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Research Article

Innovative Environmental Monitoring for Timber Frame Structures Using a Wireless Sensor Network

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Abstract

The rapid development of connected devices and Internet of Things (IoT) technologies has enabled real-time environmental monitoring through low-cost sensor networks. Wireless Sensor Networks (WSNs) offer a flexible, scalable, and cost-effective solution for continuous monitoring of environmental conditions in building structures. This study presents the design, implementation, and evaluation of a low-cost WSN for environmental monitoring of timber frame structures, with particular emphasis on moisture-related degradation in Welsh larch buildings. The proposed system employs wireless sensing nodes to continuously monitor and record predefined environmental parameters relevant to timber performance, durability, and moisture accumulation. Although IoT-based monitoring systems have been widely adopted in smart buildings and environmental applications, limited research has focused on timber-specific environmental behaviour using adaptable and open-source WSN architectures. The developed system addresses this gap by integrating low-cost sensing, wireless communication, and real-time data acquisition into a scalable monitoring framework. The experimental evaluation demonstrates the feasibility of the proposed approach for continuous environmental monitoring of timber frame structures and provides a basis for identifying environmental conditions associated with moisture accumulation and potential material degradation. The proposed WSN architecture offers a practical and cost-effective approach for condition monitoring and long-term assessment of timber structures.

Keywords: Internet of Things; Wireless Sensor Networks; Raspberry Pi; IEEE 802.11; Environmental Monitoring.

INTRODUCTION

The rapid evolution of the Internet of Things (IoT) has enabled the deployment of distributed sensing systems capable of monitoring physical environments in real time. Wireless Sensor Networks (WSNs) [1], as a core component of IoT, have been widely adopted in domains such as smart cities, industrial automation, and environmental monitoring. Environmental monitoring systems have the ability to collect data tirelessly using inexpensive, networked sensors. For construction and sustainable architecture, environmental monitoring has become an important factor in long-term structural reliability, especially for timber-based structures [2]. Timber is a material that is severely affected by the environment, especially temperature and humidity, as they directly correlate with the moisture content of a building, and ultimately its durability. Although basic environmental monitoring systems exist, it is necessary to build a low-cost environmental monitoring system for timber frame structures [3].

Current WSN monitoring systems generally provide environmental sensing without any consideration to behaviour. Also, several previous systems use proprietary hardware or are not designed to be adapted for small applications or community-based projects. In this paper, WSN based on open-source hardware using Wi-Fi and dedicated to environment monitoring by timber is developed. It is for installation in environment friendly buildings.

This study explores the capabilities of a the low-cost, open-source IEEE 802.11 Wireless Sensor Network [4] for timber frame building environmental monitoring. The contribution is not an implementation of a new wireless protocol or sensor but it is the integration and evaluation of readily available sensing, computing and networking technologies within a timber-specific monitoring scenario, including distributed environmental sensing, network performance assessment and local estimation of timber equilibrium moisture content (EMC).

The main contributions of the study are as follows:

- Timber-Specific Monitoring Framework - A WSN architecture tailored for timber frame structures, incorporating environmental sensing aligned with moisture-related degradation factors.
- Low-Cost Open-Source Architecture - A fully deployable system based on Raspberry Pi nodes, enabling reproducibility and accessibility for small-scale and research applications.
- Physical implementation and timber-context validation - Validation through deployment in a Welsh larch timber building, providing real-world insights into environmental variability and system performance.

To address the identified research problem, the study is guided by the following research questions (RQ) and testable hypotheses (H):

- RQ1: Can a low-cost IEEE 802.11-based WSN provide reliable communication between distributed environmental sensor nodes and a central hub within a timber-building monitoring scenario?
- RQ2: Can temperature and relative humidity measurements acquired using low-cost sensor nodes be processed locally to provide continuous estimates of timber equilibrium moisture content?

- H1: Network connectivity: The proposed WSN will establish communication between the central hub and the distributed sensor nodes across the experimental topology.
- H2: Communication performance: Node position and physical separation will produce measurable differences in latency, packet loss and throughput, but available bandwidth will remain sufficient.
- H3: Environmental data acquisition: Sensor nodes will autonomously acquire and record environmental measurements.
- H4: Moisture estimation: Temperature and relative humidity measurements can be processed using the implemented estimation model to continuously estimate the equilibrium moisture content of the monitored timber environment.

RELATED WORK

Environmental monitoring has evolved substantially with the development of the Internet of Things (IoT) and Wireless Sensor Networks (WSNs). WSN-based systems enable distributed sensor nodes to acquire and transmit environmental parameters such as temperature, relative humidity, air quality, and other physical variables to a central processing or monitoring platform, see Figure 1. Such architectures have been investigated extensively for smart buildings, industrial environments, infrastructure monitoring, and other applications requiring continuous and distributed sensing. This data is then sent to an application for further analysis and communication.

