Hybrid Wireless Smart Sensor Network for Full-scale Structural Health Monitoring of a Cable-stayed Bridge

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ABSTRACT

Rapid advancement of sensor technology has been changing the paradigm of Structural Health Monitoring (SHM) toward a wireless smart sensor network (WSSN). While smart sensors have the potential to be a breakthrough to current SHM research and practice, the smart sensors also have several important issues to be resolved that may include robust power supply, stable communication, sensing capability, and in-network data processing algorithms. This study is a hybrid WSSN that addresses those issues to realize a full-scale SHM system for civil infrastructure monitoring. The developed hybrid WSSN is deployed on the Jindo Bridge, a cable-stayed bridge located in South Korea as a continued effort from the previous year's deployment. Unique features of the new deployment encompass: (1) the world's largest WSSN for SHM to date, (2) power harvesting enabled for all sensor nodes, (3) an improved sensing application that provides reliable data acquisition with optimized power consumption, (4) decentralized data aggregation that makes the WSSN scalable to a large, densely deployed sensor network, (5) decentralized cable tension monitoring specially designed for cable-stayed bridges, (6) environmental monitoring. The WSSN implementing all these features are experimentally verified through a long-term monitoring of the Jindo Bridge.

Keywords: structural health monitoring (SHM), wireless smart sensor network (WSSN), cable-stayed bridge

1. INTRODUCTION

The paradigm of structural health monitoring (SHM) research has been moving toward the use of wireless smart sensor networks (WSSNs) away from traditional wired methods. Although smart sensors have been readily available for nearly a decade, full-scale implementations are still limited. Several researchers have employed WSSNs to monitor bridge structures[1~5], which provided important insight into the challenges for long-term operation of SHM system using WSSNs. Critical issues discovered by the previous works include (i) efficient power management with optimized power consumption and harvest, (ii) environmentally hardened hardware, (iii) autonomous operation, and (iv) fault tolerant for unexpected hardware and software malfunctions.

As the part of collaborative research efforts between three institutes, University of Illinois at Urbana-Champaign (USA), KAIST (South Korea) and the University of Tokyo (Japan), an autonomous long-term SHM system using Imote2 smart sensor platform has been successfully implemented on a cable-stayed bridge in South Korea[6~8]. As the extension of the autonomous SHM system, in this study, recent updates for more stable, power efficient, robust SHM system using WSSNs is explored and experimentally validated through full-scale deployment on a cable-stay bridge in Korea and long-term operation.

In this deployment, the energy harvesting system was applied to all sensor nodes and the flash memory of Imote2 was used to have stable and power efficient data storage. To effectively consider environmental effects on the structural behavior and the SHM system, more number of wind sensors and autonomous monitoring system of temperature/humidity/light/charging status were considered. In addition to the centralized sensing, the distributed sensing strategy was adopted as option to reduce data communication that is one of the main sources of power consumption[9]. As the specialized application for SHM of a cable-stayed bridge, autonomous cable tension monitoring has been implemented[10], and upgraded multi-hop protocol has been implemented on one of sub-networks. In perspective of hardware, small number of high-sensitivity sensor (SHM-H board) were used as reference sensors in distributed sensing to have better quality measurements from the other low-cost sensors, and newly developed data acquisition board (SHM-DAQ board) was used to interface with 3D ultra-sonic anemometers. All these components and applications of the hybrid WSSN for full-scale SHM are operated with the continuous and autonomous monitoring system provided by the Illinois SHM Project (ISHMP) Services Toolsuite[10] that has been upgraded to easily accommodate additional applications.

As the 2nd year deployment, the hybrid WSSN is being operated and tested on a cable-stay bridge in Korea. In total, 669 sensing channels with 113 sensor nodes have been deployed; it would be the largest WSSN for full-scale SHM.

2. HYBRID SHM FRAMEWORK FOR WIRELESS SENSOR NETWORK

For the long-term operation of full-scale SHM system using WSSNs, diverse consideration should be taken into account including self-powering, weather resistance, power efficient, reliable communication, monitoring environmental effects, high-quality sensing, scalability to large network, continuous and autonomous monitoring and fault tolerant features. The ISHMP has tried to resolve those issues with a number of hardware and software developments and implemented all the up-to-date technologies and experiences on a cable-stayed bridge. The hybrid SHM framework for full-scale deployment using WSSNs are shown in Figure 1 and the introduction of main components in the framework are continued.

