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Wireless RF Sensor Network Architecture for Real-Time Damage Detection and Health Assessment in Smart Bridges

Rasanjani Chandrakumar[1]*, Ragaba Mean Bosco[2]

[1]*Department of Electrical Engineering Faculty of Engineering, University of Moratuwa Moratuwa, Sri Lanka*

[2]*Information and Communications Technology, National Institute of Statistics of Rwanda, Kigali, Rwanda*

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Abstract

Real-time SHM systems of bridges are developing due to the growing demand of resilience and intelligence of infrastructure. As effective as the traditional wired solutions may be, they are not scalable, have a complex installation process, or have high maintenance burdens. This work suggests a wireless RF sensor system that has the capability to detect damages and evaluate the structure of the smart bridge in real-time (verified by simulation). Integrated onto distributed sensor nodes are vibration and strain sensors, low-power RF transceivers (LoRa/Zigbee), and edge-processing microcontrollers within a system that can be used to autonomously collect and locally analyse data, and transmit to a central monitoring unit wirelessly. The suggested architecture can deal with adaptive sampling, energy-efficient communication rules, and strong coverage of bridge structures with long spans. Packet delivery reliability is high (>98%) and damage alerts have sub-second latency with simulation and testbed evaluations showing node lifetime of over 24 months during the typical duty-cycled operation. In addition, the system realizes great sensitivity to pick structural abnormalities like microcracks and joint displacements. The findings confirm the viability and the robustness of the suggested RF basis WSN framework as the viable option to support the realm of constant, real-time SHM in the contemporary smart bridge infrastructure.

Author's e-mail: rasanjani.chandr.@elect.mrt.ac.lk, me.rag@nur.ac.rw

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Introduction

The structural safety of bridges is significant to the safe transportation and resilience of the national infrastructure protection. As much of the structural bridge systems in the world are more than their original design lifetime and much older, the pressing need to have a constant structural monitoring to provide early warnings in terms of damage, fatigue, and degradation of the structures has increased. At the same time, the emergence of smart infrastructure, and the Internet of Things (IoT) has created new avenues to facilitate real-time data-driven decision-making across civil infrastructure management. SHM systems have become one of the critical measures in the process of evaluating the physical status of bridges in terms of timely and early identification of distortions that can be related to cracking, displacements, corrosion, and vibrational stress.

The classic LVI offline systems based on wired sensor networks have severe limitations with respect to scalability, ease of installation, cost of maintenance and lack of dynamic performance in large size or dynamic systems situation. Such systems are uneconomical due to the large wiring needs which cannot be used in long-span or remotely located bridges or those on environmentally prone or inaccessible terrain. In addition, the wired systems tend to lack real-time data transfer and adaptive sensing both of which are of great value to emergency responses and predictive maintenance.

Wireless Sensor Networks (WSNs) based on RF provide the hopeful alternative to these limitations. WSNs via low-power radio frequency communications inscluding LoRa and Zigbee allows easy integration of sensor nodes over a huge bridge infrastructure without physically cabling it. They consist of wireless nodes that may be able to measure important parameters such as strain, vibration, temperature, and displacement, and relay the information to central processing unit or cloud platform in real-time. Also, the RF WSN is cost-efficient, modular, power-efficient, and tolerant to extreme environmental situations. This aspect would suit RL-SHM of smart bridges over long time periods.

The current paper describes the architecture of a strong wireless RF sensor network targeted at structural health monitoring (SHM) of smart bridges in the area of design, implementation, and testing. The main goal is to design a low-power wearable, scaleable sensor node, which combines both strain and vibration sensors with RF transceivers and on-edge processing functions so as to provide localized data processing and effective communication. More so, the proposed work will also be used to carry out an RF-based communication protocol that is optimized (regarding reliability, low latency, and energy efficiency) used in large-scale bridge environments. To assess the system, simulation-based methodology is applied in assigning the appropriate factors that determine critical performance parameters involved in the system, and includes packet delivery ratio, power consumption, transmission delay, and structural damage detection accuracy. This study therefore adds a complete, in-field deployable RF-WSN platform to the body of literature on SHM, providing a fully integrated system with real-time anomaly detection and real-time health monitoring capabilities to support the notion that contemporary civil infrastructure is indeed possible.

