

FEM-Guided Placement and AEAR Routing for Heritage Arch SHM: The Great Mosque of Sfax

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Abstract—This paper proposes a proof-of-concept WSN framework for heritage-building SHM, addressing three constraints general-purpose WSN design ignores: sensor positions fixed by structural criticality, exhaustive non-intrusive coverage, and irreversible energy exhaustion. The framework couples FEM-driven sensor placement, K-means-based dynamic sink selection, and an Adaptive Energy-Aware Routing (AEAR) protocol maintaining dual priority-differentiated paths. Validated on a representative arch of the Great Mosque of Sfax, it retains 34% of nodes above 60% residual energy, within the frontier tier against six benchmarked WSN protocols, despite a stricter placement constraint than any baseline faces. The authors frame this as a bounded, single-structure case study and outline the multi-site validation needed to establish generality.

Index Terms—Structural health monitoring; wireless sensor networks; sensor placement; energy-aware routing.

I. INTRODUCTION

Architectural heritage embodies centuries of cultural identity, yet many historic structures face progressive threats from environmental degradation, seismic activity, and material fatigue [1], [2]. Because periodic visual inspection is labor-intensive and reliant on expert judgment, Structural Health Monitoring (SHM) has emerged as a continuous, data-driven complement to conservation practice. Wireless Sensor Networks (WSNs) are a natural sensing substrate for this task. Heritage SHM, however, breaks three assumptions on which general-purpose WSN protocols are built. First, sensor positions are fixed to structurally critical zones identified through mechanical analysis and cannot be relocated to balance energy load. Second, coverage of high-stress zones must be exhaustive and permanent, since even a temporary gap may let damage go undetected. Third, because battery replacement on a protected monument is either restricted or physically impractical, energy exhaustion is effectively irreversible. Existing work treats sensor placement, sink/cluster-head selection, and routing as largely separate problems, none of which is designed against this specific constraint set.

This paper reports a proof-of-concept framework that co-designs the three layers around a single objective (maximizing network lifetime under FEM-dictated placement) and validates it on a real heritage structure. Our contributions are:

- 1) A **FEM-driven sensor placement strategy** that classifies a monitored arch surface into stressed and unstressed zones and applies a differentiated placement policy to each, minimizing sensor count while guaranteeing complete coverage of mechanically critical regions.
- 2) An integrated **energy-aware network layer** combining K-means-based dynamic sink selection with an Adaptive Energy-Aware Routing (AEAR) protocol that separates high- and low-priority traffic across two continuously recalculated paths.
- 3) A **validation on the Great Mosque of Sfax**, benchmarking residual energy distribution against six published WSN protocols, and an explicit discussion of what a single-structure case study can and cannot establish.

II. RELATED WORK

Sensor placement for SHM has been optimized through sparse Gaussian process regression [3], statistical FEM-based digital twins [4], modal-strain-energy-driven genetic search [5], simulated annealing [6], and Bayesian experimental design [7], with heritage-specific application reported for the Monastery of San Jerónimo de Buenavista [9]. These methods share a common limitation for our setting: they optimize an information-theoretic or reconstruction-accuracy criterion over where placement is free to vary, and none couples placement density directly to a binary stress-based zone classification that can drive a coverage-constrained deployment decision. Energy management has likewise been studied independently of this constraint. Clustering- and mobile-sink-based strategies [10]–[13] and self-reconfiguring tree topologies for structures under motion [14] achieve energy balancing and delivery reliability, but do so by treating node placement as a free variable they

can exploit. Network lifetime itself has been defined inconsistently across this literature, from strict first-node-failure criteria [15] to more tolerant formulations permitting partial depletion [16], with [17] offering a holistic system-level treatment; this inconsistency makes cross-study lifetime comparisons difficult even before the placement question is introduced. The six benchmark clustering/routing protocols evaluated later in this paper ([19]–[24]) exemplify the same gap at the routing layer: each was designed for general-purpose WSNs where node placement is itself an optimization variable available to the routing protocol, which heritage SHM does not permit. Taken together, the literature treats placement, sink management, and routing as three separable design problems, each solved under the implicit assumption that at least one of the other two remains free to compensate. The gap this paper targets is precisely the case where that assumption fails: joint design of placement, sink management, and routing under a single, fixed, structurally-dictated node layout — a constraint set that, to our knowledge, has not been addressed as an integrated pipeline in the reviewed literature

