Sheer-Dam: A Structural-Health and Energy-Efficient Routing Protocol for Wireless Sensor Networks in Dam Monitoring

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Abstract *– Large dam vibrations will be assessed by using a sensor network as part of the proposed protocol. The other main components of the proposed protocol are dual-threshold selective reporting and structurally-based clustering methods which provide for nodes to report only vibration readings that have deviated from what is normal operationally; all vibration readings need not be reported. The communication overhead associated with this protocol is reduced through local filtering. Furthermore, the selection of cluster heads in this protocol is based on a probabilistic weighted function of the remaining node power, which distributes power consumption among the various structural components of the dam. This protocol was simulated using a first-order radio energy consumption model, employing 500 spatially distributed sensors over 4000 monitoring cycles. Simulation-based comparisons between the proposed protocol and two existing protocols, LEACH and TEEN, demonstrated that the proposed protocol extends network life time by more than 120% compared to LEACH and TEEN, reduces the number of transmitted packets by more than 60%, and provides a significantly lower response time for detecting anomalous vibration activity than both. The simulation data indicate that the protocol proposed in this study is an efficient and robust method for monitoring vibration phenomena originating from distributed sources across dams, with a rapid response time for detecting anomalies.*

Keywords: *DAM, LEACH, TEEN, Wireless Sensor, Cluster Head*

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1. INTRODUCTION

Dam and reservoir infrastructures are important for flood mitigation, generation of hydroelectric power, agricultural irrigation, and long-term water resource management. [1] therefore, ensuring that dam's function reliably is a critical concern both nationally and internationally if a minor structural deterioration is not noticed, it can gradually become a serious structural failure. and lead to catastrophic structural failure [2,3]. Dam deterioration usually appears as micro cracks and low amplitude vibrations which cannot be detected visually, and therefore, may go undetected until it is too late, potentially resulting in severe economic losses and threats to public safety [4-7]. Although traditional structural health monitoring (SHM) systems employ permanently installed, wired sensors (accelerometers, strain gauges, and fiber optic sensing systems) [8-12], they have disadvantages including high installation costs; reduced spatial coverage; potential wiring failures; and inability to scale well in large concrete structures. On the other hand, wireless sensor networks (WSN) present a much more versatile option by allowing for distributed, long term monitoring of large civil structures [13-18]. Many studies have researched methods to optimize energy consumption and ensure WSNs can be used over a long period for wireless structural health monitoring using different types of adaptive communication and energy saving strategies

for data transmission [19-21]. Although most current WSN-based Structural Health Monitoring (SHM) systems are based on a "Sense & Collect" model that focuses on data acquisition accuracy; reliable collection of sensor data; and efficient monitoring [22-25]; there is relatively little attention being paid to the issues of energy-efficient communications in these networks; adaptive transmission scheduling; routing optimization mechanisms; and managing the lifetime of batteries used to power them within larger scale monitoring scenarios [26- 28]. Moreover, several recent studies of dam safety monitoring have demonstrated the importance of accurately estimating warning thresholds using SHM methods and providing confidence estimates for monitoring decisions as means to improve both the structural reliability of dams and their operational safety [29]. Most existing wireless sensor network routing methods that are designed for structural health monitoring do this either by focusing on maximizing the effectiveness of communications or minimizing time-to-detect events but little research has addressed how to create an integrated framework that combines these characteristics along with long term energy efficiency to support real-time monitoring applications for dams. To address these issues this paper proposes an integrated routing strategy called SHEER-DAM (Structural Health and Energy Efficient Routing for Dams) that uses a combination of cluster formation based on the structural properties of the dam, energy-aware rotation of the cluster head and two-threshold event selective reporting of structural health-related events. The use of two thresholds will allow the sensors to report structural health related events to the sink node only after a structural damage has been detected, which in turn reduces the amount of communication traffic generated by the sensor network. Thus, it ensures that the energy consumption will be distributed evenly among all segments of the dam structure and enables the sensor network to provide reliable continuous structural monitoring of the dam over time.

The remainder of this paper is arranged as follows: Section 2 examines prior art in WSN based structural monitoring. Section 3 defines the problem. Section 4 lists the research contributions. Section 5 defines the system model and the protocol architecture. Section 6 illustrates the operational workflow of SHEER-DAM. Section 7 describes the simulation environment. Section 8 describes the experimental results. Finally, Section 9 summarizes this paper and identifies areas for further study. While LEACH and TEEN have improved the efficiency of communication in WSNs; they are not appropriate for dam structural health monitoring. The spatial variation of vibration behavior in dams is distributed unevenly throughout different sections like the crest, mid-section and foundations. Therefore, LEACH's assumption of a uniform distribution of sensor nodes will lead to an unbalanced energy consumption and premature death of some of the most important sensor nodes located in these critical areas.

TEEN has attempted to address the need for event-based transmission by introducing the use of threshold values; however, since the threshold values are constant, TEEN can miss critical events, or send excessive amounts of data about non-critical events. Thus, while both LEACH and TEEN are effective at increasing communication efficiency in WSNs, neither protocol takes into consideration the unique requirements necessary for long term reliable dam monitoring. As such, a new protocol with a focus on energy balance, spatial awareness and event sensitivity is required.

