Original Article

Structural Health Monitoring
1–43

DOI: 10.1177/1475921719854528
journals.sagepub.com/home/shm
SAGE

Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction

Mohammed Abdulkarem[1], Khairulmizam Samsudin[1], Fakhrul Zaman Rokhani[1] and Mohd Fadlee A Rasid[2]

Abstract
The importance of wireless sensor networks in structural health monitoring is unceasingly growing, because of the increasing demand for both safety and security in the cities. The speedy growth of wireless technologies has considerably developed the progress of structural monitoring systems with the combination of wireless sensor network technology. Wireless sensor network–based structural health monitoring system introduces a novel technology with compelling advantages in comparison to traditional wired system, which has the benefits of reducing installation and maintenance costs of structural health monitoring systems. However, structural health monitoring has brought an additional complex challenges in network design to wireless sensor networks. This article presents a contemporary review of collective experience the researchers have gained from the application of wireless sensor networks for structural health monitoring. Technologies of wired and wireless sensor systems are investigated along with wireless sensor node architecture, functionality, communication technologies, and its popular operating systems. Then, comprehensive summaries for the state-of-the-art academic and commercial wireless platform technologies used in laboratory testbeds and field test deployments for structural health monitoring applications are reviewed and tabulated. Following that, classification taxonomy of the key challenges associated with wireless sensor networks for structural health monitoring to assist the researchers in understanding the obstacles and the suitability of implementing wireless technology for structural health monitoring applications are deeply discussed with available research efforts in order to overcome these challenges. Finally, open research issues in wireless sensor networks for structural health monitoring are explored.

Keywords
Wireless sensor network, structural health monitoring, power efficiency, high data rate and throughput, fault tolerance, time synchronization, distributed processing, scalability, energy harvesting, Mobile-SHM, Cloud-SHM

Introduction

Structural health monitoring (SHM) is a process of estimation of the integrity of civil structures, based on suitable analysis of in situ measured data. This technique is performed in various kinds of structures by means of detection, localization, and assessment of the damage at earlier stages, which in turn results in increasing safety and decreasing costs of maintenance. A typical SHM system contains three main elements, namely, a sensor system, a data processing system, and a health evaluation system.[1] First, the aim of the sensors used for SHM is to measure not only the required data parameters of a structure (e.g. acceleration, displacement, and stress) but also those effective environmental parameters, such as humidity, temperature, and wind speed. Here, the accuracy and precision of the collected data are fundamental for the correct

[1]Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor, Malaysia
[2]Research Centre of Excellence for Wireless and Photonic Network (WiPNET), Universiti Putra Malaysia, Selangor, Malaysia

Corresponding author:
Khairulmizam Samsudin, Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor 43400, Malaysia.
Email: khairulmizam@upm.edu.my

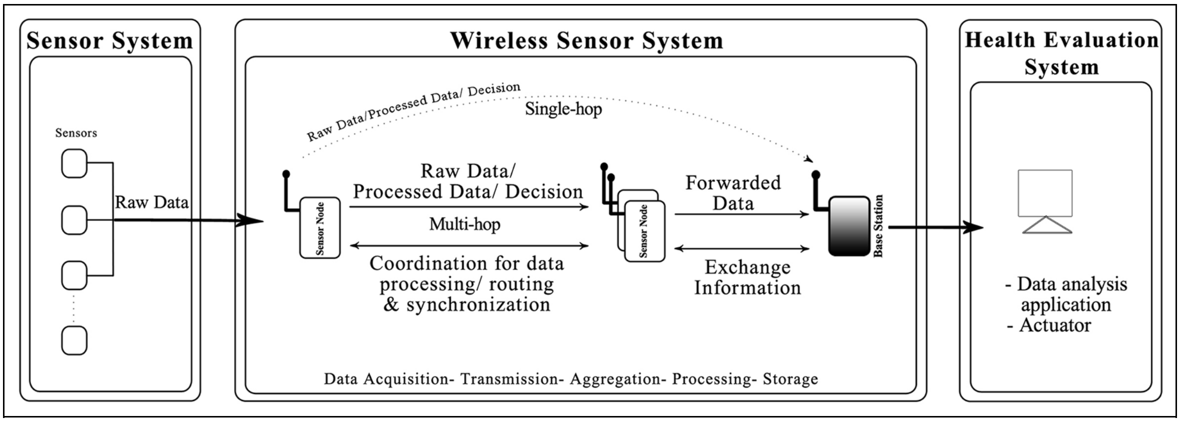

Figure 1. Architecture of SHM system using WSN.

diagnosis of the structure. Second, data processing system consists of data acquisition, transmission, aggregation, processing, and storage. Wireless sensor network (WSN) system was studied as data processing system for SHM and applied to replace traditional wired system.[2] WSNs contain sensor nodes deployed over a structure, and each node is able to collaborate with the other nodes to transmit data through the network toward a base station. Because of the availability of traditional wired system in the market before the existence of wireless system, it was utilized in SHM applications. The difference between using traditional wired sensor and wireless system in SHM is that the latter has sensor nodes, which need a little bit of maintenance and no cables to be installed, and thus they can be installed in the remote locations, which used to be impractical or inaccessible.[3,4] In WSNs for SHM, data acquisition is achieved by sensor nodes which, collect data from SHM sensors. Then, according to the communication network type (single-hop and multi-hop), sensor nodes can transmit the measured data either directly or by forwarding data packets of each other to the base station. Data aggregation and processing, which is essential for extracting features of SHM algorithms, can take place in various positions (such as sensor nodes, cluster heads (CHs), and/or base station) and can occur before or after data transmission depending on the data processing strategy and network topology. Third, health evaluation system is devised to evaluate the overall safety and/or stability of a structure when the monitoring criteria are exceeded.[5] The architecture of SHM system using WSN is illustrated in Figure 1.

There existed many constraints related to WSN in terms of resource and design, as the constraints of the resource contain a low bandwidth, short range of communication, limited processing, and limited storage as well as limited amount of energy in each node, whereas the constraints of the design depend on monitored environment and on applications. For instance, failure of wireless communication can be caused by phenomena, such as path loss (due to air humidity, terrain, and distance between the sender and receiver), structural interference (such as that caused by a building, wall, or other factors), and the like. The environment is considered essential in the determination of the deployment scheme, the network topology, and the size of the network.[6] Therefore, various designs for wireless sensor platforms were enabled along with the advances in sensing technology to suit the requirements and environment of SHM. Consequently, several studies[5,7–10] provided a summary review of the inventory of academic wireless prototypes and commercial wireless platforms, which researchers used for SHM applications.

A distinguished survey of wireless sensors and sensor networks for SHM up to March 2005 was summarized by Lynch and Loh.[7] The solutions of historic (beginning mid-1990s) academic sensing applicable to SHM were summarized, and a range of commercially available sensor nodes were comparatively assessed. Moreover, an overview of the embedded computing capabilities of academic and commercial wireless sensor platforms was presented in Dragos and Smarsly,[10] yet only one academic prototype, that has been recently developed, was introduced with no existence of up-to-date commercial platform. A brief survey of full-scale deployments of WSNs for bridge monitoring was tabulated and discussed in Rice and Spencer,[8] which contained limited platforms for both academic and commercial platforms up to 2008. Similarly, Aygün and Cagri Gungor[5] updated the summary proposed in Lynch and Loh[7] to 2009. In addition, Sabato et al.[9] provided a survey about the developed sensor boards of wireless microelectromechanical systems (MEMS)–based accelerometer between 2006 and 2016, in which the sensing side of the designed accelerometer boards was pointed out, not the design of wireless sensor platforms used for SHM, which is the main focus of this work. A technology development in the area of bridge health monitoring using WSNs was introduced by Zhou and Yi;[11] however, MEMS-based accelerometer sensor boards were introduced as well as it contained a limited number of studies for academic and commercial wireless platform for SHM. However, to the best of our knowledge, available studies in literature were neither comprehensively studied nor up to date. Therefore, one of the contributions of this work is to provide a state-of-the-art comprehensive review of academic wireless prototypes and commercial wireless platforms used for SHM.

Concerning today's complex structures, data collection via wireless sensor nodes over extended period creates many challenges due to the enormous amount of data, which is generated and transmitted in each data sensing period.[5] Moreover, synchronizing and transmitting massive amount of data in WSNs are considered to be a real challenge due to limitation of battery and data rate related to sensor node. Another challenge is the complexity of most SHM algorithms, as this entails incorporating raw data from all deployed sensor nodes, and is commonly developed to be processed at a centralized station to evaluate the structural condition.[12] What complicated the above is the power consumption associated with those sophisticated SHM algorithms due to their need for computational resources and process procedures. For example, vibration-based damage detection algorithms take place through a process consisting of three steps, namely:[3] (a) data preprocessing, (b) feature extraction, and (c) feature classification. The steps are explained in brief as follows. After the first step of preliminary processing of data, the second step occurs by extracting damage-sensitive features from the vibrations, which has been preprocessed, and then, the third step takes place by using a specific classifier for classifying the extracted feature to detect if such vibrations are related to the damaged or undamaged state. Thus, this process needs substantial computational power, which has not been obtainable yet in wireless sensing units.

Existing reviews[5,8] have provided a general overview of the challenges for SHM using WSNs, which mainly focused on wireless sensor design, constraints such as power consumption, and deployment in field test, yet no up-to-date issues have been discussed. In addition, summaries[13–15] discussed the requirements, challenges, and design of hardware and software for WSN-based SHM systems, but future research directions were not highlighted. Moreover, Noel et al.[16] provided a detailed review of existing challenges and future direction in SHM using WSN application, which focused on the communications component. Notwithstanding, this article focuses more on network design, communications, and computation components by providing a comprehensive summary about theoretical, laboratory testbed, and field test works. Furthermore, more challenges are identified and investigated with deep details, and more classifications for each challenge and summary review are provided when applicable. The correlations among those challenges, which can introduce a conflict with other challenges' solutions, are also discussed. Moreover, open research issues are explained through a review of theoretical studies and empirical research.

Finally, this article, broadly speaking, provides a contemporary review with a complete picture from sensors and wireless node hardware design, network design, and the key challenges and open research issues that associated with WSNs for SHM to assist the researchers in understanding this multi-disciplinary field and the obstacles and suitability of implementing wireless technology for SHM applications.

The article is organized as follows. In the "Sensors and wireless technologies for structural monitoring" section, a background of sensors and wireless technologies for structural monitoring is provided. The "Hardware design of wireless sensors for structural monitoring" section presents the hardware design of wireless sensors for structural monitoring. "The key challenges of WSNs for SHM" section provides recent research and key challenges of WSN for SHM: sampling rate limitation, power efficiency, high data rate and throughput, fault tolerance, time synchronization, data processing, and network scalability. The "Open research issues" section suggests future open research issues. Finally, the article is concluded in the "Conclusion" section.

Sensors and wireless technologies for structural monitoring

Recent advances on sensing, communication, and storage technologies enabled the use of full-scale SHM system to the infrastructures. Refinements were carried out by researches on the monitoring system and their implementation on the actual structures. The function of the sensors, used in the SHM (such as acceleration, displacement, and stress), is monitoring not only the structural status but also environmental parameters, which are prominent, including humidity, wind speed, and temperature. Generally, the more sensor node locations located on a structure are, the more detailed data can be gained. WSN system was studied and applied to replace conventional wired system for SHM. Moreover, WSN is essential for scalability; thus, full-scale deployment of hundreds of sensor nodes in SHM systems would be much easier than traditional wired system due to the expensive cost and complexity of installing and maintaining a monitoring system with a wired system for hundreds of nodes.[3,4]

In this section, available SHM sensors and technologies of wired and wireless sensor systems along with sensor node architecture, functionality, and communication technologies are discussed. Popular operating systems (OSs) of the existing systems are also investigated.

SHM sensors

In SHM system, sensors are implemented at several locations over a structure for collecting information about their surroundings. Traditional sensors used for structural monitoring, like accelerometers, strain gauges, vibrating wires, linear variable differential transformers, and MEMS, can measure different parameters and have a vast experience in usage. Nevertheless, at the present time, comparing to other sensors, the fiber optic–based sensor systems become immensely widespread as a result of their various advantages. In addition, according to Rice and Spencer,[8] the performance of a sensor can be determined on the basis of the following factors: (a) sensitivity, (b) linearity, (c) resolution, and (d) signal-to-noise ratio. Moreover, all aforementioned measurement sensors can be classified into two diverse categories depending on their mechanisms of acquisition. Sensors (e.g. accelerometer) obtain sufficient data amount over a long period of time (continuous data), while other sensors (e.g. strain, linear voltage differential transformer (LVDT), temperature, and humidity) are considered as samples of single data (average data) over a short period.[17] Common sensors used in SHM systems are discussed in the following sections.

Accelerometer. Accelerometer is a typical kind of sensors utilized in measuring the vibration of a structure, stiffening trusses, pylons, and hanger cables in SHM. There are various kinds of accelerometers, yet piezoelectric accelerometer was one of the most common used ones, and the new applications like the MEMS-based accelerometers become more common, which can be found in several models such as single axis, dual axis, and three axis, as well as in various ranges.[18] Accelerometers differ in their types on the basis of the place and the reason of measuring them. That is to say, the sensors of the accelerometer undergo an in-depth examination for measuring range and resolution in order to make sure the suitable utilization of accelerometers. Moreover, the minimum requirement of sampling resolution is at least 16 bits with a sampling frequency of 100 Hz.[19]

Zhang et al.[20] and Zhu et al.[21] summarized and discussed wireless MEMS-based accelerometer sensor boards used for structural vibration monitoring. In addition, in Kohler et al.,[22] a multi-tier, portable, vibration sensing platform called ShakeNet was developed for testing a new communication protocol with accelerometers to collect ambient motions. The developed board includes Imote2 sensor node, analog-to-digital converter (ADC) board RT505 from RefTek, Inc., and three Si-Flex 150 accelerometers from Colibrys, Inc. The prototype was deployed and tested on Vincent Thomas Bridge, California. Likewise, Rice and Spencer[23] developed a board called Structural Health Monitoring Accelerometer (SHM-A), which was mounted on an Imote2 platform. The components of the board were chosen to meet the requirements of vibration-based SHM applications, and LIS3L02AS4 accelerometer was utilized. The prototype was tested in laboratory and the result demonstrated the efficiency of the proposed system.

Strain sensor. Strain sensor is commonly used in SHM, as it is cheap, simply installed, and perfectly sensitive to identify a potential danger, which might occur or ruin the structure. Strain sensors utilized for SHM can be categorized to piezoresistive or embedment strain gauge. For example, cement-based strain sensor is usually piezoresistive and able to measure strain.[24] Commercial MEMS-based sensors and studies associated with MEMS moisture, temperature, and strain were illustrated in brief by Ceylan et al.[2]

A high-precision strain sensor board (SHM-S) with Imote2 wireless sensor was developed and deployed by Jo et al.,[25] in addition to ISHMP Services Toolsuite for cable-stayed bridge monitoring. For fast and easy deployment, SHM-S was developed to embed a friction-type magnet strain sensor, besides conventional foil-type strain gages. The proposed system was able to measure low-level ambient strain and could obtain up to 2507 times high gain. Moreover, for railroad bridge monitoring, measuring responses of a bridge wirelessly, under real-time train loads in the field to help evaluating bridge condition, is a sophisticated task and challenging. Therefore, Moreu et al.[26] implemented and deployed wireless strain and accelerometer sensors on a bridge to measure associated bridge responses under revenue service traffic. Wireless sensor, Imote2, was used, which interfaced with two boards including a strain sensor board (SHM-S) and accelerometer board (SHM-A) to measure loading and dynamic properties, respectively. Also, to enable simpler and easier strain measurement and enhance railroad bridge monitoring, the FGMH-2A magnetic strain gauge was implemented for the measurement of pseudo-static properties.

Furthermore, Zhang and Bai[27] introduced a radio frequency identification (RFID)–based wireless strain sensor technology, which utilized building information modeling (BIM) computing environment for structural condition assessment and health management of civil infrastructures. A hybrid testing of a truss structure under monotonic loading took place to validate the proposed RFID-based wireless breakage-triggered (BT) strain sensor for non-contact structural deformation monitoring. Through the validation test on comparatively large-scale structural members, the performance of BT sensor for preset threshold strain level detection was demonstrated.

LVDT. LVDT is an accurate and reliable electromechanical transducer, which measures the displacement and operates on the principle of a transformer. The LVDT offers infinite resolution, and its main advantages compared to similar sensors are its frictionless measurement, infinite mechanical life, high degree of robustness, excellent resolution, and good repeatability.[28,29] A wireless LVDT prototype was developed, implemented, and tested alongside a similar wired sensor in Veilleux et al.[30] An experiment was performed in WiSe-Net lab at the University of Maine and at NASA Marshall Space Flight Center (NASA MSFC) using an RDP D2/200a LVDT to compare operational performance of both wireless and wired system. Experimental results demonstrated that the proposed wireless displacement prototype can be a promising replacement for current wired sensors by providing a similar performance while maintaining reliability and accuracy.

Fiber optic sensors. Fiber optic sensors (FOSs) are mostly fixed on the surface of already built structures or put inside recently built civil structures (e.g. bridges, buildings, and dams) as they are multi-purpose sensors applied for SHM applications. FOSs are suitable to be used for SHM as they are able to operate in harsh natural environment, they are of a distributed and wide scope of sensing, they can be joined with low transmission loss, and they are of an interface, which is anti-electromagnetic SHM.[31] Notwithstanding, the FOS sensing ability for long term under field test conditions, as a result of aging, has not been completely established and is required to be further studied.[32]

Pang et al.[33] developed a multi-functional optical wireless sensor platform to miniaturize traditional bulky optical measurement systems. Imote2 was used, which has extra extension sockets for further functionality development. The optical sensor was successfully embedded with Imote2 to build a wireless optical platform with a small overall size. The result of the experiment for glucose weight concentration measurement with a chemical sensor along with the wireless optical platform demonstrated the multi-functionality of the optical MEMS sensor platform.

Wired-based systems

Several current SHM implementations still apply conventional wired data acquisition system for collecting data from numerous structure locations. Data of sensor system are processed intensively by data processing system after being transmitted through coaxial wires to be analyzed and evaluated by health evaluation system. However, this system has many drawbacks, such as high cost, low efficiency, difficult installation, susceptible disturbance, inflexibility, inadequate design, power consumer, or some combination of these shortcomings.[2,5] For instance, the system of traditional data acquisitions utilizes wires in order to connect sensors to a central server, which requires long cables all over the structure to perform the monitoring process. Thus, installation and maintenance of this kind of system are usually costly and associated with difficulties and safety concerns.[1] Moreover, this system has limitations for long-term SHM, which is often vulnerable to damage. As for the application of wired SHM systems, this constraint of retrofitting hinders their utility.

Wireless-based systems

The fast progress of wireless technologies has considerably improved the implementation and development of structural monitoring systems with the integration of WSN technology. WSN consisted of many senor nodes fitted out with sensors. Sensor nodes contact with each other via a wireless network and data are directed toward the base station.

Contrasted with the wired system solution, a wireless monitoring system provides outstanding advantages, because it is installed in a simpler way by means of low-cost hardware, less installation time, and easy to be maintained.[34] Moreover, data processing and interpretation can be distributed through the senor nodes of the network using cooperative protocols and embedded algorithms, which significantly decrease the redundancy of raw data, and save storage space and considerable amount of energy. In addition, wireless communication plays an important role for scalability; thus, full-scale deployment of hundreds of sensors in wireless structural systems would be much easier than conventional system. Likewise, installing and performing maintenance for a monitoring system with wired networks cost a lot and would be complicated for hundreds to thousands of nodes. Table 1 summarized a comparison between WSN-based SHM and wired SHM systems, which was presented by Aygün and Cagri Gungor.[5]

Wireless sensor node

Sensor node. Mote is defined as the core building block of WSN, which can sense, measure, and collect

Table 1. A comparison between WSN-based SHM and wired SHM systems.[5]

	WSN for SHM	Wired for SHM
Cost	Economic (~US$100)	Expensive (~US$1000)
Scalability	Easy	Difficult
Deployment	Rapid	Difficult
Flexibility	Yes	No
Design level	Difficult	Easy
Sensibility to environmental effects	Yes	No

WSN: wireless sensor network; SHM: structural health monitoring.

data from the environment, and then process and transmit the measured data wirelessly. It is a battery-powered sensor with constrained resources, and it is inexpensive compared to conventional sensors. Sensor node is utilized for a number of applications to monitor a multitude of natural and man-made phenomena, that is, industrial process monitoring and control, traffic control, environment monitoring, patient monitoring, battle field surveillance, home automation, military, and so on.

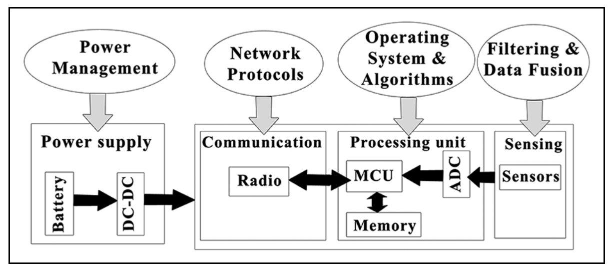

Figure 2. Sensor node block diagram.[35]

Sensor node architecture. The architecture of sensor node as demonstrated in Figure 2 is made up of four basic units:[35] power supply, communication, processing, and sensing units. The first unit of the sensor node, that is, the power supply unit, is used for powering the node as this unit commonly has a battery and a dc–dc converter. The second unit of the sensor node, that is, the communication unit, has a bidirectional wireless communication channel, which frequently selects a short-range radio. The third unit of the sensor node, that is, the processing unit, has an internal memory, a microcontroller, and an ADC, which are utilized for saving data and application programs, processing data, and receiving signals from the sensing unit, respectively. The main function of the sensing node is to connect the sensor node to the physical world as it contains a set of sensors and actuators, which rely on the WSN applications. In addition to the internal memory, a sensor node can have an external memory device as a storage unit, which operates as a secondary memory for keeping a log of data.

Functionality of sensor node. In WSN for SHM, choosing a suitable sensor node is important due to the dependence of the performance related to the entire SHM system on the individual sensor node. As a result, this always necessitates WSN for SHM as a first attack line for monitoring behavior of the structural system in such a manner that an appropriate signal processing and extracting of damage features can be carried out effectively on the collected data. Therefore, enabling WSN for SHM requires sensor node to be able to provide basic functionality in the following:[36] (a) Data acquisition forms diverse sensors; (b) tentative storage of the measured data; (c) on-board data processing and analysis (signal processing and feature extraction) for diagnosis and in some cases actuation is needed; (d) self-monitoring (e.g. power supply, energy-harvesting devices, and wireless charging); (e) scheduling and execution tasks of the measurement; (f) receiving command from base station for reconfiguration (e.g. reconfiguring data processing algorithms and changing the sampling rate); (g) reliably receiving, transmitting, and routing of data packets; and (h) managing and coordinating communication and networking.

Base station. Base station (also known as sink) is a device, which has much higher communication capabilities, more memory, and much higher processing power than the wireless senor node. It usually acts as a gateway to other sensor nodes, which receives and sends data between sensor nodes and remote user. Also, it has the task of processing and analyzing the measured data based on the application used. In applications of WSNs, all data packets are directed toward the base station even directly or over multi-hop routes based on the network topology used. Therefore, the power consumption for base station is not a critical issue, because it can be directly connected to the power supply, whereas the location of the base station can significantly affect the lifetime performance and throughput of the network. Several researchers used a commercial base station for SHM application, for instance: Anastasi et al.[37] designed and implemented a framework for monitoring historical structures in Sicily, Italy. Stargate node is selected to function as a base station to supervise time synchronization between nodes and also to be responsible for sending appropriate commands. In addition, at the base station, collected data are processed and compressed again, routed to the local storage, and then to the central processing unit wirelessly.