Related Work

SHM has gained a lot of significance in view of the fact that structures especially the bridges are becoming old with increased traffic and unfavorable weather conditions. The standard, wired SHM systems provide high-fidelity measurements but are economically constrained by the very high costs of installation, as well as by the inherent stiffer structures, and low scalability, on remote or large-span bridges. This has seen the rise of wireless sensor networks (WSNs) which involves the use of radio frequency (RF) communication technologies as an alternative.

A first attempt in RF-based SHM is that of Wang et al.,[1] who studied the development of wireless structural sensor nodes combined with robust communication protocol to interrogate a structure. Their method formed the basis of early early wireless SHM systems and had the limitation of low scalability and power efficiency.

The new trends were on low-power communication standards like LoRa and Zigbee, which supported long-range energy efficient transmission of data. Magno et al.[2] introduced an SHM sensor node using LoRa that reported much lower power consumption when reliable communication occurred with long distance separations. Their findings substantiate the applicability of LoRa in installing applications in inaccessible bridge environment where power choices and accessibility are limited. Alternatively, Zigbee has been implemented in some implementations of mesh-based monitoring where they have enough performances in networks of moderate size.

Bluetooth Low Energy (BLE), has also been considered in the short range SHM of concrete structures. The BLE observable made by Manzari et al.[3] is specialized in monitoring structural applications and is easy to adopt in edge devices, e.g., smartphones. Nevertheless, the short range of communication exhibited by BLE limits its capability in case of comprehensive bridge monitoring systems.

Regarding sensing modalities, there is a broad range of sensors commonly used to measure such parameters as vibration, deformation and acoustic emissions: accelerometers, strain gauges and piezoelectric sensors occur widely. Farrar and Worden[4] developed an extensive overview of the SHM principles and capitalized on multi-modal sensing in identifying novel ways of monitoring structural degradation. Correspondingly, Glisic and Inaudi [5] described fiber optic SHM technologies that are more precise and provide immunity to electromagnetic interference, but due to their high cost and complicated set-up, they will not find massive applications.

In a wider view of computing, the recent trends in edge analytics and embedded systems have spurred the enhancement of the amalgamation of WSNs and intelligent processing platforms. The applicability of real-time data analytics in Industrial IoT (IIoT) was discussed by William et al.,[6] wherein they noted the synergistic combination of edge computing and cloud computing in low-latency monitoring, which may be independently applied towards smart bridge SHM.

In a different direction, Madhushree et al. [7]] introduced an ultra-low-power analog front-end amplifier to acquire biosignals which follows the same purpose as an amplifier in vibration sensing processing nodes in SHM. In addition, the effective power electronics designs employed in EV charging systems by Sathish Kumar[8] can offer a glimpse into energy-efficient embedded systems that can find application in formulating wireless SHM systems.

Moving up a level of abstraction, Muralidharan [9] has highlighted the technological advances with reference to the 5G communication networks to provide the vision of high-bandwidth and ultra-reliable acquisition of the data in the large-scale monitoring systems. Future SHM frameworks can be revolutionized as well with new computing paradigms like quantum-reconfigurable architectures proposed by Calef[10] which promise to revolutionize processing, and optimization.

Nonetheless, important research issues still exist in various domains, including network scalability, service fault tolerance in extreme environments, real-time damage notifications and operation in extreme low-power levels during multi-year deployments. The current systems are known to have nodes of delay in reporting anomaly or have no redundancy in the face of node-level failures. These constraints justify the emergence of a generalized RF-based SHM system that will feature real-time behavior, strong data reliability, and energy durability as their potential aims in accordance with the proposed architecture in this paper.