This study contributes to the literature as follows:

1. A framework for structural health monitoring is proposed that includes a hierarchical approach to clustering, which will be utilized to provide an equal amount of monitoring in each area of the dam by organizing sensor nodes into the same areas where they are physically located.
2. An Event-Driven Reporting Mechanism is presented that employs two different threshold values. The first value represents what is referred to as a "Hard Threshold" (HT), and the second value represents a "Soft Threshold" (ST). Both threshold values will help to minimize data redundancy; however, both will also enable the system to quickly identify anomalous changes or deviations in the monitored vibrations.
3. An Energy-Aware Cluster Head Rotation Strategy has been developed utilizing the remaining energy at each of the individual nodes, thus providing a method to distribute loads among all nodes within a cluster and extend the life time of the Wireless Sensor Network.
4. A low-cost and energy efficient communications architecture was designed and implemented to reduce communication costs (i.e., overhead) and transmission delays associated with real-time monitoring over extended periods of time.
5. Comprehensive simulations were run to determine how well SHEER-DAM performed compared to LEACH and TEEN when applied to large-scale dam structural health monitoring. These performance metrics include:
    - Network Lifetime
    - Residual Node Energy
    - Packet Transmission Overhead
    - Event Detection Responsiveness

2. RELATED WORK

Studies utilizing sensor technology along with data analytics have shown a marked increase in the ability to accurately detect structural damage through the use of machine learning algorithms, statistical analysis as well as spatiotemporal predictive methods [30, 31]. The majority of existing studies utilize central processing

systems for analyzing data which increases communication costs and decreases response time. In addition to energy aware routing and clustering based wireless sensor network (WSN) protocols to increase the overall lifetime of the WSN and communication efficiency, there has been research into improving stable election mechanisms and mobile sink-based energy management techniques to improve energy consumption within WSN's [32].

There is additional research that utilizes SEP- and MODLEACH based clustering protocols to utilize load balancing and hierarchical structures to increase communication efficiency. However, most of these cluster membership selections are dependent upon remaining node energy levels rather than structurally aware events and/or anomalies [33, 34].

Multi-hop and/or multi-path routing is used in order to enhance the reliability of packet delivery relative to a single hop approach. A negative consequence of using this type of routing technique, however, would be an increase in routing overhead as well as transmission delay, a higher degree of complexity for synchronizing nodes within each hop, and increased processing time.

These issues could be detrimental to real-time SHM systems that require both rapid anomaly detection as well as the timely delivery of data [35]. Table 1 summarizes the main categories of existing SHM-related WSN studies, their primary methodologies, and the key limitations identified in previous research.

In addition, recent research on wireless sensor networks (WSNs) has focused on studying how to coordinate the timing of events in order to increase timing accuracy and communication reliability [36].

Table 1. Selected Related Work and Their Limitations

Category (with References)	Method / Focus	Key Limitation
Energy-efficient routing [32-34]	Energy-aware routing and clustering protocols	Lack of structural awareness and anomaly-driven communication
Sensing technologies [30]	Dam safety monitoring and warning-domain estimation	Limited scalability and centralized analysis
Data-driven analytics [31]	ML-based deformation prediction and spatiotemporal analysis	High computational overhead and centralized processing
Time synchronization [35]	Cluster-based synchronization for multihop IoT networks	No routing integration and no event-driven support
This work	SHEER-DAM framework	Structure-aware, energy-efficient, and event-driven communication architecture

2.1. ENERGY AWARE ROUTING APPROACHES

The goal of many routing algorithms is to maximize WSN performance (lifetime & communication efficiency). Most routing protocols are based on an assumption that each piece of data is equally important. They also don't account for how different parts of a structure may function differently and therefore fail as effective methods of monitoring dams.

2.2. SENSING TECHNOLOGIES FOR INFRASTRUCTURE

Sensing technologies using fibers and wireless communications collect reliable structural information about dams. These sensing technologies, however, have focused more on collecting high-quality sensor data than they have on efficient communication or long-term power consumption to support continuous dam monitoring.

2.3. DATA-DRIVEN SAFETY ANALYSIS

The use of data-driven techniques has improved anomaly detection as well as structural assessment. Data driven safety analysis generally relies upon a central processor and does not consider communication overheard (i.e., time needed to send sensor data from a node to the base station) and limited energy resources found in distributed WSN environments.

2.4. LIMITATIONS OF LEACH AND TEEN

The LEACH and TEEN protocols have been two of the most commonly used cluster-based routing techniques within WSN's; however, neither protocol is well suited to Structural Health Monitoring of Dams. LEACH has CH selection that is random, and a uniform node assumption that does not account for variations in node density or the unevenness of critical structurally related areas leading to an imbalance in node energy consumption and premature node failure at structurally critical locations. TEEN incorporates threshold-based communication; however, TEEN uses static threshold values that do not account for the differences in vibration characteristics along different sections of a dam. Therefore, as with LEACH, both protocols will be unable to provide the accurate, energy efficient and structure aware monitoring required for reliable assessments of a dam's health.

In addition, many researchers have proposed a variety of approaches for improving the energy efficiency, dependability and communication performance of Wireless Sensor Networks (WSNs) that include clustering, synchronization, and secure data aggregation. There are protocols, such as SEP and MODLEACH, which improve the network's ability to be stable and reduce its overall power usage. Similarly, there are multi-path routing methods such as EAMMH, which can increase the reliability of delivering data. Recently some authors who have also published papers within this Journal

have developed cluster-based time synchronization, and cluster based secure data aggregation schemes to improve the timing accuracy of WSNs, and data security in WSNs respectively.