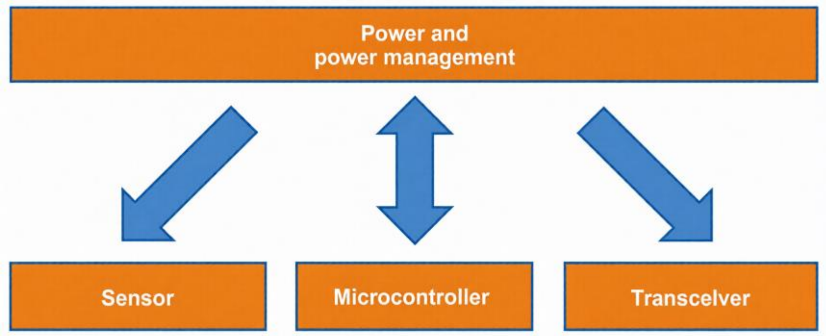

Figure 1. Hardware Structure of a Network Sensor [5]

The early WSN based devices were based on low power microcontroller driven sensor nodes that communicated over networks such as Zigbee and 802.15.4. Newer IoT architectures have integrated Wi-Fi, cellular and long-range communication technologies such as LoRaWAN and the cloud and at the network edge see Figure 2 [6]. The type of communication technology is determined based on many parameters such as range, power use, network capacity, deployment difficulty, cost and amount of data and frequency of use [7-10]. When building scale environmental monitoring is concerned, Wi-Fi based architectures can offer a good compromise, provided the network infrastructure is in place, and fast transmission of data from the sensor nodes is desired.

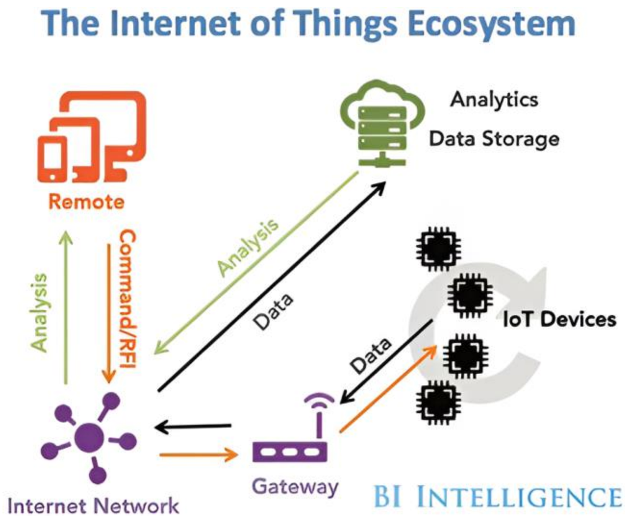

Figure 2. Internet of Things Diagram [6]

Although the WSN and IoT technology are already matured, many of the applications in environmental monitoring are still application generic. Its sensing and communication architecture are generally designed to assess environmental parameters, with little attention given to the properties and degradation process of the monitored material or structure. This is essential for timber frame building, as environment plays an important role in influencing the timber moisture condition and the subsequent effects on dimensional stability, biological durability and long-term performance.

Several studies have investigated sensor-based monitoring of timber and wooden structures, including the measurement of temperature, relative humidity, moisture-related parameters, and structural response [11-19]. These studies demonstrate the potential of distributed sensing for identifying environmental conditions associated with timber deterioration. However, existing approaches differ considerably in sensing architecture, communication technology, data-processing strategy, cost, and degree of deployment complexity. In particular, many systems are developed for specialized research or commercial applications and may depend on proprietary hardware or infrastructure, limiting their reproducibility and adaptation to small-scale timber buildings.

Additionally, table 1 depict the state of art (SOTA) comparisons between different studies. Early studies highlighted the utility of continuous wireless humidity monitoring in heritage buildings [20], and continuous moisture monitoring of dry-service wood [21]. Open-source environmental monitoring systems [22] provided the foundation for developing adaptable and low-cost distributed sensing platforms. At the building scale, authors in [23] monitored moisture conditions in an eight-storey mass-timber building for over a year during construction and occupancy, illustrating the importance of continuous moisture monitoring during the lifecycle of timber buildings. Authors at [24] in their review of timber structural health monitoring, further detail the effects of moisture, material variability, sensor calibration and installation configuration, upon the application of timber-monitoring systems.

