Purpose
The purpose of this paper is to provide a contemporary look at the current state-of-the-art in wireless sensor networks (WSNs) for structure health monitoring (SHM) applications and discuss the still-open research issues in this field and, hence, to make the decision-making process more effective and direct.

Design/methodology/approach
This paper presents a comprehensive review of WSNs for SHM. It also introduces research challenges, opportunities, existing and potential applications. Network architecture and the state-of-the-art wireless sensor communication technologies and standards are explained. Hardware and software of the existing systems are also clarified.

Findings
Existing applications and systems are presented along with their advantages and disadvantages. A comparison landscape and open research issues are also presented.

Originality/value
The paper presents a comprehensive and recent review of WSN systems for SHM applications along with open research issues.

Keywords
Sensors, Structural engineering, Wireless, Communication technologies, Condition monitoring

Introduction
The catastrophic events like earthquake, flooding, and terrorist attacks cause enormous damage to the health of infrastructures. In addition to these events, the buildings could undergo gradual deterioration over its life span due to corrosion, fatigue, scour, etc. Given the increasing age of many structures, intelligent and low-cost structure monitoring systems are required to prevent damages in such systems and thus, to take necessary precautions accordingly. Most of the structure monitoring methods includes visual checks, which can only identify damages visible on the structure surface. To detect the problems timely and take necessary actions accordingly, there is an urgent need for reliable structure monitoring systems that can automatically and quantitatively analyze the real-time condition of structures (Choi and Sweetman, 2010).

The general purpose of structural health monitoring (SHM) includes hazard mitigation, improvement of safety and reliability of the structural system, sustainability and life cycle cost reduction. In general, the structural monitoring technology consists of sensing, signal processing, health/damage assessment, and system integration (Mechitov et al., 2004). Traditionally, SHM systems include wired data acquisition systems, which can acquire structure data periodically. These systems measure structural conduct and assess structural safety circumstances using various types of sensing devices and certain damage diagnosis and prognosis methods (Farrar et al., 2004; Glaser et al., 2007). However, the wired structure monitoring systems require expensive communication cables to be installed and regularly maintained, and thus, they are not widely implemented because of their high cost.

With the recent advances in wireless sensor networks (WSNs) and micro-electro-mechanical-systems (MEMS) technology, the realization of low-cost wireless structure monitoring systems have become feasible (Lynch, 2006; Alahakoon et al., 2009; Chang et al., 2003). In these systems, wireless sensor nodes are installed on the structure and monitor the parameters critical to structure safety based on a combination of measurements, such as strain values and vibration characteristics. These data are then wirelessly transmitted to a sink node that analyzes the data from each sensor and notifies any potential problems as an advanced warning system. In this way, catastrophic events are prevented timely.

The collaborative nature of WSNs for SHM applications brings several advantages over traditional wired SHM systems, including self-organization, rapid deployment, flexibility, and inherent processing capability (Kim et al., 2001a, b, 2002; Kim and Jofreb, 2003; Lynch, 2002). In this regard, WSNs play
a vital role in creating a highly flexible and low-cost SHM system that rapidly responds to real-time events with appropriate actions. However, to realize the envisioned SHM applications and, hence, take the advantages of the potential gains of WSNs, efficient and reliable communication protocols, which can address the unique challenges posed by such systems are required.

Recently, many researchers have been engaged in developing schemes that address the unique challenges of WSN-based SHM systems (Pakzad et al., 2008). In this paper, first, technical challenges and design goals are introduced. Specifically, hardware and software properties of the existing systems are clarified. Existing applications and systems are presented along with their advantages and disadvantages. A comparison landscape and open research issues are also presented. In addition, WSN standards are presented for the system owners, who plan to utilize new industrial wireless sensor networks technologies for SHM applications. In this paper, our aim is to provide a contemporary look at the current state of the art in WSN-based SHM systems and discuss the still-open research issues in this field and, hence, to make the decision-making process more effective and direct.

The organization of the paper as follows: in the second section, advantages and disadvantages of WSNs in SHM systems are presented. In the third section, design goals are explained. In the fourth section, existing applications of WSN-based SHM systems are discussed. In fifth section, technical approaches, such as system and network topology of WSN-based SHM systems, hardware and software features, communication protocols and standards, are explained. In the sixth and seventh sections, different energy harvesting solutions and open research issues have been described, respectively. Finally, this paper is concluded in eighth section.

Advantages and challenges of the WSN-based SHM systems

The main advantages of WSNs for SHM can be summarized below:

- **Low cost.** The majority of SHM systems installed in structures use great lengths of cables to communicate sensor data to centralized data server. Wired sensors are difficult and expensive to install. Wireless communication in SHM reduces the monetary and time cost for installing lengthy cables in a SHM system. Sometimes, the cost of cables can be more expensive than the cost of sensor nodes. In Jang et al. (2008), it is denoted that the wire cost is $2.20 per meter for new constructions and $7.19 per meter for existing constructions. Implementing wired sensor network system can cost $5000 per sensor for a system with 12-15 sensors. Typically, a WSN-based system costs about $50-$100 per mote.
- **Scalability.** Wireless communication is advantageous in terms of scalability because installation and maintenance of a monitoring system with a wired or tethered communication network would be too expensive and complex for huge number of nodes. A scalable network is the system that can be enlarged in terms of the number of sensors, complexity of the network topology, data quality (e.g. sampling rate, sensor sensitivity), and quantity of data, while the cost of the augmentation is no worse than a linear, or nearly linear, function of the number of sensors. To improve WSN scalability, an integrated view of hardware and software features needs to be considered together (Pakzad et al., 2008).
- **Easy to deploy.** WSN nodes are relatively easy to deploy within a few meters of each other. The spatial determination of data collection rises along with dense deployment. In this way, the quality of damage appraisal increases (Chintalapudi et al., 2006).
- **Reliability.** Similarly, the programming/retasking data for sensor operation, command and queries are reliably delivered to the target sensor nodes to assure the proper functioning of the WSN for SHM in a flexible manner. Nevertheless, for many SHM applications, the sensed data are exchanged over a time varying and error prone wireless medium. Hence, data verification and correction on each communication layer, and self-recovery procedures are extremely critical to provide exact results to the end-user.