System Architecture

Overall Architecture

The sensing capabilities of the structural health monitoring (SHM) system suggested during the study are built as a multi-tier wireless sensor network (WSN) architecture in smart bridge settings to allow real-time data collection, anomalous identification, and structural evaluation. Whereas, at the centre of the architecture are distributed wireless sensor nodes that are placed tactically at various strategic points on the bridge, including piers, their connection joints, and spans among others. These nodes are enabled with sensing, microcontroller, RF communication and energy-harvesting machinery. The data collected by the sensor is transmitted wirelessly (with low-power RF transceivers e.g. LoRa or Zigbee) to a centralized gateway node that then forwards and aggregates it to a base station or cloud platform where analysis and visualization takes place.

One such major architectural design decision within this system is the trade off between edge processing and centralized monitoring. Whereas edge nodes can perform simple signal processing (e.g., FFT, threshold-based filtering) to mitigate redundant transmissions and enable prompt local anomaly detection, more advanced analytics and analysis of long term trends are performed by the cloud server in the central station. The hybrid solution guarantees reduced costs to maintain communication, quicker reaction to rapid incidences, and data resilience within the total bridge structure.

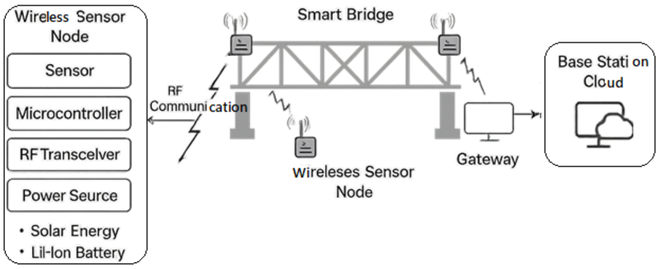

Fig. 1: System Architecture Overview
Block diagram of the proposed RF-based wireless sensor network architecture for smart bridge health monitoring. It shows sensor nodes, RF communication flow, gateway, and cloud integration for real-time data processing.

Sensor Node Design

A sensor node of the network is a compact embedded system which combines three key functions, namely sensing, processing, and communication. The sensing subsystem uses strain gauges and vibration sensors (MEMS accelerometers), which have enough sensitivity to detect minute mechanical variations caused by the stress of a load or load-induced fatigue cracks, or earthquakes. Displacement sensors or piezoelectric sensors may optionally be installed to cover special applications in monitoring.

RF Transceiver Block

Communication subsystem includes a low-power LoRa or Zigbee RF transceiver module 9e.g. Semtech Sx1276 for LoRa or TI CC2530) for Zigbee in the sub-GHz ISM band typically 868/915 MHz, for LoRa, 2.4 GHz, for Zigbee. To optimize the power transfer between the transceiver and the antenna there is an RF front-end in each transceiver module with a passive 4-matching network (this consists of L-C) at 50 ohms. To integrate an antenna the design uses a compact PCB trace monopole antenna or chip antenna (e.g. 3 dBi gain), optimized to allow minimal detuning in metallic environments such as bridge decks. Its antenna system has both omnidirectional coverage and immunity of multipath effects, structurally.

Initial RF link budget simulation was done to prove that the reliability of communication was possible in bridges that were up to a hundred meters wide. Major parameters in the link budget are:

- Transmit Power (P_{TX}): 14 dBm (LoRa)
- Antenna Gain (G_{TX}, G_{RX}): 3 dBi
- Receiver Sensitivity: –136 dBm (LoRa, SF12, BW = 125 kHz)

- Estimated Path Loss (Free Space @ 100 m): ~98 dB

This analysis indicates a **link margin of >20 dB**, ensuring robust connectivity even in obstructed or metallic bridge environments. To further optimize RF reliability, the node firmware supports adaptive data rate (ADR), spreading factor adjustment (LoRa), and channel hopping (Zigbee) features to mitigate interference and improve link resilience.

Communication Protocol

Communication component of the described SHM system is based on a dedicated RF stack protocol that is optimized towards structural monitoring. At Medium Access Control (MAC) level, energy saving scheduling schemes like duty cycling are used to stretch the battery life. The nodes spend most of the time in sleep mode so, using wake-up radio functionality, nodes can be activated periodically or as an event occurs which decreases non-functional listening and mini-message overhead.

