connected nature of smart building ecosystem, security and privacy mechanisms are required to protect the data exchange among physical assets, integration agents, knowledge processing techniques, smart services and user interfaces in all above-mentioned layers. This layer includes standardised security/privacy mechanisms (e.g. FIWARE Security Enablers) to allow end-to-end data protection, devices/systems authentication, privacy preserving, services access control and user management.

B. Main Innovations beyond State of the Art

The PHOENIX architecture provides 5 main innovations beyond State of the Art (SoTA) in different technological areas described below.

1) **Hardware solutions for connection and smart control of legacy systems and appliances.** The proposed architecture enables to upgrade a large number of legacy systems and appliances in existing buildings by using Plug-&-Play gateways and smart controllers. Diverse communication technologies (e.g. Modbus, Zwave, Zigbee) are supported by PHOENIX to connect the legacy systems and appliances. The greatest novelty brought by PHOENIX in this area is the seamless integration and adaptation of heterogeneous technologies and communications protocols in existing buildings to upgrade the smartness of all legacy systems and appliances.
2) **Interoperability for multi-systems data exchange.** This work aims at creating an ICT-based architecture that is highly versatile, modular and interoperable based on standardised semantics and interfaces. To achieve that, it provides automatic semantic labelling and an IDS for enabling the multi-systems data exchange with Building Management Systems (BMS) and external data sources. This architecture supports the heterogeneity and multi-systems nature of the data relevant to smart buildings. The modular and openness features makes the architecture easily adoptable and used by various smart buildings administrators.
3) **Data analytic and Artificial Intelligence toolbox for smart building domain and human-related data.** Unlike traditional BMS focused on energy saving, this work proposes to exploit all the data integrated using a toolbox of data analytic and artificial intelligence to maximise both the well-being of building's occupants and energy efficiency. To do that, PHOENIX provides data analytics and AI algorithms for predicting energy consumption, production, storage as well as human behaviour and predictive maintenance patterns based on various sources of data.
4) **Smart services for the grid sector and building users.** The architecture offers multiple smart services to end-users, to optimise the energy saving, the occupants' satisfaction, the overall performance of the buildings and grid operations. It provides to grid operators and other energy agents the provision of up-to-date, nowcast and forecast information of the current energy situation of the building to optimise the demand response, load shifting, grid flexibility. For building users, cost-effective services with user-friendly interfaces enable decisions-support for energy efficiency considering user-profile preferences to preserve the comfort, convenience and well-being.
5) **Security, Privacy and Trust.** Instead of considering security and privacy concerns like isolated issues, a combined protection cross-layer is implemented with standardised FiWARE Security Enablers and IoT security protocols for lightweight authentication, authorisation, privacy preserving, identity management and access control in order to allow trustworthy multi-party and multi-systems data exchange. This cross-layer also includes a lightweight federation-like approach for supporting distributed interoperability as well as blockchain-based Distributed Ledger Technology (DLT) for smart billing.

Fig. 3. Real-World Spanish Pilot for Smart Building

IV. REAL-WORLD PILOT OF SMART BUILDINGS AT EUROPEAN LEVEL

For demonstrating the real impact and replicability of the proposed architecture, five diverse pilots have been proposed at European level (i.e. Ireland, Greece, Sweden and Spain). Due to the limit of pages, we focus on describing the real-world Spanish pilot in the University of Murcia (UMU).

In UMU premises, the first building of the pilot has a plot area delimited for the construction of the building which is practically square and has an area of 10,982.77 m2 (see Figure 3). It consists of five floors in addition to the ground floor, spread over four blocks. Block one has five floors, block two has three floors and building three has three floors. The fourth block is a library with two elevations. Horizontally the building is organised around a large corridor axis that separates the research areas of the Library area, whose extension would allow connecting in the future with extensions. The orientation of the building is 20º with respect to the North axis, having latitude of 38º. This building has in its car park a PV installation which energy production is sent to the grid. This

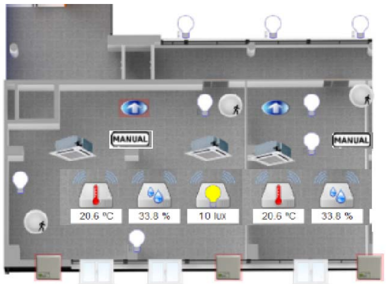

Fig. 4. Diagram of Building Equipment & Systems Available in the Pilot

installation is being monitored in real time, and historical records are available.

Also, a fleet of electric vehicles are available what allows to have a complete set of storage solutions. The vehicles are equipped with lead-acid batteries that can be used as storage of electrical energy to cover peaks. The chargers for these vehicles are monitored and actuation is possible over them to optimise the charging scheduling.

A. Existing Building Equipment & Systems

This pilot includes the following relevant building equipment and systems to be integrated and upgraded by the intelligent PHOENIX architecture:

- Smart meters for the whole building and sub-circuits,
- Temperature, humidity and luminosity sensors,
- Existing building management system (BMS),
- Centralised air conditioning and handling unit,
- Individual ventilation systems,
- Solar thermal installation for domestic hot water,
- EV charging points for a fleet of electric vehicles,
- Solar Photo-voltaic panels for energy generation,
- Dedicated Weather Station.

V. CONCLUSIONS AND FUTURE WORK

To achieve more comfortable and sustainable cities, this paper proposed an interoperable and intelligent architecture based on recent ICT technologies such as IoT, AI and Cybersecurity for upgrading the smartness of existing buildings with highly heterogeneous equipment and systems. To do that, this work identifies the main challenges of future smart buildings and follows standardised reference architectures (i.e. IIRA, IDS and FIWARE). Concretely, the proposed architecture consists of five horizontal layers and a vertical security layer in order to provide five main innovations such as adapt-&-play hardware integration, standardised multi-systems interoperability, building/human behaviours prediction, security/privacy protection and smart services provision for increasing the building energy-efficiency, the occupants' well-being and grid flexibility. To demonstrate and evaluate the impact of the PHOENIX architecture, five different European pilots have been proposed. Mainly this paper described a real-world Spanish pilot including a wide set of building equipment and systems such as energy PV generation, batteries storage, e-vehicles charging points and different types of sensors and devices like HVAC, lighting, ventilation, domestic hot water among others. As future work, we will deploy the proposed architecture with its hardware/software innovations in the real-world pilots to evaluate occupants' satisfaction, energy saving and overall performance of the buildings.

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