The major technical challenges for realization of WSN-based SHM can be outlined as follows:

- **Environmental conditions.** Especially, impedance based SHM systems are sensitive to temperature and require a temperature compensation scheme. The impedance analysis using a piezoelectric patch is sensitive to the ambience temperature (Giurgiutiu et al., 2002; Lynch et al., 2003c, d, 2005). Former studies prove that the amplitude of the real part of the impedance reduces as the temperature increases, while peaks of the imaginary part shift toward the lower frequency band (Park et al., 2007). Therefore, the precision of impedance-based SHM cause false alarms or missed detections. To compensate the temperature effects, some algorithms for the selection and estimation of the baseline profiles are proposed (Zhou et al., 2009b). An overview of the structure sensing algorithms is shown in Table I (Lynch and Loh, 2006). In addition, SHM sensors can produce data at high rates and these data from sensors should be transported across the network reliably. However, reliable communication in noisy wireless environments might be a significant challenge (Chintalapudi et al., 2006).
- **Limited bandwidth.** Low bandwidth WSNs cannot perform well with high-volume data transfer. Data compression mechanisms might be helpful to aggregate the data. In addition, multiple sink nodes (i.e. base stations) can enable simultaneous sensing and communication.
- **Data aggregation.** The density of the network can be very high to monitor for giant structures. Thus, sensor observations can be highly correlated in the space domain. To handle a large amount of correlated data, data aggregation needs to be employed.
- **Multiple communication hops.** WSNs for SHM may contain several sensor nodes, which might be spread randomly over large structures. In addition, the requirement of predetermined network infrastructure may need the WSNs to set up connections and continue network connectivity autonomously.
- **Rare charging period.** Constrained by the limited physical size and low-cost nature, sensor nodes have limited battery energy supply. Also, it is difficult to recharge the battery over the structures (Gungor and Hancke, 2010). Table II summarizes advantages and technical challenges of WSNs for SHM.
**Design goals**

The basic focus of the SHM is to determine the circumstances of the observed structure and identify potential causes at an early phase, by analyzing the output of sensors connected to the structure (Mechitov et al., 2004). To deal with the technical challenges and meet the diverse structure sensing algorithm requirements, the following design goals need to be followed:

- **Real-time aggregation.** With the current WSN technology, it may not be easy to sample sensors at high frequency while transmitting data over the network. On the other hand, a reliable SHM system must evaluate structural health rapidly or in real time (Hann et al., 2009; Lynch, 2005). To improve system accuracy in low-data rates, data aggregation algorithms need to be developed.

- **Low-cost nodes.** The wireless sensors must be inexpensive in order to make economically feasible dense arrays of sensing units, perhaps hundreds of nodes in a single structure. Compact and low-cost sensor devices are essential to accomplish large-scale deployments of WSNs. In addition, the smaller the sensor is, the easier the deployment would be.

- **Adaptive network operation.** This is a crucial feature to provide adaptive network operation in different environment conditions. For example, a typical SHM system has to resist a 230 to 80°C temperature range, 10-100 percent relative humidity range and 1,000 G shock range (Krüger and Grosse, 2004).

- **Long-network lifetime.** WSNs installed on a structure should operate long without recharging or replacing batteries. The WSNs reduce the energy consumption by adopting a low-power wireless radio. Wireless sensors installed on a structure should perform well without frequently recharging or replacing batteries. Low power consumption of nodes is important for the SHM system (Zhou et al., 2009a). To improve network lifetime, some energy harvesting techniques have been proposed in the literature. These approaches propose energy generation through external sources, such as vibration, solar, wind, and thermal, using energy harvesting devices, like batteries, ultra capacitors, and fuel cells. In addition, renewable energy sources, such as solar, can be stored by convenient devices in outdoor SHM systems.