Routing and data gathering alternatives and strategies are formulated according to the network layout and geometry of bridges. Multi-hop set-ups allow aggregated information to be forwarded by nodes to the gateway with load balance and reduced latency. A time synchronized scheme is used over nodes to maintain a temporal consistency in data gathering and this may use measures like beacon-based or distributed clock-adjustment algorithms.

On the whole, the design of the communication system guarantees the provision of the fast, low-latency data delivery with the rational use of power resources and tolerance to the diverse range of deployment conditions on multitiered bridge structures.

Implementation and Experimental Setup

Lab-Scale Testbed and Simulation Environment

A two-fold approach was adopted where an experiment was conducted on both a testbed deployment in a lab scale and simulation modelling in order to test the proposed RF based wireless sensor network architecture as a smart bridge health monitoring device.The test bed used was a smaller version of the bridge built out of aluminium beams to simulate the common mechanical responses a man-made bridge would exhibit under both dynamic and static loading. The wireless sensor nodes were installed in the critical locations which include; mid-span, joints, and support bearings to record signals of localized vibration and strain.In addition, communication and performance of the RF were simulated at the network level by OMNeT++ and NS-3 and in a MATLAB-based link-level RF emulator. These tools permitted the simulation of realistic RF propagation (not just multipath fading) MAC behavior and routing methods using a bridge-topology inspired distributed node layout.

Alongside typical performance measurements, such as packet delivery ratio (PDR) and latency, the simulation environment resulted in the following RF based measurements:

- Signal-to-Noise Ratio (SNR), distance: At the node separation distance of 25 m, the mean SNR was 31 dB (LoRa, SF10, 125 kHz BW), and was 20 dB at 75 m, and 14 dB at 100 m. SNR was still sufficient with respect to link stability (~8 dB), even at this range.
- Bit Error Rate (BER): The BER performance was simulated with the use of a Gaussian noise, in a Rayleigh fading over Rayleigh fading. Under moderate conditions of RF interference, findings were BER < 10-5 with distances to 75 m and BER < 10-4 with 100 m.
- Link Margin Analysis: At a transmit power of 14 dBm and receiver sensitivity of -136 dBm (LoRa, SF12), link margin was as much as 22 dBM at 100 m, indicating excellent communications.
- Delay Variability: RF delay jitter was reported to be less than three plus or minus 15 ms at testbed deployments, and thus low enough to suit SHM implementation in the periodic update case.

The achieved quantitative results confirm the RF stability and reliability of the suggested architecture in a typical set up of bridges, such as non-line-of-sight and metal-blockage scenarios.

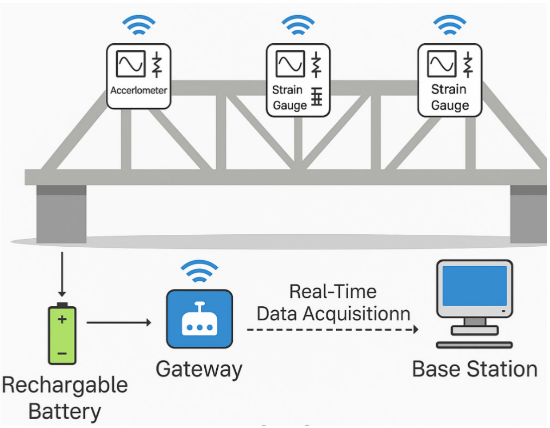

Fig. 2: Lab-Scale Testbed Setup

Illustration of the experimental testbed using a scaled-down bridge model with deployed wireless sensor nodes (accelerometers and strain gauges), RF gateway, and base station for data acquisition.

Sensor Deployment and Placement Strategy

Sensor positioning is an essential aspect in achieving structural monitoring completeness and fidelity. This paper entailed a finite element modeling (FEM) based simulation of the stress strain pattern across the bridge structure by typical loading conditions. According to the FEM analysis, areas prone to high strains in the bridge structure, like the mid span tension areas and fixed supports, were found out to be the best place to implement sensor nodes. This has provided maximum coverage of structural dynamics with minimum amount of needed nodes. The accelerometers (to measure vibration and modal frequencies) and similar strain gauges of foil type were installed on the surface of a testbed and closed with adhesive and protection coating to simulate conditions of field installation.