2.5. RESEARCH GAP

Although many of the previously-mentioned research studies have made significant improvements on each one of the above areas individually; however, few have taken into account both the integration of structural knowledge into clustering and also the design of adaptive (event driven) communication strategies. Thus, due to this oversight, most previous work has lacked adequate event-based reporting mechanism necessary for detection of critical vibration variations within dams. As such, an integrated framework which integrates both structure aware clustering as well as dual threshold event-based reporting with energy efficient communication is needed.

3. PROBLEM STATEMENT

The majority of vibration data collected by existing structural monitoring systems based on (WSNs) are continuously sent through the airwaves - regardless of whether the data relate to "normal" or "non-critical" mechanical conditions. Since wireless transmission consumes the greatest amount of power of all operations conducted by a node, the continuous transmission of such vibration data results in significant energy expenditure and greatly reduces the lifespan of WSNs. The vast majority of clustering methodologies do not take into account the segmental nature of structures (such as dams), and therefore organize sensors uniformly throughout the structure; thus, the methods fail to model actual stress distributions and vibration gradient patterns. As a result, the degree of energy depletion varies greatly throughout the structure, and may also create areas where structural monitoring is impossible (i.e., "structurally under-monitored regions "). Therefore, it is evident that a new monitoring strategy must be developed that will transmit only those portions of the monitored system that have structural significance while organizing its sensor nodes consistent with the physical configuration of the dam so as to minimize communications overhead and provide continued, long term structural monitoring capabilities.

4. SYSTEM MODEL

This section explains how SHEER-DAM enables the organization of wireless sensor node activities within a dam structure. These sensor nodes are placed throughout the crest, mid-body and foundation areas that continuously measure changes in vibration and strain, which are combined by clustering units organized into layers, with a cluster head (CH) assigned to each layer. The cluster heads then combine the measurement data collected by all other sensor nodes on their respective layers using local data fusion before transmitting only selected data to the sink. By organizing the sensing and communication functions hierarchically, it is possible to continuously monitor the dam's condition while conserving network power and reducing packet congestion, as intended by SHEER-DAM in a very large dam environment.

4.1. DAM STRUCTURAL LAYOUT AND SENSOR DEPLOYMENT

Sensors will be placed vertically along the dam wall in three different areas: crest, mid, and foundation. Each level is organized into a cluster of nodes (A1-A6, B1-B6, C1-C6), where the last node in each group (A6, B6, C6) serves as the cluster head (CH) according to the SHEER-DAM clustering strategy. As illustrated in Fig. 1, the CHs aggregate measurements from their corresponding level and forward selectively filtered and compressed information to the sink node located outside the dam body, significantly reducing packet transmissions and improving overall energy efficiency.

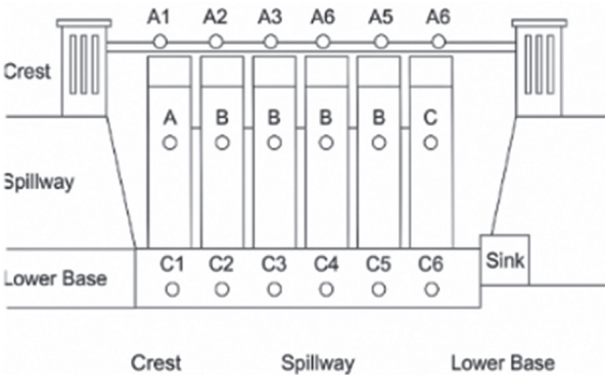


Fig. 1. Dam wall sensor layout

4.2. WIRELESS SENSOR NETWORK MODEL

The wireless communication energy consumption in the proposed monitoring system is characterized using the classical first-order radio model. The dominant energy component for each sensor node is associated with radio communication rather than sensing or computation.

The energy required to transmit and receive k-bit messages is modeled as follows:

$$E_{tx(k,d)} = kE_{elec} + k\varepsilon_{fs}d^2 \quad if\ d < d_0 \tag{1}$$

$$E_{tx(k,d)} = kE_{elec} + k\varepsilon_{mp}d^4 \quad if \quad d \geq d_0 \tag{2}$$

$$E_{rx(k)} = kE_{elec} \tag{3}$$

Where (E_{elec}) represents the total energy used by the radio electronics in Joules/Bit, ($\varepsilon_{\{fs\}}$) and ($\varepsilon_{\{mp\}}$) are the free space and multipath amplifier coefficients, respectively, (d) is the distance of communication, and (d_0) is a threshold distance to determine if we will use the free space (d^2) or multipath (d^4) propagation models.

In this work, the commonly adopted parameter values are defined as follows:

$$E_{elec} = nJ/bit50$$
$$_{fs} = \varepsilon pJ/bit/m^2 10$$
$$_{mp}{}^{\varepsilon} = pJ/bit/m^4\ 0.0013$$
$$EDA = nJ/bit5$$

Example - transmitting a 2000-bit packet over 50 m (free-space)

$$_{tx}E=J^{4-}\ 10\times1.5 \approx {}^{2}50\cdot2000\cdot10pJ+2000\cdot50nJ$$

Receiving a 2000-bit packet:

$$_{rx}\ E=J^{4-}\ 10\times1.0 = 2000\cdot50\ nJ$$

These values show that communication energy is dominant, motivating clustering and selective reporting to extend network life time under the proposed SHEER-DAM protocol.