- **Time synchronization.** The sensors’ clocks are important to be synchronized within a certain error bound. Sensor readings

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### Table I Wireless sensor node features used in SHM applications

<table>
<thead>
<tr>
<th>Data acquisition specifications</th>
<th>Wireless channel specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D channels</td>
<td>Embedded processor</td>
</tr>
<tr>
<td>8</td>
<td>16-bit</td>
</tr>
<tr>
<td>4</td>
<td>16-bit</td>
</tr>
<tr>
<td>1</td>
<td>16-bit</td>
</tr>
<tr>
<td>–</td>
<td>16-bit</td>
</tr>
<tr>
<td>5</td>
<td>8-bit</td>
</tr>
<tr>
<td>1</td>
<td>16-bit</td>
</tr>
</tbody>
</table>

### Table II Advantages and challenges of WSNs for SHM

<table>
<thead>
<tr>
<th>Cost</th>
<th>Scalability</th>
<th>Deployment</th>
<th>Flexibility</th>
<th>Design level</th>
<th>Sensibility to environmental effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic (−$100)</td>
<td>Easy</td>
<td>Rapid</td>
<td>Yes</td>
<td>Difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Expensive (−$1,000)</td>
<td>Difficult</td>
<td>Difficult</td>
<td>No</td>
<td>Easy</td>
<td>No</td>
</tr>
</tbody>
</table>
must be correlated on a mutual time scale to combine sensor readings properly (Mechitov et al., 2004). Thus, time synchronization among sensor modules is needed to determine the collected data for structural monitoring. In most of the WSNs, time synchronization within 1 ms is enough for sampling period of 10 ms and target frequency range of natural period of buildings and dominant period of vibrations. Hence, the tolerance for the errors in the data synchronization is on the order of milliseconds. The challenges and the design goals are summarized in Table III.

Applications and existing systems

Sensor data can be used for long-term circumstances appraisal, traffic-load regulation, tunnel monitoring (Cheekiralla, 2004), emergency response, seismic safety applications (Matsuoka and Yamazaki, 2004; Hasokawa et al., 2008), bridge damage detection (Medda and De Brunner, 2009), railway bridge health detection (Rajkumar, 2007), highway bridge assessment (Whelan et al., 2009; Sazanov et al., 2009; Chowdhry et al., 2007), vehicle health monitoring (Zhang, 1993), space access vehicles and satellites (Tansel and Li, 2007; Fitch and Maybeck, 1994), machine health monitoring (Suiyi and Shuqing, 2006). Recent research efforts focus on the development of reliable sensor networks, efficient computer vision and damage detection methods and data analysis (Elgamal et al., 2003; Sohn et al., 2003; Serker et al., 2010). The classification of WSN for SHM applications is shown Figure 1.

The main approach to set up WSN for SHM is to deploy sensors at critical locations of the structure. The sensors are to sense cracks with thicknesses exceeding a predetermined threshold. In these systems, a wireless network is designed to report the sensor data in near real-time to a remote control center Seth et al. (2005) and Chin et al. (2009).

Table III Challenges and design goals of WSN for SHM

<table>
<thead>
<tr>
<th>Design goals</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>Noisy wireless environment</td>
</tr>
<tr>
<td>Scalability</td>
<td>Limited bandwidth</td>
</tr>
<tr>
<td>Low cost nodes</td>
<td>Large communication hops for structures</td>
</tr>
<tr>
<td>Real-time aggregation/sensing</td>
<td>Challenges to data aggregation from giant structures</td>
</tr>
<tr>
<td>Adaptive network operation</td>
<td>Possibility of enlarge scope of network</td>
</tr>
<tr>
<td>Low energy consumption</td>
<td>Rare charging period because of scattered sensor deployment on structure</td>
</tr>
</tbody>
</table>

In circumstances prognosis, the prognosis pattern uses convenient examination to predict next performing circumstances of the mechanism. From these prognostic results, remaining useful life of mechanism can be predicted. A compounded model, in which multiple classification and regression trees (CART) models namely p-CART, are connected in parallel for long-term prediction purpose. Each sub-model in the p-CART is trained independently (Tran et al., 2010).

SHM applications for tower structures may be deployed one sensor per 20-100 m. More advanced SHM applications require more frequent deployment. To get accurate results, sensing frequencies should be over 100 Hz (Mechitov et al., 2004). In Sweden, WSNs for SHM are extensively used. Arsta Railway Bridge, Götaælvbridge, The New Traneberg Bridge, The New Svinenund Bridge, Giralda Tower, Kajima-Shizuoka Building are some examples to SHM with WSNs (Enckell, 2007; Solis et al., 2010; Seth et al., 2005).

Recently, distributed network architecture for autonomous SHM system using smart sensors has been proposed (Solis, 2010). This architecture is appropriate for the reliable operation of the network, including densely distributed smart sensors. In addition, with the development of tiered sensor network architectures, network performance was improved (Cho et al., 2008; Nagayama et al., 2007). This system also includes back up data acquisition, processing, monitoring and measurement functionalities. In Jamil and Zain (2009), wireless intelligent sensor and actuator networks were proposed to obtain lower cost and more scalable SHM system.

A WSN-based SHM monitoring system was deployed at the Golden Gate Bridge (Kim et al., 2007a; Kurata et al., 2008). Also, Imote2 and MicaZ are used for different SHM applications. Using the mote platforms, the necessity of a dense array of smart sensors for structural monitoring was investigated. WSN-based networks were improved to satisfy the application-specific requirements, such as low-duty cycle, low power monitoring applications to high-fidelity applications (Mainwaring, 2002; Tolle et al., 2005).

Furthermore, MEMS-based accelerometer and strain sensor board for a WSN for SHM was designed (Ruiz-Sandoval et al., 2006; Lynch et al., 2007). The field distribution of WSN on a highway bridge was proposed in Maser et al. (1996). A seven node wireless network with MEMS accelerometers is compared with conventional wired accelerometers in different field tests (Lynch et al., 2003a). In addition, 14-node WSN was tested to monitor forced acceleration response of Geumdang Bridge in Korea (Pakzad et al., 2008; Pattern and Sack, 1994).