III. CASE STUDY: THE GREAT MOSQUE OF Sfax

The Great Mosque of Sfax (*Elgamaa Elkibir*), part of the UNESCO-listed medina of Sfax, is a ninth-century stone, clay, and olive-wood structure whose prayer hall is articulated through a succession of horseshoe arches. Because the mosque is an active place of worship under heritage protection, in-situ instrumentation for validation purposes is restricted; numerical simulation was therefore used as the primary analytical tool. A representative semicircular arch was modeled in SketchUp and analyzed in MATLAB using the Finite Element Method (FEM), discretized with triangular elements at a target mesh edge length of $H_{max} = 0.01$. Boundary conditions were applied at the fixed support faces, and the model was solved for nodal displacement (along the three coordinate axes) and stress distribution. Displacement was largest at the arch extremities and pier bases, consistent with vertical load transfer from extrados to supports; stress concentrated along the intrados curvature, particularly near the pier bases. These results define a binary zone classification: *stressed* versus *unstressed*, that drives the placement strategy in Section IV.

IV. PROPOSED FRAMEWORK

The framework integrates FEM-guided placement with an energy-aware network layer, so that the same stress analysis that determines *where* sensors go also shapes *how* the network manages the energy consequences of that fixed layout.

A. Sensor Placement Strategy

The binary zone classification produced by the FEM analysis in [8] partitions the arch surface into two

structurally distinct regions that require fundamentally different monitoring strategies. The guiding principle is the following: the higher the mechanical stress in a zone, the denser and more robust the sensor coverage must be. Accordingly, two complementary placement approaches are proposed.

In *unstressed zones*, where the probability of structural deformation is low, the priority is to minimize the number of deployed sensors while preserving monitoring reliability. Two lightweight geometric methods are introduced for this purpose: the Parallel Elementary Sensors Placement (PESP) and the Angular Elementary Sensors Placement (AESP). Both methods require only a small number of sensors and rely on simple measurable parameters to detect structural changes.

In *stressed zones*, where the probability of deformation is significantly higher, complete and redundant coverage of the entire critical surface must be guaranteed. Sensor placement is accordingly formulated as a minimum coverage optimization problem, solved by a greedy heuristic algorithm.

1) Sensor Placement for Unstressed Zones

a) Parallel Elementary Sensors Placement (PESP)

The PESP method is derived from the FEM displacement results, which show that deformations in unstressed zones are generally uniform across the external layer of the arch. This uniformity allows the three-dimensional monitoring problem to be reduced to a simplified two-dimensional model requiring only four sensors.

As illustrated in Figure 1(a), two sensors are placed at the crown median and one at each pier base, forming two collinear pairs under normal structural conditions. The key monitoring parameter is the relative displacement Ω between previously aligned sensor pairs:

- If $\Omega \approx 0$: the arch geometry is stable, no intervention is required.
- If $\Omega > \Omega_{th}$: a measurable geometric deformation has occurred, potentially compromising structural integrity.

The detection threshold Ω_{th} is established by structural engineers according to the material properties and design tolerances of the monitored arch. PESP thus provides a cost-effective solution with only four sensors, exploiting the geometric regularity of unstressed regions.

b) Angular Elementary Sensors Placement (AESP)

The AESP method complements PESP by exploiting the geometric symmetry of the arch through an angular measurement approach. As illustrated in Figure 1(b), three sensors are installed: one at the crown median and one at each pier base. These three points define a reference triangle whose crown angle α characterizes the arch geometry under normal conditions.

