

# Application-Oriented Sensor Network Architecture for Dependable Structural Health Monitoring

Md Zakirul Alam Bhuiyan<sup>\*†</sup>, Guojun Wang<sup>†§</sup>, Jie Wu<sup>\*</sup>, Xing Xiaofei<sup>‡</sup>, and Xiangyong Liu<sup>†</sup>

<sup>\*</sup>Department of Computer and Information Sciences, Temple University, Philadelphia, PA 19122, USA

<sup>†</sup>School of Information Science and Engineering, Central South University, Changsha, Hunan, P. R. China, 410083

<sup>‡</sup>School of Computer Science and Education Software, Guangzhou University, Guangzhou, 510006, P. R. China

<sup>§</sup>Correspondence to: csgjwang@gmail.com

**Abstract**—The applicability of wireless sensor networks (WSNs) to data-intensive structural health monitoring (SHM) is being heavily studied recently by the computer science domain. The aim is to monitor complex events (e.g., damage, crack) in structures (e.g., a high-rise building, a long-span bridge), which is usually carried out by civil/structural engineers. However, regarding methods from engineering domains, detection of such events directly over large structures in a centralized manner is extremely costly due to severe resource constraints of WSNs. Although there exist network organization or grouping algorithms (e.g., clustering) developed in distributed manners, they still suffer greatly from high resource usage and a lack of dependability (in terms of ability/quality of monitoring and low false alarm rate). We discover that the dependability is greatly affected by such grouping schemes, as they do not satisfy application-specific aspects. We present an SHM application oriented network architecture (SHMnet) and analyze health event monitoring performance with it. We propose a substructure-oriented sensor organization (SOSO), considering the formation of engineering structures and finding that a large physical structure consists of a number of substructures. We enable deployed sensors to be organized into groups (unlike dynamic clusters/trees) in such a way that each group of sensors can monitor a substructure independently. We evaluate SHMnet via simulations using real data traces. The results, compared to existing work, show that SHMnet achieves at least five times the energy saving (including the energy for communication) in WSNs and dependability in terms high ability of monitoring and low false alarm rate.

**Index Terms**—Wireless sensor networks, sensor grouping, structural health monitoring, dependability, resource-efficiency.

## I. INTRODUCTION

Wireless sensor networks (WSNs) have been deployed in a wide variety of applications. Examples include environmental monitoring, event detection, military operations, and rescue operation [1]. In recent years, using WSNs for structural health monitoring (SHM) has received increased attention from diverse domains, such as civil, structural, mechanical, and aeronautical (CSMA) engineering and computer science. Reasons include advantages such as low-cost, low-maintenance, flexibility, and fast and easy installation over wired sensor networks [2], [3], [4], [5]. The target is to monitor complex events (e.g., damage, cracks, corrosion, and the like) in a physical structural system (e.g., a high-rise building, a long-span bridge, etc.) by

analyzing the dynamics in elements/components of them [4], [6], [7], [8], [9].

Currently, wired network systems dominate SHM systems in the CSMA engineering domains [8], [10]. In a typical WSN-based SHM system, sensors are deployed on different locations of a structure to collect the structures responses under ambient or forced excitation. This data is then transmitted via wires or wireless to a base station (BS), where one or more SHM algorithms are implemented to extract structural event-sensitive vibration characteristics. By examining these characteristics, an event can be detected and located globally/centrally [7].

Manipulating such global/central systems is cumbersome with large-scale structures. Using short-range (hop-by-hop routing) and long-range (single-hop) transmission in WSNs, data collection over the large structure becomes impossible. For example, the Guangzhou New TV Tower (GNTVT) [11], [12], that peaks at 600m above ground or a bridge/tunnel that is longer than several kilometers, even given only a substructure of them (e.g., a part of the building, a long span of the bridge), such methods are extremely costly for WSNs. Due to severe resource constraints (radio bandwidth, energy, computation, etc.) in WSNs, detection of a health event over such a large structure by the BS is extremely costly.

To overcome these difficulties, there are distributed WSN-based SHM systems that perform monitoring operation in hierarchical manners. They use flat/hierarchical/clustering network architectures. Heuristic and dynamic clusters/trees organization are used, but their performance is not analyzed for SHM. Although there exist network organization or grouping algorithms (e.g., clustering) developed in distributed manners, they still suffer greatly from high resource usage and a lack of dependability (in terms of ability/quality of monitoring and low false alarm rate). We discover that the dependability is greatly affected by such grouping schemes, if they do not satisfy application-specific aspects. If a group of sensors that detect a damage event fully changes over time (if there is a new group), they may fail to detect the damage event further.