Importantly, aircraft health monitoring is one of the applications for SHM systems (Bo-lin et al., 2008; Kumagai...
functions, offers continuous health monitoring based upon vibration samples (Carpenter et al., 1992; Yen and Meesad, 2001). For example, neuro-fuzzy SHM system was used for a steel bridge located in Missouri. Vibration data collected from the structure was processed and fed into the fuzzy logic decision system. The fuzzy logic decision system utilizes fuzzy clustering to detect the possible existence of damage in the structure (Meyyappan et al., 2003; Wang et al., 2006; Faravelli and Yao, 1995a, b). To calculate the “Damage Index” and train a neural network, frequency response functions of tested structure are compared before and after the damage. Importantly, this approach considers the fact that structural damages may change the dynamical behavior of the structure (Bovio and Lecce, 2005).

Since structures behave as wave guides, the measured vibration data varies with time. Namely, the propagation of waves in materials is identified as a time-varying incident. This time-varying signal signature cannot be described by using standard time domain or frequency-domain techniques. To address this challenge, an advanced signal processing and classification method is presented in Chakraborty and Kovvali (2010). This method considers that data collected from sensors are decomposed into linear combinations of highly localized Gaussian functions.

Another type of damage detection techniques is based on acoustic emissions (Lèdeczí et al., 2009; Grosse and Finck, 2004). The changes in the internal structure cause acoustic emissions that are the stress waves produced by the sudden internal stress redistribution of the materials. Possible causes are craze beginning and growth, craze opening and closure, disruption repositioning, winning, and phase transformation in monolithic materials and fiber breakage and fiber-matrix debonding in composites. Most of the sources of acoustic emissions are damage related. Therefore, the detection and monitoring of these emissions are generally used to forecast material failure (Miller, 2006).

### Network topology and deployment issues in WSN-based SHM

The architecture of WSN-based SHM systems can be configured as clusters. For example, the distributed sensor units (SUs) are segregated into clusters in Kottapalli et al. (2003). In this system, a local site master (LSM) is assigned to each cluster with the aim of organizing the SUs in its cluster and collect the data from SUs. Power saving, which the SUs operate on, is the primary aim in this design approach. The LSMS are typically supported with a backup battery, in case the power failure becomes. The clusters of SUs communicating with their LSMS constitute the lower tier, whereas the network of LSMS constitutes the upper tier. The LSMSs retrieve the data from the SUs and transmit the data to the central site master (CSM) over the upper tier.

Furthermore, WSN-based SHM system can be structured according to a star topology. In Bocca et al. (2009), the main aim was to reconfigure the parameters of the monitoring application depending on the needs of the end-user operating at the sink node. The implemented procedures of sampling, data transmission, and retrieval of the lost packets can be ported to more composite multihop topologies while the star topology represents a rather straightforward scenario. The critical issues for network topologies, such as the synchronization protocols and the synchronization of the clocks of the nodes, were...
presented in Sundararaman et al. (2005). The nodes were differentiated by a unique identification number, deployed on the tested structure and communicated with the sink node.

The other network topology type is hybrid connection network. At the first level, a number of sensors are connected to a relay node. That device can serve both as a multiplexer and signal router. It will control the distributed sensing network, handle the modes of sensing and actuation, and multiplex the measured signals. At the next level, multiple parts of the hardware are connected to a decentralized data control and processing station. The decentralized data control and processing station was provided with data acquisition boards, onboard computing processors, and wireless telemetry. It will carry out the duties of a relay-based hardware control, data acquisition, local computing, and transmission of the required results of the computation to the central system. At the highest level, multiple data processing stations are connected to a central monitoring station that delivers a damage report to the user. This sensing network effectively checks several dispersed sensors and active sensors. It preserves low-cost ratio, since only few data acquisition and telemetry units are needed. The WSN is vital for greater numbers of active sensors, as the number of channels on a decentralized wireless sensor is restricted due to the processor sharing and scheduling (Farrar et al., 2006; Dove et al., 2005; Swartz, 2007; Hashemian et al., 1995).

To optimize sensor topology parallel bionic algorithm is one of the solutions. This algorithm is based on nearly orthogonal property of wavelet kernel function. Using least square support vector machine, the procedure can be simpler, and faster operation speed can be achieved compared to classical approaches (Jianhong, 2008).

In Merlino and Abramo (2009) and Abramo et al. (2008), contactless sensors were proposed the use of near-field coupling to sense the structure vibrations and deploy a local communication network. The algorithm presumes that each node collects the positions of the neighboring ones, temporarily acting as local nodes, which know their exact position and updates its own position through an asynchronous, decentralized optimization procedure. The localization algorithm ensures the whole decentralization of the calculation and implements a localization strategy largely insensitive to the irregularities of the network topology.

In Kijewski-Correa (2006), multi-scale network architecture is proposed with aim of satisfying needs to minimize packet loss and latency and decrease power loss. Multi-scale approach is based on data fusion and spatially distributed, heterogeneous detection and a limited input network activation design.

An illustrative architecture of the WSN-based SHM system is shown in Figure 2. In this architecture, tiny sensor nodes have the capability to collect data and route data back to the sink node in a multi hop manner, whereas the sink node monitors the overall network and communicates with the remote control center to decide the appropriate actions. The operation of this system can be considered as a timely event detection, decision, and acting loop.