Table 1. SOTA Comparison

Study	Application	Sensing approach	Communication/platform	Deployment/ evaluation	Key strength	Difference from present study
[20]	Heritage-building microclimate /pollutants	Temperature/ humidity smart buttons; Hg-vapour prototypes	Wireless smart-button network	In-situ campaign in Villa della Regina, Italy	Discreet sensing for conservation environments	Not timber-moisture focused; no EMC estimation.
[21]	Wood moisture in floors/structural timber	Wood-moisture monitoring	Wireless sensor network	Continuous-monitoring concept/procedures	Early timber-specific continuous WSN approach	Focuses direct wood moisture; present study integrates local T/RH-to-EMC processing and Wi-Fi.
[22]	Open-source environmental monitoring	Multiple meteorological/environmental sensors	Open-source WSN/EMS (4ONSE)	27 systems reported in Sri Lankan river basin	Low-cost, open and adaptable environmental platform	Generic environment rather than structural timber.
[23]	8-storey mass-timber building	Wireless wood-moisture sensors	Wireless monitoring infrastructure	One-year transport/construction/operation monitoring	Long-duration real-building moisture evidence	Higher field-validation maturity; present study is low-cost open-source feasibility.
[24]	Timber structural health monitoring	Review of moisture, vibration, strain, displacement and other methods	Multiple SHM technologies	Review and case studies	Comprehensive timber SHM synthesis	Review rather than deployable open-source prototype.
[25]	Remote timber moisture	Direct resistance-based wood-moisture device	Bluetooth Low Energy + web/cloud	Multi-node remote monitoring system	Compact, low-power, direct MC measurement	Present study uses Wi-Fi/Raspberry Pi and indirect EMC estimation from T/RH.
[26]	Heritage and wooden buildings	Wood-moisture sensing unit	LoRa/LoRaWAN IoT architecture	Integrated smart-building monitoring	Long-range, low-power timber-specific IoT	Present study uses standard IEEE 802.11 and local open-source processing.
[27]	Mass-timber construction	Review of MC sensor types and deployment practices	Multiple sensor/platform types	State-of-the-art review + case-study analysis	Highlights inconsistent deployment/calibration and proposes practice guidance	Supports need for explicit placement/calibration reporting; present study supplies a practical low-cost implementation case.

More recent work has scaled toward more timber-specific IoT architectures, remote moisture monitoring and integration with wireless Long Range (LoRa) / LoRaWan networks for heritage buildings and wooden structures [26]. On the moisture content sensing side, a resistance-based wood moisture sensing system has been implemented with Bluetooth Low Energy (BLE) and web remote monitoring [25], and work on mass-timber buildings has identified issues of sensor type, placement and installation and the reliability of monitoring [27].

The literature therefore indicates a need for monitoring architectures that combine low-cost sensing, accessible wireless communication, local data processing, and timber-specific environmental interpretation. Such a system should not only acquire environmental data but also provide a practical means of relating temperature and relative humidity conditions to timber equilibrium moisture content. This creates an opportunity for open-source and reproducible WSN architectures that can be deployed in real timber-frame buildings without requiring specialized communication infrastructure.

Accordingly, this work is situated in a hybrid position without inventing a new moisture transducer, or implementing a specialised in situ low-power wireless solution, it instead provides low-cost computing (Raspberry Pi), generic IEEE 802.11 networking, on-board (local) sensing and timber-specific moisture content estimation within a suitable monitoring context. Its novelty and contribution therefore are systems oriented, determining whether an open-source overall platform is able to combine distributed sensing, local computation with standard IP communications and timber-specific moisture content predictions.

Environmental Monitoring

While environmental monitoring isn't necessarily a new trend, due to the similar systems being used by companies that deal with hazardous materials such as power plants and transportation of petroleum. Through advancements in technology environmental monitoring is a vital tool used by businesses to ensure compliance with environmental regulations, evaluating clean-up operations and for ensuring safety. Environmental monitoring is also used for investigations into the state of an environment including both its natural changes as well as the impact of human activity [15].

Current systems used within European and Central Asian lack an international methodology across different monitoring metropolitans, even their forms of classification and documentation are often incompatible due to each nation using their own standards [16]. Based on it, UNECE Ministers endorsed recommendations for establishing environmental monitoring systems in European and Central Asian countries prepared by the UNECE Working Group. These documents provide a road map for strengthening, monitoring, and reporting in the European and Central Asian subregion.

Environmental Monitoring of Heritage Buildings

This study aimed to develop a discreet environmental monitoring system for heritage buildings and the artifacts they contain [17, 20]. The introduction outlined the challenges associated with installing conventional monitoring technologies in such structures, where the absence of modern infrastructure necessitates solutions that are unobtrusive and sensitive to conservation requirements. The research was conducted in a Roman-style Italian villa, where maintaining visual discretion was a key design consideration.

The paper also detailed the building's presence of mercury within mirrored surfaces. Over time, mercury can evaporate and form toxic vapours. To address these concerns, two types of sensors were deployed. Compact temperature and humidity sensors designed to remain visually unobtrusive, and specialised mercury sensors to detect hazardous vapor levels.