Considering both domain aspects, we present an SHM application oriented network architecture (called SHMnet) and analyze structural health event monitoring performance with it. We propose a substructure-oriented sensor organization (SOSO), considering the formation of engineering structures

and finding that a large physical structure consists of a number of substructures. We enable deployed sensors to be organized into subnetworks (unlike dynamic clusters/trees) in such a way that each subnetwork of sensors can monitor a substructure independently.

The crucial aspect is that collected data or structural health event detection results made by each sensor or subnetwork head can only be transmitted to the BS if there is an ‘event’ in the corresponding substructure. As a result, the total energy and bandwidth cost required for wireless data transmission can be drastically reduced. It is vital to note that the whole structural modal analysis (e.g., mode shape, usually required by the engineers) extracted from substructural model analysis can also be generated accurately if there is an ‘event’ in a specific substructure. Since sensor organization into groups/subnetworks may have an impact in the health event monitoring quality compared to tradition centralized/global SHM system. To investigate this, we consider SHM system dependability in terms of the monitoring ability/quality and false alarm rate, thinking that offering such dependability can give more option to CSMA engineering in designing future SHM systems. We evaluate SHMnet via both simulations using real data traces. The results, compared to existing work, show that SHMnet achieves at least five times the energy saving (including the energy for communication) in WSNs and superior dependability.

The rest of this paper is organized as follows. Section II reviews related work. The detail of SHMNet architecture is discussed in Section III. Section IV provides the SOSO algorithm. Performance evaluation through simulations is conducted in Section V. Section VI concludes this paper.

## II. RELATED WORK

Monitoring civil structures using WSNs have recently become an active area of research [4], [5], [7], [13], [14], [15]. It has been gradually accepted that WSNs systems have many intrinsic advantages over wired systems [3], [12]. In the SHM system implemented on the Guangzhou National TV tower (GNTVT) [12], [16], [17], the WSN deployment is partially adopted [12]. Existing work mainly focuses on data acquisition and compression methods, reliable data transport protocols, and so on [5], [18]. However, application-specific dependability through WSN architecture has not been addressed.

Considering severe constraints in WSNs, we can find distributed or decentralized decisions on the structural health event of each substructure independently by the subnetwork. To achieve it, it can be better if we can still organize the nodes according to the physical substructure orientation. In recent years, a number of WSN approaches from both CSME and computer science domains has employed hierarchical WSN architectures for structural monitoring [5], [19], [20], [21], [22], [23].

Liu et al. [19] propose two centralized and one decentralized clustering schemes for SHM applications, which mainly discuss distributed modal analysis. Clusters generated by these schemes meet the requirements of SHM applications: all

nodes are included in at least one cluster and connected to cluster heads with single-hop links; minimum cluster size is enforced; and all clusters are connected via overlapping nodes. They assume that clusters around the requirements of distributed modal analysis. Using their singular-value decomposition (SVD)-based SHM scheme as a motivating example, Jindal and Liu [5] propose a general, near-optimal distributed clustering algorithm for WSNs. However, these approaches do not figure out how to get such a WSN deployed for SHM. Thus, we have to find a way that can create subnetworks of a WSN without identifying substructures.

We can gain the above benefits through a substructure-oriented subnetwork deployment. According to the construction nature of engineering structures, a large physical structure consists of a number of substructures. In other words, a structure can be divided into a number of substructures based on different sections. After deployment, sensor nodes in a WSN can be organized into groups (or subnetworks) in such a way (in a hierarchical manner) that each subnetwork can provide local monitoring results for a substructure independently. However, such substructures are usually identified by wired sensor networks (having constant power supply). This cannot be possible by the wireless sensors, as the identification requires a huge amount of high-complexity computation and communication. The optimal sensor locations in such substructures can also be identified by the wired sensors. For example, see the identification of substructures (sections/regions/subspaces) of a structure using wired sensors and the group of wired sensors connected to each other, and to the BS [24], [25], [26].

SHMnet takes inspiration from the above prominent schemes, and addresses some important issues or gaps.

- *Data transmission considering the ‘event’/‘no event’ situation in a specific substructure.* Typically, the common situation in SHM is that a structural event is a relatively rare event. We thus argue that it is not necessary to always broadcast a huge amount of data over the WSN; after all, the sensors may only need to transmit local decisions to their neighbors or the upstream sensors.
- *Local and long-term SHM.* SHM is still assumed to be a global scheme. We argue that global damage detection is becoming increasingly difficult as the structures become larger and more complex. What we need is to find a local SHM considering the exact formation of civil structures (i.e., substructural orientation). When damage occurs at a particular location, the corresponding substructure can be given higher priority by allocating more time to the sensors in the area. Thus, the event area can be localized by the substructure.