**Hardware properties**

Hardware structure of WSN for SHM can be considered in three subsystems. First subsystem is a sensing interface, which offers for the aggregation of structural response data from multiple analog sensors (accelerometers, filter, strain gages, displacement transducers). The next is the computational core, which receives the sensor data in digital form from the sensing interface. The last subsystem is the core, which executes data management and preprogrammed data interrogation tasks (Swartz et al., 2005). Hardware properties of sensor nodes used in WSN for SHM are summarized in Table IV (Gotzhein et al., 2009; Chou, 2008).

In these systems, accelerometers, the components of first level, measure accelerations of the surface. Accelerations are converted into changes in electrical properties. These analog signals are then sampled at a determined frequency. Accelerometers are characterized by several performance parameters, such as sensitivity, dynamic range, and noise. Sensitivity presents the smallest measurable acceleration. Dynamic range presents the range of accelerations that the device can measure. Noise is expressed as a function of the frequency of vibration (Xu et al., 2004; Antunes et al., 2009). In the literature, several techniques can be found based on simple interferometer, Fabry-Perot filters, matched gratings, acoustic-optic tunable filters, long-period gratings, Sagnac loops based on the peeped FBGs, and multiprot fiber Mach-Zehnder interferometer for multisensor interrogation (Antunes et al., 2009; Kersey et al., 1992, 1993; Jackson et al., 1993; Volanthen et al., 1996; Zhang et al., 1998; Jung et al., 2000; Zhao et al., 2002; Jiang, 2008). Other common sensing technique is to use strain gauges to measure the actual deflection on the structural members and advance the damage sensing based on deflections and strain energy (Guo and Li, 2008; Abdallat et al., 1999; Yen and Meesad, 2001). The output of an accelerometer is a time series of sensor readings with a specified resolution and a specified sampling rate. These are parameters related with the analog-to-digital circuitry attached to an accelerometer (Xu et al., 2004). There are some alternative vibration measurement methods using accelerometer, such as Hilbert-Huang transform for identification of structural modal parameters (Jing et al., 2008).

In the SHM system, impedance-based approach usually employs a digital-to-analog converter to generate samples of sensing signals and an analog-to-digital converter (ADC) to sense the response signal. The sensing sample signals activate a piezoelectric patch. A processor to determine the impedance at the sampling frequency processed the response signals conveyed by the ADC. In case that the impedance

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**Figure 2** An illustrative architecture of the WSN-based SHM system

![Diagram of WSN-based SHM system](image)
Information of the structure under test (SUT) is not the same as the baseline impedance, the system decides that the SUT has been disfigured (Ayers et al., 1998; Kim et al., 2001). The sampling rate for structural response amounts, the lower vibration frequencies of a structure are commonly on the order of 0.1–10 Hz. In addition, local features of responses are characteristic of much higher vibration frequencies. High-frequency sampling can be utilized to suppress noise and increase the signal to noise ratio. Therefore, higher sampling rates are desirable. On the other hand, high-frequency sampling makes time synchronization of nodes complex over the network. More samples mean of acquiring larger volumes of data that need to be managed, processed, and possibly transmitted (Park et al., 2005). MicaZ is one of the most popular series of Mica. An alternative to the MicaZ mote would be iMote2, which has similar functionality as MicaZ, but consumes more power. Another wireless sensor which is used for SHM systems is Mica2. Mica2 uses low rate design of communication protocol. Given that the sensor on WSNs operate on a limited power supply, the choice of low rate is uncompromisable. Thus, these low bandwidth wireless networks cannot perform well with high-volume data transfer, which is unavoidable in any centralized SHM applications. The alternatives of Mica series can be summarized WiMMS, DuraNode, Husky, RIMS sensor nodes (Cho et al., 2008).

### Communication protocols and standards

In general, the WSN for SHM applications use IEEE 802.15.4 standard. This standard focuses on the following layers of the communication protocol stack: physical (PHY) and medium access control (MAC) layers.

In the IEEE 802.15.4 standard, the PHY layer organizes the physical radio to modulate and demodulate data upon carrier radio frequencies. The MAC layer proposes standard packet structures for data transmission as well as procedural rules for autonomous users to allocate the main bandwidth. The layer structure admits upper layers to have services offered by the lower layer through well-defined application program interfaces. The application layer can collaborate with the MAC layer which controls beacon management, channel access, guaranteed time slot management, frame substantiation, and acknowledged frame delivery. The MAC layer also interfaces with the PHY layer, which checks activation and deactivation of the energy sensing, radio transceiver, channel selection, link quality indication, and the act of physically transmitting and receiving.

