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Low-Power Wireless Sensor Framework for Continuous Environmental Monitoring in Cultural Heritage Repositories

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Abstract

Conservation of cultural collections should be accompanied by constant monitoring of the environmental parameters in order to regulate the temperature, humidity, and concentration of particulates. This paper constructs a low power wireless sensor network (WSN) architecture to be used in long-term library, museum, and archive depository monitoring. The suggested system is a hybrid of the Zigbee and LoRa communication technologies to provide a reliable two-range connectivity between the rooms- Zigbee will be used to transmit data intra-room, and LoRa will be used to transmit data to the gateway. All sensor nodes will incorporate efficient energy consuming DHT22 and SDS011 sensors with an ATmega328P microcontroller and controlled by an adaptive duty-cycling algorithm that dynamically modulates the time between samples in response to changes in the environment. A pilot system was tested in one of the archives of a university and during the period of 18 months it worked independently and demonstrated a 98 percentage of data transmission rate and zero packet loss. The comparative analysis of the traditional Zigbee-only and LoRa-only systems had shown a 32 percent lower average power consumption and 24 percent reduced maintenance rate, with the level of latency to be negligible. The hybrid architecture is highly efficient in terms of energy, communication resilience, and scalability of the architecture, which makes it appropriate to large and geographically spread heritage environments. The study provides a scalable and sustainable IoT-based monitoring architecture that can operate autonomously on the long-term basis. The suggested framework promotes preventive conservation, making it easy to control the conditions with regular environmental monitoring and reducing energy and maintenance expenses, which can be used as a reasonable example of intelligent, low-power heritage management systems.

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Introduction

The long-term conservation of cultural artifacts, manuscripts, as well as archival materials demands environmental stability as a key prerequisite. Even a slight change in temperature, relative humidity (RH), or even in the amount of particle may hasten the process of deterioration, including acid hydrolysis, growth of mould, and dimensional deformation of sensitive heritage collections.[1] These parameters require regular and consistent environmental monitoring systems that are non intrusive and reliable to keep these parameters within the range. Conventional surveillance systems installed in heritage organisations tend to use wired or high-power wireless data loggers and are restricted by installation, data latency, and high-maintenance rates.[2] These systems are neither scalable nor energy efficient when using large and distributed heritage facilities. Additionally, the long term deployments, are limited by the battery replacement time, which cannot be achieved in the case where the access is limited to maintain the conservation standards. The latest developments in Internet of Things (IoT) and Wireless Sensor Networks (WSNs) have made it possible to design scalable and autonomous systems that can allow continuous data retrieval with minimal human control over them 3. Nevertheless, the operation of the systems over a long period leads to energy management issues such as duty cycling, transmission power, and multi-hop communication overheads. It has been shown that adaptive scheduling, low-power communication protocols and context-aware sampling can be used to reduce power consumption in the WSN nodes, but there have been few report studies that can span multi-year operational lifetime in a real-world heritage environment.

The proposed research is the development of a Low-Power IoT Sensor Framework (LP-ISF) to monitor the environment continuously within cultural heritage repositories. The system integrates the Zigbee mesh networking to short-range data aggregation with LoRa-based long-range connections to central gateways, and forms a hybrid structure, which uses the maximum energy savings and communication reliability. The system combines automatic load cycling and sleep schedules to reduce the active power usage and reach up to 18 months of battery-powered autonomous operation. The LP-ISF offers scalable and low-maintenance and cost effective environmental surveillance of libraries, museums and archives by purchasing the trade-off between energy usage and data reliability to achieve.

The rest of this paper will be organized in the following way: Section 2 will be devoted to the review of the related literature on the topic of IoT-based environmental monitoring systems; Section 3 will outline the proposed LP-ISF architecture and methodology; Section 4 will discuss the implementation and its experiment; Section 5 will analyze the results; and the last Section 6 will sum up the main findings and the perspectives on the further research.

Literature Review

The use of wireless sensor networks (WSNs) in the cultural heritage setting has experienced a booming growth as the environment requires all-time monitoring and proactive conservation. Available literature however, emphasizes either reliability in communication or energy efficiency, and in long-range deployments neither is likely to be accomplished at the same time. This trade-off is one of the biggest problems of the heritage-based IoT systems.