4.3. THRESHOLD-BASED SELECTIVE REPORTING

SHEER-DAM uses the dual-threshold event driven reporting system. There is a hard threshold (HT), which represents the lowest absolute level of vibration that will initiate a transfer of data. The soft threshold (ST), represents how much difference there can be in the measured vibration as compared to the last time it was reported.

If an input is less than the HT, or if there has been a change of less than ST from the last reported reading, then this is considered negligible, and therefore it is suppressed so that unnecessary communications do not occur; yet it would still allow detection of significant changes due to structural activity. The local variation is defined as:

Let $x_i\ (t)$ denote the vibration measurement of node *i* at time *t*, and x_i (last) the most recent value previously transmitted by the same node. The local variation is defined as:

$$\Delta x_i(t) = |\ x_i(t) - x_i(\ _{\text{last}}\ )\ | \tag{4}$$

A transmission decision $D_i(t)$ is then made as:

$$D_i(t) = \begin{cases} 1, & \text{if } x_i(t) \geq HT \text{ or } \Delta x_i(t) \geq ST \\ 0, & \text{otherwise} \end{cases} \tag{5, 6}$$

If the transmission is successful, then each node will update its reference value such that $x_i\ (last) = x_i\ (t)$. Therefore, this double-threshold approach guarantees that the network will detect both large absolute vibration magnitudes, and significant relative changes in vibration data; and also suppresses all redundant or unimportant vibration data to minimize the amount of communication necessary and extend the network's overall life time.

To demonstrate how the dual-threshold approach works for determining whether or not to trigger a decision based on a node's measured values; A node with two thresholds is considered, HT = 0.25 m/s and ST = 0.05 m/s. The most recent measurement = $x_i\ (last)$ = 0.08 m/s^2 and the current measurement = $x_i\ (t)$ = 0.11 m/s^2. In this case, the difference between the current measurement and the previous measurement = $\Delta x_i\ (t)$ = 0.03 m/s^2 is less than the secondary threshold and therefore will not cause a transmission.

On the other hand, if the sensed value were to increase to = $x_i\ (t')$ = 0.29 m/s^2 then it would exceed the primary threshold and a transmission would be generated.

Table 2. Vibration threshold parameters used in SHEER-DAM reporting

Symbol	Parameter	Description (Concise)
HT	Hard threshold	Absolute vibration level required to indicate a structural event
ST	Soft threshold	Minimum change from the last reported value to trigger transmission
$x_i(t)$	Current reading	Instantaneous vibration/strain at node *i*
$x_i(last)$	Last reported value	Most recent measurement transmitted by node i
$D_i(t)$	Transmission decision	Binary decision: 1 = transmit, 0 = suppress

In actual application environments the Hard Threshold (HT) is determined by the statistical characteristics of the vibration signal data collected during "normal" operational modes; that is

$$HT=\mu_{normal}+k^*\sigma_{normal} \tag{7}$$

Where: k generally varies within a range of 2 through 3. Additionally, the Soft Threshold (ST) can be specified as:

$$ST=max\ \{\eta\sigma_{noise}, \delta_{min}\} \tag{8}$$

In which η represents a ratio relative to the standard deviation of the sensor noise, and δ_{min} represents the smallest amount of structural variation that is meaningful or significant.

It should also be noted that depending on the location of the structural zone; for example, regions at the top (crests) of structures will likely require higher sensitivities than those found along their foundations; similarly, the threshold values employed may vary based upon the importance of each region's structure rather than simply its measured amplitude of vibration.

4.4. CLUSTER FORMATION AND CH SELECTION

The cluster-formation mechanism of SHEER-DAM uses a cluster-head (CH)-selection algorithm that is energy-aware. The residual energy of node I at round r is denoted by $E_i\ I$. The average residual energy of all nodes is denoted by E_{avg}, I, and is defined as:

$$E_{avg}(r) = (1/N) * sum_{\{j=1\}}^{\{N\}} E_j(r) \tag{9}$$

Where $E_{avg}(r)$ is the average residual energy of all nodes, $E_j(r)$ is the residual energy of node *j* at round *r*, and P_{opt} is the desired probability of selecting a node as a cluster head.

$$P_i(r)=(E_i(r))/(E_{avg}(r))\times P_{opt} \tag{10}$$

A node is elected as a CH if $P_{il} > rand(0,1)$.

$$r - r_{last_{CH(i)}} >= R_{cool} \tag{11}$$

where $r_{last_{CH(i)}}$ is the last round node I was CH, and R_{cool} is cooldown rounds. The exchange of control messages that is associated with the formation of the cluster is summarized in Table 3.

Table 3. Control messages in SHEER-DAM clustering

Message	Direction	Purpose
CH_ADV	CH → all nodes	Advertises CH status and invites cluster members
JOIN_REQ	node → CH	Node requests to join a specific CH
SCHED	CH → nodes	Assigns TDMA time slots for member transmissions

For example, with N=60, P_{opt} =0.1, and $E_{avg}(r)$=0.8J, nodes with higher residual energy achieve higher CH selection probabilities, as illustrated in Table 3.