When structural deformation occurs, the crown angle shifts from α to β . The angular variation $\Delta\theta = \beta - \alpha$ quantifies the magnitude of the deformation:

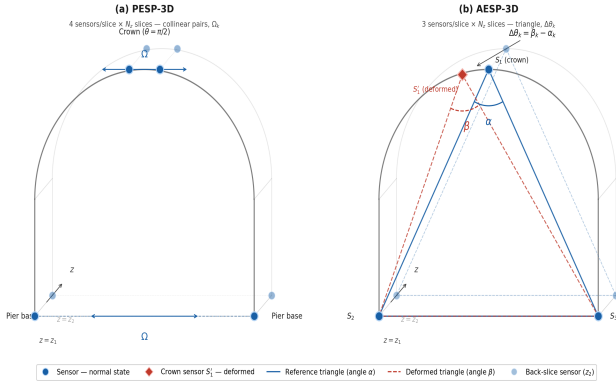


Fig. 1: Sensor configurations for unstressed zones: (a) PESP — four collinear sensors monitoring relative displacement Ω ; (b) AESP — three sensors forming a reference triangle monitoring crown angle variation $\Delta\theta = \beta - \alpha$.

- If $\Delta\theta \leq \gamma$: the deformation is within tolerable limits.
- If $\Delta\theta > \gamma$: the deformation is considered critical and requires immediate structural assessment.

The threshold γ is defined by structural engineers based on material and safety criteria. Compared to PESP, AESP requires one fewer sensor and is more sensitive to asymmetric deformations, making the two methods complementary.

2) Sensor Placement for Stressed Zones

In stressed zones, the lightweight geometric methods used for unstressed regions are insufficient: the higher deformation risk demands complete and verified coverage of every point in the critical surface. Sensor placement is therefore formulated as a *minimum sensor coverage* problem, whose objective is to select the smallest subset of candidate positions that collectively cover the entire stressed surface.

a) Discrete Representation of the Stressed Zone

The stressed surface identified by the FEM analysis is represented as a finite set of grid points:

$$\mathcal{G} = \{(x, y) \in \text{FEM grid} \mid \sigma(x, y) \geq \sigma_{th}\} \quad (1)$$

where $\sigma(x, y)$ is the local stress value at grid point (x, y) . A grid point $(x, y) \in \mathcal{G}$ is considered *covered* by a sensor placed at candidate position (i, j) if it lies within the sensor's circular detection range of radius C :

$$d((x, y), (i, j)) = \sqrt{(x - i)^2 + (y - j)^2} \leq C \quad (2)$$

b) Optimization Model

Let $\mathcal{P} = \{(N(i), T(i))\}_{i=1}^P$ denote the set of P candidate sensor positions uniformly distributed over the stressed subdomain, where $N(i)$ and $T(i)$ are the x - and y -coordinates of the i -th candidate. Let $A_{i,j} \in \{0, 1\}$ be a binary decision variable equal to 1 if a sensor is placed at position (i, j) , and 0 otherwise. The minimum sensor

coverage problem is formulated as:

$$\min Z = \sum_{(i,j) \in \mathcal{P}} A_{i,j} \quad (a)$$

$$\text{s.t.} \quad \sum_{(i,j) \in \mathcal{P}} A_{i,j} \cdot \mathbf{1}[d((x, y), (i, j)) \leq C] \geq 1 \quad \forall (x, y) \in \mathcal{G} \quad (b)$$

$$A_{i,j} \in \{0, 1\} \quad \forall (i, j) \in \mathcal{P} \quad (c)$$

$$1 \leq \sum_{(i,j) \in \mathcal{P}} A_{i,j} \leq P \quad (d)$$

where $\mathbf{1}$ is the indicator function equal to 1 if the condition holds and 0 otherwise. The four constraints are interpreted as follows:

- 1) **Coverage constraint** (b): every stressed grid point $(x, y) \in \mathcal{G}$ must be within the detection range of at least one selected sensor. This is the fundamental requirement ensuring that no critical zone goes unmonitored.
- 2) **Binary constraint** (c): each candidate position either hosts one sensor or none.
- 3) **Feasibility constraint** (d): the total number of deployed sensors must be at least one and cannot exceed the total number of candidate positions P .