## III. SHM APPLICATION ORIENTED NETWORK ARCHITECTURE: SHMNET

In this section, we first briefly describe the overall process of structural health event monitoring and then the sensor network architecture. Next, we provide the system models. Finally, we formally define the problem in SHMnet.

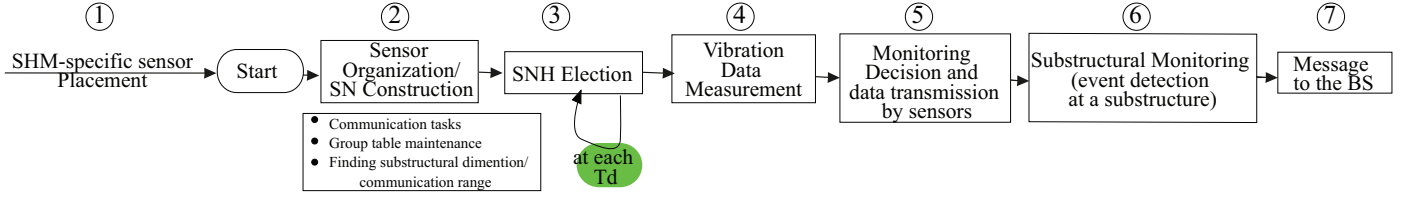


Fig. 1. The work flow of SHMnet for structural health monitoring.

TABLE I  
ABBREVIATION DESCRIPTION

Abbreviation	Full Name
LDM	Local decision maker
SNH	Subnetwork head
$T$	The whole period of SHM operation (i.e., a system run)
$T_d$	A period of monitoring in $T$
$t$	A discrete period (i.e., a round ) of monitoring in $T_d$

### A. Overview of the SHMnet

Fig. 1 illustrates a snapshot of the processes involved in the SHMnet. After deployment of a WSN (Step 1) using a deployment method either from engineering or computer science domains. In Step 2, the sensors are allowed to communicate to each other and are organized into subnetworks (SNs). In Step 3, the sensors find their initial subnetworks head (SNHs). They then become ready for the structural health event monitoring operation. Sensors are allowed to sample vibration data (Step 4). The rest of the processes (Steps 5 to 7) involves decision making and data transmission to the BS. Amongst all the labeled steps in Fig. 1, the contribution of this work is in Step 2 and Step 3, in that a subnetwork covering a substructure can be identified. By such steps, the number of subnetworks may become equal to the number of substructures, the number sensors in each subnetwork may vary. Possible reasons include the followings: there are common or boundary sensors between two or more subnetworks; some sensors may join or leave due to fault; there are connectivity problems; etc. All the sensors in a subnetwork send the collected or decision (as an SHM system user needed) data to the subnetwork head. The subnetwork head then decides if there is an event in the substructure by fusing all the collected data. Once the network starts for  $T$  (for abbreviation description please refer to TABLE I), Steps 3 to 5 repeat in each  $T_d$  until  $T$  finishes. We do not need Step 2 in each  $T_d$  and our concern is only on the substructure where an event happened at a substructure. If a user wishes, the subnetwork located in a particular substructure forwards the decision to the BS. Sensors in other subnetworks may reduce data transmission task.

### B. Network Architecture

Consider a physical structure, such as GNTVT [27] for monitoring, and a deployed WSN topology, as depicted in Fig. 2. The structure consists of a number of substructures, as shown in Fig. 2c, represented by  $\Omega_q$ , where  $q$  is the

maximum number of substructures. Given a set  $P$  of  $S$  homogeneous sensors with limited energy, we need to form such a WSN denoted by  $W = (V, E)$  over the structure.  $S$  sensors are attached to the structure by some location assignment  $L = l_1, l_2, \dots, l_M$ , where sensor  $s_u$  is placed at location  $l_u$ . Through our previously developed wireless sensor deployment algorithms for SHM applications [7], we can have some sensor nodes as subnetwork heads (much like cluster head, the decentralized decision maker or precessing center).

We consider a link quality model regarding dynamic structural environments and interference. This adopts the idea of the log-normal path loss model [28], which is a popular radio propagation model, enabling us to have the formation of IEEE 802.15.4 links into three distinct reception regions: connected, transitional, and disconnected. According to this model, the strength of a radio signal decays with some power of distance. We let  $R_{min}$  and  $R_{max}$  denote the communication range for connected region and transitional region, respectively. We take  $R_{min}$  as the range that a sensor can easily communicate with 100% packet transmission rate (PRR).

However, there are significant challenges when a sensor needs to find  $R_{max}$ . In our model, any two sensor nodes within a range of  $R_{max}$  are predicted to be in communicable range of each other. We calculate  $R_{max}$  based on a statistical link quality on a initial sensor deployment. If a sensor experiences that its  $R_{max}$  is more than a threshold value, we attempt to deploy one or two redundant sensors around of it so that the link quality or PRR can be improved.