In summary, this approach to forming clusters will help to balance communication overheads (load), reduce energy usage by each device, extend the overall lifespan of the network as a whole, and provide reliable structural monitoring coverage. As illustrated in Table 4

Table 4. Example CH selection probabilities

Node	Residual energy E_{it} (J)	E_{avgt} (J)	P_{it}
A6	1.0	0.8	0.125
A3	0.6	0.8	0.075

The notation of the key parameters used in the model is provided in Table 5.

Table 5. Notation of Key Parameters

Symbol	Description
E_{elec}	Radio electronics energy (J/bit)
ε_{fs}	Free-space amplifier coefficient
ε_{mp}	Multipath amplifier coefficient
E_{DA}	Data aggregation energy (J/bit)
d	Communication distance (m)
d_0	Threshold distance
P_{opt}	Optimal cluster-head probability
R_{cool}	Cluster-head cooldown rounds
HT	Hard threshold
ST	Soft threshold

5. PROPOSED SHEER-DAM PROTOCOL

The SHEER-DAM communication protocol is built on the concepts of Power and Structural Event Importance and uses them to create a framework for sensor networks (WSN). It is different from most existing models for WSN because this model does not treat all of the sensor's measurements equally; it instead treats them based on the relevance of the measurement to the physical stresses affecting the structure, making the SHEER-DAM protocol well-suited to the long term deployment in structures such as dams where there will be gradual changes in the dynamic behavior of the structure over time and require persistent observation at select points in the structure, but not necessarily a steady stream of data.

The SHEER-DAM system consists of four repeated phases of sensing, selecting the cluster-head, reporting to the sink node, and allocating energy; with each phase, the network configures itself in a different way (i.e., which nodes are in what locations), and only the changes in physical behavior that result from these configurations lead to additional communication loads, thus preserving structural monitoring and extending the duration of the system operation. To perform intelligent vibration sensing across entire dams, the SHEER-DAM system uses a combination of structure-guided clustering and selective reporting based on a set of threshold values. The sensor nodes are clustered by structural zone (level) to form a cluster head (CH), which represents a meaningful segment of the dam's structural zone. The CH will initiate transmission only when the vibrations it senses exceed a predetermined threshold; thus, only transmissions containing the most meaningful information will occur, thereby extending the life time of the nodes.

5.1. SHEER-DAM PROTOCOL PHASES

The SHEER-DAM protocol performs the different phases (energy-efficient vibration monitoring, data reporting based on events) to enable data collection from dam structures in an energy efficient manner. Before the creation of clusters, all sensor nodes measure the remaining energy to select an energy aware Cluster Head and also for the creation of the Structurally Guided Clustering, to reduce transmission distances and ensure fair distribution of the load over the entire network.

While operating, each sensor node will always measure vibrations. A double threshold decision mechanism is then applied by each sensor node to filter out non-relevant vibration measurements (thus avoiding unnecessary transmissions). Each sensor node will only send information concerning vibration events that have exceeded one of the pre-defined thresholds (hard or soft) to the cluster head of the corresponding group.

Each cluster head will then locally aggregate data to eliminate redundant data and send compact summaries about the structure to the sink node. At the sink node, it is possible to conduct the global analysis and the long-term assessment of the structural health. The overall process of the proposed protocol is represented in detail in Algorithm 1 and depicted as Fig. 2

Algorithm 1: SHEER-DAM Main Workflow

Input:

HT, ST, $Rcool$, initial node energies $E_i(0)$

Output:

Aggregated monitoring reports at sink

For each round r do

Select CHs based on residual energy and role rotation

Perform cluster formation and TDMA scheduling

For each node I do

Sense vibration $x_i(t)$

if $x_i(t) \geq HT$ or $|x_i(t) - xi_{last}| \geq ST$ then

Transmit data to CH

end if

end for

CH aggregates data and forwards summary to sink

Update node energies

end for

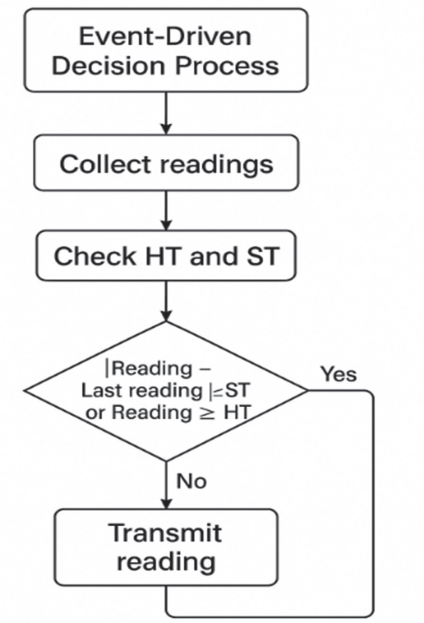


Fig. 2. SHEER-DAM protocol flowchart

6. SIMULATION SETUP

The proposed SHEER-DAM protocol was tested through simulations in a wireless sensor network (WSN) setup in the MATLAB R2023a environment to measure its performance in an environment simulated as a large-scale structure of dam monitoring. In this scenario, a total of 500 sensor nodes were randomly placed across a two-dimensional space measuring 300m x 120m to represent the physical characteristics of a common dam construction type that include a crest, mid body region, and foundations.

A sink node was located outside the area being monitored (at position 150, 140). Each of the sensors had been assigned an initial energy value of 1.5 Joule.