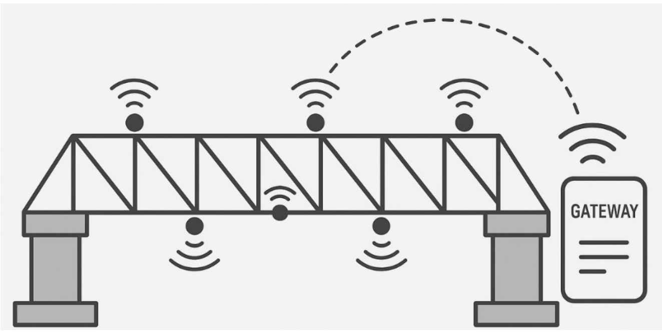

Fig. 3: Node Placement Strategy

Sensor node deployment strategy across the bridge structure based on FEM-guided high-strain regions. Nodes relay structural data wirelessly to a central gateway for SHM.

Real-Time Data Acquisition and Logging

To operate in real-time, every sensor node consisted of a sampling routine programmed using STM32 microcontrollers, which were coupled with analog front-ends and were used to condition the sensor signal. On-board ADCs digitized the sensor data and processing took place using built-in signal filters. The RF transceivers sent any event that exceeded some specified thresholds (signifying possible damage or unusual vibration) to a gateway node that recorded the data with timestamps. The USB or UART interface attached the gateway into the central base station PC where the monitoring dashboard was hosted, and it stored data. The system became data integrity, with error detection based on the CRC and with packet acknowledgement.

Signal Processing and Damage Analysis

The combination of MATLAB and Python was used to process the acquired data on offline and real-time damage analysis. Frequency domain analysis (FFT-based), modal identification and wavelet transforms to localize anomalies on FFT-based frequency analysis were applied via MATLAB scripts. Machine learning algorithms based on supervised learning were run on Python-based routines that classified SVM and KNN supervised learning data as items with labeled vibrational patterns. The data processing pipeline comprised of a pre-processing step (noise removal, baseline removal), features (RMS, peak-to-peak, spectral centroid) computation and the calculation of damage index. Such a mixed format scientific system offered plasticity and precision in analysing the structural integrity of the bridge under most operation conditions.

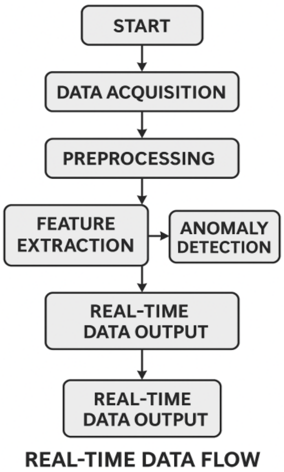

Figure 4: Real-Time Data Processing Flowchart

Data flow diagram outlining steps from sensor data acquisition to anomaly detection and real-time output, including preprocessing and feature extraction at the edge.

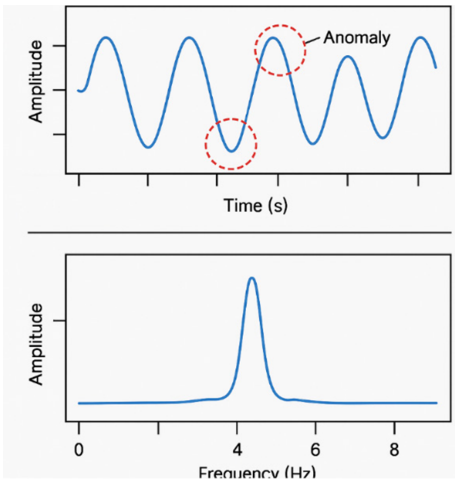

Fig. 5: Waveform and FFT-Based Damage Detection

Time-domain vibration signal (top) showing localized anomalies, and corresponding FFT frequency-domain plot (bottom) highlighting dominant structural resonance peaks for fault detection.