Wireless network topology. The topology of a WSN refers to the manner in which the sensor nodes are arranged in the network. Different topologies are required for WSNs to fulfill the requirements of various application characteristics in SHM. Network topology plays an important role for wireless network communication, which affects the network component connectivity and thereby various performance metrics. Therefore, network topology must be chosen carefully according to SHM application requirements. Moreover, ZigBee/IEEE 802.15.4 standard permits three kinds of topologies, including star, cluster tree, and mesh networks.[38] In addition, star and cluster tree topologies are usually used for SHM applications. Moreover, since mesh topology needs more power due to redundant transmission of data, and a complex routing scheme is required, it is rarely applied in the WSN-based SHM system.[11] Further details on comparisons of the network topologies were discussed in several studies.[39–41]

OS of the motes. This section presents a brief overview of the main popular OSs involved in SHM studies and implementations. In resource-constrained hardware devices, response in the target application is greatly affected by the effectiveness in the OS. Therefore, four main functions have to be involved in OS of wireless sensor nodes.[42] (a) Low-power consumption: Power management and computing power allocation must be the fundamental concern of OS. (b) Efficient resources management: While the sensors are resource constrained in terms of communication bandwidth, processor time, storage, memory, and energy, OS should efficiently manage the available resources. Moreover, it should contain an effective communication stack to handle different application approaches and its sophisticated requirement (e.g. for SHM, damage detection, and localization algorithms). (c) Concurrency: Microcontrollers are more rapid than flash and sensors in WSN. In the OS, various tasks are performed late as a result of operations that consume time (e.g. sampling) and block other tasks (e.g. communication or computation). Consequently, OS must have the ability to support multiple threads or processes for parallel processing. (d) Flexibility: OS must be able to support various types of hardware modules (e.g. accelerometer, strain sensors).

In the sensor network research community, in addition to hardware platforms and standards, there are several OSs that have been developed, as they separately provide a dissimilar solution for the essential problems. Contiki and TinyOS may be the two most popular OSs in case of SHM application or other applications.

TinyOS. TinyOS is an open-source OS and has been the first event-driven OS developed for resource-constrained wireless-embedded devices like those used in sensor networks, smart buildings, and personal area networks.[43] It was developed at the University of California (Berkley) as a combination of components that performed basic operations and it was programmed using nesC (an extension to the C language). According to Levis et al.,[42] TinyOS supports deferred computation called tasks, asynchronous events, an event-driven concurrency model based on split-phase interfaces, and complex programs, which require very low memory (applications platform usually fit within 16 KB of memory and 400 B for the core of OS). In addition, a supporting simulator can largely minimize the workload in application development; thus, TinyOS has an emulator, namely, TOSSIM, which is useful for assessing and evaluating application code in TinyOS by providing a scalable simulation environment. TinyOS became the effective OS for WSN, because it combines an efficient memory footprint with an easy-to-use interface for small WSN devices like MICAz, Tmote, and Zolertia.

Contiki. Contiki is an open-source OS, which has been developed at the Swedish Institute of Computer Science as it is written in standard C language. It is constructed around an event-driven kernel. In addition, protothreads' introduction is considered as Contiki's key contribution, as it enables developers to block conditions, which stop a thread waiting for activating an event from another simultaneous thread. Besides, it enables the replacement of programs and drivers meanwhile run-time without linking again with the kernel. Furthermore, the support of transmission control protocol/internet protocol is provided as well via the μIP stack. Applications for Contiki can be simulated using Cooja simulator to evaluate networks behavior before deployment into the hardware. Contiki runs on a wide range of embedded platforms, like the Atmel AVR and the TI MSP430, which are utilized in the Mica families, Telos, and Tmote.[44]

Moreover, there are several constraints associated with the OS that have effects on the performance of a sensor node, which in turn become obstacles to embed SHM algorithms. For instance, complexity of the Netstack, separation of MAC (media access control) and radio duty cycle layers, centralization of the Netstack on a unique packet buffer, all of them are constraints in Contiki OS.[45]

Hardware design of wireless sensors for structural monitoring

Nowadays, SHM characterizes one of the principal applications of the technologies related to the wireless sensor. The rapid development of WSNs technology in recent years promotes the emergence of many novel and outstanding concepts in SHM, which makes the performance of the system improve dramatically. Therefore, monitoring infrastructures' condition is demanded increasingly for increasing cities' security and safety, particularly at the areas where earthquakes take place.[46] Thus, wireless monitoring systems transition from the laboratory into the field (e.g. highways, bridges, special structures, and buildings) was demonstrated by assessing the various wireless sensor platforms' performance for the responses of the accurate structural sensors' measurement meanwhile monitoring the performance and integrity of the structures and nowadays toward structural damage detection and localization.[47] Therefore, many prototypes, designs, and experiments, related to WSNs for SHM, were developed and implemented in both commercial and academic fields for many years in order to monitor the status of the structures.

In this section, a state-of-the-art comprehensive summary of academic and commercial wireless platform technology used in literatures for structural monitoring is proposed. It might be noteworthy to say that the summary provided is not meant to be an exhaustive listing; rather, it points out art state in wireless platforms used for structural monitoring up to 2019.

Academic wireless sensor prototypes for structural monitoring

Wireless sensor node may look like a simple device; however, there exist diverse challenges relevant to their design and utilization. Especially, the design of the sensor node needs an analysis that is reasonable in order to clarify the trade-off between functionality and consumption of power (functionality frequently comes at the cost of power). Generally, two approaches are used for designing academic wireless prototypes. On one hand, the first approach utilizes commercial-off-the-shelf sensor nodes with a customized sensor board and the use of a customized platform integrated with a customized sensor board, which is convenient and facilitates a speedy development.[11] Nevertheless, the platform's operation and performance may be restricted by using those sensor nodes. On the other hand, the second approach is concerned with the customized platform development, which involves a complicated design and a long development cycle.[9] The main task of developing a sensor node is choosing appropriate components and connecting those components using the proper integrated circuit. At the same time, special control programs are configured to achieve presetting functions.

The academic prototypes to be illustrated in this section are summarized chronologically in Table 2 and chosen prototypes are depicted in Figure 3. It might be noteworthy that some of the tabulated details were extracted from authors' previous work or from data sheet of the selected chip when it was applicable. Moreover, due to the long list of summarized platforms; some of these studies are chosen to be discussed based on the publication year and field test.

To balance the competing requirements for long transmission ranges, the ability to calculate on-board sophisticated SHM algorithms, and low-power consumption, a compact four-layer printed circuit board (PCB), namely, Narada was developed by Swartz et al.[48] at the University of Michigan with refinement over previous designs. An Atmega128 microcontroller attached with 128 KB of external static random access memory (SRAM) provided computational capabilities of Narada for extra data storage as the Narada had a 16-bit four-channel (ADS8341) ADC able to collect high data at sampling frequencies up to 100 kHz. A Chipcon CC2420 was selected as a wireless radio. Narada also utilized the scheme of network communication summarized in the IEEE 802.15.4 standard enabling it to compose network typologies of star and peer-to-peer. As a result, it is appropriate for distributed computing tasks in dense to use ad hoc networks, which are entirely scalable.

To further enhance the functionality of sensor nodes, a two-layer PCB for sensor node was designed by Wang et al.[49] The PCB, batteries, and wireless transceiver were stored within a 10.2 cm by 6.5 cm by 4.0 cm-dimensioned and off-the-shelf container that was weatherproof and plastic. Furthermore, the sensor signal digitization module of the wireless unit had a four-channel 16-bit ADS8341 ADC from Texas Instrument (TI) as this module converted the 0 to 5 V analog output of up to four sensors into digital formats functioning by the computational core of the sensor node.

Table 2. Summary of academic wireless sensor prototypes for structural monitoring (2005–2019).

			Data acquisition specifications		Embedded computing specifications		Wireless channel specifications		
Year and Reference	Test	Prototype name	A/D ch.	A/D resolution	Embedded processor	Data memory	Radio	Frequency band	Data rate
2005[48]	Laboratory	Narada	4	16-bit	Atmel Atmega128	128 KB	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 75 m
2007[49]	Geumdang Bridge in Icheon, South Korea	PCB	4	16-bit	Atmel Atmega128	4 KB SRAM + 128 KB Flash memory	MaxStream 9XCite	900 MHz	38.4 Kbps O/R = 300 m
2007[50]	Laboratory	Impedance-based SN	–	12-bit	Atmel ATmega128L	4 KB SRAM + 128 KB Flash	Xbee	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m
2009[51]	Bridge in Potsdam, NY, USA	Self-powered wireless system	–	10-bit	TI MSP430F2xxx series	128B + 2 KB Flash	Nordic nRF24L01	2.4 GHz IEEE802.15.4	2 Mbps
2009[52]	Laboratory	SmartBrick	2	12-bit	TI CC2480	8 KB SRAM + 128 KB Flash	CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 75 m
2010[53]	Laboratory	ASN-2	6	12-bit	TI MSP430	4 + 32 KB	CC2500	2.4 GHz IEEE 802.15.4	500 Kbps
2010[54]	Bridge-Town of Lisbon, NY, USA	WISAN	12	12-bit	TI MSP430F1611	10 + 48 KB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 75 m
2010[55]	Alamosa Canyon Bridge	Thinner	8	10-bit	ATmega128 L	4 KB SRAM + 128 KB Flash	XBee	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m
2011[56]	Laboratory	AEPod	8	12-bit	Atmel ATmega1281	8 KB	Atmel AT86RF23	2.4 GHz IEEE 802.15.4	250 Kbps
2011[57]	Laboratory	ISMO-2	8	12-bit	TI MSP430F1611	10 KB RAM + 48 KB Flash	CC2420	2.4 GHz IEEE802.15.4	250 Kbps
2011[58]	Laboratory	GENESI Node v1.0	12	10-bit	TI MSP430F2274	1 KB RAM + 32 KB Flash	CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 75 m
2012[59]	Bridge in Spanish	Prototype	4	24-bit	ARM90	40 KB SRAM + 512 KB Flash	–	2.4 GHz IEEE802.15.4	–
2012[60]	Laboratory	SP v.2	6	12-bit	TI MSP430	4 KB	CC1101	915 MHz	600 Kbps
2013[61]	Zhengdian Bridge	S-Mote	–	12-bit	TI MSP430F1611	10 KB SRAM + 48 KB Flash	CC2420	2.4 GHz IEEE802.15.4	250 Kbps
2014[62]	Yangtze River Bridge	Prototype	8	12-bit	TI MSP430F5438	16 KB RAM + 256 KB Flash	CC1101	433 MHz	500 Kbps O/R = 500–800 m
2015[63]	Laboratory	WSNG2	–	16-bit	2 processor, ARM STM32F103/Intel 8051	8 KB SRAM + 128 KBF lash	CC2430	2.4 GHz IEEE802.15.4	250 Kbps
2015[64]	Laboratory	ODCWSN	6	12-bit	TI MSP430	4 + 32 KB Flash	CC1101	920 MHz	250 Kbps
2015[65]	Laboratory	SSB	12	10-bit	ATmega32U4	2.5 + 32 KB	XBee	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m
2016[66]	Quayside cranes	PWSMS	–	–	TI MSP430F149	2 KB RAM + 60 KB	CC2530	2.4 GHz IEEE802.15.4	250 Kbps
2016[67]	Laboratory	Prototype	–	12-bit	ARMCortexM3 EFM 32G222F128	16 KB SRAM + 128 KB Flash	ADF7242	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m
2017[68]	Laboratory	Active Wireless System	8	10-bit	ATmega644PA	4 KB SRAM + 64 KB Flash	Digi XBee S2 C	2.4 GHz IEEE802.15.4	250 Kbps O/R = 1.2 km
2017[69]	Laboratory	Wireless AE	2	12-bit	ARMCortexM4 STM32F407 V GT6	192 + 4 KB SRAM	CC3200	IEEE802.11 b/g/n	6 Mbps
2017[70]	Bridge	Prototype	16	10-bit	Microchip PIC18	4 KB RAM + 128 KB Flash	CC2500	2.4 GHz	500 Kbps
2018[21]	Laboratory	Xnode	8	24-bit	NXP LPC4357	32 MB SDRAM	Atmel AT86RF23	2.4 GHz IEEE802.15.4, 6LoWPAN	250 Kbps O/R = 1 km
2019[71]	Laboratory	WSHMS	24	12-bit	STM32L476ZE	128 KB SRAM + 1 MB Flash	XBee	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m

PCB: printed circuit board; SRAM: static random access memory; ASN-2: Autonomous SHM Sensor 2; SSB: Smart Sensor Box; A/D: Analog-to-digital ;Ch.: channel.

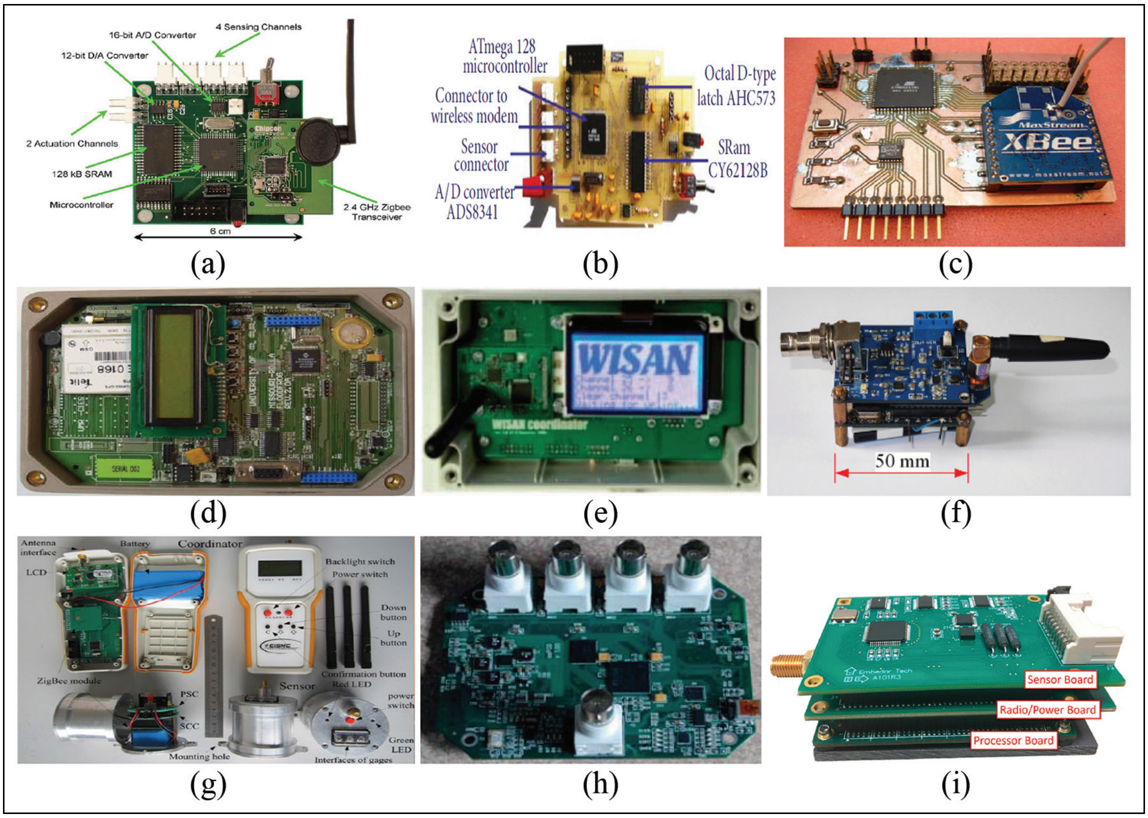

Figure 3. Academic wireless sensors prototypes: (a) Narada wireless prototype,[48] (b) PCB two-layer circuit board,[49] (c) Thinner wireless sensor node,[55] (d) SmartBrick V2.0,[52] (e) WISAN coordinator,[54] (f) WSNG2 Prototype,[63] (g) PWSMS portable wireless system,[66] (h) AEPod Prototype V1.0.,[56] and (i) Xnode smart sensor.[21]

Moreover, the data related to the digitized sensor were transmitted into the computational core (8-bit microcontroller), which has an external 128 KB SRAM for data storage. For wireless communication among the sensing units, a 900-MHz MaxStream 9XCite wireless transceiver was employed. The fabrication, assembly, and validation were implemented for an integrated prototype system in both laboratory tests and a large-scale field test, which was carried out upon the Geumdang Bridge in Icheon, South Korea.

To utilize the impedance method for SHM, Mascarenas et al.[50] developed wireless impedance sensor node provided with a microcontroller that performed on-board processing, a low-cost integrated circuit chip that could measure and record a piezoelectric transducer electrical impedance, and a wireless telemetry module that transmitted processed data to a base station. The four-channel 16-bit ADC ADS8341 was utilized as ADC, and the 8-bit ATmega128, which is cheaper and consumes less power, was chosen as a microcontroller. The XBee (Digi International, Inc.) with 2.4 GHz frequency was selected as the wireless radio, of which the outdoor range is up to 100 m. Analog device for impedance measurement chip AD5933 was utilized. Creating a self-contained miniaturized impedance measuring system can be used by this chip. With comparing the precise measurements that were obtained from a traditional impedance analyzer, the proposed sensor node demonstrated its capability to make in the tens of kilohertz range accurate active dynamic measurements, which showed its promise as an efficient sensor node for applications of SHM.

Recognizing the importance of alleviating the limitation associated with sensor nodes in terms of high cost of battery replacements and the limited life spans of batteries. Sazonov et al.[51] introduced a new wireless sensor system, which harvested bridge vibrations produced by passing traffic. By using a linear electromagnetic generator, such vibrations were converted into utilizable electrical energy. In practice, the sensor node was developed depending on a microcontroller from a series of MSP430F2xxx that characterized by so speedy start-up time when utilizing an RC oscillator as well as by low consumption of power. From Nordic Semiconductors, a 2.4-GHz nRF24L01 chip was selected as a wireless radio. By means of built-in 10-bit ADC and SPI/I2C, the design of the sensor node allowed the interfacing of various analog digital sensors. An analog temperature sensor TC1047, which features a low supply current of 35 μA, from Microchip Technology, was utilized. Field tests conducted on a State Route 11 bridge in Potsdam using this self-powered prototype showed the possibility to implement the proposed solution.

Sensors and sensor nodes, which were able to wirelessly interact with a mobile host were illustrated by Mascarenas et al.[55] A capacitive-based sensor node, which was called a Thinner, was developed, as such a Thinner was equipped with an 8-bit microcontroller, a XBee radio, and an AD7745 capacitance to digital converter. Furthermore, it was demonstrated that the proposed wireless sensor was able to collect in an outstanding manner the measurements assigned for peak mechanical displacement for SHM applications. There were two features that made Thinner distinctive from other sensors: the first one was the design of Thinner in a manner that made its power came from wirelessly delivered power, whose provision was from unmanned aerial vehicle (UAV); the second one was that contrary to most sensor nodes, which utilized the conventional voltage-based ADC converter, Thinner employed a capacitance-to-digital converter. The selected ADC converter was the AD7745 from analog devices. Such diminutive and portable devices' capabilities were displayed in both the laboratory and the field, which was conducted on the Alamosa Canyon Bridge in the United States.

Kevin et al.[60] designed and carried out a sensor node for targeting earthquake, seismic, and SHM applications, as it was characterized by low-power consumption. This was made for implementing a low consumption of power with a physically small-sized sensor node, which was able to independently work and act as a smart tiny mote underground or inside the structures of the building. The designed prototype was a second generation of the previous version, which was referred to as smart pebble. The microcontroller of the proposed prototype was developed with ultra-low power 16-bit 20 MHz MSP430 microprocessor and radio chip CC1101, which has 1 GHz frequency in a form factor of 7 mm × 7 mm and consumed 2 μA sleep current and 160 μA/MHz active current. It had six 12-bit ADC. The microcontroller had 4 KB of data memory and 32 KB of program memory for a very lightweight OS, protocol stacks, or accommodating customized software applications. Examination for prototype took place to check its consumption of power and its abilities in measuring data in earthquake simulation. The result showed that the node operated for more than 2 weeks on a standard 3 V Lithium battery, with a constant sampling at 50 Hz using accelerometer and 30 min of daily effective radio transmission.

Hu et al.[61] developed a customized platform for monitoring with a tailored S-Mote, a strain sensor board, and an acceleration sensor board. The flexibility and scalability of system architecture enabled the system to support a large number of sensing tasks for structural monitoring. For S-Mote, the ultra-low-power microcontroller MSP430F1611 was chosen for S-Mote, consumed 2 mA of current. It had 10 KB data memory, 48 KB flash memory, a 12-bit ADC, and a maximum conversion speed more than 200 Kbps. Chipcon CC2420 radio, with data rate of 250 Kbps and 2.4 GHz, was chosen for S-Mote. Moreover, implementation of the system took place in the Zhengdian Highway Bridge. The validity of S-Mote's ability in data acquisition, data transmission via multi-hop network, and analyzing measured data were proved through experiments conducted on the highway bridge for continuous monitoring of in-service bridges.

The development of a wireless measurement system for large bridges was designed on the basis of WSN principles as demonstrated by Liu et al.[62] In addition, such a system adopted the protocol of time division multiple access (TDMA). The Microcontroller unit utilized TI 16-bit MSP430F5438 processor, and a AT24C1024B electrically erasable programmable read-only memory (EEPROM) chip was selected as data memory. The module selected CC1101 as a high-performance radio chip, which worked at 433 MHz (non-ISM). Its maximum transmission rate of data was 500 Kbps, sensitivity of the receiver was up to 110 dBm, and distance communication was up to 500 to 800 m. A MEMS accelerometer model ADXL202E was selected for having the ability to sense both static acceleration (e.g. gravity) and dynamic acceleration (e.g. vibration). Experiments were carried out in the laboratory and field test (Nanjing IV Yangtze River Bridge) for verifying the designed system's performance. The results of the field tests for the bridge demonstrated that it is possible to extend the distance of signal transmission to 200 m, as well as enhancing its anti-jamming capability, and reducing packet loss rate to 1.2%, and this in turn prominently improved the reliability of data transmission.

An effective, safe and low-cost implementation of MEMS through the use of a WSN for SHM was presented in Buttarazzi et al.[65] A device known as Smart Sensor Box (SSB) was developed for reducing the potential damages that can take place to structures owing to natural phenomena. The prototype of SSB utilized a 8-bit ATmega32U4 microcontroller, which has 2.5 KB data memory and 48 KB of flash memory. The 2.4 GHz frequency XBee was chosen as the wireless radio, of which the outdoor range was up to 100 m. An ultra-low power, 3-axis ADXL362 MEMS accelerometer was selected for providing 12-bit output resolution and consuming less than 2 μA at a 100-Hz output data rate. So, to fulfill voltage-level requirements of XBee and ADXL362 modules and minimize consumption of power, the microcontroller is run at 3.3 V/8 MHz.

To improve the efficiency of monitoring large metal structure, a portable strain monitoring system integrated with WSN technology—namely, portable wireless strain monitoring system (PWSMS)—was developed and verified in Yao et al.[66] It illustrated the impacts of three major capabilities, which were affecting the efficiency of work, namely: design of low power, portability, and miniaturization. PWSMS was made up of an MSP430F149 microcontroller, a ZigBee CC2530 wireless radio chip, and strain conditioning circuit (SCC). The supply of power for SCC was controlled by the radio chip via a MOSFET switch. Comparative tests were conducted on quayside cranes after calibration on a similar strength cantilever occurred. The finding of the tests demonstrated that the system had an equivalent precision contrasted with the measurement of the conventional system.

To distribute a large-scale wooden SHM, a wireless acoustic emission (AE) sensor platform was developed in Wo et al.[69] AE was a sensor node with two-channel AE that provided high transmission data rate and high sampling frequency, also enabled detecting and precise localizing fracture cracks. The proposed prototype was characterized by an ARM processor of STM32F407 and an enhanced IEEE 802.11 b/g/n CC3200 radio chip with data rate up to 6 Mbps. Even though, due to the use of WiFi communication technology in AE, which rapidly drained out the power, this prototype definitely necessitates a kind of energy harvesting (EH) for long-term consumption as a result of not deeply studying the node's power consumption yet.