After the deployment of all sensors, sensors are organized into (possibly overlapping)  $g_i (i = 1, 2, \dots, K)$  subnetworks/groups. Each subnetworks contains a subset of  $s_m$  sensors around a substructure for monitoring.  $g_i$  is variable, which relies on the WSN density and diameter of a substructure. We assume that the number of subnetworks is equivalent to the number of substructures, say,  $q = K$ . In the network, each sensor acquires periodically dynamic response measurements (i.e., excitation caused by harmful vibration, heavy wind, load, etc.). Each sensor in a subnetwork works as a local decision maker (LDM). After the first election, one of the sensors in the subnetwork is elected as an SNH before  $T_d$  finishes. A sensor can adjust its  $R_{min}$  according to the connected region based on diameter  $d$ , as shown in Fig. 2d. At  $R_{max}$ , an SNH can connect to its neighbor SNHs or the BS. During a monitoring operation, we restrict communication between two neighboring sensors in a group, except between a sensor and one or

more SNHs. In SHMnet, new SNHs, but not new groups in the WSNs, are chosen at  $d$ th time period  $T_d$  to provide fairness and to avoid single node failure and maintenance overhead. At each  $T_d$ , a new sensor as a LDM may join or leave the group due to various environmental and fault factors, but the group still remains. Hence, as regard the static substructures, the idea of static group-based data delivery/forwarding (quite similar to generic cluster-based routing [5], [29], [30], together with our SHM specific data processing) is adopted.

### C. Sensor Decision Making

We adopt a structural health event (damage) detection algorithm [15]. Each sensor is enabled to process and make a decision on an event detected locally and independently. After making a decision, if there is an event of damage, it transmits it to its SNH. An SNH fuses and confirms the decisions made by sensor whether or not there is damage in a substructure. Generally, data fusion is an effective signal processing technique, which is often used for generic WSN applications [31], and can also be used to improve the performance of SHM applications. However, our aim is mainly to focus on in-network decision-making rather than decision fusion.

It is vital to note that the whole structural modal analysis (e.g., mode shape, usually required by the engineers) extracted from substructural model analysis also be generated accurately if there is an ‘event’ in a specific substructure. Since sensor organization into groups/subnetworks may have impact in health event monitoring quality compared to tradition centralized/global SHM system. To investigate this, we consider SHM system dependability in terms of the monitoring ability/quality and false alarm rate, thinking that offering such dependability can give more option to CSMA engineering in designing future SHM systems.

Having a decision reliably at a sensor is subject to a false alarm rate, because the noise and interference from the sensor device is different from the real vibration threshold for a structural event with a high noise level from the measurement and is also different times at different sensor subnetworks/substructures. Therefore, a WSN-based SHM system is likely to give a false alarm when there is no real structural event. In our case, we define the false alarm rate when *there is actually no structural event, but the SHM system detects an event nevertheless*.

### D. Energy Cost Model

One of the major objectives is to minimize the energy cost of the WSN. This entails making a decision on an event detection, getting a confirmation from an SNH, and getting an acknowledgment as the decision confirmation from the SNH reaches the BS. We briefly describe here how energy consumed in transmitting/receiving a packet is computed. Given a routing algorithm [12], we term  $x[s_u] = p_u$  as the  $u$ th hop LDM or SNH on path  $x$ , and  $\lambda_x$  as the amount of traffic that passes along path  $x$  within one round of monitoring data collection. Then,  $x[s_u]x[s_{u+1}]$  is the communication range that can be

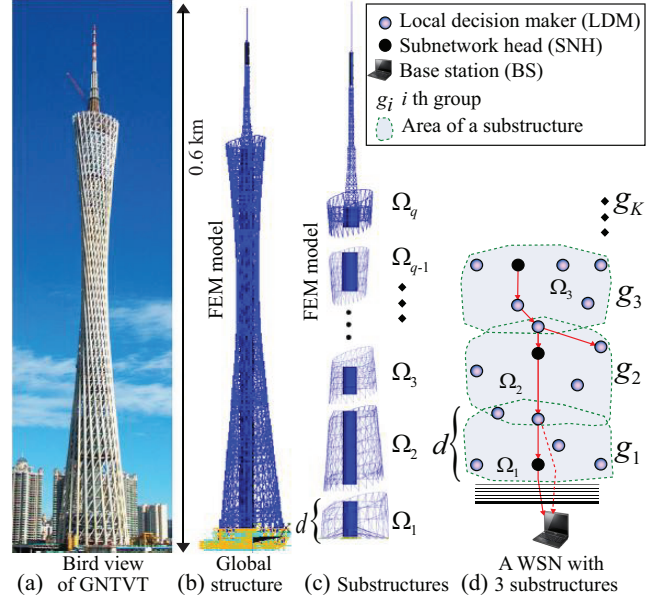


Fig. 2. A WSN-based structural health monitoring framework: (a) GNTVT structure; (b) finite element model (FEM) [12] of GNTVT; (c) breaking the GNTVT structure into substructures; (d) sensor grouping.

either  $R_{min}$  or  $R_{max}$  between any two sensors  $x[s_u]$  and  $x[s_{u+1}]$ , and  $R_{min} \leq d \leq R_{max}$ .