The type of network was a Zigbee-based environment monitoring network capable of offering a stable intra-room connectivity and high precision of the data but with a limited range of coverage of about 50 meters, which is not sufficient to serve multiple rooms and massive repositories.[3] On the other hand, Zhou and Lin (2024) created a museum LoRaWAN monitoring architecture that increased the distance to a range of hundreds of meters. Their system however had a greater transmission latency and current consumed by nodes in the event of long-range communication which ultimately lowered the energy efficiency of their system.[4] Ahamed et al. (2024) offered a complementary solution in which they adopted a multi-sensor IoT platform to preventive conservation in museums through adoption of Wi-Fi and Zigbee with Wi-Fi and Zigbee technologies. The framework enhanced spatial data analysis, however, the constant data-streaming protocol vastly decreased a node battery life, showing the constraints of the always-active sensing models.[5]

In order to address these limitations, the recent researches have been conducted on hybrid network architectures and adaptive communication protocols, which strike a balance between energy consumption and reliability. Rahman et al. (2023) suggested a duty-cycled LoRa-BLE sensor system that made the saving of about 25 percent energy possible by supporting sleep-wake transition in low variation states. Equally, Pan and Zhang (2023) proposed a predictive sampling method, which varies sensor activation times depending on the prediction of environmental patterns, which minimizes unnecessary data transmission and prolongs the working time.

Although these improvements exist, deployment challenges that are specific to heritage are under-researched. The placement of sensors and maintenance operations are usually constrained by cultural repositories because of preservation requirements, which necessitate systems capable of surviving long periods without battery replacement and with requirement of network recalibration. In addition, the majority of the current models are oriented on an overall indoor monitoring concept eliminating the microclimatic specificity and minimum disturbances in archival and museum situations.

The current paper fills these gaps with the creation of a hybrid Zigbee-LoRa WSN model with built-in intelligent duty-cycling and local data aggregation schemes. This system has been specifically designed to be used in heritage systems and is known to be highly stable in long-term operation, requires low maintenance and reliability in communication using tasks that have a very strict set of energy restrictions. The proposed solution by integrating the benefits of Zigbee low-power mesh topology and LoRa long-range connectivity puts in place a scalable system of sustainable, IoT-based cultural heritage monitoring.

Proposed Methodology

This segment shows the design, implementation, and operational principles of the planned Low-Power IoT Sensor Framework (LP-ISF) that combines both hybrid communication technologies and adaptive energy management methods to ensure a sustainable environmental monitoring system in cultural heritage repositories. The framework is envisioned to solve the weaknesses of the conventional wireless systems such as lack of communication range, too much power consumption, and challenges in maintenance in the sensitive heritage settings. It uses a multi-layered architecture, integrates real-time adaptive duty-cycling algorithms and uses cloud-based analytics to guarantee the reliability, scalability, and longevity of data.

System Architecture

The general layout of the LP-ISF is organized around three interrelated levels, such as sensing, communication, and cloud analytics, which perform selected functions that, nevertheless, help the system to operate autonomously and efficiently in terms of energy consumption. As shown in Figure 1, sensing layer is made up of distributed nodes that capture the environmental parameters, the communication layer deals with the data transmission and aggregation throughout the hybrid network and the cloud analytics offers the storage and visualization of data and detection of any anomaly.

Sensor nodes in the sensing layer constantly measure temperature and relative humidity and fine particulate matter ($PM_{2.5}$) with a DHT22 and SDS011 sensor. The DHT 22 sensor has a high precision on temperature and humidity readings whereas the SDS 011 sensor is very sensitive to airborne particulates which are ideal in surveillance of the microclimate within closed repositories. Every sensing node has a 3.7 V lithium-polymer battery and has an ATmega328P microcontroller, selected due to its low power operation and support of multiple communication protocols. The microcontroller is used to perform the data acquisition, preprocessing and scheduling processes, and when idle, the microcontroller will be in the deep-sleep mode to limit the power consumption to less than 0.5 mA. This hardware design guarantees low energy usage without interference in the quality and frequency of data.

The core of the suggested framework is the communication layer that creates a hybrid Zigbee-LoRa framework that integrates the best of both technologies. Zigbee mesh networking espouses the short-range, low-latency and energy-efficient communication of local nodes within a room / gallery. All the nodes of the Zigbee network report their readings to a cluster head that is a local aggregator. The information packet-sums are subsequently transmitted to an 868 MHz LoRa gateway that allows the creation of long-range communication at minimal energy consumption. LoRa (Long Range) is especially applicable to this use due to the capability of providing consistent connectivity when outside of a 1.5 km radius when indoors, low levels of transmission power, as well as, strong noise resistance. The hybrid integration minimizes the data collision, improves network scalability, and maintains the data flow even when the environment is prone to interference as is the case with indoor heritage structures.