A next-generation wireless sensor solution (WSS) prototype—namely, Xnode—was proposed in Zhu et al.,[21] which was embedded with a low-noise and high-resolution triaxial digital MEMS accelerometer. Xnode has three PCBs, namely: (a) the processor board, (b) the sensor board, and (c) the radio/power board. The processor board, modified Mini4357, was characterized by Arm Cortex-M4 LPC4357 microprocessor. Such a microprocessor functioned at frequencies up to 204 MHz with a dual Cortex M4/M0 core. The Mini4357 had 32 MB of SDRAM. The 2.4 GHz frequency Atmel AT86RF233 was chosen as the wireless radio and the outdoor transmission range was up to 1 km and with data rate of 250 Kbps. The efficacy of the developed node was demonstrated through experiments in the laboratory of University of Illinois.

On the other hand, despite recent successful deployment of several wireless platforms for monitoring large-scale civil structures, the low-cost MEMS sensors commonly utilized in wireless platforms cannot readily sense low ambient vibration due to of their relatively low resolution.[72] Furthermore, due to the conversions of analog signals of MEMS sensor to digital signals come prior transmitting data wirelessly, this conversion introduces a low sensitivity to the important low-amplitude and low-frequency signals. Therefore, Sabato and Feng[73] developed wireless MEMS-based accelerometer prototype for measuring low-frequency and low-amplitude dynamic responses. A single-axis MEMS accelerometer, Colibrys SiFlex SF1600, was embedded with the developed wireless board. The results illustrated that the developed prototype was accurate in terms of measuring vibration including those of low amplitude (in the order of $10^{-1} \mathrm{m} \cdot \mathrm{s}^{-2}$) and low frequency (up to 0.2 Hz).

In addition, Jo et al.[72] developed a high-sensitivity accelerometer (SHM-H) board for Imote2 platform as reference sensor nodes in the natural excitation technique (NExT) in conjunction with the eigensystem realization algorithm (ERA)–based decentralized WSN data processing scheme for stochastic modal identification of a steel-truss structure. The experimental results demonstrated that the proposed prototype could provide a cost-effective model with enhancement on the performance of NExT/ERA-based decentralized WSN data processing for applications of SHM. Furthermore, Sabato et al.[74] developed a wireless accelerometer prototype called Acceleration Evaluator (ALE) to detect low-frequency and low-amplitude vibrations (microvibrations). A voltage-to-frequency (V/F) converter was used, instead of traditional ADC to provide accurate wireless vibration measurements by utilizing full bandwidth of the implemented MEMS accelerometer.

The full-scale applications discussed in this section demonstrated the rapid progress observed in the implementation of WSNs for SHM. A variety of academic prototypes discussed in this comprehensive review were chronologically summarized and chosen based on the developed year and field test.

Commercial wireless sensor platforms for structural monitoring

In addition to the developing of academic wireless sensor prototypes, many commercial wireless sensor platforms were developed in the industries and used for SHM applications, as the University of California–Berkeley developed the first commercial wireless platform with embedded MEMS sensor node, and after that Crossbow Technology, Inc., commercialized it in 1999.[75] MEMS sensor node is called mote, which can be considered the most popular commercialized platform. The popularity of early mote platforms related to Crossbow was due to being an open-source wireless sensor platform (both designed hardware and OS) and being accessible for the public.[36] Nowadays, there are different commercial platforms having various features related to software architecture, sensor interfaces, computing resources, and so on, and this enables dealing with a lot of civilian applications. While commercial platforms are considerably different in terms of their capabilities, on the basis of application, certain sensor types further considerably differ. Thus, generally speaking, the existing commercial platforms can be categorized into two groups based on the utilized application and their capabilities.

Moreover, several research[7,36,75] discussed and charted commercial wireless sensor platforms used for structure monitoring. However, recent sensor nodes, which were used for structure monitoring and not discussed in the previous studies are elaborated in this section. Table 3 summarizes the major characteristics of popular commercial wireless platforms, and up-to-date platforms used in the literature for SHM.

Zolertia Z1 platform. Zolertia Z1 platform is a general purpose development platform for WSN designed for developers, researchers, hobbyist, and enthusiasts.[76] It is a platform compatible with Tmot family motes with several enhancements. Moreover, it is integrated with digital sensors, which are ready to operate: a TMP102 digital temperature sensor and a ADXL345 digital programmable accelerometer are compacted on the main board. In addition, Z1 platform has a second-generation low-power MSP430F2617 microcontroller; as such, a microcontroller is characterized by a powerful 16-bit RISC central processing unit (CPU) with clock rate of 16 MHz, 8 KB data memory, and a 92 KB flash memory. It contains the CC2420 radio chip, and functions at 2.4 GHz with 250 Kbps data rate.

Some studies selected Zolertia Z1 mote for their implementation, for example; a dynamic pattern matching technique, which was able to effectively cope with environmental and stimuli-related variability in various cases of SHM, was presented by Contreras and Ziavras,[77] and Z1 was chosen for their simulations and experimental system. A case study involving railroad monitoring was discussed and its results revealed that, for railroad application, consumption of power as a result of transmission could be decreased by 50% by applying a distributed approach over a centralized architecture. Likewise, as illustrated by Liu et al.,[78] Z1 was adopted to develop a "stick-and-detect" prototype for detecting a fatigue crack. A reference-free crack detection approach was proposed and embedded in Z1, based on the nonlinear ultrasonic modulation strategy. Field test using Z1 was deployed to Yeongjong Grand Bridge.

AdvanticSYS motes. There are diverse wireless platforms within the sky platform manufactured by AdvanticSYS,[79] which have been being used for SHM such as AS-XM1000, CM3000, CM3300, CM4000, and CM5000. They are IEEE 802.15.4 compliant wireless platforms based on the original design of the open-source "TelosB" platform with some differences in integrated programmer/USB interface, antenna type (external 5 dBi or PCB), and on-board sensor configuration. AS-XM1000 has TI MSP430F2618 microcontroller and CC2420 radio chip. However, the other platforms utilized MSP430F1611 microcontroller and CC2420 radio chip. Surmacz et al.[80] utilized variants of wireless platforms, XM1000, CM3300, CM4000, and CM5000, which were deployed in greenhouse for data collection for long-term monitoring.

Waspmote Pro. Waspmote Pro is a modern open-source wireless sensor node developed by the Spanish company Libelium.[81] It is a low-cost wireless system with low-energy consumption. In addition, it can sense acceleration and surrounding parameters (humidity, temperature) relying on the extra peripheral sensor. It can be utilized in numerous industries, for instance, agriculture, radiation detection, smart metering, and monitoring of events and gas, because several sensor boards are compatible to be employed with the sensor node. The MCU uses ATmega1281 microcontroller, with 14 MHz frequency band. It has 8 KB data memory, 128 KB flash memory, and 4 KB as a program memory. The module uses XBee radio module, which works at 2.4 GHz, as data rate is 250 Kbps, and outdoor range is up to 100 m. Waspmote Pro was utilized by Pentaris et al.[46] for designing and implementing a cost-effective wireless SHM system, which could monitor man-made acceleration and/or seismic in buildings.

Shimmer3. Shimmer3 is a flexible, low-power wireless platform designed for qualified personal conducting research in the applications of wearable sensors, which manufactured by Shimmer technology from 2008.[82] There are various versions of Shimmer platforms, including Shimmer 2R and Shimmer3, which were produced in 2010 and 2013, respectively. Shimmer3 provided enhancements to the original design according to years of deployments and field test, including improved user interface and more powerful CPU. Shimmer3 was developed with MSP430F5437A CPU, 16 KB RAM, 256 KB Flash, and a capacity of microSD slot up to 32 GB. Dondi et al.[83] used Shimmer wireless sensor and provided a high performance, battery-less wireless-embedded platform that was powered by an energy harvester (provided from both wind and sunlight) for active ultrasonic SHM. In total, 16 piezoelectric sensors

Table 3. Summary of popular commercial wireless sensor platforms and up-to-date platforms used for SHM.

Year and producer	Platform name	Data acquisition specifications		Embedded computing specifications		Wireless channel specifications			OS
		A/D ch.	A/D resolution	Embedded processor	Data memory	Radio	Frequency band	Data rate	
2003 Crossbow	Mica2	8	10-bit	Atmel ATMega 128L	4 KB	Chipcon CC1000	310, 433, or 868/916 MHz	38.4 Kbps	TinyOS
2004 Crossbow	MICAz	8	10-bit	Atmel ATMega 128L	4 KB	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m	TinyOS
2005 Moteiv	Tmote sky	8	12-bit	TI MSP430F1611	10 KB SRAM, 48 KB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 125 m	TinyOS
2005 MEMSIC	TelosB	8	12-bit	TI MSP430	10 KB RAM	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 100 m	Contiki, TinyOS
2006 Crossbow	Imote2	–	–	Intel PXA271 Xscale	256 KB SRAM + 32 MB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps O/R = 30 m	TinyOS
2010 Zolertia	Zolertia Z1	–	–	MSP430F2xxx	8 KB RAM + 92 KB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4/6LoWPAN	250 Kbps	Contiki, RIOT, TinyOS MansOS
2011 AdvanticSYS	XM1000	8	12-bit	MSP430F2618	8 KB RAM + 116 KB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps	Contiki, TinyOS
AdvanticSYS	CM3000 CM3300 CM4000 CM5000	8	12-bit	MSP430F1611	10 KB RAM + 48 KB Flash	Chipcon CC2420	2.4 GHz IEEE802.15.4	250 Kbps	Contiki, TinyOS
2013 libelium	Waspmote	12	10-bit	ATmega1281	8 KB SRAM + 128 KB Flash	XBee	Depend on Teq.: e.g. WiFi, ZigBee, 3G, GPRS	Depend on Teq.: e.g. WiFi, ZigBee, 3G, GPRS	–
2013 Shimmer	Shimmer3	–	12-bit	MSP430F5437	16 KB RAM + 256 KB Flash	Bluetooth	2.45 GHz	24 Mbps	–
2015 Panstamp	Panstamp NRG2	6	12-bit	MSP430	4 KB RAM + 32 KB Flash	CC11XX	433/868/915/918 MHz	–	–
2018 STMicroelectronics	B-L072Z-LRWAN1	4	12-bit	STM32L072CZ	20 KB RAM + 192 KB Flash	SX1276	137–1020 MHz	37.5 Kbps	–

SHM: structural health monitoring; OS: operating system; SRAM: static random access memory.

were used and placed on the structure surface for analyzing SHM. The proposed solution demonstrated that Shimmer can perform an average of 350 analyses per day, corresponding to 80% refinement over a greedy-based solution. In addition, Bell[84] evaluated the accuracy and reliability of utilizing Shimmer3 platform as wireless seismic sensor and introduced a solution to the time synchronization challenge.

Panstamp NRG2. Panstamp NRG2 is a powerful wireless platform based on CC430F5137 SoC, which was produced by Panstamp.[85] It is provided with precise 12-bit analog inputs and digital ports though it did not equip with any on-board sensors, making all analog inputs available in the pinout. According to Garces Demera and colleagues,[86] Panstamp NRG2 was implemented for early earthquake alert detection. The data collection was performed for earthquake accelerations when it occurred with support of Mercalli scale, which was able to provide high-level earthquake alert based on the earth structure damages, in addition to low-level earthquake alert based on human perception.

LRWAN1. The B-L072Z-LRWAN1 is a discovery kit, which was produced to provide solutions based on LoRa, Sigfox, and FSK/OOK technologies, and included a wireless platform that was developed to be powered in various ways.[87] It characterized by an all-in-one LoRaWAN communication module Murata CMWX1ZZABZ-091,[88] which in turn was composed of a STMicroelectronics STM32L072CZ MCU, based on an ARM Cortex M0+, and a Semtech LoRa radio chip SX1276. Loubet et al.[89,90] used B-L072Z-LRWAN1 as a wirelessly powered and battery-free wireless platform for the cyber-physical systems (CPSs) allocated to SHM applications. The measurements of relative humidity and temperature were collected simultaneously and transmitted wirelessly using LoRa technology and LoRaWAN protocol.

Other platforms. There are several alternative low-cost platforms that are used for SHM application instead of existing commercial wireless platforms. For instance, Arduino is an open-source microcomputer platform that provides several board variants from the simplest Arduino UNO, to the enhanced Arduino Mega 2560 and YUN for Internet of Things.[91] In order to support wireless data communication, NRF24L01 and Xbee transceivers modules are preferred to be implemented with the Arduino platform. However, power consumption in Arduino-Xbee constitutes a challenge, and further studies are required, particularly in MAC and PHY layers to reduce the power consumption.[92] A low-cost wireless Arduino Uno-based sensing platform for railroad bridges monitoring was proposed by Ozdagli et al.,[93] which was able to calculate the dynamic transverse displacements in real time. A low-cost accelerometer MMA8451Q was used to extract dynamic displacement from collected acceleration data using a built-in algorithm of displacement reconstruction. The results of the laboratory experiments for railroad bridges showed that the introduced wireless system could provide a cost-effective, real-time, and accurate dynamic transverse displacement measurement.

The key challenges of WSNs for SHM

Several years ago, researchers devoted considerable efforts, and some academic and commercial WSN prototypes for SHM systems were designed. However, SHM characteristics and requirements added extra complications and issues to the available limitation of WSN technology. Some of these issues are a result of the location, a harsh natural environment of civil infrastructure, large sensing scope of wireless monitoring system, a generation and transmission of huge amount of data in each data sensing period, and complexity of SHM algorithms, which were also developed to be processed at a centralized station. This section discusses diverse key challenges that hindered broader use of WSNs for SHM with deep details and classifications, and also identifies the relations among them to assist the researchers in understanding the suitability of wireless technology for their specific SHM application. The existing challenges associated with WSNs for SHM in the rest of this section include the following: limitation of sampling rate, power efficiency, high data rate and throughput, fault tolerance, time synchronization, data processing, and network scalability.

Sampling rate limitation

In a real-time WSN, the sampling rate is an imperative parameter, as it is closely linked to the quality of service (QoS) of applications. For majority of applications, as a high data sampling rate is implemented, a better QoS can be obtained. Notwithstanding, there are various practical constraints frequently encountered by typical WSNs. Such constraints are as sensors' computation limit, EEPROM access latency, bandwidth limitation, and scheduling algorithms like First in, first out (FIFO), which create a barrier to achieve high sampling rates.[94–96] Thus, here arises a significant research topic, especially in WSNs for SHM, about the manner in which system resources are allocated for maximizing the sampling rates and aggregating network performance subject to such constraints.

To collect information about a particular environment or structure, SHM sensors are deployed at different locations, which must be measured over high sampling frequency and above the range interested (based on the theorem of Nyquist, the sampling frequency should be two times greater than the maximum frequency component). Therefore, getting the measurements (particularly acceleration) with high sampling over a continuous period with a large size of sample is a must for having sufficient data amount for performing the structural analysis.[17] Furthermore, at the time of selecting each node, it is necessary to consider the selections of the sensor network sampling frequency (from tens of hertz to hundreds of kilohertz), working principle, and compatibility.[14] Moreover, for generating the required features, it is necessary to collect these measured data from all the sensors for longtime period. Depending on what has been already mentioned, SHM applications need high sampling frequency, and as a result, an increase in distributed processing and transmitting of data is required. Hence, before passing the following sample, any tasks of processing on the current sample such as the calculation of global time for synchronization and transmission must first take place. Otherwise, the queue of the task will be slowly filled and the nature of the real-time monitoring gets lost. Consequently, the interval of the sample is restricted by the total time necessary for processing and transmission.[96]

The sampling rate is determined based on criteria in what follows.[47] (a) The sampling rate should be sufficiently high to guarantee preciseness and higher than the modal frequency value of interest. (b) For meeting the Nyquist theorem, it must be twice the highest modal frequency of interest. Moreover, there is another challenge related to such applications, such as combining three factors of large sample size, high sampling rate, and longtime period of measurement that generates an enormous amount of data in SHM system. There are specific criteria for determining the number of collected data samples. First, measured data samples have to be sufficient for getting good returned resolution in power, as this means better accuracy for the determination of the modal frequencies. Second, it is a must to be power of 2, because it is a data entry condition in fast Fourier transform (FFT) method. Third, capacity of sensor storage must not be exceeded.

Regarding the sampling frequency for structural response amounts, structure's lower vibration frequencies are usually on 0.1 to 10 Hz order.[5] Furthermore, local response characteristics are featured with much higher frequencies of vibration as the utilization of sampling with high frequency is desirable to minimize noise and maximize signal-to-noise ratio. A typical SHM application includes vibration measurements, sampled at 100 Hz for 10 min at a time,[97] and 10 kHz is the maximum sampling frequency that can be used in WSN-based SHM system.[34] Therefore, due to the huge amount of data associated with high sampling rate for a long measurement period, the measured data are required to be stored in an external flash memory (e.g. data samples of 2 B gathered at 100 Hz produce 12 KB of data every minute).[11] Moreover, sensor node cannot perform data collection, processing, transmission, and receiving simultaneously; rather, it can execute one of these functions at a time.

Important progress was accomplished in meeting the requirements of specifically high sampling rate in WSNs for SHM. Therefore, studies of deployment of WSNs for SHM with high sampling rate consideration are discussed first, and then summarized and tabulated them in Table 4 in terms of network description, data delivery, number of sensor nodes, and sampling rate. Finally, the implications of using high sampling rate on power consumption and time synchronization are explored.

In this regard, Dos Santos et al.[47] proposed a localized algorithm, namely, Sensor-SHM. For the allowance of detecting, localizing, and extent determining damage on a structure, WSN was used with techniques of information fusion to reduce the data transmission. In addition, it was suggested that WSN topology was hierarchical, where clusters were formed by gathered sensors and CH manages each cluster. Implementing Sensor-SHM algorithm of two programs prototyped a sensor network that included MICAz motes. One of such programs was embedded inside motes to operate as CHs and the other program was integrated in motes to function as sensor nodes. In their experiments, the authors identified the duration of each data acquisition stage, to be fairly enough to gather 512 acceleration samples at a frequency of 1.0 kHz. This, in turn, led to a collection period that continued for approximately 500 ms. Thus, as for the usage of network resources, experimental findings illustrated that the algorithm functions in a good manner.

A similar effort by Kim et al.[99] was exerted, as a sampling rate of 1.0 kHz was utilized, with a hardware analogous to that utilized in Dos Santos et al.[47] It was found that such sampling rate could be used in SHM real field implementation. In this implementation, sensor nodes were deployed and they were examined on the 4200 ft long main span and the south tower of the Golden Gate Bridge (GGB). In total, 64 sensor nodes were deployed over GBB, collected ambient vibrations with sampling frequency at 1 kHz, with jitter less than 10 μs, and with an accuracy of 30 μG. The measured data were gathered dependably through a network that contains 46-hop, with 441 B/s bandwidth at the 46th hop. Therefore, this was one of the largest number of full-scale sensor nodes deployment in SHM applications that was found in the literature, which used 64 sensor nodes at a sampling rate of 1 kHz (the largest was 113 senor nodes).[104] Likewise, according to Rice and Spencer,[8] illustration of the development and validation related to a proposed SHM-A board was given in addition to the experimental verification with a total of 70 Imote2 sensor nodes with SHM-A sensor boards deployed on Jindo Bridge. However, a low sampling rate of 50 Hz was used for this implementation.

A prototype implementation built using TinyOS OS operating on Imote2 wireless sensor platform was presented in Zimmerman and Lynch.[105] Selection significance of an optimal partitioning point between the distributed and centralized processing with high sampling rate was identified. Hence, a 3.7-s vibration was collected in 5 s, which included 2048 samples at a sampling frequency of 560 Hz (0.002 s/sample). Ability of the system to precisely localize the damage on the structure was demonstrated by the experiments carried out utilizing two dissimilar physical structures.

Mechitov et al.[101] developed a distributed sensing system for high-frequency data collection on Mica2 platform for applications of SHM, which sampled single-axis vibrations in the implementation at a frequency of 250 Hz and stored measured data locally. However, limitation of the data memory on the sensor node enables sampling only for 1 min. All measurements were made with 18 sensor nodes, which located on 18-story building models and sensing was performed at 250 Hz for 1 min.

A deployment in the Torre Aquila heritage building was illustrated in Zonta et al.,[102] where lossless compression was utilized in order to deliver heterogeneous sensor data to base station. Certain data types required for the monitoring of the building's health eased the deployment network burden. In such deployment, only three acceleration sensors were needed, where only 1 to 10 readings per 10 min were produced by the environmental and deformation sensors. With a lowest inter-message interval of 1 s, the outcome of a 30 s compressed data collection at 200 Hz took about 8 min.

As mentioned earlier, the effect of EEPROM access latency on the sampling frequency was examined by Paek et al.[94] using Wisden, and its performance was evaluated on 14 MICAz nodes deployed in the seismic test structure and prepared to collect data at 200 Hz along a single axis parallel to the structure movement. Proposed Wisden system was capable to dependably transmit time-synchronized triaxial structural vibration data through numbers of networks' hops with low latencies at a frequency of up to 200 Hz. Moreover, it was found that at the worst case of EEPROM latency, it was secure to work at a 160-Hz sampling rate. However, practically, it was found through careful experimentation that while it was feasible to sample at

Table 4. Summary review of deployment of WSNs for SHM with high sampling rate consideration.

References	WSN sensors and description	Data delivery and strategy	SHM sensors and sampling	Sampling rate
Bhuiyan et al.[98]	10 sensor nodes. Decentralized processing	Events monitoring and off-line analysis at sink	10 accelerometers. Sampled for 16 s	0.25–4.1 kHz
Dos Santos et al.[47]	Fully distribute processing. A hierarchical topology was used, where sensor nodes were gathered into clusters and every cluster was coordinated by CH	Just natural frequencies were sent from the nodes to the CH, produced 28 B of traffic per second of network operation	10 s to make decision over 0.5 s vibration transmitted of 512 samples at a frequency of 1 kHz (20 ms/sample)	1.0 kHz
Bocca et al.[57]	8 sensor nodes. Star topology. A wooden model bridge	Real time	8 accelerometers + 16 wired accelerometers	200 Hz–1.0 kHz
Kim et al.[99]	64 sensor nodes	Data were first logged into the flash memory and then sent to base station	Each acceleration board has four channels. Every 20 samples averaged and logged to flash.	1.0 kHz
Hackmann et al.[100]	11 sensor nodes. Partially distributed	Just coefficients were sent for carrying out a curve fitting, produced 300 B of traffic per second of network operation	5 s to gather 3.7 s vibration transmitted of 1358 samples at a frequency of 560 Hz (2 ms/sample)	560 Hz
Mechitov et al.[101]	18 sensor nodes. An adaptive self-healing tree routing service for establishing a mesh network	Local data processing on the raw data and transfer only the extracted features	18 accelerometers and 18 strain gages	250 Hz
Zonta et al.[102]	16 sensor nodes distributed on four floors of medieval tower	110 readings every 10 min.	3 accelerometers, 2 fiber optic sensor, and 11 environmental	200 Hz
Paek et al.[94]	14 sensor nodes. A multi-hop communication network	Two packets per second. Combination of hop-by-hop and end-to-end delivery schemes	14 accelerometers	200 Hz
Whelan and Janoyan[103]	20 sensor nodes. Single peer-to-peer network. Multi-sensor wireless network deployed on steel girder bridge	Real time	40 channels, mixed 29 accelerometers/11 strain transducers	128 Hz
Rice and Spencer[8]	70 sensor nodes. Jindo Bridge peer-to-peer network communication data transmit to the base station	One event per day, event-based monitoring	Each acceleration board has 3 channels	50 Hz

WSN: wireless sensor networks; SHM: structural health monitoring; CH: cluster head.