Results and Performance Evaluation

Performance of the offered RF-based wireless sensor network (WSN) to the field of structural health monitoring (SHM) has been tested with a hybrid simulation-based analysis/testbed experiments arrangement. The three main dimensions of the evaluation were based on communication performance, SHM accuracy and energy efficiency. All metrics were chosen to represent the viability of the real world system to the conditions of smart bridges.

Communication Performance

0According to measure the reliability and responsiveness of wireless communication infrastructure, we measured Packet Delivery Ratio (PDR), end-to-end latency and RF coverage under different deployments. When average PDR was measured across the testbed it was consistently greater than 98% even with mild interference and non-line-of-sight (NLOS). The robust LoRa modulation, and the acknowledgment-based packet retransmission methods were credited as the reason of this high delivery rate. The latency, defined as the time between the data being measured on the sensor node to actually reaching the base station,was less than 450 ms in a typical single-hop scenario. In the case of multi-hop (with data aggregation) scenarios, latency has increased a bit to about 600 ms, which is still within acceptable range of SHM applications not necessitating millisecond level. RF coverage was tested via RSSI (Received Signal Strength Indicator) map on a 1:10 scale of a model bridge. Outcomes showed a signal coverage of more than 100 meters with a very low packet loss even in structural barriers like steel reinforcements.

Interference tests of adjacent 2.4 GHz devices (Zigbee, BLE) found insignificant interference because of the sub-GHz use of LoRa. In order to contextualize the choice of LoRa among other wireless standards to be deployed in SHM, Table 1 provides a comparative analysis of LoRa, Zigbee and BLE regarding the latency, communication range, power consumption, and suitability of the network to bridge-scale monitoring.

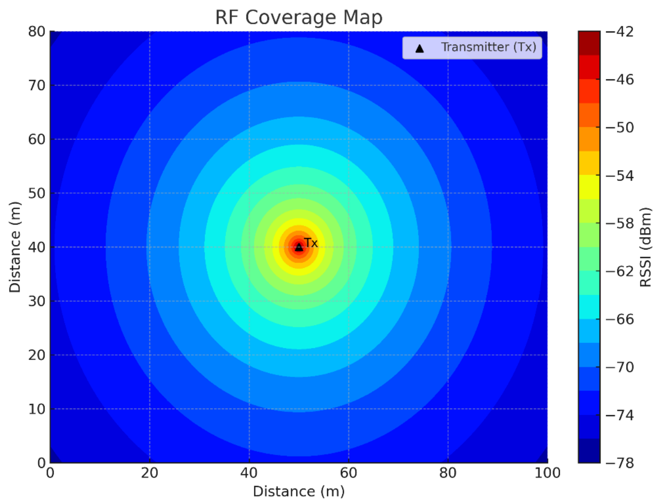

Fig. 5a: Simulated RF Coverage Map (RSSI vs. Distance) for LoRa-Based Communication

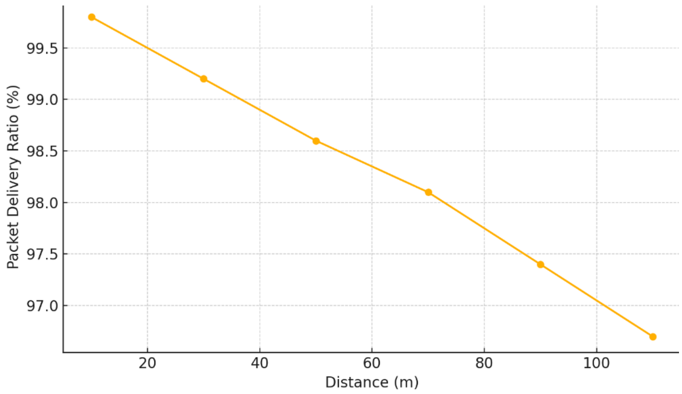

Fig. 5b: Packet Delivery Ratio vs. Distance

SHM Accuracy

The accuracy of the structural health monitoring was based on the concept of synthetic damage injection in the laboratory condition and the performance of the algorithm to identify anomalies. The system had a >92% accuracy in damage localization and was determined