SYSTEM DESIGN AND IMPLEMENTATION

In designing the proposed WSN, we have been following the requirements for monitoring the environmental conditions of the timber frame building. The system has been designed with effective accurate data acquisition, low-cost, nonintrusive installation to the building and reliable message passing between nodes in mind. We describe the architecture, hardware and prototype design process leading to the final system design.

Design Parameters

The test structure was a one-storey timber building, made entirely from Welsh larch, with the internal walls filled using a clay-like material reinforced by wool fibres. The roof was made from compacted soil to take advantage of natural insulation, and the structural timber frame was left exposed inside the building and can be seen in Figure 3. The design of the test structure dictated the layout of the sensors.

Figure 3. Research Test Site, Welsh Larch

From the above, Figure 4 shows the proposed sensor-node topology and installation in the timber frame monitoring context. The topology is colour coded and indicating the position of the node, the orange nodes are to be installed outside and underneath attached to the pillars which support the first floor, the purple are indoors attached to the pillars which support the roof, and the green nodes are used either outside or attached to a pillar partially exposed outside.

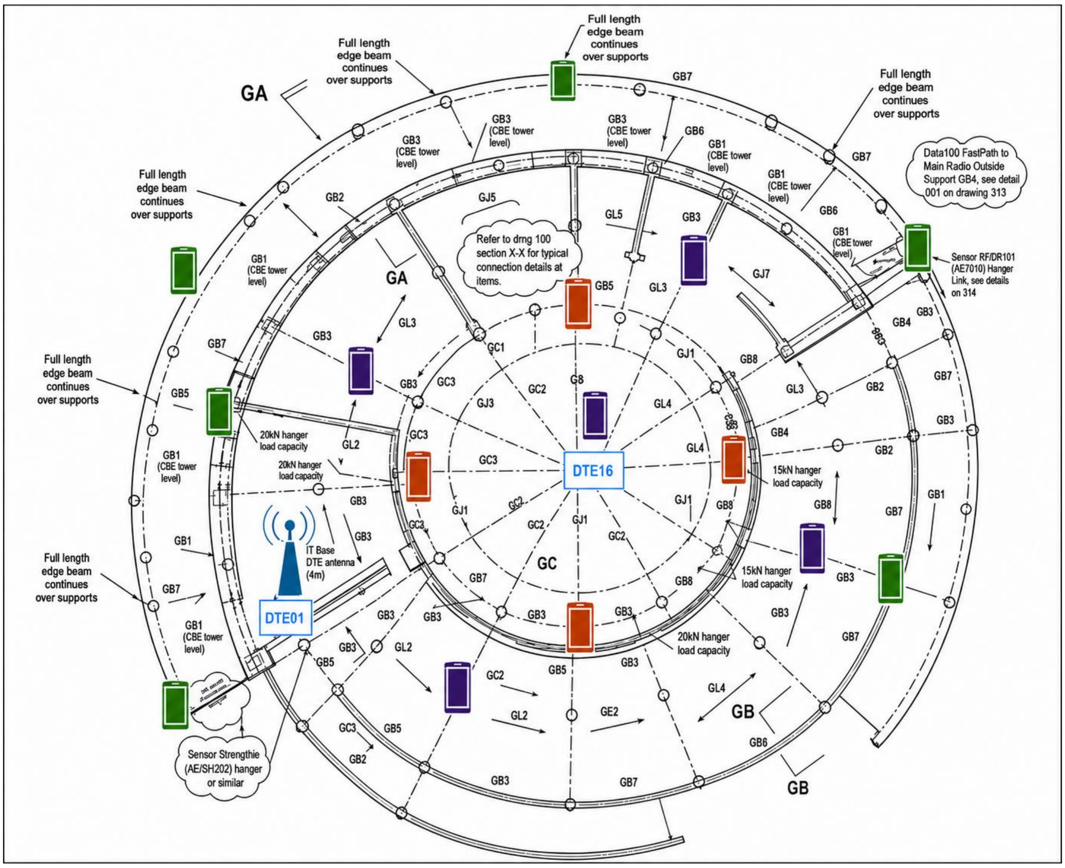

Figure 4. Proposed Sensor-Node Topology and Placement Within the Timber-Frame Monitoring Environment

In the present study each sensor-node is expected to run on the 15-minute acquisition cycle. This duration was a compromise between the aforementioned requirement of multiple ecological observations and the undesirability of load due to processing and communications. Furthermore, the planned rural deployment site imposed two real-world constraints, such as maintained Internet access through a relatively low satellite link and difficulty in power supply to spatially distributed nodes. These constraints justified the need of local processing and storage, as an alternative to an always on cloud backend.

Degradation of the timber is greatly affected by the moisture levels present. For that reason, the state of the timber was assessed during design. The natural splitting of the larch beams, usually the result of drying was taken into account when designing the least intrusive means of probing ambient conditions possible without jeopardizing the integrity of the wood.