### Table IV Hardware properties

<table>
<thead>
<tr>
<th></th>
<th>Program memory</th>
<th>Data memory</th>
<th>Data rate</th>
<th>Maximum outdoor range</th>
<th>Sleep mode</th>
<th>TX</th>
<th>RX</th>
<th>IDLE mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiMMS (Straser and Kiremidjian, 1998)</td>
<td>16 KB</td>
<td>32 KB</td>
<td>19.2 Kbps</td>
<td>304.8 m</td>
<td>1 mA</td>
<td>130 mA</td>
<td>140 mA</td>
<td>80 mA</td>
</tr>
<tr>
<td>RIMS (Aoki et al., 2003)</td>
<td>128 KB</td>
<td>2 MB</td>
<td>–</td>
<td>50 m</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Husky (Farrar et al., 2005)</td>
<td>256 MB</td>
<td>Compact FLASH</td>
<td>230 Kbps</td>
<td>9.1 m</td>
<td>42 uA</td>
<td>198 mA</td>
<td>105 mA</td>
<td>70 mA</td>
</tr>
<tr>
<td>Mica (Crossbow)</td>
<td>512 KB serial FLASH</td>
<td>32 KB EEPROM</td>
<td>250 Kbps</td>
<td>100 m</td>
<td>15 uA</td>
<td>11 mA</td>
<td>19.7 mA</td>
<td>20 uA</td>
</tr>
<tr>
<td>Mica2 (Crossbow)</td>
<td>512 KB serial FLASH</td>
<td>128 KB FLASH</td>
<td>250 Kbps</td>
<td>300 m</td>
<td>1 uA</td>
<td>27 mA</td>
<td>10 mA</td>
<td>27 uA</td>
</tr>
<tr>
<td>iMote2 (Intel)</td>
<td>32 MB FLASH</td>
<td>256 KB RAM</td>
<td>76.8 Kbps</td>
<td>30 m</td>
<td>390 uA</td>
<td>44 mA</td>
<td>66 mA</td>
<td>426 mA</td>
</tr>
</tbody>
</table>

**Note:** The table includes details on various wireless sensor nodes and their characteristics, focusing on their power consumption, memory size, and communication capabilities for SHM applications.
packets. The WSN can be programmed so that the user only needs to give commands in the application layer. In other words, the MAC and PHY layers will automatically fulfill necessary functions without additional user commands (Chipcon AS, 2004). Importantly, WSNs for SHM applications are associated with some standards such as ZigBee, Bluetooth and Bluetooth low energy. Low-energy consumption and support for different topologies (such as mesh topology) are advantages of ZigBee (Adams, 2006). Nevertheless, ZigBee may not provide QoS requirements (such as real-time deadlines), especially in large-scale networks. In 2007, the ZigBee Alliance has approved the ZigBee PRO profile stack, which adds advanced features and greater flexibility to the original specification, particularly related to ease of use and support for larger networks.

The other WSN standard, i.e. Bluetooth, operates at the 2.4 GHz ISM band and employs a frequency hopping spread spectrum modulation technique. On the other hand, due to its high complexity and inadequate power characteristics for sensors, Bluetooth-based WSN applications may not be preferred. In general, Bluetooth is designed for high throughput applications between small numbers of terminals.

The Bluetooth low-energy specification is a part of the Bluetooth specification as an ultra-low power technology addressing devices with very low-battery capacity. This extension to Bluetooth allows for data rates of up to 1 Mbit/s over distances of 5-10 m in the 2.45 GHz band. Although Bluetooth low energy is similar to Bluetooth and can employ the same chips and antennas, it has some important differences. Bluetooth low energy has a variable length packet structure, compared to Bluetooth’s fixed length. It also employs a different modulation scheme. Additionally, the implementation of the security algorithm (AES) has been taken into account from the start (Gungor and Hancke, 2010).

Ultra-wide band (UWB) channel is a radio technology that consumes low energy for short-range high bandwidth applications. It is suitable for the design of high data rate WSN-based applications. The development and optimization of these systems need exact information of the radio transmission medium. In Table V, ZigBee, UWB and Bluetooth have been compared to have a better understanding of current IEEE WPAN standards.

### Software properties

The software of WSN-based SHM consists of reliability regarding command spreading and data transfer, handling of large volumes of data, and scalable algorithms for studying the data (Pakzad et al., 2008). Structural response from different locations can be used to parameterize a model of the structure so that when damage occurs; the parameters of this model alter, allowing the system to infer. There is no reason for such systems to be centralized; WSNs utilizing decentralized detection and localization algorithms are acceptable.

As the first generation of WSN, Wisden was designed (Paek et al., 2005). Wisden provides the opportunity to iterate sensor deployment to determine suitable placements. A Wisden deployment generally consists of tens of wireless nodes. These nodes are self-configured to construct a tree topology and transmit reliable time-synchronized vibration data to the sink (the tree root), potentially over multiple hops (Chintalapudi et al., 2006). Its advancement has provided insights on the design of a more general programmable system named netSHM. NetSHM is a second-generation WSN-based SHM system that enables structural engineers to apply and assess algorithms in a high language (Chintalapudi et al., 2005).

TinyOS is the most common operating system for programming Mica motes, which is an open source framework (Hill et al., 2006; TinyOS, 2007). TinyOS divides one big component into levels. Low-level components execute basic tasks, and higher level components use sequences of low-level components to achieve more complex functionality. Effectiveness and straightforward of coding is retained. The components range from providing simple diagnostic operations to sophisticated components for routing of data packets in a self-configuring wireless communication network (Pakzad et al., 2008).

An active WSN user community has improved various software tools. For retrieving and viewing data, it was decided to use a web-based system instead of improving a platform-specific application (Jang et al., 2008; Tasker et al., 1999; Liu et al., 2008). For SHM, an application named Sentri was improved based on TinyOS, for high-level control of a wireless network from a central unit (Kim et al., 2007a). Using this software, the mote can listen to the network, join the network, control the sensor board (sampling, filtering, and logging), and can be a sender/receiver for multihop communication. It is developed for a very limited memory capacity since the memory spaces are limited for the motes. The central control unit software has more functionality for sending analysis to all nodes in the network, assessing connectivity communications, and executing commands on certain parts of the network or whole network (Pakzad et al., 2008).