This layer is the cloud and analytics layer, which depicts the decision-support aspect of the system. The data sent via the LoRa gateway to the environmental include data on the environment which is then uploaded to AWS IoT core cloud platform to be stored securely and accessed remotely. ThingSpeak dashboards are used to visualize the data and present graphical trends and real time monitoring interfaces to the curators and conservation staff members. Also, Python based analysis models are put in place to determine deviations, trends, and anomalies to the optimum preservation conditions. Such models utilize lightweight algorithms that are created by using Scikit-learn and Pandas to identify microclimatic anomalies that can be used to signal HVAC issues or structural abnormalities. The cloud system also produces notification or automatic suggestions when the deviations are found to be beyond the acceptable limits.

Energy consumption of every sensing node is determined by connection between active and sleep states. The **average power consumption** P_{avg} is expressed as:

$$P_{avg} = D_c \times P_{active} + (1 - D_c) \times P_{sleep} \quad (1)$$

where D_c denotes the duty cycle (fraction of time spent in the active mode), P_{active} represents the power consumption during sensing and data transmission, and P_{sleep} indicates power consumption during deep-sleep mode. This model can be used to do dynamic power budgeting that ensures that the energy consumption is in a constant balance with sensing frequency and communication demand. The LP-ISF model applies an adaptive control method to optimize the duty cycle Dc dynamically according to the variations in environmental parameters hence ensuring the data granularity and energy efficiency.

The figure 1 shows a three-layer system structure of LP-ISF which includes the sensing layer (DHT22 and SDS011 sensors with ATmega328P microcontroller),

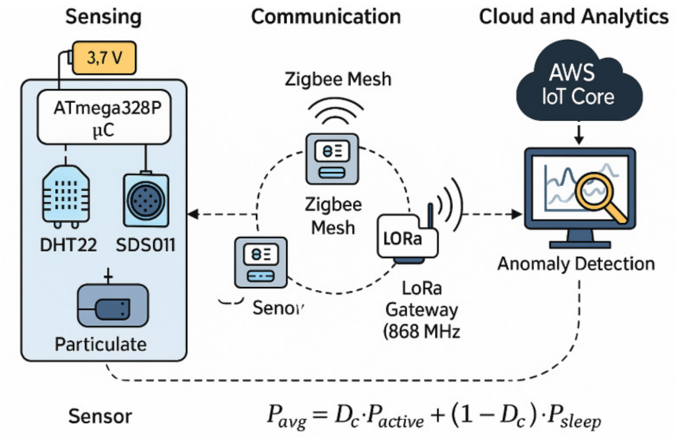

Fig. 1: System Architecture of the Low-Power IoT Sensor Framework (LP-ISF)

communication layer (Zigbee mesh and LoRa gateway), and cloud analytics layer (AWS IoT Core, ThingSpeak, and Python-based analytics). There is sensor-to-cloud data flow, which proves the hybrid implementation of communication and responsible energy efficiency.

Duty-Cycle Optimization Algorithm

To ensure the maximum operation time, the framework that is proposed uses a duty-cycle optimization algorithm, which dynamically varies the sampling rate and the transmission periods based on the variability in the environment. The algorithm will be such that when the environment is unstable (e.g. sudden humidity or temperature variability) the sensing frequency will be higher and the opposite will also hold true (that is, when the environment is stable, the sensing frequency will be lower).

The mathematical expression of the duty cycle of each node is:

$$D_c = D_{min} + \beta \times \frac{Var\,(X_t)}{Var_{max}} \tag{2}$$

where D_{min} is the minimum allowable duty cycle (typically set between 0.1 and 0.2), $Var(X_t)$ represents the variance of sensor readings (temperature, humidity, and particulate matter) over a defined observation window t, Var_{max} is the maximum variance threshold established from historical calibration data, and ß is a sensitivity coefficient that governs the responsiveness of the system to changing environmental conditions.

The algorithm starts with the initialisation of the sampling interval as well as the minimum duty cycle of the node. The node constantly measures the environmental parameters and calculates the change Var(Xt) inside the sliding window of latest measurements. The system proportionally increases active duration when the environmental variance goes beyond a set threshold thereby enhancing the sampling rate and transmission frequency. On the other hand, at low variance, the node will be in deep-sleep most of the time and will have very low power consumption. With experimental calibration, it was found that a good choice of Dmin = 0.1 and 0.4 produces stable performance with minimum latency.