The entire WSN topology was designed such that there were a central server and fifteen sensor-nodes scattered throughout the structure. Five sensors were deployed within the building while the other ten sensors were deployed outside the building to define a digital boundary encompassing all exposed woodwork.

Prototype Design

Preliminary prototypes were developed using an Arduino MKR1000 equipped with environmental sensors and a capacitive soil-moisture sensor. Two prototype nodes were constructed to distinguish system-level failures from isolated hardware faults or assembly errors. Initial testing identified two important limitations. First, the microcontroller configuration provided insufficient computational and software flexibility for the intended processing workflow. Second, the capacitive soil-moisture sensing approach was designed to characterize volumetric water content rather than the timber moisture-related parameter required by the study. These findings motivated a redesign based on a Raspberry Pi platform and an equilibrium moisture content (EMC) estimation approach derived from temperature and relative humidity measurements.

The Raspberry Pi Zero was then chosen for the sensor-node platform. Like the C.O.P.T. node, it is a single-board computer, this time running the Raspberry Pi OS operating system. It provided a more powerful, more configurable and more software flexible system than the first microcontroller-based node. Being Linux-based, it could also make use of a wide range of further software packages and implementations.

For system consistency, the network hub was also built on a Raspberry Pi 3B model. The built-in Wi-Fi interface allowed the hub to function as an access point, and also a file transfer server. Once configured on the private network set up by the network hub, the sensor-nodes and the central system could communicate directly, without relying on the internet or other external networks.

The prototype implementation of the IEEE 802.11 wireless network was set to use security through WPA2 authentication, and data encryption via CCMP. A randomly generated network password was used, and to improve network configuration SSID broadcast was disabled. Timestamp synchronization was achieved by way of the Network Time Protocol (NTP). However, since the test site has limited access to the Internet and the Raspberry Pi nodes were not equipped with consistent real-time clocks, this presents a limitation in terms of the example implementation.

Figure 5 depict the main components of the prototype design that we need to implement on timber placement.

Additionally, the equation (1) has been used to calculate the equilibrium moisture content (EMC) principles which has been adapted and implemented directly within the Python processing script running on each node as can be seen in the Figure 6.

$$EMC = \frac{1800}{W}\left[\frac{Kh}{1-Kh} + \frac{K_1Kh+2K_1K_2K^2h^2}{1+K_1Kh+K_1K_2K^2h^2}\right] \quad (1)$$

Where *h* is relative humidity and *W*, *K*, K_1, K_2 are the temperature-dependent coefficients for our case study.

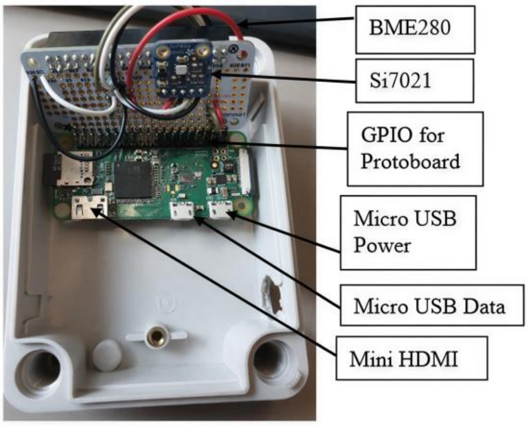

Figure 5. Sensor-Node Components

```
W = round(330 + 0.452 * Temperature + 0.00415 * Temperature**2, 4)
K = round(0.791 + 0.000463 * Temperature - 0.000000844 * Temperature**2, 4)
K1 = round(6.34 + 0.000775 * Temperature - 0.0000935 * Temperature**2, 4)
K2 = round(1.09 + 0.0284 * Temperature - 0.0000904 * Temperature**2, 3)

Moisture = round((1800 / W) * ((K * Humidity / (1-(K * Humidity))) + (((K * K1 *
Humidity) + ( 2 * K1 * K2 * K**2 * Humidity**2))) / (((1+(K * K1 * Humidity) + (K1 * K2
* K**2 * Humidity**2))))), 3)
```

Figure 6. Script Node for EMC Model

The BME280 sensor module was selected for its ability to capture temperature and relative humidity both required inputs for the EMC calculation. Sensor readings were processed locally by the Raspberry Pi Zero and logged to a spreadsheet automatically generated by the system.

The finalised sensor-node represents a convergence of compact environmental sensing hardware and embedded computing. Its small physical footprint enables installation within confined or visually sensitive areas of a timber frame structure. Furthermore, the integration of autonomous network management, data processing, and environmental sensing allows the system to be deployed with minimal technical expertise.