Each sensor's communication capability is based upon the first order radio energy model. Each sensor's transmitting distance has been limited to be between 30 and 50 meters so that there will be connectivity among all sensors. The path loss exponent values used are; 2 for free space, and 4 for multi-path propagation.

The simulation was run for 4000 cycles to assess long term network behavior. The parameters of dual thresholding have also been developed as follows: Hard Threshold (HT) = 0.25 m/s 2 and Soft Threshold (ST) = 0.05 m/s 2 forms the absolute and relative threshold to identify vibrations. Each test run had over thirty separate independent trials with various randomly generated seeds used in each trial along with placement of the nodes. The experimental data from these trials were averaged together to provide a mean value. Standard deviations are also reported as they capture the variability associated with the averages. Finally, the 95% confidence interval for the two most important performance metrics (i.e., throughputs) have been calculated. Table 6 summarizes the simulation set up.

Table 6. Simulation Parameters

Category	Parameters
Environment	Area: 300 × 120 m; Nodes: 500; Rounds: 4000
Network	Initial energy: 1.5 J; Packet size: 2000 bits; Range: 50 m
Sink	Located outside the dam
Radio model	E_{elec}=50 nJ/bit; ε_{fs}=10 pJ/bit/m^2; ε_{mp}=0.0013 pJ/bit/m^4
Aggregation	E_{DA}=5 nJ/bit
Clustering	P_{opt}=0.1; R_{cool}=10 rounds
Thresholds	HT=0.25 m/s^2; ST=0.05 m/s^2
Events	Synthetic vibration model (10-15% abnormal events)
Runs	30 independent runs

6.1. GENERAL OVERVIEW OF THE METHODOLOGY USED

The researchers positioned approximately 500 static sensor nodes across the dam's surface, with each node assigned to one or more structural layers, to determine whether there would be differences in vertical vibration among sensors as they moved through each layer. Each sensor was initially given 1.5 Joules of energy and operated using the classical first-order radio model. Each static sensor node used a dual threshold reporting behavior to determine which data from the structure were structurally significant enough to transmit. To understand how well the nodes behaved over time, the researchers simulated the network behavior over 4000 rounds. The researchers used three performance metrics to compare the SHEER DAM protocol with LEACH and TEEN: packet volume, residual energy, and life time metrics (FND, HND, LND).

7. RESULTS AND DISCUSSION

All reported data have been averaged across 30 simulations that were independently run on the same network topology with each of the nodes randomly deployed. Standard deviation was used to quantify variability within the results. In addition, selected performance metrics were also reported as having a 95% confidence interval for their respective data.

This part provides an overall assessment of the proposed SHEER-DAM protocol in relation to LEACH and TEEN protocols. Network life time, energy consumption, communication overhead, and response times for detecting vibrations are used as indicators for evaluating its performance. On the whole, this will reveal the effectiveness of applying structural knowledge to cluster and dual threshold method as potentially useful in dam monitoring systems.

7.1. LIFE TIME OF THE NETWORK

In addition to comparing the performance of SHEER-DAM, LEACH, and TEEN with respect to other important parameters as shown in Table 7, we can see that SHEER-DAM has improved the life time of the network much better than LEACH and TEEN.

For example, for FND, which represents when the first node dies, the life time was extended by 2100 rounds and this represents an increase of 133% from that of LEACH. Also, HND and LND were postponed in time; these two results indicate increased reliability and longer operational life time for the network.

The reason why the improvements were realized is due primarily to selecting the cluster head based on energy awareness and balancing loads among the structural zones of the dam. The performance of the evaluated protocols was summarized in Table 7. All the outcomes are described as a mean ± with standard deviation involving 30 independent simulation runs.

Table 7. Performance comparison of SHEER-DAM, LEACH, and TEEN

Metric	LEACH	TEEN	SHEER-DAM	Improvement
First Node Death (FND) [rounds]	900 ± 85	1350 ± 110	2100 ± 120	+133% vs LEACH
Half Nodes Dead (HND) [rounds]	1300 ± 95	1900 ± 130	2850 ± 140	+119% vs LEACH
Last Node Death (LND) [rounds]	1480 ± 105	2100 ± 150	3350 ± 160	+126% vs LEACH
Total Packets Transmitted	58,000 ± 2,400	39,500 ± 2,000	23,100 ± 1,500	–60% vs LEACH
Avg. Packets per Round	14.5 ± 1.2	9.8 ± 0.9	5.77 ± 0.6	–60%
Packet Loss (%)	2.4 ± 0.3	3.1 ± 0.4	1.7 ± 0.2	Best
Residual Energy (round 2000) [J]	0.51 ± 0.05	0.68 ± 0.06	0.93 ± 0.07	+82% vs LEACH
Residual Energy (round 3000) [J]	Depleted	0.39 ± 0.05	0.71 ± 0.06	Sustained operation
Event Detection Delay [ms]	112 ± 9	94 ± 8	62 ± 6	–45%
Communication Latency [ms]	41 ± 4	36 ± 3	29 ± 2	Lowest
Network Life time [rounds]	1480 ± 110	2100 ± 140	3350 ± 150	+126% vs LEACH

In comparison to LEACH and TEEN (as shown in Fig. 3) SHEER-DAM is able to maintain a larger number of active nodes as well as preserve a greater amount of residual energy during the entire length of the simulated time frame. The increased usage of energy as a result of the proposed method for clustering and communication can lead to a reduction in the rate at which energy is depleted from the nodes and an extension of the overall lifetime of the network.

