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A secure and distributed message oriented middleware for smart building applications

Georgios Lilis*, Maher Kayal

EPFL STI IEL GR-KA, Station 11, Lausanne CH-1015, Switzerland

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ABSTRACT

In the era of the Internet of Things (IoT) and heterogeneous Information and Communication Technology (ICT) systems, monolithic and proprietary Smart Building (SB) systems are unable to address the challenges of scalability, adaptability, and security. Improved integration and interoperability of the existing and future technologies are essential for overcoming the barriers of SB adoption. This paper proposes a real-time, brokerless, and message-oriented middleware (MoM) system for interfacing and interconnecting the digital and physical assets of the SB. It provides a holistic abstraction to the building management system (BMS) of the underlying device protocols and building construction properties, simplifying the design and reducing the overall system cost. Its distributed architecture scales to any building construction regardless of the devices' performance and connectivity limitations. A secure architecture ensures the integrity of data and operations, and an extensive performance and energy efficiency study validates the proposed design. While MoM systems have been traditionally used in cloud computing, it is the first time that such approach, based on building-distributed embedded electronics and the efficient ZeroMQ messaging library, is successfully validated for a cyber-physical system like the SB.

1. Introduction

Nowadays, with the technological advancements in ubiquitous computing and automation technologies, the SB has grown beyond wireless sensor networks [1]. The next generation of SB are complex cyber-physical systems (CPSs) [2,3]. A characteristic of SB's CPS are their extreme variance in topology, scale and involved technologies, which can jeopardize the reliability and efficiency of the SB system.

Traditionally, embedded systems have always been considered to have better reliability and predictability compared to general-purpose computing [4], and which should be maintained regardless of the system complexity. However, there are still critical limitations in their performance, range, and functionality. Moreover, especially with IoT-based management systems, there is high market fragmentation [5,6], and rapid obsolescence. Additionally, each building's construction is unique and its occupants' activities are diverse [7–9]. Thus, the ICT topologies [10] and the occupant requirements differ between SBs. Therefore, any CPS architecture to effectively address the reliability, interoperability, and design adaptability requirements is of high value for sustainable SB architectures.

This paper proposes a viable solution for addressing those challenges with a middleware system. The middleware is a well-understood terminology which enables the efficient management of the complexity and heterogeneity in distributed and cloud computing environments. SB systems have similar, yet smaller in scale, challenges and the authors were motivated in investigating the potential of a SB-specialized middleware. Fig. 1 visualizes such middleware concept within a SB architecture. It provides a universal, flexible and scalable ICT abstraction to the building management entities such as the BMS or the energy management system (EMS).

Specifically, this work assessed the feasibility of an embedded and distributed variant of MoM. Fig. 2 illustrates such system deployment across a hypothetical building floor in order to interconnect incompatible, or range and performance limited device networks. Each middleware node, denoted in brown, interfaces one or more device networks for which it implements their protocol stack on embedded low power hardware. The nodes communicate in a peer-to-peer manner over high-performance computer networks, e.g., Wi-Fi and Ethernet. The data protocol that governs such communication is universal regardless of the interfaced standard, thus, the middleware enables a protocol-agnostic communication between heterogeneous ICT networks and the BMS. Finally, a low latency, security layer ensures the safety of data and integrity of operations.

The rest of this paper is organized as follows. Section 2analyzes the

* Corresponding author.
E-mail address: georgios.lilis@epfl.ch (G. Lilis).

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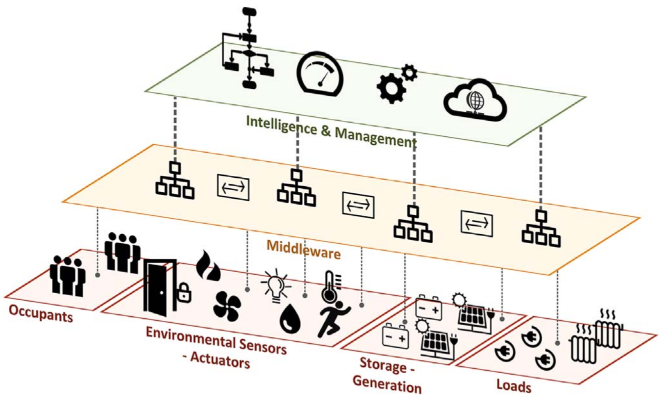

Fig. 1. The layered approach in a smart building system design.