Design Physical Sensor-Node Implementation and Timber Placement

All final sensor nodes were built on a Raspberry Pi Zero W. The BME280 and Si7021 environmental sensors were soldered to a protoboard, which was connected to the Raspberry Pi GPIO. The electronics were housed in a miniature protective case with provisions for power and data connections. During the site survey, the unprotected Welsh-larch frame was tested to find internal, external, and under-floor positions similar to those planned with minimum disruption to the timber. Existing drying cracks could be seen in a number of members, so these were taken as a design constraint; they were not deliberately exploited as insertion points.

The planned network configuration was fifteen sensing nodes plus the central hub, with five internal and ten external/perimeter positions. The design was such that nodes would be sited next to exposed timber members so that the BME280 could record the local temperature and relative humidity, inputs to the embedded EMC model. An early prototype had employed a capacitive soil-moisture probe, but this was abandoned as the principle of the sensor's operation was not appropriate for the quantity of timber-moisture needed, and as the final design would not have inserted a traditional moisture probe into the timber. Instead, the approach was to determine moisture content estimation from the local hygrothermal environment of the timber.

The proposed physical distribution of the sensor nodes across the timber-frame structure is illustrated in the above Figure 4. The deployment of the sensing nodes was such that local environmental variations affecting the timber members could be monitored in both internal and external/perimeter locations. The sensor nodes were designed to transmit wirelessly to the hub node, which served as the collection point of the distributed monitoring system

Access restrictions meant that the entire network was not installed at the original rural site at the final test period. The complete network was therefore installed in the laboratory to mimic the planned node-to-hub arrangement, with some nodes fixed against timber samples. A smaller sample of nodes was also installed against timber of the same species and rough size in a timber-framed setting to demonstrate sensing, automated data logging and EMC calculation. This is relevant because the experiment demonstrates the viability of construction and operation in a timber context, without being able to evaluate long-term performance in the field.

The sensor-node configuration was also tested in close proximity to wood samples in order to exhibit a realistic setup of the electronic sensing apparatus in the environment to be monitored. As seen in Figure 7, the encased sensor node with Raspberry Pi was placed next to a piece of wood, with the environmental sensors reading the conditions of the attached wood.

Figure 7. Final Raspberry Pi Zero W Environmental Sensor Node Mounted Against a Timber During Implementation Testing

This implementation shows the non-invasive qualities of the final design, as the sensing unit could simply be put beside the member of timber without the electronic sensor assembly having to be embedded in or cause any physical change in the structural member.

DATA ANALYSIS AND RESULTS

The evaluation of the proposed Wireless Sensor Network (WSN) focused on three key areas: node connectivity and reliability, network throughput performance, and verification of environmental data acquisition and equilibrium moisture content (EMC) estimation. A sequence of controlled tests was conducted within the deployed network to assess its operational stability and suitability for timber-specific environmental monitoring.

Experimental Protocol

The evaluation functioned in two parts: firstly, the entire WSN was configured to emulate the designed topology; to determine the extent to which individual nodes could be reached or communicated with. The whole network was then subject to node reachability and throughput testing via a Python testing script accessing each sensor sequentially and iPerf client/server relationship testing. Selected near and far nodes are investigated in detail for location-dependent variation [28]. Secondly a sample of sensor nodes was populated in a timber-framed environment, to verify acquisition under environmental conditions; to automate recording of data; and to perform the required EMC calculation. Measurements are stored according to the programmed 15-minute cycle. The evaluation thus evaluated node access, packet loss and/or response times, network throughput, the generation of structured environmental records and the generation of an unbroken sequence of EMC calculation results.

Connectivity and Node Availability

An initial connectivity test was implemented using a Python script executed on the network hub. The script sequentially transmitted test packets to each of the fifteen sensor nodes and awaited a response before proceeding to the next device. Nodes that responded within the defined timeout interval were classified as online, whereas nodes that failed to respond were labelled offline.

At the time of the initial connectivity experiment, all fifteen sensor nodes successfully responded to the hub, demonstrating complete reachability for that test cycle. More detailed inspection nevertheless showed that connectivity quality was not uniform: the reported comparison recorded 10% packet loss for DTE02, whereas DTE14 completed the sampled transmission without packet loss. This result supports H1 for the evaluated topology while also showing that successful association with the hub does not imply identical link quality across node locations. The architecture therefore benefits from spatial redundancy, but the experiment does not establish long-term uptime.