Compared to TinyOS, there are some alternative operating systems used in WSNs. Contiki is one of operating system

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**Table V** ZigBee vs Bluetooth vs UWB

<table>
<thead>
<tr>
<th>Features</th>
<th>ZigBee</th>
<th>UWB</th>
<th>Bluetooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE standards</td>
<td>IEEE 802.15.4</td>
<td>IEEE 802.15.4</td>
<td>802.15.1</td>
</tr>
<tr>
<td>Peak data rate</td>
<td>250 Kbps (2.4 GHz) and 40 Kbps (915 MHz)</td>
<td>1 Mbps</td>
<td>723.2 Kbps</td>
</tr>
<tr>
<td>Frequency range</td>
<td>2.4 GHz, 902-928 MHz (US) and 868.3 MHz (EU)</td>
<td>5.6-10.9 GHz</td>
<td>2,402-2,480 MHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>5 MHz</td>
<td>500 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1 (868 MHz), 10 (915 MHz), 16 (2.4 GHz)</td>
<td>–</td>
<td>79</td>
</tr>
<tr>
<td>Multiple access</td>
<td>CSMA/CA with FDMA and TDMA</td>
<td>Impulse Radio</td>
<td>TDMA or CDMA</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK (868/915 MHz) and OQPSK (2.4 Hz)</td>
<td>TH-PPM and TH-A-PAM</td>
<td>GFSK</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Range performance</td>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>Localization</td>
<td>Bad</td>
<td>Very good</td>
<td>Good</td>
</tr>
</tbody>
</table>
used in WSN-based SHM. Contiki is a lightweight operating system. It includes event-based kernel, but supports optional privileged multithreading (Dunkels et al., 2004). Simple operating system (SOS) is another operating system used in WSN-based SHM. SOS includes classical core kernel and the modules kernel, which can be loaded. Modules can both communicate via messages and use faster function calls, therefore it decreases system overhead. SOS schedules tasks using priority queues, sharing the processor through cooperative scheduling. SOS is more energy efficient than TinyOS and supports greater system flexibility. Also, SOS supports a high-level programming interface for developing advance modules and integrating them into the SOS kernel at run time (Han et al., 2005). ERIKA is the real-time operating system supporting IEEE 802.15.4/ZigBee protocol. As it is introduced in (Severino, 2006), ERIKA is only adequate for some hardware platforms. It provides useful mechanisms and programming features to support microcontrollers and multicore systems on a chip.

### Energy harvesting solutions

Most of the time, WSN-based SHM systems may not address the need for AC power. On the other hand, to prolong the system lifetime, the batteries of the system have to be replaced periodically. However, replacing the batteries of the sensor nodes include difficult and expensive process. In this regard, energy harvesting from the ambient sources may help the WSN-based SHM system to improve the system lifetime. When the energy of medium is used, the battery life is prolonged or the unlimited power source is obtained. Specifically, typical ambient sources of energy harvesting are vibration, sunlight, thermal gradient, and RF energy. Other potential energy sources are thermoelectric generators (TEGs), mechanical vibration devices, exotic portable energy sources (Park et al., 2008).

One of the most common methods of energy harvesting system is to use ambient vibration. Piezoelectric devices interchange from mechanical motion or force to electrical energy. Ambient vibration around the piezoelectric bonded to the pitch link material is converted to electric energy. In addition, to obtain higher efficiency, the resonance frequency of the piezoelectric material and the most distinct frequency of the vibration source can be coordinated (Park et al., 2008). Another way for energy harvesting using ambient vibration is electrostatic energy harvesting. Ambient vibration changes capacitance of vibration dependent varactors. In this mechanism, vibrations divide the plates of initially charged varactors, and then mechanical energy is converted to electrical energy (Chalasani and Conrad, 2008). Third type of energy harvesting using ambient vibration is electromagnetic systems formed a coil and a permanent attached to a source. Structural vibration makes mechanical movement of magnet, and then a voltage is generated at the coil terminal. The energy is then conveyed to an electrical load. To maximize power, it is proved that the resistance of an electrical load should be equal to the sum of the coil internal resistance and the electrical analogue of the mechanical damping coefficient. Addition to that, the output power depends on system coupling coefficient, quality of factor of the device, the mass density of the generator (Park et al., 2008). The advantage of the electromagnetic induction is high reliability and low-mechanical damping. However, they may have large size and thus it could be difficult to integrate them with MEMs (Chalasani and Conrad, 2008).

Other source for energy harvesting is thermal sources. The working principle of thermal-based energy harvesting device is that the junction of two dissimilar metals experiences the temperature difference. TEGs capitalize on thermal gradients. When electrical current is applied to the TEG, a thermal gradient is produced. When thermal gradient is applied to the device, TEG produces electrical current. The researchers tried to utilize liquid head exchangers or forced convection to improve heat flow and power generation. However, the complicated cooling loops are needed. Hence, it is investigated that TEG is used as power harvesting devices, which function as passive scavenging system using solar radiation and harvesting of waste heat (Park et al., 2008; Seah et al., 2009).