Let  $cost(s_u)$  be the total energy cost of a sensor in  $i$ th group  $g_i$  and  $cost(g_i)$  be the energy cost of the group of sensors.  $cost(g_i)$  is decomposed into the following three parts:

$$cost(g_i) = \sum_{u=1}^n cost(s_u) \quad (1)$$

where  $cost(s_u) = e_T + e_{samp} + e_{dm}$

We describe the terms as follows. i)  $e_T$  is the energy cost per bit for transmission over a link between a transmitter and a receiver, which includes  $e_s$  and  $e_r$  as the energy cost for sending and receiving data, respectively. It is given as follows.

$$e_T = \sum_{\forall x, \exists s_u, x[s_u]=l_u} \lambda_x \cdot e_s \overline{x[s_u]x[s_{u+1}]} + \sum_{\forall x, \exists s_u, x[s_u]=l_u} e_r(x[s_u]).$$

ii)  $e_{dm}$  is given by (2). iii)  $e_{samp}$  is the energy required by sampling for  $N$  data points; in taking vibration signal measurements, assuming that there is a maximum 40% overlap,  $N = (n_a/2 + 1/2) \cdot c_r$ , where  $n_a$  and  $c_r$  are the number of averages, mainly for denoising purposes. These basically vary from 10 to 20, and are cross-correlational factors [19].  $n_a$ ,  $c_r$ , and  $N$  are set by fixed values on a sensor.

The problem is to find an application-specific sensor grouping method such that  $i$ th group/subnetwork  $g_i$  of sensors can exactly cover a substructure and provide monitoring for the substructure only. Applying such a group, a decision on the presence/absence of the structural event can be made by subnetwork  $g_i$  that and report a confirmed decision to the BS. The objectives are to increase the system dependability and minimize the total energy cost  $\sum_{i=1}^M cost(g_i)$ .

#### IV. SOSO ALGORITHM: SENSOR GROUP ORGANIZATION

In this section, we propose the substructure-oriented sensor organization (SOSO) algorithm.

##### A. Substructure-Oriented Sensor Organization

We think that only a small part (say a specific sensor location) of a substructure may be damaged at first and needs continuous monitoring. Note that physical substructures are normally identified by wired sensors in civil engineering for substructure oriented monitoring, but it is quite impossible by wireless sensors. Thus, we ignore the structure identification, but we grab the idea of substructural monitoring. Our focus is to provide substructure-oriented monitoring rather than concentrating on a whole structure, in which length or diameter can be from X00m to Xkm (X=1,2,3..). One or more LDMs around the specific location should detect the event. An SNH confirms an event when it is able to know all of the decisions in the group (that covers a substructure).

A substructure is considered by the area of a number of floors of a building, a long-span or two small spans of a bridge, a long span of a subway tunnel, one or more sections of an aircraft, and so on [24]. It can be fixed based on the scale of a structure and part or section orientations. The communication range of a sensor,  $R_{min}$ , is important, which is first adjustable to the link quality and then adjustable to the diameter of a substructure (see Fig. 2c). We need to organize sensor groups, where each group of sensors is required to completely cover the area of a substructure, and sensors in each of the group are strongly connected. In a physical building structure, since it is possible that not every floor has its own sensor, as is common with engineering placement methods like [7], [12] or others, the grouping must therefore meet the following constraints:

- A sensor in a group  $g_i$  belongs to the same substructure, and is connected to an SNH.
- A sensor in  $g_i$  is within a single hop to multi-hop of an SNH, where it is able to adjust its communication range.
- All of the groups in the network are connected together through the overlapping sensors.