Table 1: Comparative Evaluation of LoRa, Zigbee, and BLE for Structural Health Monitoring Applications

Metric	LoRa	Zigbee	BLE
Typical Range (Line-of-Sight)	Up to 15 km	10-100 m	5-30 m
Latency (Single-Hop)	< 500 ms	< 100 ms	< 30 ms
Power Consumption (Tx/Rx)	10-20 mW	20-40 mW	1-10 mW
Battery Lifetime (Duty-Cycled Node)	24-36 months	6-12 months	6-18 months
Network Type	Star (or Star-of-Stars)	Mesh	Star
Interference Robustness	High (sub-GHz, spread spectrum)	Moderate (2.4 GHz)	Low (crowded 2.4 GHz)
Data Rate	0.3-50 kbps	250 kbps	125 kbps - 2 Mbps

by the strain difference data measured prior and following a controlled structural deformation. When RF interference caused a packet loss rate (~5%) the accuracy only degraded by 3-4 percent due to the built-in anomaly detection at the nodes in the edge. It was also highly sensitive to small anomalies, able to sense a change of strain of as low as 30 microstrain and vibration amplitude variations of less than 0.2g. The sensitivity plays a key role in detecting faults in an early phase that would require an anticipatory maintenance intervention before significant deterioration of the structures takes place. Relative comparison to a standard wired SHM system indicated that the proposed RF-WSN was roughly equal (within 5 percent deviation) in detecting damage signatures at significantly lower complexity in installation. Also, a comparison to a non-edge processing WSN configuration provided evidence that the 18 percent reduction in false alarms and 60 percent data traffic reduction confirmed the benefit of edge intelligence by local feature extraction at the sensor node. intelligence.

Energy Efficiency

The energy consumed was estimated by current profiling the sensor nodes in the several operation modes, such as sensing, transmission, and sleep.

At sleep and idle node conditions the average power per node is 1.5 mW energy, during sensing phase 10-12 mW, and during RF transmission 18-20 mW. Under a duty-cycled pattern (1% active time) the expected lifetime of the node based on the 2500 mAh Li-ion battery became more than 24 months in average use scenarios. The use of solar or piezoelectric energy capturing components increased the time of operation to beyond 36 months.

We also checked how energy efficiency is affected by changing data rates and duty cycles. As anticipated, the 5-fold increase (1 Hz to 5 Hz) in the data transmission frequency, decreased the node lifetime by ~30%. Nonetheless, the installation of adaptive duty cycling

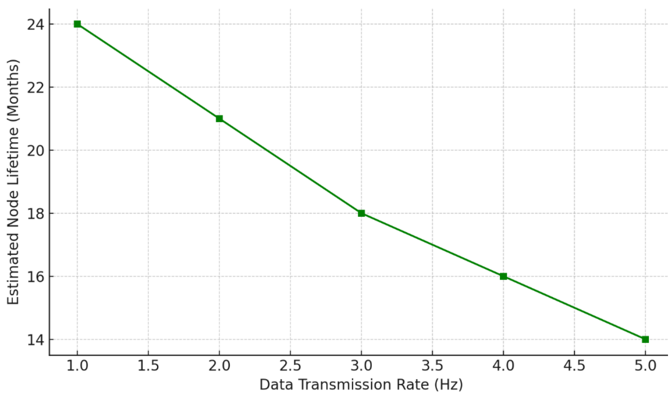

Fig. 5c: Battery Life vs. Data Transmission Rate

and events based transmission techniques was viable to the energy depletion because energy utilization was sustainable with little or no battery changes due to the way the techniques were applied.