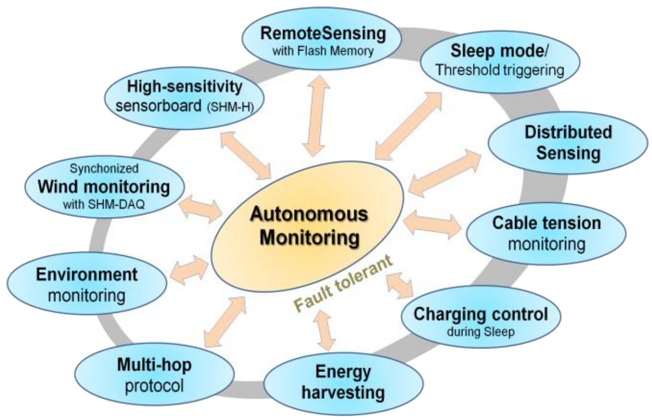


Figure 1. Hybrid SHM framework using WSSNs

2.1 Imote2 & ISHMP Services Toolsuite

The smart sensor platform used in this study is the Imote2 from MEMSIC (Figure 2, left). The Imote2 includes a high performance X-scale processor (PXA27x), the variability of the processor speed based on application needs, from 13MHz for low power operation to 416MHz for intensive tasks, enables efficient power management. Another differentiated feature of Imote2 from other smart sensor platform is the onboard memory. It has 256k SRAM, 32MB FLASH and 32MB SDRAM, which enables intense onboard calculation required for up-to-data SHM applications as well as longer measurements. For the sensor board, SHM-A sensor board (commercially available as ISM400 from MEMSIC) is used[12~13], which includes a 3-axes capacitive type MEMS accelerometer (LIS344ALH, ST Microelectronics), and the acceleration signals are digitize through a 4-channel high-quality ADC (QF4A512, Quickfilter). The Quickfilter ADC is the key component of the SHM-A board; which is supported with programmable sampling rate and digital filter. The driver and software to use the Quickfilter ADC based sensor board has been implemented in the ISHMP Service Toolsuite and the diverse applications are explained hereinafter. All the possible up-to-date technologies are implemented in the ISHMP Services Toolsuite and experimentally verified through full-scale testing on the test bed. It should be noted that the words expressed in *Italic* font are the actual application name of ISHMP Services Toolsuite.

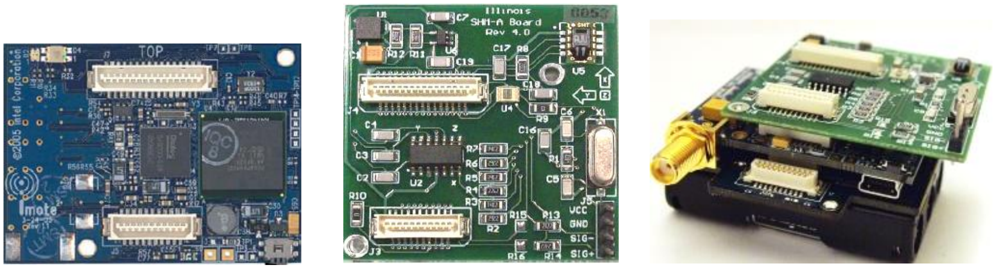


Figure 2. Imote2 (left), ISM400 board (middle) and ISM400 stacked on Imote2 (right)

2.2 *RemoteSensing* using non-volitile memory

RemoteSensing is a basic sensing application of the ISHMP Services Toolsuite[11]. Detail about the *RemoteSensing* has been introduced by Jang et al, 2010[7]. The important update on this application for this deployment is saving data to the flash memory. Because of the non-volatile characteristic of the flash memory, the data saved in the flash memory can be retrieved anytime later even after sensor nodes reset; this unique feature ensures the reliable data storage in unexpected network instability. Moreover, because the sensor node can switch to a sleep mode as soon as sensing completes without waiting until the gateway requests data from all sensor nodes as it did; consequently, more power efficient WSSN is available.

2.3 Sleep mode & threshold triggering

One of the most fundamental approaches to achieving power efficient WSSN is to allow the sensor nodes to sleep while inactive. The Imote2 allows the processor to be put into a deep sleep mode, whereby only the clock component of the processor is supplied power. The *SnoozeAlarm* service of the ISHMP Services Toolsuite makes the sensor nodes sleep for a set period time then wake up for a short period of time so that they can listen and receive a message from a gateway node; which can allow the gateway node access the sensor nodes even during sleep mode[12]. For this deployment, 10 seconds deep sleep and 0.5 seconds wakeup cycle is used. In order to wake up the entire sleeping network, threshold triggering strategy is utilized. The *ThresholdSentry* application installed on the gateway node wakes up a subset of sentry node one by one periodically. Then the sentry node senses data for given period of time and check if the threshold value is exceeded. If the measurement is exceeded a threshold value, then the gateway node wake up the entire network to initiate sensing. If the threshold is not exceeded, then it wakes up another sentry node in order, and repeats this.

2.4 Decentralized data aggregation

As a WSSN based on centralized data collection and processing is not scalable due to the limited bandwidth in wireless communication, decentralized in-network processing that reduces wireless data transfer is essential to realize densely deployed large networks. ISHMP Services Toolsuite provides *DecentralizedDataAggregation*, as an implementation of decentralized processing approaches. Instead of sending the raw data from the all sensor nodes back to the gateway node as *RemoteSensing* does, the *DecentralizedDataAggregation* sends only condensed data after in-network processing that reduces the amount of data wirelessly transferred in the network significantly as well as power consumption[9]. In *DecentralizedDataAggregation*, the network consists of three types of nodes based on their functions: (1) gateway node, (2) cluster-head, and (3) leaf node (see Figure 3). Both cluster-head and leaf nodes measure acceleration and conduct data processing to calculate correlation functions with respect to reference data provided by the cluster-head. Cluster-heads organize data processing and collection in their local communities. As such, raw sensor data is condensed to correlation functions while keeping spatial information of each local sensor community.