200 Hz with no data loss occurrence, rates above 250 Hz caused significant losses.

WSS was proposed by Whelan and Janoyan,[103] which implemented 20 sensor nodes on a single-span bridge to support the utilization of a high sampling frequency, real-time dense sensor network for SHM. Simultaneous acquisitions of up to 40 channels were employed: 29 accelerometers and 11 strain transducers, at a sampling rate of 128 Hz in real time to measure ambient vibration and quasi-static. The measured data were profusely collected to increase the resolution, filtered, and then down-sampled by a low-pass digital filter at a frequency of 128 Hz. Then, the data were transmitted to the central coordinator in near real time. Coordinated radio transmission protocol with acknowledgment mechanism was used to guarantee that typically no data loss occurred with a functional data rate of 97 to 126 Kbps. It was verified through field deployments that the system was able to detect natural frequencies and could also precisely develop mode shapes. In addition, it could log the localized strain profiles, which were caused by vehicular traffic.

On the contrary, the power consumption associated with higher sampling rates is also a crucial issue. In this regard, an event-sensitive adaptive sampling and low-cost monitoring scheme called e-Sampling were designed in Bhuiyan et al.[98] to find a solution for this issue. e-Sampling was able to acquire data at high sampling frequency (between 250 and 4100 Hz) and permitted data transmission through multi-hop network in an energy-efficient manner. This had the ability to be operated in small and low-power microcontroller-based motes. The findings of the evaluation demonstrated that when using both approaches of adaptive sampling and distributed event indication, e-Sampling saves up to 87% of the energy consumed.

Furthermore, high sampling rate complicated nodes' time synchronization over the network. Whereas, more samples mean of collecting larger data volumes that need to be managed, processed, and possibly transmitted. Vibration monitoring usually required a higher sampling rate, which in turn needed more accurate synchronous acquisition. Hence, as aforementioned, Paek et al.[94] proposed Wisden system with lightweight time synchronization schemes to handle the complication of acquiring accurate time synchronization among sensor nodes due to implementing high sampling rate. Proposed Wisden system was capable to dependably transmit time-synchronized triaxial structural vibration data through number of networks' hops with low latencies at a frequency of up to 200 Hz.

It is noteworthy that Bocca et al.[57] discussed three key challenges of using WSNs for SHM; time synchronization, and high sampling rate and throughput. Designing and evaluating of a time synchronized and configurable WSN was carried out for experimental modal analysis in SHM as the developed wireless sensing prototype operated an MAC-layer time synchronization protocol (μ-Sync). This guaranteed that a synchronicity, that was highly accurate, among the collected samples by the nodes, had the absolute error being constantly below 10 μs. Similarly, the same accuracy of synchronization was ensured when applying high sampling rate (up to 1 kHz) and prolonged measuring time (up to 10 min). It was demonstrated through the experiments' findings, in comparison with the findings obtained from the signals of the acceleration acquired by wired sensors of high quality, that the synchronized sensor nodes allowed an accurate identification of the natural frequencies related to vibration of the monitored structure with maximum 1% relative difference. Moreover, results showed that the obtained ratio of packets delivery was 99.95%.

In conclusion, it might be noteworthy that increasing sampling rates and aggregating performance of the wireless network is an important research topic especially in WSNs for SHM. Therefore, two groups of classified factors must be considered and evaluated into responding to the challenge of high sampling rate; first, the combination of three factors: large sample size, long measuring period, and high sampling rate; second, network size and data delivery reliability. Moreover, Nyquist theorem and the criteria that determined the number of collected data samples were identified with related literature studies. Finally, a summary review of WSNs for SHM deployments with high sampling rate consideration were discussed and tabulated.

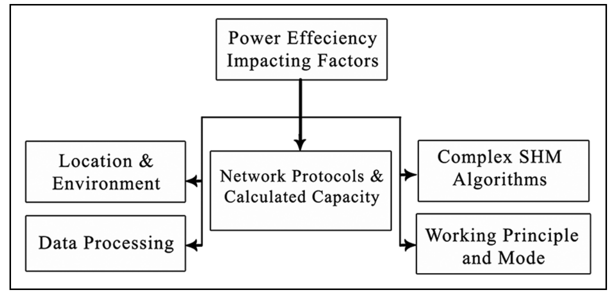

Figure 4. Impacting factors that make power efficiency of sensor nodes an essential consideration in WSNs for SHM.

Power efficiency

Power efficiency is a primary crucial aspect in the development of WSNs. In most cases, battery is used to power the sensor nodes and there is extreme limitation in the available energy amount. Relying on the frequency of making a diagnosis, a wireless SHM system once deployed is anticipated to be effective for months or even years. Therefore, reducing the consumption of power is a major issue in WSNs for SHM, particularly in the resource-constrained sensor networks. Hence, in this section, the impacting factors, that make power efficiency of sensor nodes an essential consideration in WSNs for SHM, are discussed (see Figure 4) and then the available WSNs' power-efficiency techniques in existing literatures that used for SHM applications are identified and explored.

Owing to the location and environment of wireless monitoring system, installation and maintenance brought great economy and convenience to SHM, but they also showed all types of difficulties in the service process, such as rapid draining out of sensor node power, which caused wireless SHM system paralyzed. Moreover, the environments, in which most of the sensor nodes in SHM applications work, have no available direct power supply, providing a regular maintenance operation is not possible for battery replacement. Complicating the above, WSN-based SHM systems typically have a very high sampling frequency and resolution and might involve intense use of CPU, as well as the power consumption of radio communication is greater than data acquisition and computations.[20,106]

Moreover, each sensing system has a different working principle and mode. Each of such sensing system adopts various physical principles for detecting diverse phenomena of strain, displacement, deflection, damages, sampling rate, and working power consumption, which has a highly distinguished working principle. In addition, the working mode of each sensing system substantially affects consumption of power related to the overall WSN.[14]

Furthermore, comparing to typical WSN algorithms, SHM algorithms (e.g. damage detection) are complicated as they need raw data to be incorporated from all the deployed sensor nodes, and they are commonly developed in a way to be processed at a centralized station.[12] Hence, the number of measured data at each sensor node in a single cycle can reach the amount of tens of thousands, which is continuously needed to transmit the raw data to base station in order to centralize processing, which rapidly drain out sensor node's power. Therefore, distributed processing has constantly been considered the first option to address this issue rather than centralized processing.[16]

In addition to the complexity of SHM algorithms, there is another difficulty is that integrating the SHM algorithms within WSN platforms is associated with the computational resources they need. Complex signal processing methods, like matrix computation and system identification, are required by numerous SHM algorithms, especially for those using centralized processing strategy. Thus, those algorithms cannot be directly embedded in the commonly resource-constrained wireless platforms.[12]

Finally, the impact of network protocols and calculated capacity; as the requirement of SHM in terms of low power usually incompatible with the available WSN communication protocol; hence, it is important to consider the effect of MAC layer protocol (e.g. CSMA, TDMA) in terms of power consumption for SHM applications. Therefore, integrated algorithms and cooperative protocols prominently decreased the measured data redundancy and saved considerable power amount and storage space. In addition, the complexity of an OS's architecture and networking protocol stack overhead can hinder processing the collected redundant data from measuring sensors, which can play a significant role for power conservation.[107] Moreover, there is an immediate influence of calculated capacity requirements of hardware and of the node itself on the node's function.[14]

While power consumption is a critical problem affecting the lifetime of sensor nodes, a variety of techniques have been proposed to solve this problem. Such techniques are as follows: radio optimization, data reduction, sleep/wakeup approaches, power-efficient routing, and battery repletion, as they can be used for extending the WSNs life span.[108,109] Thus, the rest of this section investigated those techniques including existing studies' solutions to WSNs for SHM.

Data reduction leads to a mitigation in the required inter-node communication, which is the main power consumer in WSNs. Generally, in-network data reduction in WSNs for SHM can be obtained using various techniques: distributed processing, data compression, network coding, data prediction, and data aggregation. Among aforementioned proposed techniques, distributed processing was constantly considered the first choice to address this issue, which was implemented to different SHM problems, including task scheduling, model updating, and modal estimation.

Here arises the problem of difficulty or impossibility of wireless node continuous transmission for the measured data to the respective recipient because of the enormous amount of the produced raw data in the SHM and the commonly restricted wireless communication bandwidth and power supply in WSNs. For this reason, distributed processing strategy plays an important role for data reduction, as only significant data or decision (that utilizes much fewer bits than the raw data) requires to be transferred. Therefore, it can conserve power and wireless bandwidth and enhance network scalability, without sacrificing system's performance.

It might be noteworthy that for detecting structural damage, they commonly utilized distributed SHM algorithm, which can attain the same accuracy of the corresponding centralized technique utilizing less wireless communication and computational resources. Hence, Liu et al.[12] selected a classical SHM algorithm: the ERA proposed a distributed approach for WSNs. The effectiveness and efficiency of such distributed algorithm were demonstrated by achieving the same quality of the original ERA by means of less wireless communications and computational resources via simulation and experiment.

Hu et al.[110] addressed the energy consumption associated with SHM distributed algorithm applied in clustered network and proposed a method in how to cluster the sensor nodes to produce a damage detection system with more energy efficient. In addition, in order to perform processing and wireless communications, the deployed sensor nodes were split into clusters for minimizing the total consumed energy. The evaluation showed that their adjusted approach was more power efficient than conventional auto-regressive and auto-regressive with exogenous inputs (AR-ARX) and it realized a data-level fusion, which was more dependable than decision-level fusion.

A holistic approach to SHM was proposed by Hackmann et al.,[100] which integrated a distributed computing system with the damage localization assurance criterion (DLAC) algorithm. Unlike centralized strategy, which necessitated the transmission of enormous amounts of measured data to a base station, the proposed partially distributed approach was utilized along with the DLAC algorithm. This enabled the sensor nodes to carry out processing on the collected data, and thus reduced the consumption of energy as it minimized the required transmission number. Results showed that their distributed approach reduced the consumption of energy by 69.5% in comparison with a traditional centralized approach. Likewise, Dos Santos et al.[47] used a WSN for monitoring structural conditions. The proposed partially distributed algorithm was utilized along with the DLAC algorithm, enabling the sensor nodes to perform processing on the in situ measured data. However, the idea of damage detection method introduced by Dos Santos et al.[47] was primarily inspired by the idea suggested by Hackmann et al.,[100] yet a difference between them was that in Dos Santos et al.,[47] the whole proceedings of reading out the frequency values from the power spectrum were carried out on the sensor nodes, while in Hackmann et al.[100] it was implemented by the Curve Fitting period. As a result, such algorithm allowed a faster exchange of information among CHs and less energy consumption.

Data compression techniques were applied by many works to minimize the overall power consumption of a sensor node. The basis for that is the fact that data processing frequently consumes much less energy than data transmission in wireless network. Notwithstanding, compression of data increases computational overhead and makes the process of data delivery slower.[15] Furthermore, a broad survey of the research efforts for the practical data compression methods feasible for use in WSNs was made available by Srisooksai et al.[111] For instance, such methods included compressive sampling (CS), distributed transform coding, and differential pulse-code modulation (DPCM). In addition, a new data compression method in WSNs for SHM (called compressive sampling), which was able to directly collect the data in a compressed format using certain sensors, was introduced. Hence, Zou et al.[112] proposed CS-based approach. The basis of CS-based approach was that rather than the transmission of raw signal that the sensor obtained, transmission performed only to the transformed signals, which were produced by the projection of the raw signal onto a random matrix. In the field tests on the Songpu Bridge, the ability of using the designed CS-based approach in an effective way for acceleration signals, that had a segment spectral sparsity ratio above 0.85 and a maximum segment data loss ratio below 0.2, was reported. Besides, it was demonstrated that the implementation of the CS-based data loss recovery on sensor nodes was successful.

Network coding is a networking mechanism in which the key idea is to encode and decode transmitted data for minimizing the communication between sensor nodes and base station. The proposed solution for the SHM of bridges in Skulic and Leung[113] reduced the overall volume of data transfer and controlled power of transmission way for adjusting the number of sensor nodes that could overhear a data transmission by an adjacent senor node. The results revealed that suitable choices of transmission power could achieve the optimal expansion of overhearing for network coding gain, while reducing the total power consumption for the WSN.

A prediction-error-based method with specific reference to SHM applications was proposed in Yildirim et al.[114] to decrease the transmission and storage of data from the sensor nodes to the base station, without hindering the ability of the WSN-based SHM system to identify damage. The monitored structure was modeled as a time-invariant system. Its objective was predicting its response to a given excitation at each sensor node place. In the proposed strategy, only the excitation signal was transferred constantly to the base station; communication between any node and the base station occurred only if the prediction error at the sensor node exceeded a predetermined threshold value. The method was intensively examined through actual experimental data and it offered significant power conservation.

According to Skulic and Leung,[113] techniques of data aggregation are not considered the optimal solution for SHM applications. In SHM, delivery of accurate data is a must; thus, the best decision can be made. In typical aggregation, part of the measured data gets lost, because data aggregation techniques often depend on averaging, maximizing, or minimizing the values of all collected packets.

Radio optimization and data reduction techniques were presented in Zhou et al.[53] by developing low-power WSN prototype for SHM called Autonomous SHM Sensor 2 (ASN-2). There were three approaches for low-power development of wireless prototype for SHM. The first approach was to use distributed data processing for the reduction of the radio communication time, which considerably reduced the power consumption caused by the radio. The second approach was the elimination of a digital-to-analog converter (DAC) for excitation signal generation. The third one was the omission of ADC for response sensing. Experiments' results showed that proposed prototype ASN-2 operated once per 4 h, and it was assessed to operate for almost 2.5 years with two AAA-size batteries.

Routing takes a part in determining the performance of a multi-hop wireless network, which can significantly drain energy reserves. Thus, existing literature of SHM in relation to power conservation techniques of different routing paradigms are elaborated in the following. In this regard, Zhang et al.[20] proposed a wireless routing protocol for bridge monitoring, namely, Energy-Saving Geographic Adaptive Fidelity (EGAF). MATLAB was employed to simulate the routing protocol (EGAF), low-energy adaptive clustering hierarchy (LEACH) protocol, and Geographic Adaptive Fidelity (GAF). The simulation results of a comparison between EGAF and aforementioned two conventional routing protocols LEACH and GAF demonstrated that LEACH was not appropriate for bridge monitoring networks. In addition, it showed that the network lifetime span and the balance of power consumption were notably enhanced using EGAF. A comparable work in achieving power efficiency was discussed in Agarwal and Kishor[115,116] through constructing a novel algorithm network lifetime to enhance tri-level clustering and routing protocol (NETCRP), which was appropriate for monitoring offshore wind farms. The proposed algorithm was relied on three-level hierarchy, spatial allocation of sensor nodes, and the usage of the existing power level of the sensor node for clustering and data routing to the base station. This protocol took into account the energy heterogeneity and the spatial allocation of the sensor nodes with reference to tower pairs to permit a sensor node to autonomously appoint itself as a CH. The developed protocol did not need any global awareness of energy at every appointment cycle dissimilar to LEACH protocol. The simulation outcomes demonstrated that the performance of the proposed protocol was better than LEACH with regard to energy efficiency and life span of the network.

A solution for maximizing the life span of WSNs for SHM by means of jointing optimal power and route selection was proposed by Mansourkiaie et al.[117] In the proposed heuristic algorithm, the power levels were selected from the optimal predefined values to reduce the computational complexity. The numerical results revealed that the presented algorithm was able to extend the life span of network significantly compared with the existing schemes.

Fu et al.[106] considered the WSNs for SHM deployment problem by providing optimal sensor placements to dependably evaluate the condition of a structure while consuming least power during data acquisition. Thus, they proposed a min–max fair, energy-balanced routing tree, and an optimal grid separation that reduced the consumption of power as well as provided fine-grain sensor measurements.

Event-based wakeup is a common and straightforward approach to extend system lifetime by letting the sensor nodes periodically sleep and wake up, during data acquisition and transmission. Taking into account the rapid degeneration of structure status, the sensor node can work with a very low duty cycle and network life span can run to some few months. Hence, event-based wakeup approaches are totally proper to enhance the power efficiency of WSN-based SHM system because data are collected during structural excitation. In this regard, Yang et al.[118] proposed an energy-efficient event capture scheme with the integration of the radio-triggered and vibration-triggered unit, and fundamentally studied the sentry selection issue, toward recognizing credible and rapid detection of the event. Simulation results showed that proposed approach outperformed the greedy and LDR naive approaches.

A comprehensive model-based decision-making scheme (MODEM) was proposed by Bhuiyan et al.[119] for CPS of structural event monitoring with WSNs. The concept of generic event detection (such as target/object) model allowed each sensor node to sense and perform a simplified local decision (0/1) on the sophisticated events. Assessment results acquired through simulations and real experiments verified MODEM's performance and capacity to make high-quality decisions and enhanced the possibility of using WSNs for SHM by notably minimizing the power consumption.

An event-based wakeup approach for monitoring a railway bridge was presented and validated in Ghosh et al.[120] A simple but robust event detection algorithm was suggested, which maintained both accuracy and low delay, and also guaranteed power efficiency by allowing the sensor nodes to work only when a train was on the bridge. As a consequence, the life span of the sensor nodes relied on the frequency of trains on a nominated bridge.

Niu et al.[121] carried out an SHM system using WSN having 17 sensor nodes, a base station, and a centralized server, as the acceleration data, which were collected from each sensor node and transmitted to a centralized server for processing and evaluation via a base station. Thus, TDMA protocol was suggested to be used because it is widely known that this protocol is able to minimize the packet collision and power consumption.

It is necessary to establish novel design concepts for recharging batteries in a way such concepts deal with the topic of power required for wireless sensors deployed in structures, as existing technologies of batteries provide battery operational life span approximately between 1 day and 1 year. Notwithstanding, many promising technologies and solutions (e.g. EH, wireless charging) aiming to recharge sensor batteries with no involvement of human are still in their early periods of development.

Numerous researchers in the structural monitoring field proposed and employed ambient EH approach. This approach is considered a rising technology for various sensing applications as it excludes the necessity of replacing batteries. Currently, the main sources and the most commonly used ambient energy, which is regarded appropriate to be used with WSNs for SHM, are solar, wind, mechanical energy, and harvesting from vibrations or strain and thermal energy. Therefore, recent research[58,122–125] efforts focus on the ability of harvesting energy from the environment, which is extremely reliant on several environmental factors to suite SHM application. In addition, recent technologies in EH for SHM applications were reviewed in Davidson and Mo[122] and demonstrated the effective of an energy harvester with frequency tuning capability.

An autonomous wireless condition monitoring sensor system whose power source was from the harvested vibrational energy was illustrated in Torah et al.[123] Despite the fact that the electromagnetic generator had only a volume of 150 mm^3, it produced enough electrical energy. The source of such energy was a very low vibration of 0.2 ms^{-2}, yet it was able to power the whole microcontroller sub-system without needing extra battery or supply of power. In addition, Wardlaw et al.[124] demonstrated an SHM system of bridges utilizing bias magnetic field sensor, signal conditioning circuits, and impulse radio ultra-wideband transmitter. Moreover, such an SHM system used magnetic shape memory alloy (MSMA) for converting the vibrations into a change of magnetization at first and then into an alternating current via a pick-up coil. Furthermore, in such a system, circuits were suggested for imperative elements related to the system. Some of the major parts of the system, like rectification circuitry, were also developed and invented.

According to Boyle et al.,[58] a new smart power model was designed; having intelligence, ambient available EH, storage, and electrochemical fuel cell integration; and recharging capability. Such a unit acted as layer of power for the sensor node. Prototyping, demonstrating, and characterizing the proposed sensor node took place in various working modes. Likewise, a direct application model was outlined by Magno et al.[125] It was used for extending the sensor node life span by means of a MEMS piezoelectric EH device together with a Nano-Watt wakeup radio receiver for building an efficient power device.

On the contrary, the method of wireless energy transmission was innovated on the basis of a wide area of current research. Such a method proved to be very influential in providing power to the SHM sensor nodes and it provides another method for supplying power to sensor nodes that are utilized in SHM application or other engineering applications. RFID-based wireless applications present both the power supply to sensor nodes and data transmission. It catches the transmitted energy and saves it in tentative capacitive storage unit, so it was used in Farinholt et al.[126] microwave radiation, which has been tested as an alternative approach for powering compact, wireless impedance sensor node. The design of a prototype microstrip patch antenna was made to function in the 2.4 GHz. It was utilized for collecting directed radio frequency (RF) energy in order to power a wireless impedance device, which provided effective sensing capabilities for applications of SHM. The proposed system was implemented in the laboratory, and it was also deployed in field experiments on the Alamosa Canyon Bridge. Likewise, Wang and Mortazawi[127] illustrated the fabrication and test of RF scavenger functioning at the AM frequency band. Besides, the optimization of the RF front end was described on the basis of an analytical calculation. Moreover, a control circuit with low-power overhead was developed for the sake of improving efficiency and sensitivity of the proposed circuit.

In conclusion, sensor nodes' low consumption of power is significant for the SHM applications. Impacting factors that make power efficiency an essential consideration in WSNs for SHM and recent power-efficiency techniques that are used for SHM applications to improve network lifetime have been discussed in this section. It also clear that power efficiency and other WSNs for SHM challenges are strongly dependent; thus, several performance parameters have to be simultaneously optimized. Indeed, various challenges such as high sampling rate, data processing strategy, and time synchronization directly influence power efficiency. Therefore, it is further required to design solutions that are able to accomplish a satisfying trade-off between those different challenges. Finally, if sensor node recharging mechanisms are promising, power conservation techniques remain essential.

High data rate and throughput

Data rate is vital as it provides information about the network throughput requirements for near real-time performance. Moreover, it is dependent on the sampling frequency, which in turn is relying on the structure's essential modes of vibration. In numerous monitoring applications, the traditional uses of WSNs are cases with low data rate, small data size, low duty cycle, and low consumption of power. However, SHM requirements mostly for data-intensive applications need high data rate, large data size, and a comparatively high duty cycle.

In the field of SHM, various types of sensors are used, for collecting information about their surrounding like acceleration, displacement, strain, and stress, which differ with the environmental conditions, for example, temperature and moisture. Hence, high data rate guarantees acquiring a lot of data samples before completing mitigation of the seismic response of a structure and the disclosure of high-frequency accelerations.[46]

To gain adequate data amount for performing the structural analysis, the acceleration measurements ought to be acquired with high sampling rate over a long period of time (continuous data) with a large sample size, which requires a high data rate and enough node memory with maintaining maximum throughput. Nevertheless, in such a data-intensive application, the generation of data takes place much faster than it can be transmitted. Also, failures, which take place meanwhile data transmission, usually cause data loss, considerably declining the performance and accuracy of monitoring that can be implemented. Therefore, it is essential to ensure a reliable data transmission for high-throughput data applications.[46,57,128]

On the contrary, having a reliable network for high-throughput data is a serious topic in WSNs for SHM. Applications of WSNs for SHM concerning requirements of throughput can be categorized into two types: low- and high-throughput applications.[128] As for the category of low-throughput applications, the data may be consisted of many packets. As a result, it can be streamed in an easy manner as it is produced for taking the small amount of data as single data samples (average data). Such single data samples represent the average over a short time required to be transmitted. This type can be applied to environmental conditions (e.g. temperature and humidity), strain deformation, or structural control systems monitoring to check the integrity and material fatigue of the system (e.g. viscoelastic damper), which needs only a slow altering signal sensing and transferring. However, in the high-throughput applications, requirements of network communication are entirely dissimilar, in which the data are utilized for vibration measurements, fatigue assessment, as well as damage detection of a structure.

According to Wijetunge et al.,[17] system requirements in terms of data rate and memory of the sensor node can be derived for the two categories: continuous data and average data. Data rate and memory requirement for the measurement of continuous data (e.g. acceleration) and average data (e.g. displacement, strain, wind speed, humidity, and temperature) are illustrated in Table 5.