Throughput and Communication Performance

To evaluate communication performance between each sensor node and the hub, network throughput was measured using the iPerf speed-testing tool [19]. Two representative nodes were selected to illustrate differences associated with physical placement: one positioned in close proximity to the hub, and one located at the furthest practical distance within the deployment topology. As shown in Figure 8, the nearer node exhibited substantially higher transfer rates compared to the more distant node.

```
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 10.3.141.2, port 46166
[  5] local 10.3.141.1 port 5201 connected to 10.3.141.2 port 46168
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-1.00   sec  2.17 MBytes  18.2 Mbits/sec
[  5]   1.00-2.00   sec  1.84 MBytes  15.4 Mbits/sec
[  5]   2.00-3.00   sec  1.90 MBytes  16.0 Mbits/sec
[  5]   3.00-4.00   sec  2.80 MBytes  23.5 Mbits/sec
[  5]   4.00-5.00   sec  2.83 MBytes  23.7 Mbits/sec
[  5]   5.00-6.00   sec  3.13 MBytes  26.2 Mbits/sec
[  5]   6.00-7.00   sec  2.90 MBytes  24.3 Mbits/sec
[  5]   7.00-8.00   sec  3.17 MBytes  26.6 Mbits/sec
[  5]   8.00-9.00   sec  3.24 MBytes  27.2 Mbits/sec
[  5]   9.00-10.00  sec  3.38 MBytes  28.4 Mbits/sec
[  5]  10.00-10.05  sec   219 KBytes  34.8 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-10.05  sec  27.6 MBytes  23.0 Mbits/sec
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
```

Figure 8. Sample of Node Throughput Test

Throughput varied by approximately 6 Mbytes in data volume and 5 Mbit/s in bitrate between the two tested devices. This disparity aligns with expectations based on Wi-Fi signal attenuation and environmental interference within timber-based structures. Although notable, the observed performance remained within acceptable limits for this application. The system requires only small, periodic data transfers from each node, meaning that reduced throughput does not impede functionality. However, the findings suggest that significant increases in data payload size such as incorporating higher-resolution sensor data could introduce transmission delays in future system iterations.

Environmental Data Output and Moisture Content Estimation

The final stage of the evaluation focused on verifying data acquisition and the correct execution of the adapted moisture content model incorporated into each sensor node. Table 2 displays an excerpt from the automatically generated data output produced by the network.

All required fields, including temperature, relative humidity, and calculated moisture content, were successfully populated with numerical values. Although independent laboratory equipment was unavailable to validate absolute accuracy, two indicators confirmed correct system behavior:

1. Successful file generation, demonstrating that the embedded Python script processed sensor data and executed the equilibrium moisture content formula without error; and
2. Consistent incremental variation between successive measurement cycles. Observed differences ranged from 1–4%, which is characteristic of natural fluctuations in environmental conditions rather than systemic malfunction. Large or erratic deviations would have indicated computational or sensing errors, none of which were detected.

Table 2. Output Data from Sensor Node

Temperature (⁰C)	Humidity (%)	Moisture (%)	Pressure (hPa)	Altitude (m)	External Temperature (⁰C)	External Humidity (%)
25.5984	60.0512	11.353	1000.2966	109.7966	29.4268	60.7457
21.5423	59.2077	11.131	999.4509	117.0783	24.3110	58.0907
21.7863	57.8775	10.872	999.0201	120.3465	24.4718	56.8395
218931	57.7491	10.871	998.7122	123.1094	24.4397	56.4961
20.7039	64.2556	12.157	996.4188	142.6069	23.2277	62.1037
21.1052	62.4928	11.811	995.8973	146.8803	23.6782	60.2422
21.2781	61.7541	11.659	995.3627	151.3669	23.8498	59.3419

These results support H3 and show achievement of the functional implementation of H4. The nodes successfully produced a semi-structured environmental record and the implemented EMC algorithm produced numerical data regarding the moisture estimated during the programmed cycle. Due to the unavailability of reference calibration instrumentation, the experiment only verifies software execution and output continuity and not the absolute accuracy of the estimated moisture.

The experiments illustrate the distinctness of communication capability and measurement accuracy as shown in table 3. Network capability was established through reliably-placeable- end-to-end reachability and throughput adequate for the light-duty 15-minute sampling cycle, despite the litany of DTE02 packet-loss points and the roughly 5 Mbit/sec bit rate differential between the demonstration-MOS and representative-MOS positions, thus confirming installation layout as an important factor in IEEE 802.11 performance. The sensing pipeline, meanwhile, was successfully tested: environmental measurements were obtained, transmitted, and deposited without human intervention; the EMC calculation provided a continuous series of numbers. These pertain to the architecture's operation, not to its metrological precision; a calibrator was not available during the tests.