This problem belongs to the family of *minimum disk cover* problems, which are NP-hard in the general case [?]. For the arch surface dimensions considered in this work, the candidate set remains computationally tractable.

c) Placement Configurations

The greedy heuristic considers two placement configurations depending on the local stress level within the stressed zone (Figure 2):

- **Tangent placement** (Figure 2(a)): the coverage discs of two adjacent sensors touch without overlapping. This configuration maximizes the area covered per sensor and minimizes redundancy. It is preferred whenever the stress level permits.
- **Overlapping placement** (Figure 2(b)): the coverage discs partially overlap. This configuration introduces deliberate redundancy in sub-regions of particularly high stress, material fatigue, or crack susceptibility, where multiple independent sensors must confirm any anomaly to minimize the risk of false negatives.

d) Greedy Placement Proposal

Our proposal placement strategy start with maintaining a set $\mathcal{G}_{uncov}$ of stressed grid points not yet covered by any selected sensor. At each iteration, it selects a candidate position $best_k$ that best extends coverage from a current reference position i_{cur} : first seeking an exact

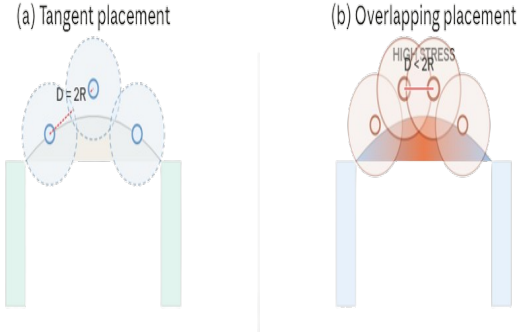


Fig. 2: Candidate sensor placement configurations for stressed zones: (a) tangent placement ; (b) overlapping placement.

tangent neighbor ($D = 2C$), and otherwise selecting the candidate maximizing D subject to $D < 2C$ (best overlapping neighbor). Once a sensor is placed, all grid points within distance C of its position are removed from $\mathcal{G}_{uncov}$. The process repeats until $\mathcal{G}_{uncov} = \emptyset$, guaranteeing that every stressed grid point is covered by at least one sensor. The proposed placement strategy achieves two complementary objectives: it minimizes the total number of deployed sensors to limit installation costs and structural intrusion, while guaranteeing that every mechanically critical point of the arch is monitored by at least one sensor. This dual objective directly serves the network lifetime maximization goal of the proposed framework: by deploying only the necessary sensors in the right locations, energy consumption is kept to a minimum without compromising structural coverage.

B. Power- and Context-Aware Sink Selection

Sensors are first partitioned into K clusters via K-means on Euclidean distance, with cluster centroids designated as initial sinks. Because sinks bear disproportionate communication and aggregation load, each sensor is further tagged by coverage context — *singular* (one sink in range), *dual* (two sinks), or *multiple* (more than two). When a sink's residual energy drops to a threshold α , it is decommissioned and reverts to a plain sensor; its orphaned nodes are reassigned according to their tag: multiple-coverage nodes join the highest-energy active sink, dual-coverage nodes join their remaining sink, and singular-coverage nodes trigger a local re-clustering to elect a replacement sink. This proactive rotation prevents hotspot formation and premature network partitioning.

C. Adaptive Energy-Aware Routing (AEAR)

Data acquisition alone does not guarantee monitoring value: a reading only counts as *significant data* if it reaches the server within a time frame that preserves its diagnostic utility. Conventional routing protocols optimize a single objective — either guaranteed delivery or minimal latency — which is insufficient here, since both anomaly alerts (latency-critical) and routine

periodic readings (energy-critical) must coexist on the same network, and the underlying topology itself keeps changing as sinks are decommissioned (Section IV-B).

Traffic classification. Each packet p generated at a source sink is classified by a priority function

$$\pi(p) = \begin{cases} \text{High,} & \text{if } p \text{ signals anomaly, threshold exceedance,} \\ & \text{or real-time-critical event} \\ \text{Low,} & \text{otherwise (routine periodic reading)} \end{cases} \quad (3)$$

This binary split is intentionally coarse: a finer-grained QoS scheme would add scheduling overhead without a clear benefit at the traffic volumes typical of periodic SHM sampling, where the dominant distinction is simply "does this reading demand immediate attention or not."