Complicating the above, SHM algorithms (e.g. damage detection, damage localization) require dense of sensors to be deployed. Thus, for hundreds of sensors and high sampling frequency, a huge amount of data in WSN are generated and transmitted in each data sensing period. Moreover, when a network composed of a hundreds of sensor nodes could instruct collecting 1 min of triaxial acceleration time history and whose data rate per sensor unit is 40 Kbps, under the best case, the base station should have the ability of handling data rates of 400 Kbps for near real-time performance.[11] Nevertheless, various WSN platforms such as ZigBee, Imote, and Tmote (IEEE 802.15.4 compliant) are deemed to provide only a data rate of 250 Kbps. Thus, due to this restriction and higher frequency for each sensor node, it is clear that continuous data collection from even a few tens of sensor nodes is impractical. Thus, it is obvious that limitation of data rate of sensor nodes is considered a serious issue in WSNs for SHM.

Table 5. Measurement requirements for SHM sensors.[17]

Measurement	Data rate requirement	Minimal memory requirement
Acceleration	9.6 Kbps	11.52 MB
Strain	9.6 bps	6 B
Displacement	6.4 bps	4 B
Temperature	1.6 bps	1 B
Wind speed	3.2 bps	2 B

SHM: structural health monitoring.

On the contrary, communication protocols (in particular MAC protocol) and the impact of complexity of OS's architecture and networking protocol stack overhead can impact the performance of the network, node's throughput,[107] and real-time monitoring, and limit the ability of the systems to satisfy stringent SHM requirements such as high throughput and low-power consumption.[15] Thus, designing carefully communication protocol (specially MAC protocols), analyzing the causes of degrading performance of sensor node and network, and being sure that the average of data acquisition rate is less than the maximum obtainable network throughput should be taken into account to find a solution for this challenge.

Regarding this limitation, several studies[17,57,94,128,129] discussed WSNs data rate and throughput limitations, and their effects on achieving the requirements of SHM.

A deployment and evaluation of the performance of wireless structural data acquisition system (called Wisden) for SHM applications on seismic test structure were discussed in Paek et al.[94] Through series of test deployments and refining the system design, designing a novel onset detection scheme took place for overcoming the constraint bandwidth and achieving sampling of higher frequency. Moreover, comparing Wisden performance on two different platforms, the Mica2 (19.2 Kbps) and MICAz (250 Kbps) were demonstrated, and the observation of the sampling frequency and data rate constraints of these sensor nodes indicated that there were surprising influences of low-level design decisions on performance of application.

As evaluating WSN communication performance before and after performing a deployment is critical to obtain a successful WSN-based SHM systems, Kim et al.[128] suggested a model for WSNs having the ability to measure high-throughput data for long-term monitoring. Such a suggested model depended on readily available collected data sets, which represented communication performance during high-throughput data transmission. After that, authors determined an empirical limit-state function as this function was further utilized for the estimation of the probability of failure. There were two case studies that investigated the proposed approach. The first was a small-scale temporal WSN, and the second was a full-scale network. Moreover, this approach demonstrated an effective method for assessing WSN reliability with high-throughput data transfer. Bocca et al.[57] presented a similar effort in gaining high throughput with a highly accurate synchronicity among measured data by sensors at 1 kHz sampling rate. The results showed that the achieved final packets delivery ratio was 99.95% and the implemented lost packets' recovery scheme recovered 96.1% of the packets, which were previously lost.

According to Chin et al.,[129] the so-called rapid structural assessment network (RSAN) software system was designed and implemented as it was done so with experimental assessment of a WSN for real-time SHM for detecting structural damages (cracking and spalling of concrete). The reported prime data did not need structural analysis for evaluation, had a low data rate, and were naturally resilient to loss. Also, there was shown the manner of utilizing a diversity of low-cost, off-the-shelf data collection/transmission devices for supporting wireless monitoring by means of a control center. Likewise, the low data rate and natural loss resilience of the periodic data results illustrated that network could remain operative even under situations of stress. The reported data directly map important structure damage, with no requirement for sophisticated data analysis. Moreover, it was revealed that the sensor nodes in the suggested system functioned with high reliability when deployed on reinforced-concrete building.

In brief, high data rate and throughput are crucial issues in WSNs for SHM. For SHM application, enough and correlated measured data to be gathered through high sampling rate over a long period of time with a large sample size require high data rate and best throughput to minimize data loss.

Fault tolerance

There were noteworthy efforts exerted for fault tolerance in WSNs as researchers conducted extensive studies and they suggested numerous fault-tolerance approaches for many applications. However, there were many reasons such as limited amount of energy, low network bandwidth, a huge data, complex algorithms and calculation, and environment noise[130–132] that made some of the classical strategies that were used for achieving good fault tolerance in wireless networks not directly applicable in the case of SHM. Efficient design of a solution for application-specific dependability concerning sensor node fault tolerance and detection is another important challenge in WSNs for SHM.[132,133] In addition, two questions usually arise at the time of fault occurrence in WSNs of SHM: the first question is how to maintain continuity to have monitoring data, and the second question is how to ensure sensor node fault tolerance in SHM (FTSHM). Thus, having no answers about these two questions hinder the ability to know for a while whether a structure is intact or will crash.

In general, research regarding fault types in sensor nodes can be mostly classified as function fault and data fault. As for function fault, it easily identified faults such as fault caused by communication errors, network faults, base station faults, sensor faults, and the individual senor nodes' crash as a result of battery depletion and transceiver failure. Regarding data fault, it could take place at the time of reaching a sensor node's battery a specific stage, incorrect readings by sensor and could be caused by security attacks as well (inject false data via one or more compromised sensor node). Moreover, it could be noted that sensor nodes with faulty data appropriately operate, yet the values they showed were incorrect. Thus, when comparing data fault with function fault, it could be noticed that data fault was much more difficult to be detected and was probable to cause false alarms.[131,134,135]

Numerous techniques, dealing with various kinds of faults at diverse layers of the network stack, were developed by various studies. Therefore, several researches, De Souza et al.,[135] Paradis and Han,[136] and Alwan and Agarwal,[137] proposed classifications for fault tolerance in WSN. However, to our best knowledge, a limited number of researches studied fault-tolerance challenge in WSNs for SHM. Hence, to assist in understanding this challenge for SHM, a comprehensive taxonomy of fault-tolerance techniques used in WSNs for SHM is presented. Therefore, recent research into meeting the fault-tolerance requirements necessitated by WSNs for SHM could be categorized into three techniques: fault prevention, fault detection, and fault recovery. Furthermore, fault recovery can be divided into hardware- and software-based fault recovery; software approach further can be classified into three methods: retransmission, compression, and network coding. The proposed taxonomy is depicted in Figure 5. The remainder of this section discusses existed literature related to this taxonomy.

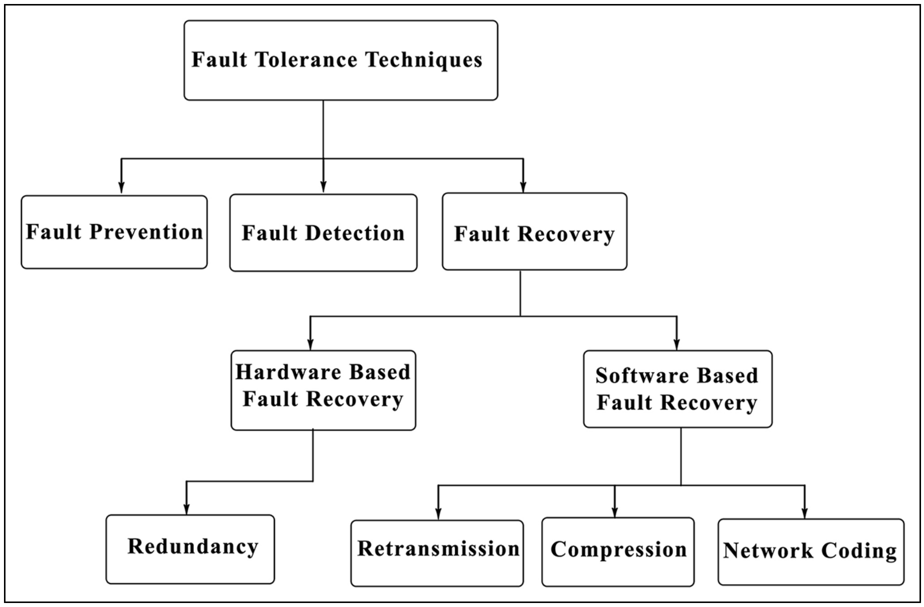

Figure 5. Taxonomy of fault-tolerance techniques.

Fault prevention techniques aim to avoid faults by monitoring network status, ensuring full network connectivity and coverage before it starts operations, and allowing routing redundancy for data delivery. Hence, to enable WSNs to be resilient to the faults, Bhuiyan et al.[132] presented an approach, termed as fault tolerance in SHM. FTSHM repaired the network before it started working to ensure a particular level of fault tolerance. Moreover, an algorithm of backup sensor placement (BSP) was also proposed, which included several subalgorithms to enable WSNs to be resilient to the faults. Simulations and real experiments demonstrated FTSHM advantages, which proved that this approach was robust against node failures while other approaches were not.

The goal of fault detection is to detect potential faults and verify that the services being provided are functioning properly. In addition, in some cases, it is required to follow processes of isolation and identification for diagnosing and determining the real sources of faults. As demonstrated by Liu et al.,[131] the integration of faulty node identification and damage detection together was efficiently performed. The proposed scheme also could elicit structural damage from faulty sensor reading. The usefulness of the proposed approaches was shown through both simulation and a laboratory test. Likewise, Liu et al.[134] proposed fault-tolerant event detection (FTED) scheme for detecting sophisticated events in the existence of faulty sensor node readings, which was applied in WSN-based SHM system. The work's major contribution was iterative faulty node detection (I-FUND) to identify faulty nodes by comparing sets of identified frequency from multiple sensor nodes.

Bhuiyan et al.[133] designed a dependable and decentralized WSN scheme for SHM (DependSHM). The ability of the DependSHM to deal with sensor faults and constraints was examined. Also, they proposed a non-faulty data acquisition approach, which enabled the use of detection online faulty sensor depending on the function of mutual information independence. Likewise, according to Bhuiyan et al.,[138] an automated online identification of faulty node scheme and a recovery scheme to rebuild signals of faulty node were proposed. In addition, Smarsly and Law[139] introduced a distributed analytical redundancy scheme for independent sensor fault detection and isolation for WSN-based SHM systems. Instead of deploying numerous redundant sensor nodes in the structure, the data inherent in the observed WSN-based SHM system were utilized for detecting and isolating sensor fault. Moreover, the analytical redundancy approach was implemented in a fully distributed fashion.

The promise of fault recovery is to provide countermeasures for faults to be recovered. One of the main approaches to achieve this goal is hardware redundancy by replicating the components of the system that are vital for its perfect operation. In this regard, as mentioned earlier, Bhuiyan et al.[132] presented FTSHM approach also for fault recovery, which repaired the network before it started working to ensure a particular level of fault tolerance via searching the repairing points in clusters in a distributed manner and deploying a group of backup sensor nodes at those points in a manner that still fulfill the requirements of network.

On the contrary, the aim of software-based fault recovery methods in terms of data loss is to deliver reliable data when fault occurs during the data transmission, especially over a noisy environment and extensive infrastructures. According to Zou et al.,[112] researchers in WSNs for SHM are still vastly employing retransmission. In this regard, and as mentioned above, Bhuiyan et al.[133] proposed DependSHM, including two complementary algorithms for detecting sensor fault and reconstructing faulty sensor's signal. The recovery could be immediately applied to any type of correlated signals resulted from many sensor faults in the monitoring system. They implemented a proof-of-concept system by means of the TinyOS on Imote2 platforms for validating their approach, which mainly implemented a communication protocol with retransmission method for data loss recovery. Likewise, as mentioned above, simulations and laboratory experiments carried out in Liu et al.[134] clarified the usefulness of the offered approach. For that purpose, SHM motes were designed to run using modified TinyOS and were configured to use retransmission method for data loss recovery.

The idea of compression method is to reduce the volume of information bits to be sent over the channel, allowing the use of more redundancy to combat the channel impairments, yet it affects data quality. It was shown by Zou et al.[112] that it is possible to integrate CS-based data loss recovery approach into WSN and to efficiently increase the reliability of wireless communication with no need to retransmit the data. Therefore, this approach was proposed to ensure reduction of communication, and thus saving power. This technique aimed the provision of precise restitution for the steady and compressible acceleration signals acquired through WSN-based SHM systems with ratio less than 20% of data loss. Likewise, Bao et al.[140] investigated a novel application of CS that aimed to recover lost data in WSN for SHM. An analysis for the collected data at the Jinzhou West Bridge and the National Aquatics Center was performed to investigate the approach's recovery accuracy. The results indicated that it is possible to have good recovery accuracy if the measured raw data possess a sparse feature in some orthonormal basis.

The purpose of employing network coding is improving the reliability and fault tolerance in WSNs. Moreover, its idea is to permit the data coding at intermediate sensor nodes and route coded packets, each of which is produced by the combination and encoding of more than one packets received from probably different nodes. Hence, Skulic and Leung[113] recommended and performed an analysis for the performance of a new algorithm that employed network coding in WSN for SHM of bridges. Therefore, when sensor nodes were deployed alongside the length of the bridge, the aim of optimization was to minimize the failure in connectivity of the link and maximize the life span of the network by reducing the transmission number required for routing measured data to the base station. Both packet relay and network coding were key factors for forwarding measured data between two base stations placed at each end of the bridge. The validity of the proposed algorithms was proven via both simulation and mathematical analysis.

It might be noteworthy that, because of resource limitations of the sensor nodes and SHM requirements, the fault-tolerance approaches should have a very low computation overhead and data redundancy to be implemented for consuming power efficiently. For that, the validation of various works by Bhuiyan et al.[132,133,138] showed that SHM using WSNs could be futile if the WSN requirements (e.g. fault tolerance and power efficiency) were not truly taken into consideration.

In conclusion, considerable progress was achieved for meeting the requirements of fault tolerance required by WSNs for SHM. The advantages of fault-tolerance techniques are to provide reliable and robust computing service for network users; thus, the network system can continue to complete the scheduled task when some fault occurs. Moreover, the hierarchy of the fault tolerance was classified based on the type of fault, which took place in WSNs for SHM, and the proposed taxonomy for fault-tolerance techniques was discussed.

Time synchronization

Time synchronization is considered an open challenge,[5,46,141] as data acquisition should be preferably made simultaneously on all sensor nodes, and in a WSN, it is necessary for routing and conservation of power. The inability of the sensor nodes to sample data simultaneously and deficiency of time accuracy can result in considerable time synchronization errors (TSEs) amid diverse sensor nodes and significantly reduce the network's lifetime.[15,142] As in several other WSN applications, network synchronization is extremely required in SHM applications and needs accurate time synchronization as a result of widespread sensor data sharing. The effects of TSEs introduce errors in modal parameter evaluation, damage localization, and detection. Notwithstanding, data synchronization is not spontaneously secured even with accurately synchronized clocks, because of the particular characteristics in SHM, including extended sensing duration, high sampling rate, and unreliability in the software and hardware.[143]

Both clock drift and clock offset between sensor nodes might be the causes for the occurrence of the

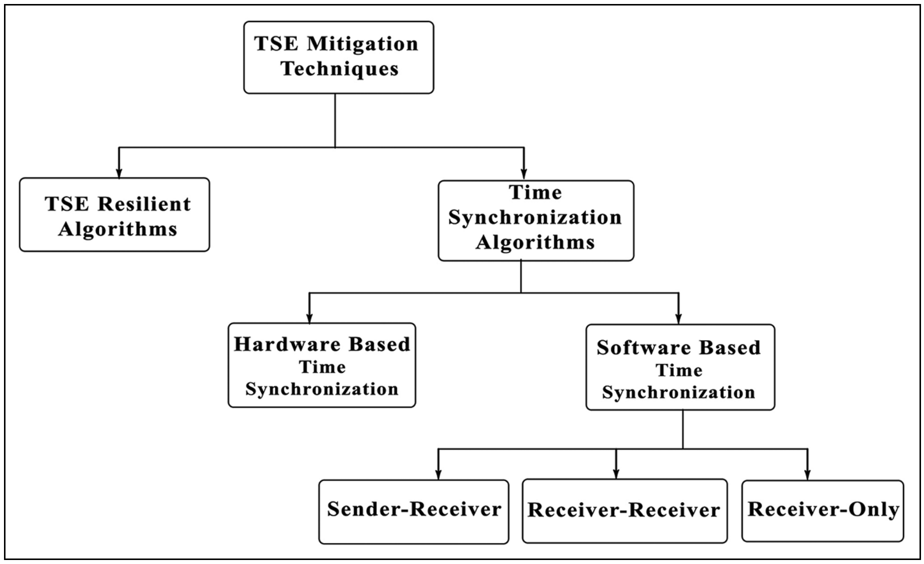

Figure 6. Classification of TSE mitigation techniques.

TSEs,[144] as clock drift takes place as a result of the clock rate of the existing crystal oscillation, which does not run accurately as a design reference clock rate, whereas the clock offset occurs due to the impracticable initializing of all the sensor nodes in a WSN at the exact same instant. Consequently, the clock of each sensor node has its own starting time.

It was shown by Noel et al.[16] that research into responding to the challenge of high time synchronization requirements in WSNs for SHM can be categorized into TSE resilient detection algorithms and synchronization algorithms. Synchronization algorithms can be further classified as algorithms that were only applied in software or which employed a combination of hardware and software. Moreover, software-based time synchronization approach can be broadly categorized into the following three classes in terms of message direction: Sender–receiver, Receiver–receiver, and Receiver-only approach.[142,145,146]

The classification for TSE correction techniques deduced from Noel et al.[16] and Yan and Dyke[142] is illustrated in Figure 6. The rest of this section discusses the obtainable literature relevant to this taxonomy, the impact of synchronization accuracy on the correctness of the SHM algorithms' results, and also the influence of sampling rate and the proposed solutions.

A TSE resilient algorithm is an approach that is intended first for enhancing the robustness of damage detection algorithms against TSEs by examining the influence of non-synchronous data acquisition on structural modal identification and reducing deformation in the identified mode shapes using non-synchronous data, and second for relaxing the recurrent sensor synchronization requirement in WSNs.[142] According to several research studies, which addressed time synchronization, it is commonly known that frequent implementation of time synchronization protocols or algorithms can mitigate TSEs. Notwithstanding, this needs a considerable amount of power. Hence, TSE resilient algorithms have a vital role in WSNs for SHM for minimizing network power consumption by preventing or reducing the utilization of time synchronization protocols. Hence, some studies,[142,147–149] which were recounted in the literatures, concern such a usage of TSE resilient algorithms.

Yan and Dyke[142] proposed a strategy for detecting a structural damage, which was robust against TSE in WSNs. At first, the manners, in which TSEs distort identified mode shapes, were examined. After that, an approach was proposed for the reduction of distortion in the mode shapes. This strategy consists of two approaches. The first approach directly used the distorted mode shapes, while the second one applied the absolute mode shapes (AMS) for detecting damage. Numerical simulation results demonstrated that the earlier proposed strategy could tolerate considerable TSEs, with no sacrifice of accuracy in identifying modal parameters and localizing structural damage. The same methodology was utilized by Abdaoui et al.[147] for analyzing the effect of TSE on the mode shape, but they did not utilize centralized processing as in Yan and Dyke,[142] rather semi-independent processing. There, each sensor node locally computed FFT of the in situ collected data, and the transmission of the FFT frequency samples to the base station took place after that. The remaining computation of the mode shape occurred at the base station.

Feng and Katafygiotis[148] investigated the effect of TSE in the acquired output response on modal identification by the use of simulations whose results showed that the identified mode shapes could be distorted due to the occurrence of small TSEs in the output response. Thus, the authors proposed a method to eliminate such errors, as such method estimated that the power spectral densities (PSDs) of outcome responses by means of non-synchronous data sampled depend on an adjusted FFT. Whenever obtaining the corrected PSDs took place, obtaining the correlation functions by inverse fast Fourier transform (IFFT) could easily take place. Such corrected PSDs or correlation functions could be then fed into diverse output-only modal identification techniques. At last, they concluded that results of simulation mostly matched the specified parameters of the synchronous data.

The effects of TSE on outcomes and performance of the techniques related to Output-only Modal Analysis (OMA) at the time of combining data from different sensor nodes were investigated in Nguyen et al.[149] Two OMA families were selected for such investigations: Frequency Domain Decomposition (FDD) and data-driven Stochastic Subspace Identification (SSI data). This study's findings displayed the robustness of FDD and the precautions required for SSI data once working with TSE. In conclusion, an integration of the technique relevant to the preferred OMA and the usage of the channel projection for the time-domain OMA technique to cope with TSE were suggested.

Hardware was also utilized in different studies to minimize TSE in WSNs for SHM. Hence, Huang et al.[63] illustrated that for improving the synchronization accuracy, a new solution that was depending on hardware cross-layer design was proposed. It was implemented with high sampling frequency and accurate synchronization acquisition to monitor machine vibration. Data were acquired in a hardware timer event happening at a definite frequency. Moreover, it is necessary for the microprocessor to complete all non-preemptable tasks before conducting a new timer event. Dual-processor technology and the high-accuracy synchronous acquisition were utilized for achieving a trade-off between high performance and low consumption of energy. Therefore, in this solution, a single-hop communication was utilized and high-precision synchronization approach for single-hop communication was achieved. While Xiao et al.[150] developed a design for hardware cross-layer, which was used in a high-accuracy synchronization acquisition algorithm as an extension of the previous work in Huang et al.,[63] they focused on implementing multi-hop communication to monitor mechanical vibration.

A complete wireless measurement system was developed by Araujo et al.[59] for SHM with a synchronization module based on ZigBee standard in which spatial jitter is below 120 μs, and can scale to extensive number of sensor nodes. Master-slave approach was used; a master device within the server transmitted a synchronization clock pulse to all the slave devices. This solution was an immediate call from physical layer to application layer, with no need for all the intermediate stack layers.

Another hardware solution was developing a system which employed a global positioning system (GPS) receiver for synchronizing the clocks of hardware. Even though GPS has high precision (nearly 200*n* second relative to Coordinated Universal Time (UTC)), it was considered inappropriate for performing time synchronization, because it exceedingly consumed power, increased the cost, and in some indoor monitoring systems, the device might not be able to capture GPS signals.

Spencer et al.[143] presented time synchronization strategy that was implemented in a tool called the Illinois SHM Services Toolsuite. Such a tool contained a two-stage synchronized sensing: in the first stage the flooding time synchronization protocol was employed for providing clock synchronization; then in the second stage, resampling data took place after sensing completed to eliminate the errors as a result of uncertainties in software and hardware. The Toolsuite was updated with more services such as a GPS-based synchronization feature. The clocks of gateway nodes were periodically adjusted by GPS receivers and the updated clock information got distributed within a sub-network. The proposed solution was implemented with 22 sensor nodes and deployed on the Arsenal Bridge. Likewise, Sazonov et al.[54] proposed a hierarchical architecture wherein beacon synchronization was employed for local clusters of sensor nodes and spatially allocated clusters were synchronized by means of GPS time reference. The proposed solution was validated in laboratory experiments, and the results showed that it was possible to maintain the TSE among any number of globally allocated sensor nodes less than ± 23 μs.

On the contrary, time synchronization protocols were extensively scrutinized to be a solution for the issue of time synchronization in WSNs. Generally, synchronization approach can be broadly categorized into three classes in terms of message direction; Sender–receiver, Receiver–receiver, and Receiver-only.[145,146] In the sender–receiver protocol, a single node synchronizes its clock to the reference node clock through bidirectional communication (e.g. timing-sync protocol for sensor networks (TPSNs)[151] and flood time synchronization protocol (FTSP)[152]). Receiver–receiver synchronization lets a reference node transmit to a group of nodes for synchronizing their clocks to its clock (e.g. the reference broadcast synchronization (RBS)[153]). In a receiver-only approach, the synchronization of a set of sensor nodes can be performed by only receiving timing messages of a pairwise synchronization (e.g. Pairwise Broadcast Synchronization (PBS)[145]).