Table 3. Summary of Experimental Outcomes

Evaluation	Observed result	Interpretation	Hypothesis	Evidence boundary
Node reachability	15/15 nodes responded during the initial connectivity cycle.	Demonstrates complete reachability in the tested topology.	H1 supported for the test cycle.	Not a long-term uptime measurement.
Packet behaviour	DTE02 showed 10% packet loss; DTE14 showed 0% in the reported representative comparison.	Link quality varied with node position even when nodes remained reachable.	H2 partially supported.	Only representative node-level results were retained in the project evidence.
Throughput	Representative near/far comparison differed by approximately 6 Mbytes transferred and 5 Mbit/s bitrate.	Spatial separation/placement affected Wi-Fi performance, but capacity remained adequate for small 15-minute sensor records.	H2 supported for application feasibility.	No complete per-node statistical distribution was preserved in the paper/project.
Environmental acquisition	Temperature, relative humidity and calculated EMC fields were automatically populated in structured records.	Confirms autonomous sensing, local processing and logging pipeline.	H3 supported.	Does not establish calibrated sensor accuracy.
EMC	The Python implementation generated numerical EMC values every 15 minutes; successive reported values varied by approximately 1–4 points.	Confirms execution and continuity of the EMC calculation under changing environmental inputs.	H4 functionally supported.	No calibrated reference moisture meter was available; absolute EMC accuracy is unvalidated.

In the context of the 10% packet loss and roughly 5 Mbit/second difference: This result further emphasizes the importance of considering placement as a design parameter of the sensing system in a timber building: construction geometry, physical distance, and the local obstruction may degrade network efficiency such that the node is logically connected but not physically together.

The results demonstrate a practical trade-off between the flexibility of an IEEE 802.11/Raspberry Pi architecture and the low-power characteristics commonly associated with conventional WSN platforms. The switch from Arduino to Raspberry Pi increased processing capability and enabled local Python-based sensing, file generation and standard IP networking, but it also introduced greater power requirements. For this application, therefore, network availability and robustness are more significant than peak throughput.

This research work further clarifies why the contribution is best evaluated as a timber-specific systems integration and feasibility study rather than a new sensing technology. The framework merged open-source single board computing appliances, environmental sensors, local processing and conventional wireless networking in a rugged timber framed shell. All nodes responded to the initial connectivity assessment and the sensing software issued the expected environmental and electromagnetic measurements. Simultaneously, the 10% packet loss produced at a single normal node and the roughly 5 Mbit/sec throughput gap between the two normal positions reflect that deployment geometry is still relevant engineering knowledge.

Limitations and Threat to Validity

The measurement validity is the primary concern. Without independent calibrated instrumentation, the absolute accuracy of the measurements derived from the BME280 and the derived EMC values cannot be determined. The moisture results should therefore be viewed only as evidence that the sensing/calculation pipeline was functioning correctly, not as validated timber moisture contents. Experimental validity is also limited as access restrictions prevented the entire network from being tested in the customary rural building environment; instead, the full WSN was configured in a laboratory to mimic the anticipated topology while 1/3 of the network was trialled in a timber-framed environment. The network measurement should therefore be considered evidence of network feasibility in the tested environment rather than conclusive performance metrics.

There are further limitations related to time synchronisation, sampling resolution and power. NTP synchronisation was hampered by limited remote internet access and the Raspberry Pi nodes had no local, persistent real-time clocks. While the 15-minute sampling interval offers good periodic monitoring, rapid environmental fluctuations may go undetected. Additionally, without data on autonomous long-term energy consumption and battery duration, conclusions about long-term operation can't be drawn. None of these limitations affects the basic achievements of the integration of distributed sensing, local pre-processing, radio networking and EMC estimation in a single native system architecture.

SUMMARY AND CONCLUSION

This study investigated whether a low-cost IEEE 802.11 Wireless Sensor Network (WSN) could support environmental monitoring within a timber-frame building scenario and whether temperature and relative humidity measurements could be processed to estimate timber equilibrium moisture content (EMC). For RQ1, the initial network test demonstrated connectivity across all fifteen sensor nodes, while the detailed communication tests identified location-dependent variations in packet loss and throughput. Despite these variations, the available communication capacity remained sufficient for the low-volume environmental data generated at 15-minute intervals. These results support the feasibility of IEEE 802.11 communication for the proposed monitoring scenario under the tested conditions. For RQ2, the sensor nodes successfully acquired environmental measurements and executed the implemented EMC model, producing structured numerical estimates without manual intervention.

The results support the functional feasibility of the proposed architecture, but the conclusions remain bounded by the available experimental evidence. In particular, the absence of independently calibrated reference equipment means that the study cannot establish the absolute accuracy of the estimated timber moisture conditions. Similarly, the limited duration and scope of the final deployment do not support claims regarding long-term field reliability or generalization to other timber structures. The principal contribution of the study is therefore the design and experimental evaluation of an open, adaptable, and timber-specific monitoring architecture integrating distributed sensing, local computation, standard IEEE 802.11 communication, and EMC estimation using readily available hardware.

Future research work should prioritize comparison with calibrated reference measurements, longer-term deployments across multiple timber structures, quantitative assessment of power consumption, improved time synchronization, and systematic comparison with alternative low-power communication technologies.

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CONFLICT OF INTERESTS

The authors confirm that there is no conflict of interest associated with this publication.

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