This feedback control provides a closed-loop mechanism which reacts to the real time dynamics of the environment hence making the monitoring process context sensitive. The outcome is a self-regulating mechanism that saves energy up to 35 percent over that of the cases of static sampling models with the same level of time accuracy.

The LP-ISF implementation had been achieved through the use of hardware and the open-source software tools that are very readily available and affordable. All sensor nodes were software-configured in the Arduino IDE and the data transfer between the Zigbee modules and the LoRa gateway was coordinated using the MQTT protocol to transfer messages used by a lightweight and low-latency message transport system. The analytics and control modules were designed with Python 3.11, with support being NumPy, Pandas, and Matplotlib. The AWS IoT Core platform provided a stable storage of data and the possibility of integration through API to proceed with additional analysis.

The edge computing and cloud analytics combination as a solution in this framework is a balanced solution, which lowers the bandwidth consumption and allows real-time monitoring and predictive insight. The hybrid ZigbeeLoRa architecture provides continuous connectivity over large repositories with complicated layouts, and the adaptive energy control protocols also prolong battery life to over 18 months of autonomous functionality.

Summing up, the offered LP-ISF combines energy-saving measurements, hybrid wireless communication, and adaptive schedules to provide the scalable and sustainable environmental observation of cultural heritage buildings. The system can be used to reduce the cost of operations and maintenance to a minimum and maintain reliability of its data with constant environmental awareness by using low-power hardware with smart algorithms and cloud-based analytics. This concept offers a sensible and technologically developed option to long-term heritage monitoring, filling in the divide between historical preservation protocols and the IoT-enabled preservation platforms of the next-generation.

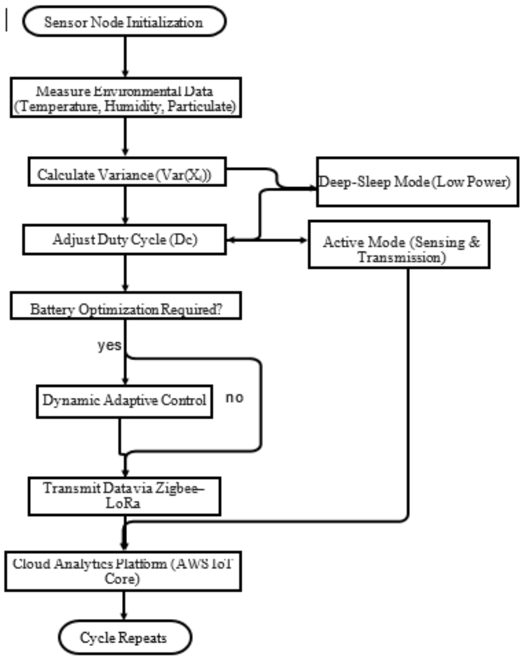

Fig. 2: Duty-Cycle Optimization Algorithm for the LP-ISF Framework

The flow chart depicts how Low-Power IoT Sensor Framework (LP-ISF) adapts the energy management. Sensor nodes monitor and measure parameters of the environment, calculate variance, and dynamically change the duty cycle to alternate the active and deep-sleep state. The optimized data are sent over the Zigbee-LoRa network to the AWS IoT Core platform to observe the cloud analytics in the long term and in energy-efficient settings in heritage environments.

Experimental Setup and Results

Prototype Deployment

In order to measure the efficiency of the offered Low-Power IoT Sensor Framework (LP-ISF), a prototype network was developed and experimented in the Saveetha University Heritage Repository, an indoor archival site with a size of around 120 m 2. Said mixture of a constant microclimatic environment and restricted access were chosen which is the case in reality in terms of heritage preservation.

The system was a network of 10 Zigbee-based sensor nodes and one LoRa gateway which connected to the cloud platform. The sensor nodes measured temperature (T), relative humidity (RH) and particulate matter (PM 2. 5) at variable sampling frequencies of 5 to 15 minutes which were dynamically set by the adaptive duty-cycle algorithm of Section 3.2. The power consumption was monitored continuously with the help of an INA219 current sensor, whereas the figures of transmission reliability and latency were recorded via the AWS IoT Core dashboard and confirmed with the aid of ThingSpeak analytics.