Although satisfying the first constraint is straightforward, it requires domain knowledge from both computer science and CSMA engineering. Before formulating the above grouping problem, we assume that a WSN has already been partitioned according to the substructures they belong to. We therefore only focus on how to further group the sensors in each substructure to satisfy the second and third requirements, and minimize the number of groups. Thus, the problem becomes: given a WSN  $W = (V, E)$ , find a grouping scheme that can group these  $V$  sensors into  $K$  groups, denoted as  $G = \{g_1, g_2, g_3, \dots, g_K\}$ , subject to the following constraints:

- i)  $(\cup_{g_i \in G} \text{ where } s_u \in g_i) = V$
- ii) Let the subgraph for group  $g_i$  be  $W(g_i, E_i)$ , where  $E_i \in E$ . Then,  $\forall g_i \in G, \exists s_u \in g_i$ , such that there is an edge  $e_{uv} \in E_i$  between a sensor  $s_u$  and other  $s_v \in g_i (s_u \neq s_v)$
- iii)  $\forall g_i, \exists g_j \in G, (i \neq j), g_i \cap g_j \neq \emptyset$  and  $\forall G' \subseteq G, (\cup_{g_i \in G'} g_i) \cap (\cup_{g_j \in G-G'} g_j) \neq \emptyset$

Objective: Minimize  $cost(g_i)$

The 1<sup>st</sup> constraint is necessary since we wish to find  $D_j$  obtained by all sensors. The 2<sup>nd</sup> constraint is to ensure that groups are generated. The 3<sup>rd</sup> constraint describes that generated groups are overlapped and connected.

##### B. Sensor Interactions and the SNH Election

At the initialization, i.e., at the first  $T_d$ , each LDM broadcasts a packet in which it announces itself as the SNH, unless it hears such an announcement from another LDM. An important fact is that each LDM uses a table of records for the group. For each LDM in the WSN, a record contains the sensor  $id$ , a flag hinting whether it is an SNH or not, its current energy level ( $e_{cur}$ ), and location. When a sensor becomes an SNH, it has extra information in the table, e.g., about neighbor SNH.

At the end of each  $T_d$ , each LDM transmits a report to the SNH. The report includes  $id$ ,  $decision$ , and  $e_{cur}$ . Before going to sleep, LDMs wait for an announcement about who is the SNH in the next  $T_d$ . After SNH fuses decisions transmitted by the sensors, SNH confirms the event and announces the next SNH. The packet includes the confirmation on an event detection and the next SNH id. When LDMs receive the announcement, they update the records by  $id$  of the SNH for the next  $T_d$ . They mark the information so that when they wake up in the next  $T_d$ , they know which LDM is their SNH.

Under SOSO, group organization is performed once, but a new SNH election is simply performed at the end of each  $T_d$  (which does not require a lot of messages to be exchanged between sensors, and is different from prior cluster-based algorithms, e.g., [5], [19], [29], [30], where clusters are dynamic). In SOSO, a sensor node (say a sensor) may enter or leave a group (such as group  $G_1$  over time due to being a boundary sensor, or due to faults in the WSNs, or due to another reason. However, the group  $G_1$  remains in SHMnet until a sensor is alive. Thus, the number of LDMs in a particular group of the WSN may vary, but the number of groups in the WSN still remain the same. Thus, groups in SHMnet are static for the whole duration of a system run ( $T$ ). In each  $T_d$ , there is no active SNH election procedure and no further group organization; LDMs wake up, connect to the SNHs, and start sampling directly. Thus, this group organization and leader election reduces maintenance overhead and offers substructural monitoring. Conversely, the dynamic clustering [5], [19] may not be suitable for substructural monitoring, because (i) a cluster may not exactly cover a substructure, (ii) a cluster may cover two or more substructures, or (iii) two or more clusters may cover a substructure.

*Remarks.* SOSO is mainly based on  $d$ , obtained from the whole length ( $H$ ) of a structure. We have also verified in another way: at our trial deployments in different structures, we first deploy a sensor at the mid or boundary location of a substructure and mark the sensor with its  $id$ . If the estimated range between two such deployed sensors is less than  $< R_{max}$ , they can roughly estimate  $d$ . Otherwise, sensors are enabled to find the marked sensors during their deployment and can

TABLE II  
DECISION-MAKING BY THE FIRST 15 GROUPS OF SENSORS IN EVERY FIRST ROUND OF 7 SUCCESSFUL SIMULATION RUNS OF SHMNET.)

Group	Sensor #															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	...
Sim. 1	1	1	0	1	1	0	0	0	0	1	0	1	0	0	1	...
Sim. 2	1	0	0	1	1	0	1	0	1	0	0	0	0	0	0	...
Sim. 3	1	1	0	1	0	0	0	0	0	1	1	0	0	0	0	...
Sim. 4	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	...
Sim. 5	1	0	0	1	1	0	0	0	0	1	1	0	0	0	0	...
Sim. 6	1	1	0	1	0	0	0	0	1	1	0	0	0	0	0	...
Sim. 7	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	...

estimate  $d$  by analyzing the communication range between two marked sensors (from a mid/boundary location to another).