Another way to harvest energy is wireless energy transmission. In these systems, energy is produced, and then transmitted to a sensor node by electromagnetic wave or RF radiation (Arms et al., 2008; Park et al., 2008). Power is conveyed to sensor node wirelessly. The sensor node executes the intended measurement and sends the results to the mobile host. Photovoltaic cell is a kind of energy harvesting method that transforms light energy to electrical energy. Common photovoltaic cells are silicon-based cells since they are more sensitive to light and easily available. Photovoltaic cells obtain electrical energy from photons by means of a semiconductor p-n junction. p-n junction term refers to a junction formed by joining p- and n-type semiconductors together in very near contact. The term junction is the boundary interface where the two regions of semiconductor meet. As a hybrid technology, multiple power sources (MPS) are used in the embedded systems. MPS scaveng energy from ambient and then that energy is used to power the system and the rechargeable battery. In Table VI, the features of different energy harvesting techniques are shown (Korber et al., 2007; Gungor and Hancke, 2010).

### Open research issues

Clearly, the realization of WSN-based SHM systems depends on the development of effective, energy-efficient, and yet practical wireless sensor nodes. However, there exist many fundamental open research issues on the design of network:

- The importance of damage prognosis should not be underestimated as for civil aircraft, over the next ten years, the cost of the system elements will raise to 50 percent of the purchase cost, while for military platforms the figure will be closer to two-thirds of the total cost (Farrar et al., 2004, 2006). Accordingly, online analysis of system and network reliability is required to estimate the remaining beneficial life of the structure under uncertainty.

- To improve WSN-based SHM system lifetime, effective methods of storing electrical energy are the key technologies that will permit energy harvesting in SHM systems. Energy storage devices, such as rechargeable batteries, capacitors, should be selected depending on application-specific requirements (Park et al., 2007).

- The reliability and robustness of the network hardware must be improved before the energy harvesting techniques can be used in operation. For example, to improve the system reliability and flexibility, the mobile sensing nodes with the capabilities of autonomously determining potential damages in the structure can be developed (Zhu et al., 2009). Also, sensor nodes for SHM should resist harsh
environmental conditions. Thus, robust sensor network hardware should be developed.

- In WSN-based SHM systems, the amount of energy generated from an energy-harvesting device depends on the ambient conditions significantly. For example, the amount of solar radiation depends on the time of day (e.g. cloud size and thickness). Hence, temporal rate optimization is desired to satisfy the application-specific QoS constraints under varying amounts of power supply (Akyildiz et al., 2007).

- In WSN-based SHM systems, energy harvesting technology can be performed in a cross-layer fashion. In this regard, energy-aware routing and MAC protocols can be integrated so that energy consumed for communication tasks can be saved. For instance, the MAC protocol can utilize the information in the routing messages to decide the sleeping and wakeup schedules without exchanging additional control messages at the MAC layer. In addition, packet scheduling can be integrated with battery management in order to synchronize battery consumption with packet transmission (Akyildiz et al., 2007).

- In WSN-based SHM applications, when degradation in channel conditions is detected, error control schemes with more redundancy (such as FEC or HARQ) can be utilized to decrease packet losses. Therefore, dynamic error control schemes with minimum energy consumption must be developed for WSN-based SHM systems. Also, the impact of packet size on the transmission efficiency and hence optimal packet size for WSN-based SHM systems must be analyzed under varying wireless channel characteristics. To test developed algorithms, field tests on real civil structures should be performed for the validation of WSN-based SHM systems (Akyildiz et al., 2007; Choi and Sweetman, 2010).

- To improve system reliability and energy efficiency in WSN-based SHM systems, new energy-efficient multi-hop routing protocols, which consider the requirements and challenges of sensor networks, such as radio interference, resource constraints, dense deployment, must be developed (Park et al. 2007).

- Low power modulation schemes should be improved for WSN-based SHM systems. The modulation scheme can be either baseband, as in UWB, or passband. Also, radio signal propagation effects on sensor networks need to be analyzed to design energy efficient network topologies. Also, adaptive real-time transport solutions must be developed to address real-time reliability requirements and application-specific QoS needs under varying channel characteristics.

- Bluetooth low energy and UWB technologies can be used for WSN-based SHM more effectively. This technology presents lower power consumption, high data rates, reduced multi-path fading, and self-localization (Elgammal et al., 2003).

Conclusions
Given the increasing age of many structures, intelligent and low-cost structure monitoring systems are required to prevent damages in such systems and thus, take necessary precautions accordingly. Traditionally, SHM systems include wired data acquisition systems, which can acquire structure data periodically. These systems measure structural conduct and assess structural safety circumstances using various types of sensing devices and certain damage diagnosis and prognosis methods. However, the wired structure monitoring systems require expensive communication cables to be installed and regularly maintained, and thus, they are not widely implemented because of their high cost.

With the recent advances in WSNs and MEMS technology, the realization of low-cost wireless structure monitoring systems have become feasible. The collaborative nature of WSNs for SHM applications brings several advantages over traditional wired SHM systems, including self-organization, rapid deployment, flexibility, and inherent processing capability. In this regard, WSNs play a vital role in creating a highly flexible and low-cost SHM system that rapidly responds to real-time events with appropriate actions. In this paper, WSN-based SHM systems are presented. The common characteristics and requirements of a structure monitoring system are presented. Design goals and existing applications are also summarized. General network architecture, communication protocol, hardware and software properties are also clarified. Finally, wireless sensor nodes, which are used in SHM system, are compared. Future work includes optimal sensor node deployment, interoperability between different WSN manufacturers, and porting a cognitive radio paradigm to low-power wireless sensor nodes to cope with RF interference and dynamic/varying wireless channel conditions in harsh structure environments.

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Further reading


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