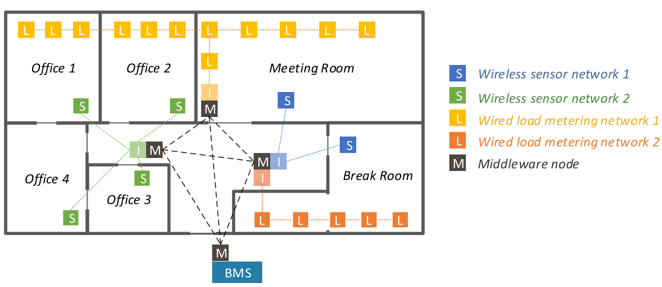

Fig. 2. Distributed middleware topology demonstration in a hypothetical building.

specific requirements of such middleware, which are also the reasons for investing in such technology in SB applications. Section 3 assesses the state of the art for middleware solutions aimed to general applications as well as SBs, while Section 4analyzes the MoM principles and standards. Section 5 scrutinizes the proposed middleware design in the scope of the SB and analyzes the security features of the proposed system. Finally, Section 6 presents a detailed performance and energy study on the proposed architecture on embedded hardware. This paper finishes with contributions and future work in Section 7.

2. Requirements

In general, the target of any middleware is to support large-scale, heterogeneous and distributed architectures. Thus, the requirements for a SB middleware reflect the desired functionality of any modern middleware. In this section, these desired features are not only presented but also correlated with the SB system requirements in general. By demonstrating in that way the alignment of both, a reader can better understand the motives behind adopting a middleware solution for SB designs.

2.1. Interoperability, heterogeneity

The interoperability challenge is well understood for both legacy automation system and newer IoT-based ones. The interoperability with the proposed middleware is achieved by interfacing both specific protocols and abstracting them with a universal data model specifically developed for the needs of the SB. The software adaptation layer makes the protocol and data model translation between the two domains. Using this universal data model and internal routing tables, the participating devices are interconnected without any statically configured gateways. Moreover, it enables a technology agnostic BMS, as the middleware exposes the monitoring and control capabilities of the building infrastructure.

2.2. Asynchronous, event-driven communication

All communication is asynchronous with the help of messages and queues, which decouples not only the data model but also the time domain of each interconnected device and network. The latter enables the participation of even the most heterogeneous types of devices. The middleware can provide this event-driven communication without latency or throughput penalty thanks to the high-performance communication layer and libraries.

2.3. Mobility, dynamic network topology

The SB is a highly dynamic environment with elevated mobility not only for its occupant but also from the ICT devices if the wearables, entertainment, and intelligent loads are considered as parts of the SB. The middleware enables a dynamic topology where self-discovery, internal addressing protocol, and routing elements allow such functionality. Thus, the continuous operation is guaranteed without BMS reconfiguration.

2.4. Scalability, adaptability

A distinct advantage of the particular middleware, as already mentioned, is its distributed nature. Each node of the middleware is distributed in various locations of the building based on the design requirements and the capabilities of the device networks. Those nodes and their interconnection make up the so-called middleware. This distributed design enables a scalable and adaptable solution to any type of building construction, overcoming the embedded network range or design limitations. Additionally, if higher throughput and lower latency are desired from a given embedded network topology, the network can be fragmented into two different middleware nodes for interfacing. Since the middleware nodes communicate over generally superior computer networks, the partitioning of the embedded networks nearly multiplies the overall performance of the initial topology.

2.5. Lower cost

The BMS to be installed in residential buildings should remain price competitive. The efficient source code of the middleware and communication libraries guarantees the optimal execution even on the cheapest of embedded hardware. Thus, the introduction of middleware does not increase the cost of the overall system. On the contrary, the interoperability layer seamlessly integrates the existing infrastructure during a retrofitting, reducing the investment size. Moreover, the abstraction layer reduces the development work-hours for the BMS, as it needs to support only the middleware protocol. Finally, the adaptability of the system requires few if any re-engineering to the overall design between different deployments. All those features introduced by the middleware can greatly reduce the overall investment cost and reduce the payback period.

2.6. Extendability, ease of development

The SB will continue to evolve over its lifetime and new ICT will eventually be introduced. The term extendability refers to the ease of creating new types of middleware nodes for supporting newer building automation protocols, IoT devices, and wireless networks. More specifically, the software design of the middleware facilitates the extendability of the system using object-oriented programming (OOP) principles and software templates. Therefore, the developer of a middleware protocol node is not required to know how the distributed architectures and messaging communications operate.