## V. PERFORMANCE EVALUATION

### A. Simulation Methodology

We validate the performance of our SHMnet through a sophisticated building structure model, the GNTVT (see Fig. 2). The real data traces collected by a large number of sensors (800 sensors) deployed on the GNTVT are used. The GNTVT was completed in 2011 and became the tallest TV tower in the world, with a height ( $H$ ) of 450m of the main tower. A set of 200 sensors is used to monitor the vibration at the transverse direction ( $z$  direction). On average, the diameter of each substructure is  $d = H/q$ , where  $q$  is the expected number of substructures,  $q = K$ . The communication range is adjusted with  $d$ ,  $R_{min} \leq d \leq R_{max}$ . Simulations are done with the Matlab Toolbox using a FEM of the GNTVT, adopted from [12], [16], [17] (we have attempted to conduct simulations with the OMNeT++ tool, but have been hindered by the fact that the FEM was not working well). Given different levels of event (damage) injection at different sensor locations (by modifying the input signal randomly in the data sets of (1-5)th sensors, (18-22)th sensors, (41-45)th sensors, (71-75)th sensors, and (95-99)th sensors). Note that it is possible to change at any point on the data using the structural FEM. We model each sensor node with six discrete power levels in the interval  $\{-10\text{dBm}, 0\text{dBm}\}$  regarding the Imote2's power settings that are tuned within the IEEE 802.15.4.

The objectives of the evaluation in this paper are to observe the performance of (i) the SHM system dependability as the quality of event detection and (ii) the energy cost in SHMnet. The quality of event detection is defined by the intensity of the damage event detected by sensors compared to different percentages of the damage event injection around the sensor locations under each subnetwork or substructure. The performance of SHMnet is compared to the following schemes: CPScluster [23] and MCluster [19] *CPScluster* is a hierarchical decentralized SHM system that implements flexibility-based damage identification and localization using clusters. The network architecture assumes a clustering scheme to designate clusters and cluster heads under simple constraints on node placement. *MCluster* is an SHM-specific clustering scheme that is designed around the requirements of distributed

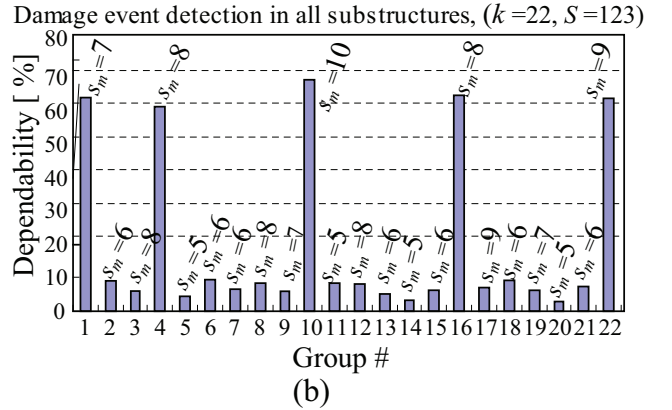
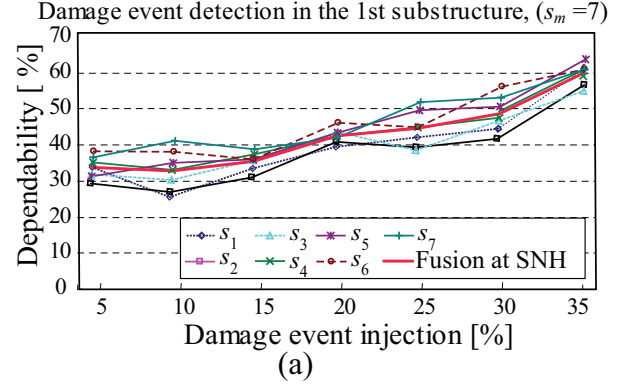


Fig. 3. Event monitoring performance: (a) the dependability of the first group of 7 sensors (LDMs) and detection fusion at the SNH; (b) the dependability of 22 groups of 123 sensors in the WSN.

modal analysis. It uses a dynamic clustering method and finds the optimal number of clusters.

### B. Simulation Results

In the beginning, we observe decisions by sensors in each subnetwork in the WSN. TABLE II depicts the results of decision-making by the first 15 groups of sensors in every first round in 7 successful simulation runs in SHMnet, while Fig. 3a depicts the dependability in SHMnet, obtained by analyzing the results from the 1st group of sensors in the WSN in the first simulation run (SIM 1). As can be seen in TABLE II, some of the sensor groups in the neighboring substructures shows '1' decisions. This is because the damage