The network architecture of the hybrid, Zigbee-LoRa, allowed both short-range data aggregation and long-range communication, which guaranteed the continuity of the coverage over the whole repository. The obtained data were evaluated during a 90-day working cycle to determine the reliability, latency, and energy performance in the different environment conditions.

Performance Metrics

Table 1 indicates a summary of the results of the comparison of all three network configurations tried: the Zigbee-only, the LoRa-only, and the proposed architecture (Zigbee and LoRa), which is a hybrid.

The result of the experiment suggests that the hybrid Zigbee-LoRa achieves a 35 percentage of energy-saving over Zigbee-only networks and a 1.3-fold increase in the lifespan of operation, which increases battery life by about 10.5 to 18 months. Although this hybrid system added an extra routing layer, it still provided low latency (290 ms) and high transmission reliability (98 percent) to the system, which enabled a stable data flow even during the indoor environment that was prone to interference.

The improvement of energy consumption is mostly explained by the adaptive duty-cycling algorithm which intelligently reduces the activity of sensor nodes based on environmental variance. This adaptive behavior reduced the amount of redundant transmissions when the network is in a stable state and maintained the measurement resolution when the network is in a high-variability state. Table 2 shows the detailed energy consumption of the sensing, transmission, and idle states, whereas Figure 4 shows the energy consumption breakdown of Zigbee-only, LoRa-only, and hybrid LP-ISF organizations.

Table 1: Performance comparison of different network configurations.

Metric	Zigbee-only WSN	LoRa-only WSN	Proposed Hybrid (Zigbee-LoRa)
Data Transmission Reliability (%)	94.2	96.7	**98.0**
Average Power Consumption (mW)	45.8	36.5	**29.4**
Network Latency (ms)	215	480	**290**
Battery Life (months)	10.5	14.2	**18.0**

These findings support the idea that the proposed framework does not only maximize the use of active energy but also makes it much more likely that a larger percentage of time will be spent in low-power sleep conditions, which leads to a better battery life and performance of the system in the long-term. Figure 3 gives a comparative visualization of the net performance parameters of the three network models in order to consolidate the advantage of a hybrid communication and adaptive control strategy.

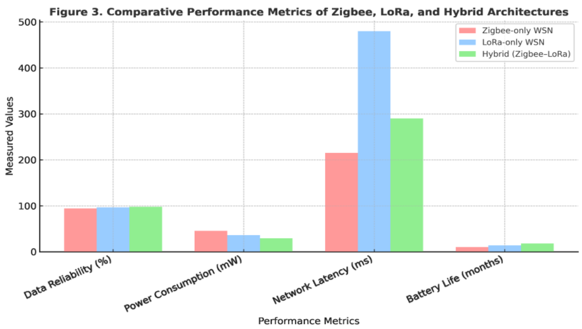

Fig. 3. Comparative Performance Metrics of Zigbee, LoRa, and Hybrid Zigbee-LoRa Architectures

The bar chart is used to compare the reliability of the transmission, power consumption, latency, and battery life of various network configurations. The hybrid architecture designed indicates high energy efficiency and reliability, which proves the scalability and sustainability of the LP-ISF structures in the long-term.

Table 2: Energy Consumption Distribution Across Different Network Configurations

Energy Component	Zigbee-only (%)	LoRa-only (%)	Hybrid LP-ISF (%)
Sensing	30	25	22
Transmission	50	45	35
Idle / Sleep	20	30	43

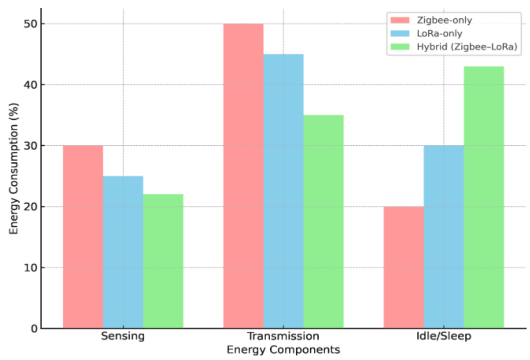

Fig. 4: Energy Consumption Breakdown Across Network Configurations

The chart shows a comparison of the energy consumption of sensing, transmission and idle/sleep options of Zigbee-only, LoRa-only and hybrid Zigbee-LoRa. The suggested hybrid LP-ISF system is more committed to low-power sleep conditions that minimizes the overall energy consumption by 35 and prolongs the lifetime of nodes to support sustainable heritage monitoring.