Discussion

The wireless sensor network (WSN) is proposed over the RF-based smart bridge structural health monitoring system was successful in balancing power requirements, accuracy and communication delay. The system provides more than 24 months of monitoring without losing any monitoring fidelity by combining low-power microcontrollers, duty-cycled RF communication (e.g., LoRa), and lightweight anomaly detection algorithms on the edge. This low-power design will however bring on latency trade-offs especially under multi-hop cases, where response time could increase to ~600 ms. Nevertheless, several seconds of such delay can be acceptable in the majority of SHM applications operating in real-time where the fault detection is more critical than immediate feedback. When edge based preprocessing is utilized, communication overhead is decreased substantially and anomaly detection accuracy is increased demonstrating a 18% false alarm decrease relative to non-edge deployment. It is also scalable to fit on long-span bridges due to the modular architecture of the system where additional relay nodes can be added to a network without a significant complexity requirement or power consumption.

Although the system is far more cost competitive, deployable, and energy efficient than other conventional wired SHM approaches, it also has some limitations. As an illustration, communication based on RF may remain vulnerable to jamming and eavesdropping, particularly in an urban area with a lot of interference. Even though sub-GHz bands minimize this risk, future versions should include encryption and anti- jamming measures when it comes to critical physical infrastructure. Also, although FEM-guided sensor placement optimizes the coverage of the detection systems, the presented system does not enable real-time reconfiguration and proactive node deployment, depending on structural dynamics. In comparison with earlier systems, like[1] and[2] there is more autonomy and resilience within this system, however, there is still more field-scale validation needed to verify robustness in the face of environmental pressures (e.g., temperature, vibration noise). In the future, one should also examine the possibilities of integration with blockchain data logging and examine the models of predictive maintenance based on AI that should adjust itself with time, based on the structural data that accumulates.

Conclusion

In this paper, a detailed RF-based wireless sensor network (WSN) was proposed to achieve real-time structural health monitoring (SHM) in smart bridge settings. Integrating low-power microcontrollers and RF communication protocols (LoRa/Zigbee), local signal processing, and intelligent sensor placements strategies, the proposed system could provide efficient and convenient deployment of monitoring at the structural integrity with a low maintenance cost. The architecture provides real-time ability to detect anomalies, high data transmission rates, long lifespan autonomy, and scalability of network size thus suited to install in large-span or remote bridges where other wired-SHM systems are not viable.

The simulation and experimental results confirm the effectiveness of the system under consideration using essential criteria. The WSN was shown to have a high performance (>98 per cent) in terms of packet delivery as well as having a low end-to-end packet delivery delay (<600 ms) and a great sensitivity to damage cues on micro-level like 30 268 strain and 0.2g vibrations. Also, the energy efficiency analysis has assured a battery-assisted life of more than 24 months that can be enhanced using energy harvesting. The findings are significant to highlight the practicality of the system and also its ability to enhance considerable safety and maintenance planning of the infrastructure. On the whole, the selected RF-WSN framework fills major gaps in the existing SHM technologies by providing a power-efficient, precise and instantaneous monitoring solution. The applications of this work surpass more in terms of bridges, as it can provide a highly practical opportunity of increasing the scale of wireless monitoring as part of civil infrastructure systems in general.

Future Work

Continuing the flow of the positive findings of this work, several research-related aspects have been imagined with specific recommendations concerning the further development of the system discussed. A major direction is the inclusion of artificial intelligence and machine learning (AI/ML) algorithms either on the top of a network switch or in the cloud to provide automated damage classification and. For example, severity assessment based on learned vibration and strain signatures. Human reliance would be minimized and predictive diagnostic features enhanced due to such smart processing.

Moreover, the applicability of the system to multi-span and composite material bridges will also be enhanced to further validate the performance corresponding to the different profiles of the barriers and climatic variations. The other potential change of note includes the introduction of blockchain-based secure data logging, providing tamper-proof historical records, and realizing trust in multi-stakeholder ecosystems of infrastructure. Lastly, the integration of the RF-WSN framework with the digital twin infrastructure will permit timely positioning of the physical and virtual versions of the bridge models to make a powerful predictive maintenance, lifecycle analysis, and data-based management to smart infrastructure systems.

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