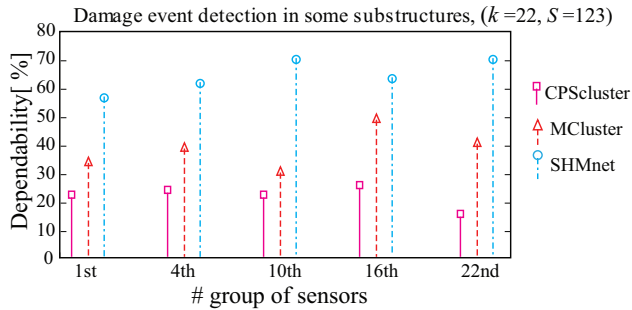


Fig. 4. Event monitoring performance: The dependability achieved and analyzed in different WSN-based SHM schemes.

event information injected into the subsets of sensors, which participate in different groups in different simulation runs, while we vary the amount of sensor group overlap from 20% to 40% when noise ratio,  $SNR = 30dB \sim 40dB$ . A boundary sensor, which has data with damage event information, may be part of the two or more groups. This sensor may provide a positive decision (may be ‘1’). However, its neighboring sensors located at the neighboring substructures may also have the positive decision (either ‘0’ or ‘1’). However, they are some false alarm in decisions: ‘I’ decisions (bold and italic marked in TABLE II). Such false alarm decisions should be recovered in the immediate round of monitoring in SHMnet.

Fig. 3b shows the dependability, obtained by groups of 123 sensors, which hints that the damage event information is coming from sensors (group-wise) in different substructures. We find  $k = 22$  and  $S = 123$  with 25% overlap. Since these results are obtained by a damage situation (i.e., ‘1’), we recover the exact damage information and estimate the ‘1’ decision. It is important to mention that the dependability from 40% to 50% in an SHM system can be enough for attention in the form of an ‘alert’. If it is more than 30%, the situation demands attention. In SHMnet, the maximum dependability is about 63% provided by the 22nd group under 35% damage injection in the structure. In a case of a small amount of damage (5% to 10%), SHMnet still offers a proper ‘alert’.

Fig. 4 shows the dependability in percent achieved in different schemes. Looking into the details, there are remarkable changes (events), detected by the (5-9)th sensors and (18-22)th sensors, as different levels of damage event information has been injected at these sensor locations. We can observe that dependability in damage detection is  $\leq 30\%$  in CPScluster in many subnetworks, while dependability  $\leq 40\%$  in MCluster in some subnetworks. It has better SHM dependability support than CPScluster. However, we cannot guarantee in dependability in damage detection in some substructures. The dependability in damage event detection in SHMnet is around 60% almost in all of the subnetworks. It is an evidence that SHMnet can be superior to other schemes.

Fig. 5 presents the average energy cost consumed by a sensor in each round of monitoring, where  $T_d = 5t$ , where sensors are grouped by substructure-wise in SHMnet. This

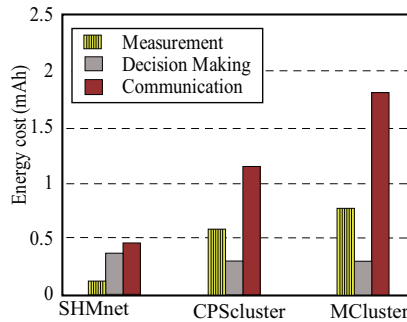


Fig. 5. Network performance: the average energy cost of a sensor in each round of monitoring in a  $T_d$ .

cost is analyzed in the presence of the damage event detection. We can see that SHMnet outperforms other schemes: it achieves a low energy cost, which is roughly at least three to six times lower than other schemes in the presence of a ‘damage event’. On an investigation, in the presence of a ‘no damage event,’ SHMnet has at least eight times lower the energy cost than that of Mcluster, and at least five times less than that of the CPScluster. This is because the amount of wireless communication in each group and computation time is drastically reduced. Here, the communication includes the interaction for sensor grouping, the frequency of transmission, and the amount of data transmission. LDMs are limited to sharing only with their neighbors with only ‘0’ values when there is no rare damage event. SNH also does not forward any data except ‘0’ and the network status if there is no event. All these are achieved by sensor in-network decision-making.

## VI. CONCLUSION

To enhance the applicability of resource-constrained WSNs for SHM, a cost-efficient and application-specific sensor organization scheme is significant for a dependable SHM system in order to fulfill the vitality of a structure and safety requirements. To achieve this, we proposed SHMnet, a comprehensive sensor organization scheme in resource-constrained WSNs for structural event detection, which to our knowledge is the first of its kind, featuring naturally a fully-distributed monitoring. Evaluation results achieved via simulations validated SHMnet’s performance and capacity to make group-wise (or substructure-wise decisions) in WSNs and improve the applicability of WSNs for SHM by significantly reducing the energy cost. Our future work includes the following: i) designing SHM-specific data fusion models; ii) designing application-specific data fusion models; iii) developing SHM-specific sensor scheduling techniques that will wake up sensors in a particular substructure.

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