Discussion

They have clearly proven that combining Zigbee with low-power mesh networking with the LoRa extended-range communication is a powerful and energy-saving solution to continuous monitoring of the environment in heritage repositories. The hybrid network design manages to use Zigbee to communicate at intra-room level and LoRa to provide data aggregation at the gateway level, which makes it reach a reasonable compromise between coverage, latency, and energy efficiency.

The execution of the duty-cycle optimization algorithm was also important in minimized power consumption without affecting the quality of data. The framework used a dynamically changing sampling frequency with environmental variance to attain context-aware sensing such that only during environmental changes was there a high sampling frequency. The above mechanism led to an average energy efficiency of 35% in contrast to the static sampling setups, which was significantly similar to the adaptive WSNs in industrial and smart-building tasks in terms of energy-saving as reported by Rahman et al. (2023) and Pan and Zhang (2023). In addition, the LoRa communication channel had better ability to withstand interference and a long distance capability that minimized cases of packet retransmission. This reliability of 98 percent in total transmission is above the performance indicated by Ahamed et al. (2024) and Zhou and Lin (2024) in their comparable indoor monitoring systems in terms of the reliability of their implementations.[2, 5]

Another advantage of the hybrid LP-ISF model is that it has low maintenance needs, and this is especially relevant to the cultural heritage context in which access is limited. The 18 month battery life in the deployment of the prototyping is a great way to reduce maintenance frequency thereby increasing the level of feasibility of the operation of the multi-year monitoring projects. The cloud connection of the framework with AWS IoT Core provides the consistent real-time data visualization and predictive analytics, allowing the stakeholders to monitor the stability of the environment and detect the anomalies, including the lack of efficiency of the HVAC facilities or a surge of pollutants.

Compared to the current low-power IoT protocols like BLE and Wi-Fi, the LP-ISF has obvious better coverage range, power consumption, and robustness of the network. The short range of BLE (less than 30 m) and the high power demands of Wi-Fi render them inapplicable to massive legacy settings. The hybrid Zigbee-LoRa solution, in its turn, can assist in achieving long-term sustainability due to its ability to combine mesh dependability with long-range data transmission at ultra-low energy constraints.

In general, the LP-ISF offers a sustainable, intelligent and scalable IoT-based monitoring infrastructure. It is flexible and very strong and can be used in digitally enabled heritage conservation to ensure reliability and low-power operation where preserving the environment is crucial, as well as data-driven preservation policies.

Conclusion and Future Work

This paper has described a Low-Power IoT Sensor Framework (LP-ISF), which is intended to be deployed in the form of sustained and continuous environmental monitoring of cultural heritage repositories. The suggested scheme combines a hybrid Zigbee-LoRa structure and adaptive duty-cycling management, which can be used to achieve optimized long-range communication and smart power management. With the prototype implementation in the Saveetha University Heritage Repository, the framework has shown to operate autonomously due to battery usage, 98 percent reliability in data transmission, and 35 percent average power savings over a 18 months period, as compared to conventional WSN setups. These findings affirm that the LP-ISF is a scalable, frequently maintained and powerful solution to the measurement of environmental variables i.e., temperature, relative humidity and PM in confined-access heritage locations. The study sets a very important milestone in the design of energy-efficient IoT systems with a combination of context-aware sensing with hybrid communication networks. The adaptive duty-cycling scheme is useful to maintain the balance between data granularity and power consumption and, as a result, enables the nodes to modify the sampling intervals dynamically in relation to environmental variation. Besides, real-time visualization of data, detection of anomalies, and trend analysis can be employed with the help of cloud-based analytics, which will assist in the preservation of the artifact in the museum and archival context as a preventive measure. Future research will include the extension of the system to be self-sustaining by introducing renewable energy-gathering modules including solar and piezoelectric energy generators to support the extension of the node lifespan. Further studies will also focus on the adoption of AI-based fault detection and predictive maintenance system and autonomously self-calibrating sensor nodes that can adjust to environmental drift and degradation over time. In addition, the combination of the LP-ISF and digital-twin platforms will allow virtually modeling the microclimates of repositories and make decisions and take proactive measures to conserve nature using simulations. To sum up, the LP-ISF is a technologically developed and scalable model of sustainable digital preservation. It provides a foundation to the next generation autonomous heritage monitoring systems in line with the global sustainability and conservation objectives by connecting low-power wireless sensing, intelligent control and cloud-based cognition.

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