Dual route formulation. Let $G = (V, E)$ be the current sink-level connectivity graph, rebuilt each time the sink set changes. AEAR maintains two routes from every sink s to the central server B :

$$R_{fast}(s) = \arg \min_{p \in \mathcal{P}(s, B)} \text{hops}(p) \quad (4)$$

$$R_{econ}(s) = \arg \max_{p \in \mathcal{P}(s, B)} \sum_{v \in p} E_{res}(v) \quad (5)$$

where $\mathcal{P}(s, B)$ is the set of feasible sink-to-server paths and $E_{res}(v)$ is node v 's residual energy. R_{fast} is energy-blind by design: it will knowingly route through a low-energy sink if that sink minimizes hop count, trading that sink's accelerated depletion for guaranteed timeliness of critical data. R_{econ} is the opposite: it is willing to add hops if doing so shifts load onto sinks with more energy headroom, since routine traffic has no strict deadline. A packet is then routed as $R_{fast}(s)$ if $\pi(p) = \text{High}$, else $R_{econ}(s)$.

Recalculation triggers. Both routes are recomputed under two conditions, not one: (i) *periodically*, at a fixed interval T_{recalc} , to reflect gradual energy drift across the network; and (ii) *on event*, immediately whenever a sink is decommissioned (Section IV-B) or a route becomes infeasible, rather than waiting for the next periodic cycle. This event-triggered path is what prevents a stale R_{fast} from silently routing high-priority traffic through a sink that no longer exists — a failure mode a purely periodic scheme would not catch until its next scheduled update, at the cost of exactly the critical-data latency the Fast Route exists to avoid.

V. EXPERIMENTAL EVALUATION

A. Simulation Setup

The FEM-driven placement strategy (Section IV-A) was executed in MATLAB on the meshed arch model. The resulting network — sensors deployed with uniform initial charge, organized into K clusters via K-means (Section IV-B) — was simulated over a 50×50 m operational plane, with the clustering, sink rotation, and AEAR logic (Algorithm 1) implemented in C for compatibil-

Algorithm 1 Adaptive Energy-Aware Routing (AEAR)

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1: Initialization Phase:
2: Deploy sensors with uniform initial charge
3: Partition network into  $K$  clusters via K-means
4: Compute initial routes  $R_{fast}$  (Eq. 4),  $R_{econ}$  (Eq. 5)
5: while average network energy  $> \alpha$  do
6:   Monitor sink energy levels
7:   if a sink's energy  $\leq \alpha$  then
8:     Decommission sink  $\rightarrow$  revert to plain sensor
9:     Reassign orphaned nodes per coverage tag
10:    trigger immediate recomputation of  $R_{fast}$ ,  $R_{econ}$ 
11:   end if
12: end while
13: Routing Phase (concurrent):
14: while network is operational do
15:   for each data packet  $p$  do
16:     Evaluate  $\pi(p)$  (High/Low)
17:     if  $\pi(p) = \text{High}$   $\rightarrow$  route via  $R_{fast}$  else route via  $R_{econ}$ 
18:   end for
19:   if elapsed time  $\geq T_{recalc}$  or route infeasible then
20:     Recompute  $R_{fast}$ ,  $R_{econ}$  from current sink energies/topology
21:   end if
22: end while

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ity with resource-constrained sensor hardware. Residual energy was recorded at the end of the monitoring cycle and compared against six published protocols spanning 2000–2025 (Table I).

B. Coverage Efficiency in Stressed Zones

Applying the greedy placement proposal, to the stressed-zone grid identified from the FEM stress field, the greedy heuristic selected 16 sensor positions from 50 candidate locations, concentrating coverage on the highest-priority sub-regions. Extending this to the overlapping-placement configuration of Fig. 2(b) closed the remaining gaps, yielding 22 final sensor positions and 100% coverage of the stressed zone — a 37.5% increase in sensor count over the initial 16-sensor solution. This trade-off is deliberate: the algorithm accepts a modest increase in deployed sensors in exchange for eliminating monitoring gaps entirely, which is non-negotiable for structurally critical regions.

C. Energy Retention and Baseline Comparison

The routing, placement, and clustering strategy we developed shows solid and competitive energy performance when placed side by side with both classical and very recent wireless sensor network protocols. Table I situates the proposed approach within a structured performance-

TABLE I: Residual energy distribution vs. published WSN protocols. Buckets show the percentage of nodes in each residual-energy range at cycle end.

