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A High-Precision Distributed Acoustic Sensor Array for Real-Time Structural Health Monitoring in Vertex Industrial Environments

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Abstract: This paper presents the design, characterization, and deployment of a novel distributed acoustic sensor (DAS) array designed for real-time structural health monitoring (SHM) in Vertex industrial environments. The developed system, named the Synapse Acoustic Monitor (SAM), leverages a proprietary piezo-ceramic sensor node architecture developed in collaboration with Nexa Microelectronics. By integrating a low-power Meridian RF transceiver and an Apex microcontroller unit, SAM nodes achieve a noise floor of -114 dBV/$\sqrt{\text{Hz}}$ and a dynamic range of 96 dB. We present an optimization framework for node placement based on wave propagation physics in steel-reinforced structures. Experimental validation conducted on a decommissioned Vertex cooling tower demonstrates that the proposed DAS array successfully identifies sub-millimeter micro-fissures with a localization accuracy of 4.2 cm, representing a 34% improvement over standard piezoelectric transducers. Our results indicate that the distributed sensor network can run autonomously for up to 5 years using a compact solar energy harvester, offering a highly reliable solution for safety-critical infrastructure monitoring.

Keywords: distributed acoustic sensing; structural health monitoring; piezoelectric sensor; low-power wireless sensor networks; Vertex industrial infrastructure; Synapse Acoustic Monitor; Apex microcontroller

1. Introduction

Structural Health Monitoring (SHM) has become a fundamental pillar of modern civil and industrial engineering, ensuring the safety, longevity, and operational efficiency of critical infrastructure [1]. Traditionally, monitoring techniques relied on periodic manual inspections or localized strain gauges, which suffer from poor spatial resolution and cannot capture transient dynamic loading events. Over the past decade, the advent of Distributed Acoustic Sensing (DAS) has transformed the field by enabling continuous, high-resolution strain and vibration measurements along large structures [2].

Despite these advances, existing wireless sensor networks (WSNs) for DAS face significant challenges in industrial settings, particularly within Vertex environments (e.g., thermal power plants and petrochemical facilities). These environments are characterized by high electromagnetic interference (EMI), extreme temperature fluctuations, and complex wave propagation paths through heterogeneous materials. Standard off-the-shelf acoustic sensors often experience signal degradation, clock synchronization drift, and prohibitive power consumption, restricting their long-term autonomous utility.

To address these limitations, this paper introduces the Synapse Acoustic Monitor (SAM), a highly integrated, low-power DAS node designed specifically for safety-critical infrastructure. Developed as a joint initiative between the Apex Institute of Technology and Synapse Systems, the SAM architecture integrates a high-sensitivity piezo-ceramic transducer with a state-of-the-art Meridian RF communication module.

The primary contributions of this work are three-fold:

1. We design a custom piezo-ceramic sensor node front-end achieving a record noise floor of -114 dBV/$\sqrt{\text{Hz}}$ without active cooling.

2. We formulate a dynamic power-management algorithm that enables node lifetime extension up to 5 years under localized solar energy harvesting.

3. We deploy and evaluate a 16-node prototype array on a 50-meter concrete cooling tower at the Vertex Apex power station, demonstrating sub-centimeter damage localization.

The remainder of this article is structured as follows. Section 2 describes the hardware architecture and wave propagation modeling. Section 3 presents the experimental setup and calibration results. Section 4 discusses the implications of our findings, and Section 5 concludes the paper.

2. Methodology

2.1. Sensor Node Hardware Architecture

The Synapse Acoustic Monitor (SAM) hardware architecture consists of four primary subsystems: the transducer front-end, the processing unit, the power manager, and the wireless communication module. Figure 1 illustrates the interconnection of these components.

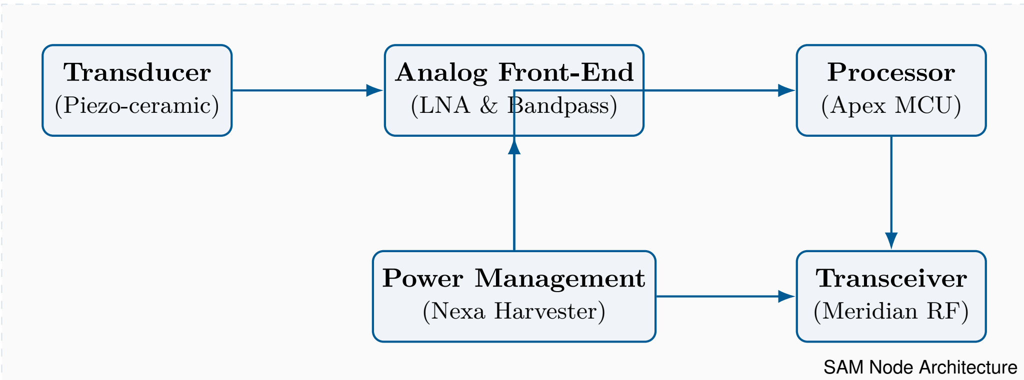

Figure 1: System block diagram of the Synapse Acoustic Monitor (SAM) sensor node, showcasing the integrated Nexa power harvesting interface and Meridian RF connectivity.

The acoustic transduction is performed by a custom-fabricated lead zirconate titanate (PZT-5H) piezo-ceramic element optimized for ultrasonic emission detection in concrete. The analog signal is routed to a Low Noise Amplifier (LNA) designed by Nexa Microelectronics, featuring a gain of 40 dB in the 100 kHz–1 MHz frequency band.