The synchronization accuracy of the aforementioned techniques is about 20 μs (different algorithms and hardware resources may result in different accuracy), which is mainly used in SHM.[63] Nevertheless, accuracy of synchronization is specified by not only algorithm but also the implemented communication layer, topology of the network, and its highly dependence on the application.[146,147,150] However, as a result of the particular characteristics in SHM, like extended sensing duration, high sampling rate, and uncertainties in the software and hardware, several algorithms were not effective in SHM.

Several algorithms were proposed in different studies to minimize TSE in WSN, particularly for SHM. For example, TPSN particularly proved its suitability in the context of SHM.[154] Likewise, Time Synchronized Mesh Protocol (TSMP) provided a good performance through implementing the combination of TDMA with frequency channel hopping, which was implemented in the MAC communication layer. The protocol was developed to reliably function in a noisy environment and to succeed in extending battery lifetime.[15]

It is necessary in modal analysis and identification algorithms to synchronize vibration data from diverse structure locations; the results may become invalid as a result of non-synchronous data acquisition.[141] Synchronization accuracy directly impacts the correctness of result analysis, particularly structural mode shapes, because it depends on the mode frequency and the relative time shift amount in the location of the sensor.[155] Actually, the errors, resulted from the time shift between the measured data from different sensor nodes, may extremely affect the integrity of data and then uncertainty to identify the mode shape of the structure under analysis. Thus, valid results are openly related to synchronization accuracy. Therefore, the effect of TSE on mode shape was studied by many researchers. Several studies focused on studying the manner in which TSE impacted the process of attaining mode shapes and the reason for necessarily being below 1 ms so as to get valid data,[147,155] whereas other studies[59,156,157] proposed solutions for minimizing that impact on mode shape.

A novel methodology designed for evaluating the impacts of sensor time synchronization on the ability to reconstruct mode shape by means of the commonly used output–output technique of FDD was presented in Krishnamurthy et al.[155] It was illustrated in the theoretical analysis that the non-synchronized data caused the errors in mode shape reconstruction proportional to $e^{w_i t_0}$, and so dependent on both the time shift and modal frequency. The proposed solution allowed assessing the time delay impact on precision of the mode shapes. Such evaluation was closely connected to the data collected by WSNs as sensor nodes were not completely synchronous with each other. Likewise, Abdaoui et al.[147] studied the effect of TSE on identification of the mode shape, damage detection, and localization in WSNs for SHM by selecting different topologies, since time synchronization is affected by the type of topology of the network.

On the contrary, while SHM has need of a high sampling frequency, it causes time synchronization of sensor nodes to be more complicated over the network. However, as discussed earlier, Araujo et al.[59] developed a complete WSN-based SHM system with high sampling rate, along with a high precision of time synchronization and low jitter. The procedure of system identification and modal analysis was carried out on measured data, and nine mode shapes, with corresponding modal parameters, were elicited. Moreover, using a simulation, two algorithms were proposed by Lei et al.[157] to synchronize measured data, that were an ARX (autoregressive with exogenous input) model for assessing the time delay between an output signal and input signals, and an ARMAV (autoregressive moving average vector) model for two output signals. Results showed that the non-synchronous data acquisition did not affect frequencies and damping ratios, though the error in mode shapes identification could be considerable. Nevertheless, using experiments, a Statespace (SS) model was examined in Wang et al.[156] for acquiring time synchronization of acceleration data of Jiangyin Bridge during a ship-bridge collision. The SS model was recommended for identifying the time shift between the accelerations of asynchronous data at various positions. The results indicated that the performance of SS model was satisfactory in identifying the time shift for synchronous and asynchronous data.

Time synchronization is important for power conservation; thus, time synchronization protocol should be energy balanced and completely reduce their utilization of communication and computational resources. Likewise, the life span of network can be considerably reduced due to lack of time synchronization accuracy. Hence, global time reference enables the sensor nodes to transfer data in a scheduled time. Therefore, power is conserved at the time of existing less collision, retransmissions, and also by preventing or reducing the utilization of time synchronization protocols. In this regard, energy-balanced time synchronization (EBS) protocol was proposed by Hu et al.,[158] which especially tailored for bridge SHM application. The EBS protocol accomplished its energy-balanced performance via employing dynamic span leader-election approach, while minimizing the number of broadcast synchronization messages. The high-accuracy performance was achieved by using

MAC-layer time-stamp as in FTSP. The EBS protocol performance was assessed and compared to FTSP.

In summary, existing studies presented different solutions to provide good synchronization, and noteworthy progress was attained in addressing the challenge of time synchronization in WSNs for SHM. However, it is necessary to take into account the accuracy of synchronization as another crucial designing factor. Classification for time synchronization was presented with the corresponding available solution in recent research. Also the impact of synchronization accuracy on the correctness of the SHM algorithms' results, the influence of high sampling rate on synchronization accuracy, and the proposed solutions were investigated. Finally, time synchronization played an important role in power conservation.

Data processing

For providing a precise evaluation of the behavior and performance of data acquisition system, the modern community of engineering will certainly become highly more dependent on sensor data, because of the continuous growth of the data amount acquired by SHM systems and because of the continuously rapid improvement of capabilities and techniques related to data processing across disciplines.

Data processing in WSNs for SHM usually indicates the implementation of SHM algorithms (e.g. modal analysis, damage detection, damage localization.) within sensor nodes or base station. In that way, raw data, processed data, or decision will be received by base station according to data processing strategy used.

Various classifications for data processing strategies were introduced and discussed by many studies.[8,11,16,34,159–163] A general classification for data processing can be divided into two primary categories: centralized and distributed data processing. Besides, from our point of view, centralized processing can be classified into two categories on the basis of communication network type: single-hop and multi-hop. In addition, distributed data processing can be divided into three approaches: independent processing, hierarchical processing, and parallel processing.

Centralized data processing is a copy of data flow and processing strategy of the conventional monitoring system, as sensor nodes transmit raw data to a base station for processing and analysis,[160] whereas distributed (i.e. decentralized) data processing employs local data aggregation and processing within sensor nodes, which is essential for scalability and energy efficiency of WSN due to its ability for reducing data communication to realize extensive deployed WSNs and prolong network lifetime, but at the cost of more complex routing protocols.[108]

The importance of employing distributed data processing in comparison to centralized strategy arises due to the following reasons: (a) WSNs in large structures aggregate data in a highly spatially distributed manner; (b) since the purpose of SHM is to determine the status of structure, transmitting a huge amount of data to a base station is not necessary and not an efficient way for WSNs; (c) embedded computation is often considered as less power consumption than data communication; and (d) reduction of raw data transmissions will preserve communication bandwidth, which leads to increase QoS (e.g. reduce data loss and system response time) and preserves system scalability.[161,164]

Centralized processing. Previously, the main focus of researchers was on implementing SHM algorithms in centralized station, which did not need cooperation between sensor nodes, wherein sensor nodes transmit raw data to a base station for processing. Centralized processing enables utilizing all algorithms assigned for detecting and localizing damage, and thus it becomes able to benefit from those which are most precise for SHM applications.[16] This strategy can either be achieved in one of two ways: the first through logging the data in the existing memory of the sensor node and then transmit it after the following acquisition; the second through delivering the measured data in a real-time manner.

According to network data flow and topologies, two categories of centralized processing are used for SHM implementation: single-hop and multi-hop. Single-hop centralized processing is the least sophisticated processing strategy and the easiest to be implemented (see Figure 7(a)). However, scalability, power consumption, and bandwidth are the main challenges encountered meanwhile using this strategy. Multi-hop centralized processing allows sensor nodes to cooperate through routing data outside the direct communication range using intermediary sensor nodes to a base station for data processing (see Figure 7(b)). However, as the network size increases, power consumption and time delay become major challenges for this strategy, due to the huge amount of data transfer in the network.[162]

An example for the implementation of single-hop centralized data processing was presented in Yan and Dyke,[142] which proposed an algorithm for detecting damage that is robust against TSE. The authors considered the case where measured data were transferred wirelessly to the base station to be gathered and that the base station carried out the entire processing of mode shape identification and damage detection. Nonetheless, the time of data acquisition and the storage capacity of the base station required optimization.

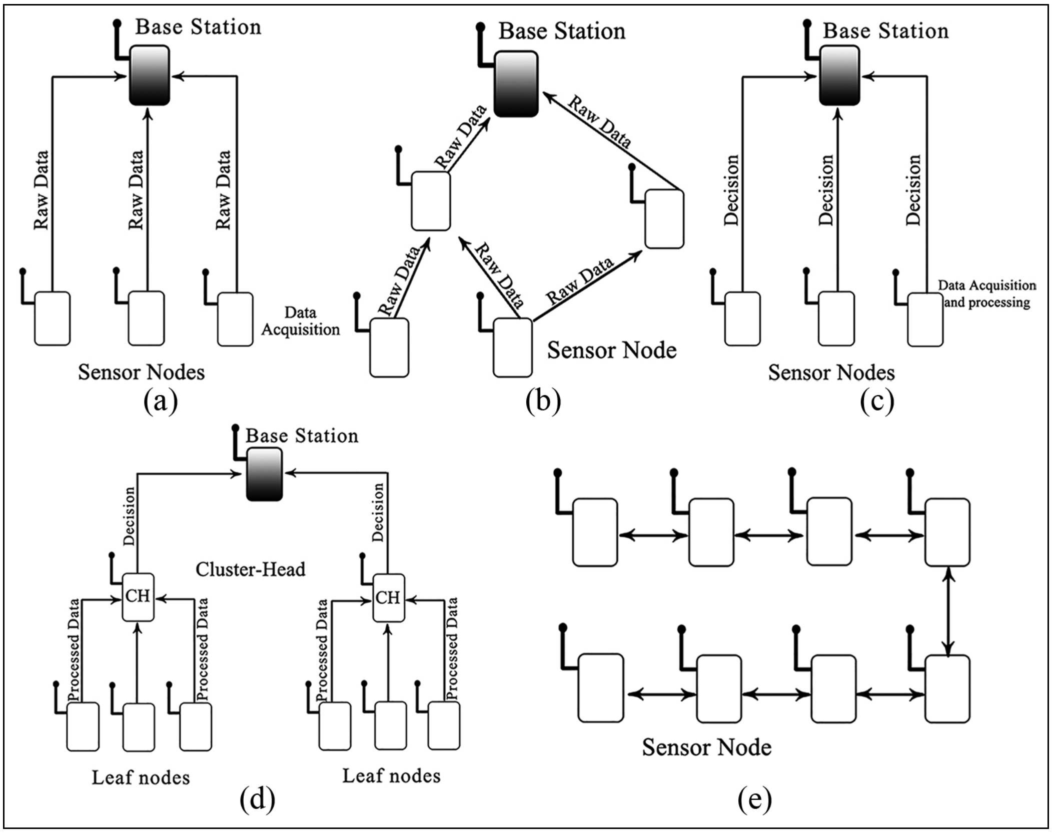

Figure 7. Data processing strategies: (a) centralized processing (single-hop), (b) centralized processing (multi-hop), (c) independent processing, (d) hierarchical processing, and (e) parallel processing.

On the contrary, multi-hop network for centralized processing was used in Zou et al.[165] to design an efficient multi-hop communication service for WSNs, which was developed practically for SHM applications. This work inherited the desirable features of their previous proposed work (called Single-Sink Multi-Hop (SSMH)) and was termed as ISSMH (Improved Single-Sink Multi-Hop). The developed ISSMH service was embedded on Imote2 and validated through laboratory experiments, as well as a full-scale field test carried out on the Rainbow Bridge, Tokyo. The tests' results showed that ISSMH is applicable and its data acquisition is efficient.

A study about the optimization of sensor placements for SHM regarding the accuracy of structural modal parameters and energy consumption was presented by Fu et al.[106] A set of sensor nodes was deployed and equipped with accelerometer sensors for data acquisition and transmitted it over multi-hop network to a base station. A rectangular shear structure was used and modal analysis was implemented for four-story building model. An energy-balanced routing tree was first built based on the model of network, supposing that all the sensor nodes on a given story can transmit their measured data to a local base station placed at the middle of that story. Then, from the energy model, estimation of the total energy, consumed for collecting all the measured data over the routing tree to the local base station, was performed for a given inter-node separation.

In spite of conducting extensive research on optimization of wireless networking protocols for SHM applications, centralized processing involved substantial communication and energy costs for data acquisition. For instance, according to Pakzad et al.,[166] a WSN employed on the GGB in 2008 took nearly 9 h for collecting 80 data samples at sampling rate of 1 kHz from 64 sensor nodes to a base station, resulting in a battery life span of 10 weeks at the time of utilizing four 6 V lantern batteries.[105]

Therefore, for helping in dealing with the huge data amount produced by a WSN-based SHM system and the significant power consumption associated with it, distributed processing can be performed locally, which made it distinguished from the conventional approach.

Distributed processing. Distributed processing is obviously an important strategy for prolonging network life in WSN, which was introduced to process the in situ measured data locally before transmitting it to a base station. The practice of performing SHM algorithms directly on the sensor node can be used to save considerable energy within WSN by taking the advantage of inherent local processing that is performed within the embedded microprocessor of the sensor node. Therefore, this strategy is very important for assessing the performance of structure and the calibration of the analytical design model by extracting the modal information (like mode shapes and modal damping) from measured data.[159] Besides, it can help to prolong network life and enhance the scalability of network through minimizing data size and reducing data loss.[160]

However, it is important to consider challenges associated with the employment of distributed data processing in WSNs for SHM. The algorithms employed in SHM using WSNs are more sophisticated than those utilized in other application of WSNs, which may reduce or even neutralize the benefits they bring.[164] Besides, SHM algorithms usually require centralized processing and can demand incorporating data from other sensor nodes.[12,167] The basic challenge here is the way of adapting the existing SHM algorithms within the mote's OS for distributed processing architecture with a low-power consumption and a minimum data communication between sensor nodes for data-intensive SHM.[11] Moreover, while WSNs can contain considerable memory and data processing resources in an aggregate sense, individual sensor nodes have only small data storage and processing capabilities.

Procedures of distributed data processing can be divided into four stages:[15] First local data filtering is used for filtering conditional monitoring (such as location, threshold values, data quality, and freshness) to achieve high efficiency of data processing. Second, data compression improves efficiency of transmission via the reduction of data size. Third, data aggregation increases transmission efficiency by the elimination of unnecessary information and the combination of data into a few numbers of fully loaded packets. Fourth, data fusion elicits semantic correlation of data and makes a holistic method available for associating various topics for more context aware data processing. Combining the aforementioned four stages is considered a difficulty, yet it is not required to implement all of them in a single SHM's algorithm for distributed processing.

In the rest of this section, three categories of distributed processing are presented, including independent, hierarchical, and parallel processing.

Independent processing. In this strategy, measured data are processed on the sensor node independently to extract essential features from the raw data with no communication with other sensor nodes. Therefore, as shown in Figure 7(c), a decision about the status of the structure is taken locally and then transferred from sensor node to the base station.[163] After processing, the amount of transmitted data through the network is significantly reduced. Thus, this strategy is relatively power efficient when compared to centralized processing. However, from an SHM perspective, because of no communication between sensor nodes, this strategy cannot utilize available spatial information from other sensor nodes (e.g. flexibility matrix and mode shapes). Failure in combining spatial information prevents this strategy from autonomously producing system spatial features that limit the effectiveness of this strategy.[167]

A new distributed processing scheme utilizing the Hilbert–Huang transform (HHT) algorithm for modal identification was introduced in Wu et al.,[159] which was based on signal decomposition technique. The HHT-based distributed processing was then embedded within the Crossbow IRIS platform. The developed method was validated with both simulation and experiment, and the result showed ability to accomplish higher accuracy for identifying modal characteristics.

A semi-independent processing strategy was used in Abdaoui et al.[147] for investigating the effect of TSE on the mode shape identification where each sensor node locally computed the FFT of the collected data and then transmitted the FFT frequency samples to the base station. Then, the base station computed the mode shapes and utilized them for detecting and localizing damage. Results revealed that the TSE implemented meanwhile transferring the FFT frequency sample to the base station tended to frequency shift at the base station.

Hierarchical processing. As depicted in Figure 7(d), it can resolve the limitations of both centralized and independent processing strategies. The communication network is classified into hierarchical sensor communities (i.e. cluster) including base station, CH, and leaf nodes. Within a cluster, data processing is distributed between each leaf node and its corresponding CH. CHs exchange information with each other to provide condensed information (like modal properties, functions of correlation), make decisions collaboratively, and then transmit decisions to a base station. Localized data processing within each cluster minimizes data congestion and processing time, improving scalability, and reducing the overall network energy consumption.[167] However, the hierarchical processing strategy requires more sophisticated communication topology, which makes the management of the network difficult.[168]

Using SSI technique, SSI-based distributed system identification (SDSI) was proposed in Cho et al.[168] that was scheduled in the hierarchical network. The first step was to measure the structural responses by the network-wide synchronized sensing; thus, each cluster then began the community-wide data processing: CH collected data from all leaf nodes in its cluster and evaluated the parameters of the correlation functions. The processed data from every cluster were transmitted to the sink. The performance of this approach was experimentally validated in laboratory by means of a five-story shear building model.

A decentralized data aggregation energy-efficient cluster (DDAEEC) algorithm of SHM was proposed and evaluated by Parashar and Ranjan.[169] Here, all sensor nodes utilized the initial and residual energy level for defining the CHs. This DDAEEC approach permitted a significant amount of data to be transmitted from CH to a base station in scheduled time. Hence, the delay of time to reach the base station was reduced and the energy efficiency of the network got enhanced.

A cluster optimization framework was analyzed and validated in Fang et al.[170] for the deployment of sensor nodes with the goal of minimizing power utilized by monitoring truss structures. Followed by a cluster-based optimization framework, a method of adopting the proposed approach was presented to attain scalable and proficient deployment, through an inclusive case study of a real WSN for SHM scenario. In the developed case study, following the determination of number of clusters, optimal clustering approach initially produced a 20-node sensor configuration with a proposed flat topology. Policies were designated for the generation of the topology of deployed 20 nodes. First, sensor nodes having the shortest distances to the sink were chosen as the CH nodes. Second, leaf nodes sent their data only to the nearest CH. Third, size of the cluster should be taken into consideration in order to accommodate an appropriate number of leaf nodes. The deployment optimization yielded a 20-node scheme in comparison with the 38-node original scheme and saved 50% of the overall power consumed in the network while provided more accurate modal information.

Many other researches concentrated and participated on hierarchical processing for implementing SHM's algorithms (e.g. for modal analysis, damage detection, damage localization) due to the advantages introduced by this strategy, mainly improving scalability and reducing the overall network energy consumption. In general, distributing processing is considered a radical departure from the traditional strategy in monitoring structures.

Parallel processing. As shown in Figure 7(e), in this strategy each sensor node exchanges information only with its neighboring sensor nodes and makes decision autonomously, which improves the scalability and robustness of the network. Even though this strategy is still addressing issues related to consumption of power and network bandwidth, it enables WSNs to use typical off-line modal analysis approaches for extracting spatial modal data from arrays of sensor nodes without the need for a base station.[171] However, this strategy depends on fixed network topologies that are incompetent to produce coherent or correct results in case of failure of communication or sensor node.[105] In addition, limited studies are available, which implemented SHM's algorithms using parallel processing, so further work is still required for modifying current methods of analysis for implementing parallel processing within WSNs for SHM.

A distributed data processing strategy, termed as parallel processing, was proposed by Zimmerman et al.[171] Three output-only modal identification methods were adjusted and amended to be implemented within wireless sensor prototypes: FDD, peak picking (PP), and random decrement (RD). The proposed methods could autonomously specify modal frequencies by means of a distributed PP method, mode shapes via a distributed FDD algorithm, and modal damping ratios through a distributed RD method. Moreover, it was found that the implemented methods yielded modal parameters similar to those attained by means of conventional off-line analyses.

In addition, Zimmerman and Lynch[105] built upon their previous work in Zimmerman et al.[171] in the parallel processing on WSNs by designing a parallelized version of the simulated annealing (SA) stochastic optimization algorithm to be implemented within a decentralized WSN. This algorithm gained efficiency due to the growth of the sensor nodes number, making it scalable to large networks. Validation of the resulting distributed model updating approach was made within WSN through the identification of stiffness, mass, and damping properties of a three-story steel building exposed to a seismic motion.

Network scalability

Scalability means the network ability in increasing the sensor nodes' number (adopting and synchronizing new nodes with the existing nodes), other sensor nodes migrating from one sub-network to another. and existing sensor nodes leaving the network, while maintaining the performance and functionality of the network. Scalability of the WSNs for SHM makes adjustment flexibility available with structure, which can be accomplished by increasing sensor nodes density in the network, leading to define higher precision of damage detection and localization.[15,31] Therefore, SHM applications cover a large geographical civil structure and generate a huge amount of measured data, which make scalability of WSNs as one of the most crucial challenges. However, many researches, Aygün and Cagri Gungor,[5] Rice and Spencer,[8] Noel et al.,[16] Araujo et al.,[59] Kim et al.,[99] Jo et al.,[104] Rault et al.,[108] and Pakzad et al.,[166] in terms of the scalability demanded by WSNs for SHM, were discussed and explored.

Network architecture, with data processing strategies and data reduction techniques, plays an important role for WSN scalability for SHM by ensuring it can be enlarged regarding the sensor nodes' number, network topology complexity, quantity of data, and data quality (e.g. sampling frequency, sensitivity of sensor). Two principal strategies for data processing using WSNs for SHM were discussed in the "Data processing" section, as all of them influence network scalability in different ways. The first strategy is to use a WSN in place of a conventional monitoring system in a centralized data processing. This approach hinders network scalability from two main aspects: first, it is restricted by the bandwidth range and is not able to widen long distances with no large supply of power; second, due to the increasing size of network, the quantity of measured data intended for transmission comes to be uncontrollable. The second strategy is to utilize distributed processing, which includes three approaches: first, independent processing, which allows data acquisition and processing locally to minimize data glut and whole traffic of network meanwhile a simple design is maintained, however, this approach is still limited to sensor nodes bandwidth range;[7,16] second, hierarchical processing, which is multi-hop communication and essential for scalability of WSN that decreases the transferring of wireless data in order to realize intensively deployed large networks, but at the cost of more complex routing protocols;[108] third, parallel processing, which leverages peer-to-peer communication capability, which improves network scalability, however, this strategy depends on fixed network topologies and still in its infancy stage.

For assessing the performance of data processing approaches regarding network scalability, a scalable low-power WSN over optimized TDMA scheme termed as SnowFort was designed by Liao et al.,[172] for data analysis in structure and environmental monitoring. TDMA protocol was implemented and the star topology was employed, which limited the bandwidth range of the sensor nodes, and hence restricting the network scalability. SnowFort addressed the limitation of scalability through the addition of spatially deployed base stations. Frequency division multiple access (FDMA) was utilized for enabling all base stations to function altogether. The base stations were synchronized by means of GPS or the network time protocol. Consequently, scalability was ensured in two methods: first by using multiple base stations with maintaining synchronization among them to expand the network, and second, by transferring the compressed data and the processing data locally through transmitting the extracted features instead of the measured data, which led to reduce overall network traffic load.