Protocol	>60%	<40%	Context
Ours	34%	44%	SHM / Arch
LEACH [19]	12%	70%	General WSN
PEGASIS [20]	17%	61%	General WSN
IEE-LEACH [21]	25%	47%	General WSN
EACUC [22]	27%	45%	Unequal clust.
IMP-RES-EL [23]	33%	37%	Corner BS WSN
EEM-LEACH-ABC [24]	38%	36%	Multi-hop WSN

tier classification. Classical protocols LEACH and PEGASIS retain only 12% and 17% of nodes above 60% energy, respectively; intermediate protocols IEE-LEACH and EACUC reach 25% and 27%; and the frontier tier: IMP-RES-EL and EEM-LEACH-ABC, both published in 2024–2025, reaches 33–38%. The proposed approach's 34% places it within this frontier tier, despite operating under a placement constraint absent from every benchmark: sensor positions are fixed by structural stress analysis rather than chosen freely to balance energy load. A finer-grained breakdown of the residual-energy distribution (Fig. 3) shows 6% of nodes above 90% initial energy, 28% in the 60–80% band, 22% at moderate depletion, and the remaining 44% more depleted but still above the minimum functional threshold: no node reached complete depletion during the simulated cycle. Reaching this profile while also guaranteeing exhaustive coverage of every high-stress zone (an objective none of the six baselines target) is the central empirical claim of this work.

The modest increase in depletion is a direct consequence of the placement constraint itself: sensor positions are fixed to the structurally critical zones identified by the FEM analysis, not chosen to optimize energy balance — a far stricter condition than any benchmark protocol faces. Despite this, the proposed approach still achieves meaningful network longevity while guaranteeing full coverage of every high-stress zone in the arch, which is ultimately the system's central objective.

D. Scope of This Evidence

These results come from a single representative arch of a single monument, simulated rather than field-deployed, under one operational and stress scenario. We treat this as a controlled proof-of-concept rather than a generalization claim: it establishes that the FEM-to-network pipeline is implementable and competitive, not that its energy margins transfer unchanged to other arch geometries, load regimes, or monument types. Section VI outlines the follow-up needed to close that gap.

VI. CONCLUSION AND FUTURE WORK

We presented an integrated framework co-designing FEM-driven sensor placement, power-aware sink se-

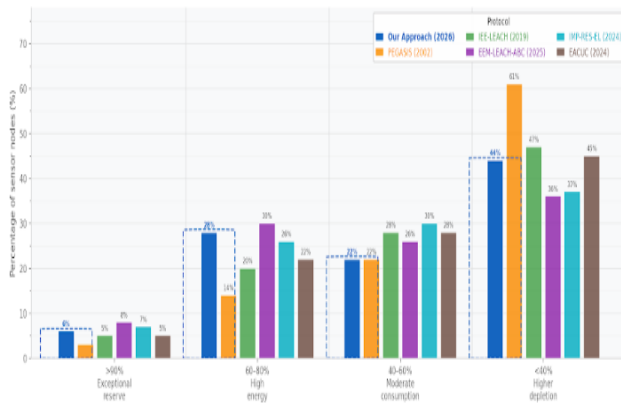


Fig. 3: Energy distribution of sensor nodes grouped by residual energy metric.

lection and routing for WSN-based SHM of heritage structures, validated on a representative arch of the Great Mosque of Sfax. The framework reaches the frontier energy-retention tier among six benchmarked protocols while guaranteeing exhaustive coverage of mechanically critical zones. As a single-structure, simulation-based study, this work is best read as a proof of concept. The immediate next steps to establish generality are: (i) replicating the FEM-to-placement pipeline on arch geometries with different curvature and span, and on non-arch heritage elements (domes, vaults, walls), to test sensitivity to structural form; (ii) varying load scenarios (seismic, thermal, long-term settlement) rather than a single static loading case; and (iii) running the network simulation under multiple random seeds and node-density settings to report variance rather than point estimates. We are pursuing this multi-site validation as the direct extension of the present work, alongside integration with digital twin models for predictive, real-time diagnostics.

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