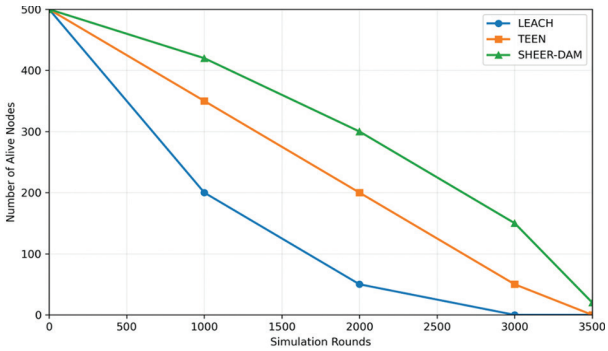


Fig. 3. Alive nodes vs. simulation rounds

7.2. Energy Consumption

In addition to comparing the network lifetime performance of the SHEER-DAM protocol to those of LEACH and TEEN (Table 7), we also compare their relative energy consumption levels. As demonstrated in the data from simulations, the overall energy consumption level throughout the network is significantly less than it would have been had either the LEACH or TEEN protocols been used.

The average amount of energy remaining on each node at round 2000 is approximately 0.93 Joules for the SHEER-DAM protocol. That is a significant improvement when compared to the average remaining energy per node of 0.51 Joules for the LEACH protocol and 0.68 Joules for the TEEN protocol. Moreover, although all of the nodes in both the LEACH and TEEN protocols are completely drained by round 3000, the average amount of energy remaining on each of the nodes in the network using the SHEER-DAM protocol was approximately 0.71 Joules.

These results imply that the offered SHEER-DAM protocol can be successfully applied to controlling the energy consumption of separate sensor nodes, which extends the time of accomplishment in the network.

As illustrated in Fig. 4, SHEER-DAM maintains higher residual energy levels than LEACH and TEEN across all simulation rounds, indicating improved energy efficiency and reduced energy depletion. The results have shown that the proposed event driven report mechanism and the energy aware clustering strategies have not only improved the overall network performance but also reduced the energy consumption and communications overhead.

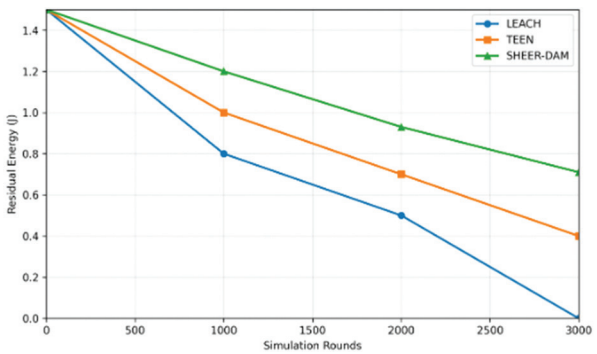


Fig. 4. Residual energy vs. simulation rounds

7.3. COMMUNICATIONS PERFORMANCE

The performance of communication is measured based on the number of packets being transmitted as indicated in Fig. 5.

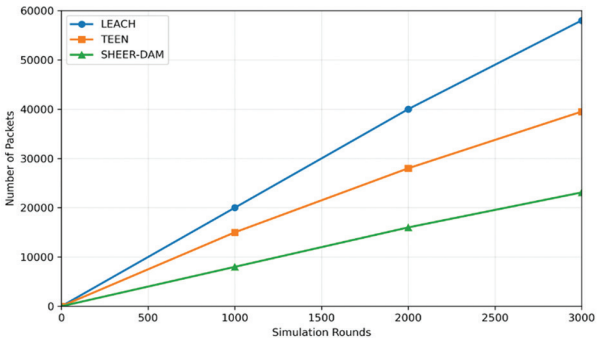


Fig. 5. Transmitted packets vs. simulation rounds

As shown in the results of Fig. 5, SHEER-DAM can reduce packet transmission compared to LEACH and TEEN which improves the communication overhead, energy dissipation and efficient network operation.

7.4. TIME DELAYS AND RESPONSIVENESS

Table 6 show how well the tested protocols responded by evaluating the detection time, start delays and transmission rates for packets after a structural failure or other type of structural event.

The test results demonstrate that SHEER-DAM has the fastest response times with respect to both LEACH and TEEN. A reduction in detection delay was achieved at 62 ms; however, a further significant reduction in communication latency occurred at 29 ms; thus, allowing for rapid as well as reliable data distribution.

SHEER-DAM's ability to outperform TEEN may be directly attributable to it being structurally aware through use of adaptive thresholding and its structure-based grouping (clustering) of sensors to efficiently detect various vibration patterns from differing sections of a dam. (*see Table 8 for response time comparison*).

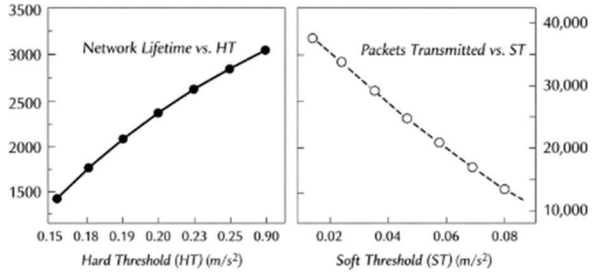
Table 8. Response time comparison

Protocol	Detect. (ms)	Delay (ms)	Pkts/100 ms	Response
LEACH	120-150	50	5-7	Slow
TEEN	80-100	30	8-12	Moderate
SHEER-DAM	25-40	8	15-22	Fast

7.5. SENSITIVITY EVALUATION

In order to evaluate how sensitive the sensor network is to changes in the parameters (HT, ST, node density and sink position), a sensitivity study was conducted. The HT was set to vary from 0.15-0.30 m/s2 and the ST was set to vary from 0.02-0.10 m/s2. As can be seen by the two figures shown below 6a,6b, it is possible to observe the effect of HT and ST on network lifetime and packet transmission.