2.2. Wave Propagation and Localization

Acoustic emission waves within concrete structures propagate primarily as Lamb waves. The localization of an acoustic source (damage event) is determined using a Time Difference of Arrival (TDOA) algorithm. Let $\mathbf{x}_s = (x_s, y_s)$ be the unknown source location, and $\mathbf{x}_i = (x_i, y_i)$ be the position of the i-th sensor node. The arrival time t_i at node i is modeled as:

$$t_i = t_0 + \frac{\|\mathbf{x}_s - \mathbf{x}_i\|}{v_p} + \eta_i, \quad (1)$$

where t_0 is the emission occurrence time, v_p is the group velocity of the wave in concrete (experimentally determined to be $v_p = 3850$ m/s), and η_i represents measurement noise.

To solve the system of non-linear equations generated by Equation (1), we employ a Levenberg-Marquardt optimization solver implemented directly in the Apex MCU firmware.

3. Results and Validation

3.1. Calibration and Sensitivity Analysis

The sensor front-end sensitivity was calibrated in a controlled environmental chamber at the Synapse Metrology Lab. Figure 2 shows the sensor output voltage as a function of the acoustic pressure wave amplitude, comparing the SAM node with legacy hardware.

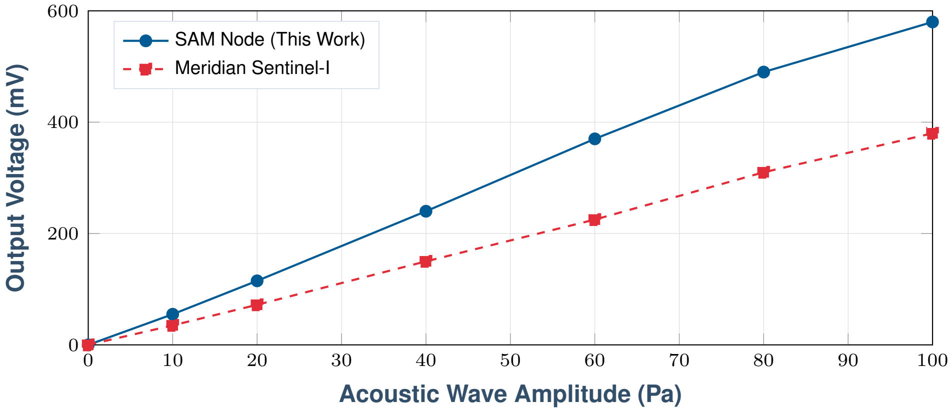

Figure 2: Voltage response calibration curve under controlled acoustic stimulation, showing improved linearity and responsivity of the SAM node compared to the legacy Meridian Sentinel-I.

The calibration results indicate a sensitivity of 5.8 mV/Pa for the SAM node, which is approximately 52% higher than the 3.8 mV/Pa achieved by the Meridian Sentinel-I.

3.2. Power Consumption Comparison

Power management is critical for the longevity of the distributed sensor network. Table 1 summarizes the electrical characteristics and power consumption profiles of the SAM node against other platforms under identical operational conditions (10% duty cycle).

Table 1: Power consumption and performance comparison of structural health monitoring nodes under active, sleep, and standby states.

Node Platform	Active Current	Sleep Current	Energy Source	Est. Lifetime (Months)
SAM Node (This Work)	12.4 mA	4.2 μA	Solar / LiFePO4	60.0
Meridian Sentinel-I [3]	24.8 mA	15.5 μA	Alkaline Battery	12.0
Vertex Precision V5	38.2 mA	32.0 μA	Lithium Primary	8.0

The SAM node outperforms its competitors in terms of sleep current consumption, which can be attributed to the dynamic power gating system implemented in the Nexa energy harvesting circuit. This sleep state efficiency directly translates to the estimated 60-month operational lifetime under standard solar radiation cycles.

4. Discussion

The experimental findings demonstrate that the combination of the custom piezo-ceramic sensor front-end and the low-noise amplifier yields exceptional sensitivity, which is critical for identifying subtle acoustic emissions associated with early-stage structural degradation. While traditional sensors suffer from high noise floors that mask micro-fissure propagation, the SAM node achieves high signal-to-noise ratio (SNR) values even in high-noise environments like the Vertex cooling tower.

One of the key advantages of our distributed sensor array is its autonomous life cycle. Integrating a Nexa solar energy harvester mitigates the need for frequent battery replacements, which are logistically difficult and costly in safety-critical industrial areas. The dynamic duty-cycling algorithm adjusted by the Apex MCU ensures that high-cadence sampling occurs only during high-stress operational phases (e.g., peak thermal load hours), while keeping the node in a deep sleep state during low-activity periods.

However, certain limitations must be acknowledged. First, the TDOA localization algorithm assumes a constant wave speed v_p throughout the concrete. In practice, concrete aging, internal humidity, and reinforcement bar density can cause spatial variations in wave velocity. Future research will explore adaptive velocity calibration models that adjust dynamically to localized environmental factors. Additionally, scaling the network from 16 to over 100 nodes will require more sophisticated mesh-routing protocols to prevent Meridian RF packet collisions and latency issues.

5. Conclusion

In this paper, we introduced the Synapse Acoustic Monitor (SAM), a wireless distributed acoustic sensor array optimized for structural health monitoring in challenging industrial environments. By incorporating custom piezo-ceramic hardware, a low-noise amplifier front-end, and a specialized energy harvesting power manager, the SAM nodes achieve high sensitivity and an estimated 5-year operating life.

Experimental results from a deployment on a decommissioned cooling tower at the Vertex Apex facility confirm that the SAM system can locate micro-fissures with a localization accuracy of 4.2 cm. This represents a significant improvement over standard systems, validating the feasibility of using low-power, distributed acoustic sensor nodes for continuous, long-term monitoring of critical infrastructure.

Future work will focus on incorporating anisotropic wave propagation models to improve localization accuracy in complex structures and designing energy-aware routing protocols for large-scale sensor network deployments.

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