The world's largest full-scale SHM deployment using WSN, which could be found in the literature, was presented in Jo et al.[104] with 113 sensor nodes and implemented on the Jindo Bridge, South Korea. Authors used decentralized data aggregation with cluster tree topology used for hierarchical processing that made the network scalability achievable. Moreover, ISHMP services toolsuite was used to implement decentralized data processing strategy. Thus, as an alternative of transmitting the measured data from the whole sensor nodes back to the base station, it sent only processed data after processing it locally that considerably minimized the amount of data transmission and consumption of power. The hybrid SHM system using WSNs was validated experimentally by the long-term function of full-scale deployment on Jindo Bridge. Likewise, Rice and Spencer[8] was the previous work of Jo et al.[104] who developed a smart sensor framework for scalable SHM that deployed 70 sensor nodes in total with SHM-A sensor node, which was deployed on Jindo Bridge. Moreover, a system was developed by Kim et al.[99] to scale to tens of nodes for enabling intensive sensor deployment on actual structures. This was validated on 64 sensor nodes and 46 hops deployed on the chief span and a tower of the GGB.

A trade-off is available between supporting scalability and achieving real-time communications, thus achieving both the scalability and accurate time synchronization is another challenge.[38] To resolve this issue, Sazonov et al.[54] developed a wireless intelligent sensor and actuator network taking into account the concern of scalability and time synchronization algorithm for applications of SHM. A hierarchical architecture was proposed and validated in which beacon synchronization was utilized for local clusters of sensor nodes and the synchronization of the allocated clusters was performed by means of GPS. The experiment results showed that even very big network is able to function with maximum TSE less than ± 23 μs. Therefore, it is possible to use the designed scalable network for creating time-synchronous sensor networks for applications of SHM.

In brief, largest full-scale SHM deployments using WSN were identified, and the effect of network architecture with data processing approaches and data reduction techniques on network scalability was investigated. Moreover, scalability can be ensured by using multiple base stations with maintaining synchronization among them to expand the network, also, by minimizing data transmission using compressed data, which consequently reduces the overall network traffic. In addition, distributed processing strategy also improves network scalability through minimizing the amount of data transferred as well as the maintaining of a hierarchy in the network. Finally, networks grow and the time synchronization with maintaining QoS of SHM system is a critical challenge and needs further investigation.

Open research issues

WSNs for SHM are vigorously growing and becoming desirable as MEMS and microelectronics progress. The implementation of more effective networks efficiently took place on various structures, as well as the analysis of measured data was implemented in order to evaluate different types of SHM parameters. In addition, solutions for the challenges associated with WSNs for SHM application in literatures proved the ability of this system to be improved and deployed in field test for real-time monitoring. However, there still exist many essential open research issues that can make qualitative transfer in WSNs for SHM, which explored in this section.

Fault tolerance

WSNs for SHM could be futile, if the WSNs requirements (such as fault tolerance and power efficiency) were not truly taken into consideration. Thus, to assure the remaining of WSNs for SHM connected in the occurrence of a fault and resilient to the faults, some studies presented approaches to maintain a definite degree of fault tolerance. However, due to the limited number of studies in this field, various open issues are available for future researchers to devote additional effort for further investigation in terms of fault tolerance to address requirements of both coverage and connectivity in WSN-based SHM system. First issue is to design algorithms for detecting sensor fault and performing recovery for SHM application.[132] Second issue is to innovate a redundant sensor scheduling approach for the backup sensor nodes that will awaken one or more backup sensor nodes in the concerned location (e.g. crack location) when a sensor fault/failure happens.[132,173]

Mobile-SHM and Cloud-SHM

Owing to the rapid development and popularization of smartphone in recent years, Mobile-SHM involved smartphones to be used for data collection and processing and dynamic features extraction for civil infrastructure. Moreover, the availability of smartphones in most of the civilian building and unique specification such as large memory and storage, powerful CPU and OS, and a variety of high-performance sensors (e.g. GPS, accelerometers, cameras, proximity sensors) are very appropriate to be used in SHM field. However, the smartphone embedded sensors have limitation in precision of measurement, which can be appropriate for only a particular measurement (e.g. cable force estimation, because cable has relatively distinctive vibration rather than the other structural element).[174] In addition, a massive data amount is generated, because big number of smartphones gets involved, which need special techniques to reduce the amount of traffic.[175] Mobile-SHM is still in its infancy stage and the realization of this approach may be considered as a milestone in making SHM common in the life of people.

Cloud computing with its data storage technology (e.g. Hadoop Distributed File System), data management technology (e.g. Big Table), and programming model (e.g. MapReduce) can be used to simplify the data storage and processing and retrieval of the big data.[176,177] Accordingly, Cloud-SHM introduced as a new monitoring approach, which proposed to involve cloud computing for rapid data collection, storage, processing, and assessment in WSNs or Mobile for SHM. For example, to validate the feasibility of Cloud-SHM using Mobile-SHM, Zhao et al.[178] developed smartphone application—namely, Orion-CC—to estimate the cable force using the accelerometer embedded in smartphone, to upload the data sharing platform, and to share it with the public. However, in general, more efforts are needed to be exerted in this field.

SHM algorithms and distributed processing

To reduce network data traffic and energy consumption, it is important to consider challenges associated with employing distributed data processing in WSN in conjunction with requirements of SHM algorithms. The algorithms used in WSNs for SHM (e.g. modal analysis, damage detection, system identification) are more sophisticated computationally than those used in other WSNs' application, which may lessen or even neutralize the obtained benefits.[164] Moreover, SHM algorithms are mostly centralized as they necessitate transmitting data from all sensor nodes within the network to a central station for data processing and evaluating the integrity of the structure and as well this algorithms can demand the incorporation of data from other sensor nodes.[3] The basic challenge here is how to adapt the existing centralized SHM algorithms for distributed processing architecture and embedded them within the mote's OS to minimize power consumption and data communication between sensor nodes for data-intensive SHM.[136,19]

On the contrary, recently hierarchical processing has been used intensively in WSNs for SHM. In a typical hierarchical WSN, total intra-cluster communication distance and total distance of CHs to base station relay on the number of CHs. Thus, to secure longest system life span, in addition to ensuring the monitoring quality, a proper cluster number should be specified cautiously in WSN, where leaf nodes are linked and organized into clusters. In this context, the issue under question is selecting the optimal number of CHs in hierarchical processing architecture in WSNs for SHM application.[170]

EH

The development of autonomous, self-powered SHM systems powered by the harvesting of ambient energy is an area of research that offers much potential and will continue to expand in combination with new developments in the field of low-power electronics.[122] EH technologies for WSNs are successfully growing and more developing as microelectronics and MEMS progress, which makes lifetime of network not constrained anymore by battery life, rather by lifetime of hardware. However, so far a limited number of WSN-based SHM systems implemented EH systems for extending the lifetime of network and optimizing design of network.[123]

The main objective of EH for WSNs is to transfer the wireless sensor nodes from the battery-powered nodes to an independent EH WSN. Existence of such EH sensor nodes, as component of the network, can address the conflicting design objectives of performance and lifetime, and an effect on network-wide protocols and solutions. Therefore, redefining the objectives of network design in WSNs will lead to a cautious adaptation of the several strategies and protocols engaged in transmitting data from the location of interest to the user,[179] for instance, adaptation of routing protocols to exploit the availability of new EH systems in the network. Likewise, for assuring reliability where data retransmission is required frequently, communication protocols and scheduling strategy must be adapted to fulfill the requirements of application level in EH WSNs for SHM.[180]

Storing electrical energy approaches are considered major technologies that will enable EH to be a power source for sensors and wireless sensor nodes, particularly for SHM large-scale and long-lasting applications. The main reason for this is that the major limitation researchers encounter in EH is the inability of the poor energy generated by harvesting devices to directly power most electronics.[181] Here, energy storage devices, for example, capacitors and rechargeable batteries, ought to be chosen based on application-specific requirements.[5] Moreover, additional efforts should be devoted by researchers for conducting more studies and evaluating the reliability performance of traditional and rechargeable battery technologies as well as for exploring the trade-offs between utilizing batteries and capacitors as storage devices.[122]

Lack of clear design guidelines of implementing EH devices is an obstacle of using this technology. These guidelines will assist in identifying how to integrate embedded sensor units with the harvesting devices, the best circuit and storage devices for a given application, and the effect of SHM environment on harvesting devices and performance. Thus, providing such guidelines requires intensive research endeavors for declaring the main parameters and predictive scheme impacting efficient EH.[181] On the contrary, practically, there exist no simulation environments, which are able to cover all aspects of EH in WSNs. This simulator will be a tool of great value having the purpose of evaluating the effect of developed EH systems on large deployed WSNs.[179]

Optimal sensor placement

While optimal sensor placement aims at obtaining a sensor layout, which offers the maximum possible dynamic information of a structure in SHM, accurate selection and placement of sensors are considered an important topic in the development and deployment of an effective WSN-based SHM system.[182] Likewise, it is important to compare the efficiency of a research proposed approach in determining optimal sensor location with other sensor placement algorithms while using large numbers of sensors on the structure.[183] Moreover, balancing the requirements of civil engineering and considerations of network design is another challenge in sensor placement in SHM using WSNs. The importance of the effect of sensor placement on other parameters, such as wireless network design parameters, should not be underestimated. Thus, it is essential to perform exploring and analyzing for the effect of data sampling and aggregation strategies, along with placement of sensor node, on life span of network and consumption of power in a more general WSN with non-uniform data intensity.[184]

Conclusion

In this contemporary review, an effort was made to present WSNs for SHM from different perspectives by attempting to encompass significant and sufficient work in this multi-disciplinary field. This article offered a thorough survey from three main dimensions. First, background information relating to technologies of traditional wired SHM and WSN-based SHM systems were clarified. Then, up-to-date academic and commercial wireless platform technologies used for SHM in literature were summarized chronologically from 2005 to 2019. Second, special attention has been devoted to the key challenges related to WSNs for SHM and to the comprehensive and systematic classification of the solutions proposed in the literature. Third, the directions of future research for WSN-based SHM systems were presented. Finally, we believe that the insights proposed in this article will encourage further research toward usage and deployment of WSNs for SHM applications to increase safety and security in the cities.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Mohammed Abdulkarem https://orcid.org/0000-0002-4424-9313

References

1. Yi TH and Li HN. Methodology developments in sensor placement for health monitoring of civil infrastructures. *Int J Distrib Sens Netw* 2012; 8(8): 612–726.
2. Ceylan H, Yavas S, Dong L, et al. Development of a wireless MEMS multifunction sensor system and field demonstration of embedded sensors for monitoring concrete pavements, vol. I, 2016, https://ceer.iastate.edu/research/completed/development-of-a-wireless-mems-multifunction-sensor-system-and-field-demonstration-of-embedded-sensors-for-mon itoring-concrete-pavements/
3. Avci O, Abdeljaber O, Kiranyaz S, et al. Wireless and real-time structural damage detection: a novel decentralized method for wireless sensor networks. *J Sound Vibrat* 2018; 424: 158–172.
4. Ji Q, Parvasi SM, Ho SCM, et al. Wireless energy harvesting using time reversal technique: an experimental study with numerical verification. *J Intell Mater Syst Struct* 2017; 28(19): 2705–2716.
5. Aygün B and Cagri Gungor V. Wireless sensor networks for structure health monitoring: recent advances and future research directions. *Sens Rev* 2011; 31(3): 261–276.
6. Yick J, Mukherjee B and Ghosal D. Wireless sensor network survey. *Comp Netw* 2008; 52(12): 2292–2330.
7. Lynch JP and Loh KJ. A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock Vibrat Digest* 2006; 38(2): 91–128.
8. Rice JA and Spencer BF Jr. *Flexible smart sensor framework for autonomous full-scale structural health monitoring*. Champaign, IL: University of Illinois at Urbana-Champaign, 2009.
9. Sabato A, Niezrecki C and Fortino G. Wireless MEMS-based accelerometer sensor boards for structural vibration monitoring: a review. *IEEE Sens J* 2017; 17(2): 226–235.
10. Dragos K and Smarsly K. A comparative review of wireless sensor nodes for structural health monitoring. In: *Proceedings of the 7th international conference on structural health monitoring of intelligent infrastructure (SHMII)*, Vol. 1, Turin, 1–3 July 2015.
11. Zhou GD and Yi TH. Recent developments on wireless sensor networks technology for bridge health monitoring. *Mathemat Prob Eng* 2013; 2013: 947867.
12. Liu X, Cao J, Song WZ, et al. Distributed sensing for high-quality structural health monitoring using WSNs. *IEEE Trans Paral Distr Syst* 2015; 26(3): 738–747.
13. Cao J and Liu X. 2016 *Requirements, challenges, and summary of hardware and software design for a WSN-based SHM system*. London: Springer, pp. 7–11.
14. Wang P, Yan Y, Tian GY, et al. Investigation of wireless sensor networks for structural health monitoring. *J Sens* 2012; 2012: 156329.
15. Nie P and Jin Z. Requirements, challenges and opportunities of wireless sensor networks in structural health monitoring. In: *3rd IEEE international conference on broadband network and multimedia technology (IC-BNMT)*, Beijing, China, 26–28 October 2010, pp. 1052–1057. New York: IEEE.
16. Noel AB, Abdaoui A, Elfouly T, et al. Structural health monitoring using wireless sensor networks: a comprehensive survey. *IEEE Comm Surv Tutor* 2017; 19(3): 1403–1423.
17. Wijetunge S, Gunawardana U and Liyanapathirana R. Wireless sensor networks for structural health monitoring: considerations for communication protocol design. In: *2010 IEEE 17th international conference on telecommunications (ICT)*, Doha, Qatar, 4–7 April 2010, pp. 694–699. New York: IEEE.
18. Enckell M. *Structural Health Monitoring using modern sensor technology: long-term monitoring of the New Årsta Railway Bridge*. Thesis, 2006, https://www.diva-portal.org/smash/get/diva2:11396/FULLTEXT01.pdf
19. Xu N, Rangwala S, Chintalapudi KK, et al. A wireless sensor network for structural monitoring. In: *Proceedings of the 2nd international conference on embedded networked sensor systems*, Baltimore, MD, 3–5 November 2004, pp. 13–24. New York: ACM.
20. Zhang W, Wan J, Yang B, et al. An energy efficient routing protocol in wireless sensor network for health monitoring. In: *IEEE symposium on electrical & electronics engineering (EEESYM)*, Kuala Lumpur, Malaysia, 24–27 June 2012, pp. 247–250. New York: IEEE.
21. Zhu L, Fu Y, Chow R, et al. Development of a high-sensitivity wireless accelerometer for structural health monitoring. *Sensors* 2018; 18(1): 262.
22. Kohler MD, Hao S, Mishra N, et al. ShakeNet: a portable wireless sensor network for instrumenting large civil structures. 2015, https://pubs.er.usgs.gov/publication/ofr20151134

23. Rice JA and Spencer BF. Structural health monitoring sensor development for the Imote2 platform. In: Tomizuka M (ed.) *Sensors and smart structures technologies for civil, mechanical, and aerospace systems*, Vol. 6932. Bellingham WA: International Society for Optics and Photonics, 2008, p. 693234.
24. Ou J and Li H. Structural health monitoring in mainland China: review and future trends. *Struct Health Monitor* 2010; 9(3): 219–231.
25. Jo H, Park JW, Spencer BF, et al. Development of high-sensitivity wireless strain sensor for structural health monitoring. *Smart Struct Syst* 2013; 11(5): 477–496.
26. Moreu F, Kim RE, Spencer BF, et al. Railroad bridge monitoring using wireless smart sensors. *Struct Contr Health Monitor* 2017; 24(2): e1863.
27. Zhang Y and Bai L. Rapid structural condition assessment using radio frequency identification (RFID) based wireless strain sensor. *Automation in Construction* 2015; 54: 1–11.
28. Al-Sharif L, Kilani M, Taifour S, et al. Linear variable differential transformer design and verification using MATLAB and finite element analysis. In : *MATLAB for engineers-applications in control, electrical engineering, IT and robotics*. Intech, 2011, https://www.intechopen.com/books/matlab-for-engineers-applications-in-control-electrical-engineering-it-and-robotics/linear-variable-differential-transformer-design-and-verification-using-matlab-and-finite-element-ana
29. Martino M, Danisi A, Losito R, et al. Design of a linear variable differential transformer with high rejection to external interfering magnetic field. *IEEE Trans Magnet* 2010; 46(2): 674–677.
30. Veilleux S, Abedi A, Wilkerson C, et al. Wireless linear variable differential transformer design and structural performance analysis. In: *2018 6th IEEE international conference on wireless for space and extreme environments (WISEE)*, Huntsville, AL, 11–13 December 2018, pp. 152–157. New York: IEEE.
31. Haque ME, Zain MFM, Hannan MA, et al. Recent application of structural civil health monitoring using WSN and FBG. *World Appl Sci J* 2012; 20(4): 585–590.
32. Sun M, Staszewski WJ and Swamy RN. Smart sensing technologies for structural health monitoring of civil engineering structures. *Adv Civil Eng* 2010; 2010: 724962.
33. Pang C, Yu M, Zhang XM, et al. Multifunctional optical MEMS sensor platform with heterogeneous fiber optic Fabry–Pérot sensors for wireless sensor networks. *Sens Actuat A Phys* 2012; 188: 471–480.
34. Bhuiyan MZA, Wu J, Wang G, et al. Towards cyber-physical systems design for structural health monitoring: hurdles and opportunities. *ACM Trans Cyber-Phys Syst* 2017; 1(4): 19.
35. Vieira MAM, da Cunha AB and da Silva DC. Designing wireless sensor nodes. In: Vassilidas S, Wong S and Hämäläinen TD (eds) *International workshop on embedded computer systems*. New York: Springer, 2006, pp. 99–108.
36. Bischoff R, Meyer J and Feltrin G. Wireless sensor network platforms. In: Boller C, Chang FK and Fujino Y (eds) Encyclopedia of structural health monitoring. Hoboken, NJ: John Wiley & Sons, 2009, pp. 1229–1238.
37. Anastasi G, Re GL and Ortolani M. WSNs for structural health monitoring of historical buildings. In: *2nd conference on human system interactions (HSI'09)*, Catania, 21–23 May 2009, pp. 574–579. New York: IEEE.
38. Tennina S, Koubâa A, Daidone R, et al. *IEEE 802.15. 4 and Zigbee as enabling technologies for low-power wireless systems with quality-of-service constraints*. London: Springer, 2013.
39. Sharma D, Verma S and Sharma K. Network topologies in wireless sensor networks: a review, 2013, http://www.iject.org/vol4/spl3/c0116.pdf
40. Sharma S, Kumar D and Kishore K. Wireless sensor networks-a review on topologies and node architecture. *Int J Comp Sci Eng* 2013; 1: 19–25.
41. Liu X and Liu X. atypical hierarchical routing protocols for wireless sensor networks: a review. *IEEE Sens J* 2015; 15: 5372–5383.
42. Levis P, Madden S, Polastre J, et al. *TinyOS: an operating system for sensor networks*. New York: Springer, 2005, pp. 115–148.
43. TinyOS. https://github.com/tinyos/tinyos-main accessed 20 August 2018.
44. Dunkels A, Gronvall B and Voigt T. Contiki-a lightweight and flexible operating system for tiny networked sensors. In: *29th annual IEEE international conference on local computer networks*, Tampa, FL, 16–18 November 2004, pp. 455–462. New York: IEEE.
45. Roussel K and Song YQ. *A critical analysis of Contiki's network stack for integrating New MAC protocols*. PhD thesis, INRIA, Nancy, 2013.
46. Pentaris FP, Stonham J and Makris JP. A cost effective wireless structural health monitoring network for buildings in earthquake zones. *Smart Mater Struct* 2014; 23(10): 105010.
47. Dos Santos IL, Pirmez L, Lemos ÉT, et al. A localized algorithm for structural health monitoring using wireless sensor networks. *Informat Fusion* 2014; 15: 114–129.
48. Swartz RA, Jung D, Lynch JP, et al. Design of a wireless sensor for scalable distributed in-network computation in a structural health monitoring system. In: *Proceedings of the 5th international workshop on structural health monitoring*, 2005, pp. 12–14, https://pdfs.semanticscholar.org/2d90/3e038c1812ea6fb8665aae9c1bf61aa8a1c9.pdf
49. Wang Y, Lynch JP and Law KH. A wireless structural health monitoring system with multithreaded sensing devices: design and validation. *Struct Infrastruct Eng* 2007; 3(2): 103–120.
50. Mascarenas DL, Todd MD, Park G, et al. Development of an impedance-based wireless sensor node for structural health monitoring. *Smart Mater Struct* 2007; 16(6): 2137.
51. Sazonov E, Li H, Curry D, et al. Self-powered sensors for monitoring of highway bridges. *IEEE Sens J* 2009; 9(11): 1422–1429.
52. Harms T, Banks B, Sedigh Sarvestani S, et al. Design and testing of a low-power wireless sensor network for structural health monitoring of bridges. In: *Sensors and smart structures technologies for civil, mechanical, and aerospace*

systems, Vol. 7292, p. 72920U, International Society for Optics and Photonics, https://pdfs.semanticscholar.org/8ee6/ 3e0604bf95e55a64da0661783013152b9153.pdf
53. Zhou D, Ha DS and Inman DJ. Ultra low-power active wireless sensor for structural health monitoring. *Smart Struct Syst* 2010; 6(5–6): 675–687.
54. Sazonov E, Krishnamurthy V and Schilling R. Wireless intelligent sensor and actuator network-a scalable platform for time-synchronous applications of structural health monitoring. *Struct Health Monitor* 2010; 9(5): 465–476.
55. Mascarenas DDL, Flynn EB, Todd MD, et al. Development of capacitance-based and impedance-based wireless sensors and sensor nodes for structural health monitoring applications. *J Sound Vibrat* 2010; 329(12): 2410–2420.
56. Lédeczi Völgyesi ÁP, Barth E, et al. *Self-sustaining wireless acoustic emission sensor system for bridge monitoring*. London: Springer, 2011, pp. 15–39.
57. Bocca M, Eriksson LM, Mahmood A, et al. A synchronized wireless sensor network for experimental modal analysis in structural health monitoring. *Comp Aided Civil Infrastruct Eng* 2011; 26(7): 483–499.
58. Boyle D, Magno M, O'Flynn B, et al. Towards persistent structural health monitoring through sustainable wireless sensor networks. In: *2011 seventh international conference on intelligent sensors, sensor networks and information processing (ISSNIP)*, pp. 323–328, IEEE, https://ieeexplore.ieee.org/abstract/document/6146587
59. Araujo A, Garca-Palacios J, Blesa J, et al. Wireless measurement system for structural health monitoring with high time-synchronization accuracy. *IEEE Trans Instrument Measure* 2012; 61(3): 801–810.
60. Kevin I, Wang K, Salcic Z, et al. Miniaturized wireless sensor node for earthquake monitoring applications. In: *2012 7th IEEE international symposium on industrial embedded systems (SIES)*, pp. 323–326, IEEE, https://ieeexplore.ieee.org/abstract/document/6356607
61. Hu X, Wang B and Ji H. A wireless sensor network-based structural health monitoring system for highway bridges. *Comp Aided Civil Infrastruct Eng* 2013; 28(3): 193–209.
62. Liu Z, Yu Y, Liu G, et al. Design of a wireless measurement system based on WSNs for large bridges. *Measurement* 2014; 50: 324–330.
63. Huang Q, Tang B and Deng L. Development of high synchronous acquisition accuracy wireless sensor network for machine vibration monitoring. *Measurement* 2015; 66: 35–44.
64. Miyazaki T, Li P, Guo S, et al. On-demand customizable wireless sensor network. *Procedia Comp Sci* 2015; 52: 302–309.
65. Buttarazzi B, Troiani G, Liguori W, et al. Smart Sensor Box: a real implementation of devices network for structural health monitoring. In: *2015 11th international conference on signal-image technology & Internet-based systems (SITIS)*, pp. 816–823, IEEE, https://ieeexplore.ieee.org/document/7400657
66. Yao H, Cao H and Li J. Design and implementation of a portable wireless system for structural health monitoring. *Measure Control* 2016; 49(1): 23–32.
67. Herrasti Z, Val I, Gabilondo I, et al. Wireless sensor nodes for generic signal conditioning: application to structural health monitoring of wind turbines. *Sens Actuat A Phys* 2016; 247: 604–613.
68. Perera R, Pérez A, García-Diéguez M, et al. Active wireless system for structural health monitoring applications. *Sensors* 2017; 17(12): E2880.
69. Wo Y, Liu W and Li K. A novel wireless acoustic emission sensor system for distributed wooden structural health monitoring. *Int J Innovat Comp Informat Control* 2017; 13(4): 1289–1306.
70. Chandankhede V. Health monitoring of highway bridges using wireless sensor networks. *Health* 2017; 6(8), http://ijarece.org/wp-content/uploads/2017/08/IJARECE-VOL-6-ISSUE-8-927-930.pdf
71. Fu H, Khodaei ZS and Ferri Aliabadi MH. An event-triggered energy-efficient wireless structural health monitoring system for impact detection in composite airframes. *IEEE Internet Things J* 2019; 6(1): 1183–1192.
72. Jo H, Sim S-H, Nagayama T, et al. Development and application of high-sensitivity wireless smart sensors for decentralized stochastic modal identification. *J Eng Mech* 2011; 138(6): 683–694.
73. Sabato A and Feng M. Feasibility of frequency-modulated wireless transmission for a multi-purpose MEMS-based accelerometer. *Sensors* 2014; 14(9): 16563–16585.
74. Sabato A, Feng MQ, Fukuda Y, et al. A novel wireless accelerometer board for measuring low-frequency and low-amplitude structural vibration. *IEEE Sens J* 2016; 16(9): 2942–2949.
75. Ramos LF, Aguilar R and Louren PB. Operational modal analysis of historical constructions using commercial wireless platforms. *Struct Health Monitor* 2011; 10(5): 511–521.
76. Zolertia. https://zolertia.io/
77. Contreras W and Ziavras S. Wireless sensor network-based pattern matching technique for the circumvention of environmental and stimuli-related variability in structural health monitoring. *IET Wireless Sens Syst* 2016; 6(1): 26–33.
78. Liu P, Lim HJ, Yang S, et al. Development of a stick-and-detect wireless sensor node for fatigue crack detection. *Struct Health Monitor* 2017; 16(2): 153–163.
79. AdvanticSYS. https://www.advanticsys.com accessed 14 April 2019.
80. Surmacz T, Slabicki M, Wojciechowski B, et al. Lessons learned from the deployment of wireless sensor networks. In: Kwiecień A, Gaj P and Stera P (eds) *Computer networks*. London: Springer, 2013, pp. 76–85.
81. Libelium. Waspmote, http://libelium.com/development/waspmote/documentation/waspmote-technical-guide
82. Shimmer. http://www.shimmersensing.com accessed 20 April 2019.
83. Dondi D, Di Pompeo A, Tenti C, et al. Shimmer: a wireless harvesting embedded system for active ultrasonic structural health monitoring. In: *SENSORS*, 2010, pp. 2325–2328, https://ieeexplore.ieee.org/abstract/document/5690935

