



Advanced IoT solutions for real-time monitoring and resource optimization in masonry structures using innovative material technologies

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Abstract

Integrating Internet of Things (IoT) technologies with masonry materials offers a fresh structure to improve real-time monitoring, resource management, and structural management in a variety of construction use cases. This research examines strategies to enable innovative deployments of IoT-enabled masonry systems, and focuses on enhanced signal propagation, energy use, and reliability of the collected data within built environments. Through the use of masonry's inherent properties such as thermal characteristics, textural qualities, and load capabilities, IoT frameworks are designed to provide seamless connectivity and strong performance. The research studies these techniques and technologies in a $6 \times 9 \times 4$ m³ masonry room, divided into 1200 segments, measuring all frame components. IoT modules embedded into masonry walls use higher frequency resonators in the 2.8–3.6 GHz range, as supported by an array of 3×3 antennas for directional communication calibration. The model incorporates environmental parameters with a scattering index of 0.85 and a reflection coefficient of 0.60 to model material interactions. Each IoT node is optimized across frequencies for 75 distinct frequency ranges for improved signal quality and lower to minimize signal propagation losses. The simulation results indicate with 15 IoT nodes arranged within masonry structures with a signal uniformity index of 0.82 ± 0.04 , a 27% improvement from the baseline (random placements and free space nodes). Each node's energy usage reduced to 0.72 ± 0.03 J or a 30% reduction in energy usage from 1.03 ± 0.05 J in the baseline, while the interference was reduced to -68 ± 2 dBm with 40% interference reduction, resulting in more reliable communication in dense deployments. Moreover, embedded resonator technology improves resource efficiency, supporting the objectives of adaptive and sustainable infrastructure. The results highlight how IoT-augmented masonry materials have the potential to revolutionise resource management, connectivity, and structural evaluation in the fields of contemporary building and historical preservation.

Keywords Masonry systems · IoT integration · Adaptive deployment strategies · Signal transmission enhancement · Embedded IoT nodes · Sustainable infrastructure · Smart construction technologies

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1 Introduction

Massive scaling of the Internet of Things (IoT) has transformed the nature of connectivity itself by creating a dynamic configuration in which devices are capable of autonomous communication across various sectors (urban infrastructure, healthcare, transportation, and agriculture) [1]. They increase capacity in decision making, drive automation, and improve operation processes [2, 3]. However, there are increasing challenges that IoT networks face as they grow-out, especially in a high-density deployed environment where conventional network architecture faces the burdens of signal reliability, bandwidth or energy consumption [4, 5]. These challenges further increase when the objective is to maintain continuous coverage and optimal performance within highly complex and dynamic spaces [6]. New strategies, which go beyond conventional paradigms of network architecture, would therefore be required. The efforts of engineers and researchers to optimize IoT network performance are putting novel materials and advanced technologies on the menu with masonry materials appearing to be one of the most promising means for enhanced structural integrity and network efficiency [7, 8]. Uniquely endowed with thermal mass, porosity, and structural resilience, masonry—the construction material of durable and versatile nature—is the most ideal for integrating IoT devices. The introduction of IoT sensors into masonry structures will turn out networks that are energy-efficient, robust, and scalable in various applications [9, 10].

This paper basically looks into the implementation of IoT-enabled masonry systems, focusing on signal optimization strategy, energy-reducing method, and performance enhancement of networked devices. Masonry materials, embedded with IoT technology, provide the prospect of enhanced connectivity under extremely challenging environmental conditions [11, 12]. Such strategy is very much applicable in scenarios of smart cities, heritage conservation, and industrial applications, where an uninterrupted and efficient connectivity forms the basis for actual system performance [13, 14]. Properties of masonry, such as handling temperature variation and heavy load-supporting capacity, render it a suitable medium for embedding IoT sensors, antennas, and resonators meant for signal transmission optimization [15, 16]. These embedded devices operate at frequency bands that intentionally minimize disturbance and maximize energy efficiency in line with green designs [17, 18]. In addition, deploying IoT networks in masonry structures ought to equally consider the environmental effects that include the reflection coefficients of the material and its scattering properties for uniform signal spread [19, 20].

Scalability remains a key determining factor in the success of IoT networks, especially as the number of connected

devices rises at an exponential rate [21]. Naturally adaptable, masonry-based IoT systems support modular design conceived to easily scale up and down according to the need of small-and large-scale applications. The systems can also evolve along with changing environmental circumstances thus reducing the need for costly infrastructure updates [22, 23]. Further, energy-efficient systems help minimize operational costs while at the same time achieving wider sustainability goals [24, 25]. This study implements advanced simulation techniques and predictive modeling to investigate the ideal approach involved in embedding IoT devices within masonry so as to achieve maximum effectiveness and resource conservation [26, 27]. The proposed solutions will deal with signal optimization and resource-allocation challenges while providing a cost-effective model that satisfies the needs of industries that operate under dynamic budget constraints [28].

Structural Health Monitoring (SHM) has become essential to maintain safety and longevity of civil infrastructure. In particular, advancements in Internet of Things enabled sensors and intelligent algorithms have helped SHM realize real time monitoring and predictive maintenance [29, 30]. Prior research has focused on optimal placement of devices and data acquisition to adequately record structural response due to dynamic loads, such as model updating for masonry structures using metaheuristic approaches [31]. Data issues remain in subsequent stages of the process, such as handling high-volume streams, filtering sensor noise, and integrating machine learning models for accurate anomaly detection [32]. The proposed benefits of a fully functioning IoT-based SHM system as discussed are improved predictive maintenance, reduction in cost, and improved structural resilience. This study is addressing these gaps through a combination of optimized positioning of sensors and advanced data processing, machine learning techniques to develop an all-encompassing intelligent framework for SHM applications with accuracy and in the real-world context.

This study offers a new paradigm for the integration of connection and resource management into contemporary infrastructure, highlighting the revolutionary potential of IoT-enabled masonry systems. This paper presents a thorough framework for integrating IoT networks into masonry by combining cutting-edge material technologies, network optimisation techniques, and workable deployment strategies. This opens the door to more intelligent and environmentally friendly building methods in a connected world [33, 34].

and antenna constraints. The experiments showed 27% improvement in the uniformity of signals, 30% decrease in energy consumption, and 40% reduction in interference power. The masonry materials presented in this study effectively reduce losses in signal transmission and promote miniaturization of devices, hence enabling the foundation of more efficient IoT systems.

Results from this interference suppression scheme strengthened the demonstration of proposed deployment techniques. Masonry-based composite materials allowed the devices to actively modulate their electromagnetic signatures, suppressing the unwanted reflections and thereby clarifying the signals. Moreover, further refinement of the estimation function improved network accuracy through decreasing RMSE values with the increasing number of Meta-IoT devices, especially with strategically placed devices. For example, with 15 devices in a $6 \times 9 \times 4$ m³ room, RMSE achieved a 25% drop as compared to the random placement configurations highlighting the importance of accuracy in placement in combination with the properties of masonry materials.

With combined deployment strategies for Meta-IoT Networks and unique properties of masonry materials, solid approaches are available for scalable, energy-efficient and sustainable IoT systems. The efforts would be geared toward other promising applications like smart cities, industrial IoT, and environmental monitoring, where performance and energy efficiency are imperative. The high expectations shown here provide us with bright prospects for the revolutionization of masonry material-enabled IoT networks in the field of optimization of wireless communication, enhancement of environmental sensing, and more sustainable large-scale IoT deployments.

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