The effects of HT and ST on the sensor network are as follows; Higher values of HT will reduce packet transmissions thus provide better energy efficiency for each node, however will increase the time taken for detection. On the other hand, Lower values of ST will enable better detection with respect to sensitivity at the cost of increased communications overhead. Increased node density will also result in improved reliability in detecting events. Finally, placement of the sink has an influence upon the way that the energy is distributed throughout the network.



(a) (b)

Fig. 6. Sensitivity of (**a**) HT and (**b**) ST on network performance

7.6. DISCUSSION AND INTERPRETATION

The data supports that SHEER-DAM has successfully achieved both goals for real-time wireless Structural Health Monitoring (SHM): 1) high levels of energy conservation during the normal operational state of SHM systems; 2) fast response times when there are unexpected structural changes occurring.

When there are no vibration above predetermined thresholds, SHEER-DAM uses selective report protocols to minimize all possible communication with remote server, and therefore reduces energy usage among all nodes in the system. Once these threshold values have been reached, the SHEER-DAM system will switch to an intensive reporting method which allows immediate detection of structural damage.

In addition to providing a balance of energy consumption per zone on the structure (i.e., crest, mid-body, and base/foundation) as it monitors, SHEER-DAM prevents premature failures in those areas by ensuring that each area is monitored similarly over time. This shows that SHEER-DAM is not only an efficient routing protocol, but is also a sensing framework adaptable to structures being monitored over many years.

8. PRACTICAL AND OPERATIONAL CONSIDERATIONS

Practical and operational considerations are provided by SHEER-DAM through its combination of operational requirements for dam operations in real-time operation as well as the structural considerations for monitoring in a dam environment and operational considerations; it provides the ability for nodes to send

only those measurements which are significantly different from what they expect as opposed to sending all of the routine information that they gather, and then using this information to focus the reporting efforts on those changes that are structurally relevant. This approach will allow the cluster head to be rotated among the nodes so that no single node becomes depleted of power, thereby extending the sensor's life.

As for the practical application of SHEER-DAM, it can be implemented on widely available MEMS accelerometers that include low-power wireless modules running TinyOS or Contiki-NG. In addition, TDMA scheduling provided by the CH eliminates the need for strict global synchronization across all clusters; therefore, timing coordination can be performed at the local cluster level. SHEER-DAM also has low computational overhead, since threshold evaluation takes constant time, and selecting the CH incurs only linear overhead proportional to the number of nodes per structural level.

The Selective Reporting mechanism reduces Network Congestion, improves Packet Delivery Success, and increases the speed at which event transmissions are generated due to abnormal Dam Structure behavior. The SHEER-DAM Architecture is inherently fault-tolerant, i.e., if a Cluster Head (CH) fails, the election process for the next round of cluster heads will automatically re-establish the hierarchy of the SHEER-DAM system.

Additionally, the sink node stores historical data on the structural behavior of the DAM structure and each sensor only stores minimal local state. These attributes of the sheer-dam system enable reliable, efficient, and realistic performance in structural monitoring over extended operational periods of actual dam structures.

8.1. PROBLEMS WITH PRACTICAL IMPLEMENTATION

The humid environment of dams along with extreme temperatures and high dust exposure can be detrimental to the sensor's performance; thus, they need to have ruggedized housings. Additionally, in these environments the batteries for the nodes are difficult to replace because of their limited accessibility (at crest level and at foundation level), which reduces maintenance complexity that the system is energy efficient thereby reducing the amount of miniatous required. The periodic MEMS can be easily calibrated, since the overhead is small computationally, and there is auto-cluster-head reelection.

9. CONCLUSION AND FUTURE DIRECTIONS

The results achieved demonstrate the ability of SHEER-DAM to operate efficiently under normal monitoring conditions and rapidly and accurately report on any abnormal structural vibration event.

The structured approach to clustering combined with the dual-threshold sensing approach reduces transmission in the network and prolongs the network life time; and provides nearly real-time reporting of vibration anomalies important to dam safety. Future work in developing this research will involve the development of an adaptive learning-based method for determining thresholds; the integration of edge-level analytics within a cluster head to determine which nodes have the highest probability of failure; and, the use of hybrid sensing modality technologies that combine accelerometers and strain-sensing modalities.

The testing and validation of the proposed framework, by implementing the sensor nodes on physical dams and using the actual vibration data collected from those dams, is also required to deploy the system in practical applications.

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USE OF AI TOOLS DECLARATION TEXT

Authors have utilized Grammarly (Grammarly Version 6.8) to edit their language and check their grammar. Authors reviewed all AI-assisted content and authored and edited it to ensure that they were responsible for the accuracy of the information in this work. None of the authors include a reference to an AI tool on the title page as an author; therefore, none of the authors will cite an AI tool as a source.

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