84. Bell SJ. Staying true to the core: designing the future academic library experience. *Portal* 2014; 14(3): 369–382.
85. Panstamp. http://www.panstamp.com/
86. Charcopa D, Daniel S, Demera G, et al. *Diseo e implementacin de un sistema de alerta temprana de sismos mediante redes SWAP con nodos panStamp NRG para la ESPOCH*. Thesis, 2016, http://dspace.espoch.edu.ec/handle/123456789/6421
87. STMicroelectronics. https://www.st.com/en/evaluation-tools/b-l072z-lrwan1.html accessed 14 April 2019.
88. Murata. https://wireless.murata.com/pub/RFM/data/type_abz.pdf accessed 14 April 2019.
89. Loubet G, Takacs A, Gardner E, et al. LoRaWAN battery-free wireless sensors network designed for structural health monitoring in the construction domain. *Sensors* 2019; 19(7): 1510.
90. Loubet G, Takac A and Dragomirescu D. Implementation of a battery-free wireless sensor for cyber-physical systems dedicated to structural health monitoring applications. *IEEE Access* 2019; 7: 24679–24690.
91. Arduino. https://www.arduino.cc accessed 20 April 2019.
92. Solahuddin YF and Ismail W. Data fusion for reducing power consumption in Arduino-Xbee wireless sensor network platform. In: *2014 international conference on computer and information sciences (ICCOINS)*, 2014, pp. 1–6, https://ieeexplore.ieee.org/abstract/document/6868379
93. Ozdagli AI, Liu B and Moreu F. Low-cost, efficient wireless intelligent sensors (LEWIS) measuring real-time reference-free dynamic displacements. *Mech Syst Signal Proc* 2018; 107: 343–356.
94. Paek J, Chintalapudi K, Govindan R, et al. A wireless sensor network for structural health monitoring: performance and experience. In: *The second IEEE workshop on embedded networked sensors (EmNetS-II)*, 2005, pp. 1–9, https://ieeexplore.ieee.org/document/1469093
95. Shu W, Liu X, Gu Z, et al. Optimal sampling rate assignment with dynamic route selection for real-time wireless sensor networks. In: *Real-time systems symposium*, 2008, pp. 431–441, https://ieeexplore.ieee.org/document/4700456
96. Linderman LE, Mechitov KA, Spencer BF, et al. *Real-time wireless data acquisition for structural health monitoring and control*. Technical Report 1940-9826. Champaign, IL: Newmark Structural Engineering Laboratory, University of Illinois at Urbana-Champaign, 2011.
97. Vasseur JP and Dunkels A. *Interconnecting smart objects with IP: the next Internet*. Burlington, MA: Morgan Kaufmann, 2010.
98. Bhuiyan MZA, Wang G, Cao J, et al. Energy and bandwidth-efficient wireless sensor networks for monitoring high-frequency events. In: *10th annual IEEE communications society conference on sensor, mesh and ad hoc communications and networks (SECON)*, 2013, pp. 194–202, https://ieeexplore.ieee.org/document/6644978
99. Kim S, Pakzad S, Culler D, et al. Health monitoring of civil infrastructures using wireless sensor networks. In: *Proceedings of the 6th international conference on information processing in sensor networks*, 2007, pp. 254–263, https://ieeexplore.ieee.org/document/4379685
100. Hackmann G, Sun F, Castaneda N, et al. A holistic approach to decentralized structural damage localization using wireless sensor networks. *Comp Comm* 2012; 36(1): 29–41.
101. Mechitov K, Kim W, Agha G, et al. High-frequency distributed sensing for structure monitoring. In: *Proceedings of the first international workshop on human-centered sensing, networking, and systems (INSS'04)*, Delft, 6–8 November 2004, pp. 101–105. New York: ACM.
102. Zonta D, Wu H, Pozzi M, et al. Wireless sensor networks for permanent health monitoring of historic buildings. *Smart Struct Syst* 2010; 6(5–6): 595–618.
103. Whelan MJ and Janoyan KD. Design of a robust, high-rate wireless sensor network for static and dynamic structural monitoring. *J Intel Mater Syst Struct* 2009; 20(7): 849–863.
104. Jo H, Sim SH, Mechitov KA, et al. Hybrid wireless smart sensor network for full-scale structural health monitoring of a cable-stayed bridge. In: Tomizuka M (ed.) *Sensors and smart structures technologies for civil, mechanical, and aerospace systems*, Vol. 7981. Bellingham WA: International Society for Optics and Photonics, 2011, p. 798105.
105. Zimmerman AT and Lynch JP. A parallel simulated annealing architecture for model updating in wireless sensor networks. *IEEE Sens J* 2009; 9(11): 1503–1510.
106. Fu TS, Ghosh A, Johnson EA, et al. Energy-efficient deployment strategies in structural health monitoring using wireless sensor networks. *Struct Contr Health Monitor* 2013; 20(6): 971–986.
107. Farooq MO and Kunz T. Contiki-based IEEE 802.15 4 channel capacity estimation and suitability of its CSMA-CA MAC layer protocol for real-time multimedia applications. *Mobile Information Systems* 2015; 2015: 398637.
108. Rault T, Bouabdallah A and Challal Y. Energy efficiency in wireless sensor networks: a top-down survey. *Comp Netw* 2014; 67: 104–122.
109. Anastasi G, Conti M, Di Francesco M, et al. Energy conservation in wireless sensor networks: a survey. *Ad Hoc Netw* 2009; 7(3): 537–568.
110. Hu Q, Liu X, Wu Q, et al. Cluster-based energy-efficient structural health monitoring using wireless sensor networks. In: *International conference on computer science & service system (CSSS)*, 2012, pp. 1951–1956, https://ieeexplore.ieee.org/document/6394805
111. Srisooksai T, Keamarungsi K, Lamsrichan P, et al. Practical data compression in wireless sensor networks: a survey. *J Netw Comp Appl* 2012; 35(1): 37–59.
112. Zou Z, Bao Y, Li H, et al. Embedding compressive sensing-based data loss recovery algorithm into wireless smart sensors for structural health monitoring. *IEEE Sens J* 2015; 15(2): 797–808.
113. Skulic J and Leung KK. Application of network coding in wireless sensor networks for bridge monitoring. In: *IEEE 23rd international symposium on personal indoor and mobile radio communications (PIMRC)*, 2012, pp. 789–795, https://ieeexplore.ieee.org/document/6362891

114. Yildirim U, Oguz O and Bogdanovic N. A prediction-error-based method for data transmission and damage detection in wireless sensor networks for structural health monitoring. *J Vibrat Control* 2013; 19(15): 2244–2254.
115. Agarwal D and Kishor N. Network lifetime enhanced tri-level clustering and routing protocol for monitoring of offshore wind farms. *IET Wireless Sens Syst* 2014; 4(2): 69–79.
116. Agarwal D and Kishor N. Network life time enhancement for routing protocol in application to wind farm monitoring, 2013, https://ieeexplore.ieee.org/document/6832336
117. Mansourkiaie F, Ismail LS, Elfouly TM, et al. Maximizing lifetime in wireless sensor network for structural health monitoring with and without energy harvesting. *IEEE Access* 2017; 5: 2383–2395.
118. Yang C, Cao J, Liu X, et al. A high quality event capture scheme for WSN-based structural health monitoring. In: *IEEE global communications conference (GLOBECOM)*, 2012, pp. 622–627, https://ieeexplore.ieee.org/document/6503182
119. Bhuiyan MZA, Wu J, Wang G, et al. Sensing and decision making in cyber-physical systems: the case of structural event monitoring. *IEEE Trans Ind Informat* 2016; 12(6): 2103–2114.
120. Ghosh SK, Suman M, Datta R, et al. Power efficient event detection scheme in wireless sensor networks for railway bridge health monitoring system. In: *IEEE international conference on advanced networks and telecommunications systems (ANTS)*, 2014, pp. 1–6, https://ieeexplore.ieee.org/document/7057276
121. Niu J, Deng Z, Zhou F, et al. A structural health monitoring system using wireless sensor network. In: *5th international conference on wireless communications, networking and mobile computing*, 2009, pp. 1–4, https://ieeexplore.ieee.org/document/5302988
122. Davidson J and Mo C. Recent advances in energy harvesting technologies for structural health monitoring applications. *Smart Mater Res* 2014; 2014: 410316.
123. Torah R, Glynne-Jones P, Tudor M, et al. Self-powered autonomous wireless sensor node using vibration energy harvesting. *Measure Sci Tech* 2008; 19(12): 125202.
124. Wardlaw JL, Karaman I and Karsilayan A. Low-power circuits and energy harvesting for structural health monitoring of bridges. *IEEE Sens J* 2013; 13(2): 709–722.
125. Magno M, Jackson N, Mathewson A, et al. Combination of hybrid energy harvesters with MEMS piezoelectric and nano-Watt radio wake up to extend lifetime of system for wireless sensor nodes. In: *Proceedings of 2013 26th international conference on architecture of computing systems (ARCS)*, 2013, pp. 1–6, https://ieeexplore.ieee.org/document/6468881
126. Farinholt KM, Park G and Farrar CR. RF energy transmission for a low-power wireless impedance sensor node. *IEEE Sens J* 2009; 9(7): 793–800.
127. Wang X and Mortazawi A. Medium wave energy scavenging for wireless structural health monitoring sensors. *IEEE Trans Microwave Theory Tech* 2014; 62(4): 1067–1073.
128. Kim RE, Mechitov K, Sim SH, et al. Probabilistic assessment of high-throughput wireless sensor networks. *Sensors* 2016; 16(6): E792.
129. Chin JC, Rautenberg JM, Ma CYT, et al. An experimental low-cost, low-data-rate rapid structural assessment network. *IEEE Sens J* 2009; 9(11): 1361–1369.
130. Federici F, Graziosi F, Faccio M, et al. An integrated approach to the design of wireless sensor networks for structural health monitoring. *Int J Distribut Sens Netw* 2012; 8(3): 594842.
131. Liu X, Cao J, Bhuiyan MZA, et al. Fault tolerant WSN-based structural health monitoring. In: *IEEE/IFIP 41st international conference on dependable systems & networks (DSN)*, 2011, pp. 37–48, https://ieeexplore.ieee.org/document/5958205
132. Bhuiyan MZA, Wang G, Cao J, et al. Deploying wireless sensor networks with fault-tolerance for structural health monitoring. *IEEE Trans Comp* 2015; 64(2): 382–395.
133. Bhuiyan MZA, Wang G, Wu J, et al. Dependable structural health monitoring using wireless sensor networks. *IEEE Trans Depend Secure Comp* 2017; 14(4): 363–376.
134. Liu X, Cao J, Tang S, et al. Fault tolerant complex event detection in WSNs: a case study in structural health monitoring. *IEEE Trans Mobile Comp* 2015; 14(12): 2502–2515.
135. De Souza LMS, Vogt H and Beigl M. *A survey on fault tolerance in wireless sensor networks*. Karlsruhe: Universität Karlsruhe, 2007.
136. Paradis L and Han Q. A survey of fault management in wireless sensor networks. *J Netw Syst Manage* 2007; 15(2): 171–190.
137. Alwan H and Agarwal A. A survey on fault tolerant routing techniques in wireless sensor networks. In: *Third international conference on sensor technologies and applications (SENSORCOMM'09)*, 2009, pp. 366–371, https://ieeexplore.ieee.org/abstract/document/5210891
138. Bhuiyan MZA, Cao J, Wang G, et al. Energy-efficient and fault-tolerant structural health monitoring in wireless sensor networks. In: *2012 IEEE 31st symposium on reliable distributed systems (SRDS)*, 2012, pp. 301–310, https://ieeexplore.ieee.org/document/6424870
139. Smarsly K and Law KH. Decentralized fault detection and isolation in wireless structural health monitoring systems using analytical redundancy. *Adv Eng Software* 2014; 73: 1–10.
140. Bao Y, Li H, Sun X, et al. Compressive sampling-based data loss recovery for wireless sensor networks used in civil structural health monitoring. *Struct Health Monitor* 2013; 12(1): 78–95.
141. Pentaris FP, Stonham J and Makris JP. A review of the state-of-the-art of wireless SHM systems and an experimental set-up towards an improved design. In: *EUROCON*, 2013, pp. 275–282, https://ieeexplore.ieee.org/document/6624997
142. Yan G and Dyke SJ. Structural damage detection robust against time synchronization errors. *Smart Mater Struct* 2010; 19(6): 65001.

143. Spencer BF, Jo H, Mechitov KA, et al. Recent advances in wireless smart sensors for multi-scale monitoring and control of civil infrastructure. *J Civil Struct Health Monitor* 2016; 6(1): 17–41.
144. Feng ZQ and Katafygiotis LS. A method for correcting synchronization errors in wireless sensors for structural modal identification. *Procedia Eng* 2011; 14: 498–505.
145. Noh KL, Serpedin E and Qaraqe K. A new approach for time synchronization in wireless sensor networks: pairwise broadcast synchronization. *IEEE Trans Wireless Comm* 2008; 7(9): 3318–3322.
146. Bae SK. *Time synchronization by double-broadcasting for wireless sensor networks*. London: Springer, 2012, pp. 21–28.
147. Abdaoui A, El Fouly TM and Ahmed MH. Impact of time synchronization error on the mode-shape identification and damage detection/localization in WSNs for structural health monitoring. *J Netw Comp Appl* 2017; 83: 181–189.
148. Feng Z and Katafygiotis L. The effect of non-synchronous sensing in wireless sensors on structural modal identification. In: *3rd international conference on computational methods in structural dynamics and earthquake engineering (COMPDYN 2011)*, Corfu, http://repository.ust.hk/ir/Record/1783.1-38716
149. Nguyen T, Chan THR and Thambiratnam DP. Effects of wireless sensor network uncertainties on Output-only Modal Analysis employing merged data of multiple tests. *Adv Struct Eng* 2014; 17(3): 319–329.
150. Xiao X, Tang B and Deng L. High accuracy synchronous acquisition algorithm of multi-hop sensor networks for machine vibration monitoring. *Measurement* 2017; 102: 10–19.
151. Ganeriwal S, Kumar R and Srivastava MB. Timing-sync protocol for sensor networks. In: *Proceedings of the 1st international conference on embedded networked sensor systems*, 2003, pp. 138–149, https://dl.acm.org/citation.cfm?id = 958508
152. Maróti M, Kusy B, Simon G, et al. The flooding time synchronization protocol. In: *Proceedings of the 2nd international conference on embedded networked sensor systems*, 2004, pp. 39–49, https://dl.acm.org/citation.cfm?id = 1031495.1031501
153. Elson J, Girod L and Estrin D. Fine-grained network time synchronization using reference broadcasts. *ACM SIGOPS Oper Syst Rev* 2002; 36: 147–163.
154. Jiang XD, Tang YL and Lei Y. Wireless sensor networks in structural health monitoring based on Zigbee technology. In: *3rd international conference on anti-counterfeiting, security, and identification in communication*, 2009, pp. 449–452, https://ieeexplore.ieee.org/abstract/document/5276977
155. Krishnamurthy V, Fowler K and Sazonov E. The effect of time synchronization of wireless sensors on the modal analysis of structures. *Smart Mater Struct* 2008; 17(5): 055018.
156. Wang WD, Jiang SF, Zhou HF, et al. Time synchronization for acceleration measurement data of Jiangyin Bridge subjected to a ship collision. *Struct Contr Health Monitor* 2018; 25(1): e2039.
157. Lei Y, Kiremidjian AS, Krishnan Nair K, et al. Algorithms for time synchronization of wireless structural monitoring sensors. *Earthquake Eng Struct Dyn* 2005; 34(6): 555–573.
158. Hu X, Wang B and Hu X. A novel energy-balanced time synchronization protocol in wireless sensor networks for bridge structure health monitoring. In: *2nd international workshop on database technology and applications (DBTA)*, 2010, pp. 1–5, https://ieeexplore.ieee.org/document/5658999
159. Wu N, Liu C, Guo Y, et al. Onboard computing for structural health monitoring with smart wireless sensors by modal identification using Hilbert-Huang transform. *Mathemat Prob Eng* 2013; 2013: 509129.
160. Ling Q, Tian Z and Li Y. Distributed decision-making in wireless sensor networks for online structural health monitoring. *J Comm Netw* 2009; 11(4): 350–358.
161. Andrew Swartz R. *Decentralized algorithms for SHM over wireless and distributed smart sensor networks*. London: Springer, 2013, pp. 109–131.
162. Sim SH and Spencer BF Jr. *Decentralized strategies for monitoring structures using wireless smart sensor networks*. Report 1940-9826. Champaign, IL: Newmark Structural Engineering Laboratory, University of Illinois at Urbana-Champaign, 2009.
163. Ling Q, Tian Z, Yin Y, et al. Localized structural health monitoring using energy-efficient wireless sensor networks. *IEEE Sens J* 2009; 9(11): 1596–1604.
164. Liu X, Cao J, Xu Y, et al. A multi-scale strategy in wireless sensor networks for structural health monitoring. In: *5th international conference on intelligent sensors, sensor networks and information processing (ISSNIP)*, 2009, pp. 361–366, https://ieeexplore.ieee.org/document/5416752
165. Zou Z, Nagayama T and Fujino Y. Efficient multihop communication for static wireless sensor networks in the application to civil infrastructure monitoring. *Struct Contr Health Monitor* 2014; 21(4): 603–619.
166. Pakzad SN, Fenves GL, Kim S, et al. Design and implementation of scalable wireless sensor network for structural monitoring. *J Infrastruct Syst* 2008; 14(1): 89–101.
167. Sim SH, Carbonell-Márquez SF, Spencer BF, et al. Decentralized random decrement technique for efficient data aggregation and system identification in wireless smart sensor networks. *Probabil Eng Mech* 2011; 26(1): 81–91.
168. Cho S, Park JW and Sim SH. Decentralized system identification using stochastic subspace identification for wireless sensor networks. *Sensors* 2015; 15(4): 8131–8145.
169. Parashar K and Ranjan KR. Distributed data aggregation energy efficient cluster protocol based structural health monitoring. In: *International conference of electronics, communication and aerospace technology (ICECA)*, Vol. 1, 2017, pp. 518–522, https://ieeexplore.ieee.org/document/8203738

170. Fang K, Liu C and Teng J. Cluster-based optimal wireless sensor deployment for structural health monitoring. *Struct Health Monitor* 2017; 17: 266–278.
171. Zimmerman AT, Shiraishi M, Andrew Swartz R, et al. Automated modal parameter estimation by parallel processing within wireless monitoring systems. *J Infrastruct Syst* 2008; 14(1): 102–113.
172. Liao Y, Mollineaux M, Hsu R, et al. SnowFort: an open source wireless sensor network for data analytics in infrastructure and environmental monitoring. *IEEE Sens J* 2014; 14(12): 4253–4263.
173. Bhuiyan MZA, Wang G, Cao J, et al. Sensor placement with multiple objectives for structural health monitoring. *ACM Trans Sens Netw* 2014; 10: 68.
174. Zhao X, Ri K and Wang N. Experimental verification for cable force estimation using handheld shooting of smartphones. *J Sens* 2017; 2017: 5625396.
175. Yu Y, Han R, Zhao X, et al. Initial validation of mobile-structural health monitoring method using smartphones. *Int J Distrib Sens Netw* 2015; 11(2): 274391.
176. Abdulkarem M and Latip R. Data transmission performance analysis in cloud and grid. *ARPN J Eng Appl Sci* 2015; 10(18): 8451–8457.
177. Aldailamy AY, Abdul Hamid NAW and Abdulkarem M. Distributed indexing: performance analysis of solr, terrier and katta information retrievals. *Malaysian J Comp Sci* 2018: 87–104, https://ejournal.um.edu.my/index.php/MJCS/article/view/15490
178. Zhao X, Yu Y, Li M, et al. Research on cloud-SHM and its applications. In: *Proceedings of the 7th international conference on structural health monitoring of intelligent infrastructure*, Turin, 1–3 July 2015.
179. Shaikh FK and Zeadally S. Energy harvesting in wireless sensor networks: a comprehensive review. *Renew Sustain Ener Rev* 2016; 55: 1041–1054.
180. Sudevalayam S and Kulkarni P. Energy harvesting sensor nodes: survey and implications. *IEEE Comm Surv Tutor* 2011; 13(3): 443–461.
181. Park G, Rosing T, Todd MD, et al. Energy harvesting for structural health monitoring sensor networks. *J Infrastruct Syst* 2008; 14(1): 64–79.
182. Yi TH, Li HN and Gu M. Optimal sensor placement for structural health monitoring based on multiple optimization strategies. *Struct Design Tall Special Build* 2011; 20(7): 881–900.
183. Azarbayejani M. *Optimal sensor placement in structural health monitoring (SHM) with a field application on a RC bridge*. PhD thesis, The University of New Mexico, Albuquerque, NM, 2009.
184. Cheng P, Chuah CN and Liu X. Energy-aware node placement in wireless sensor networks. In: *Global telecommunications conference (GLOBECOM'04)*, Vol. 5, 2004, pp. 3210–3214, https://ieeexplore.ieee.org/document/1378943