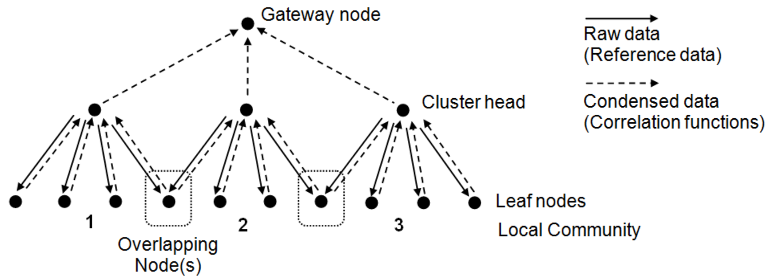


Figure 3. Cluster tree topology employed for coordinated processing.

2.5 Decentralized cable tension monitoring

Stay cables are one of the most critical loading path members of a cable-stayed bridge: stability of the cable-stayed bridge is closely linked to the cables transferring most loads from the bridge deck to the pylons. Thus, monitoring cable tension is one of the main targets of monitoring cable-stayed bridges. The ISHMP Services Toolsuite provides *CableTensionEstimation*[10], a WSSN application that calculates cable tensions based on the vibration-based method[18]. *CableTensionEstimation* measures acceleration responses of cables and calculates power spectrum to estimate natural frequencies that yield cable tension forces. As this application is based on decentralized independent processing that does not require data sharing between sensor nodes[19], demands on data communication and related power consumption is significantly lower than the centralized data collection and processing approach.

2.6 Charging control during sleep mode

The Imote2 has a DA9030 PMIC from Dialog Semiconductor, which interface directly with Li-ion battery pack and can handle an unregulated supply up to 10 volts. The PMIC charger supports constant current and constant voltage charging modes, which enables faster and more stable charging with Li-ion battery. Even with the PMIC charger, however, additional software is required to make the charger function properly with sleep mode. The *ChargerControl* of ISHMP Services Toolsuite has been developed to make the energy harvesting system work during *SnoozeAlarm* mode[14]. With the *ChargerControl* enabled, each time the Imote2 awakes from sleep mode, it checks the battery voltage and the supply voltage and decides whether it will charge or go into sleep mode. If the battery voltage is low and the supply power is sufficient, it will charge. If the battery voltage is enough or once achieves the target value, it stops charging and goes back to sleep mode.

2.7 Multi-hop communication

Large-scale deployment of wireless sensor networks gives rise to the need for multi-hop communication. The small communication range of smart sensors, and environmental effects on the radio make direct communication between all nodes impractical. On the other hand, an important requirement of any communication scheme is data transfer reliability. Multi-hop communication, together with appropriate packet-loss compensation, addresses these issues by allowing sensors to cooperate to reliably deliver data between nodes outside of direct communication range. In this study, the modified AODV (Ad hoc On-demand Distance Vector) protocol, termed General Purpose Multi-hop (GPMH), is implemented to support diverse data flow patterns such as central data collection, dissemination as well as decentralized communication that are possible in SHM applications[15]. Figure 4 shows an example of AODV route discovery method. The rout request (RREQ) message initiated from a source node is rebroadcasted by neighbor nodes until it reaches the destination node. Then, a route reply (RREP) message originating at the destination or intermediate nodes knowing a path to the destination is sent back to the source node, establishing the route in the reverse order. The source node chooses the route with the minimum hop count among the received routes. The major modifications to AODV routing protocol to meet SHM application requirement include follows;

- The standard AODV protocol uses periodic probe messages to update routing information frequently between mobile nodes; however, it consumes significant power. The GPMH omits the periodic probe messages, because the sensors mobility is not an issue in SHM system.
- In order to reduce the delay caused by the routing protocol, the GPMH does not regenerate route request (RREQ) message when route discovery is unsuccessful; instead, the task is handled by the reliable data transfer service in ISHMP Services Toolsuite.

- The GPMH implementation of AODV employs an alternative to the standard hop-count routing metric used for evaluating different paths; the hop-count routing metric may lead to the selection of long links, which in turn result in an increase in the loss ratio and power consumption. The new metric uses the link quality indicator (LQI), which is calculated using the received energy level and SNR (signal to noise ratio).

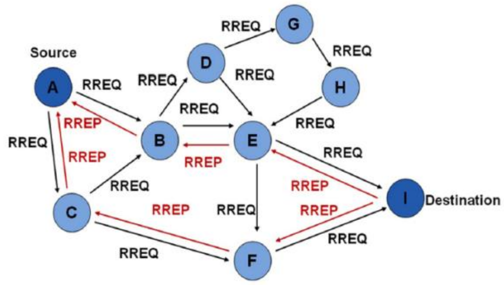


Figure 4. Example of AODV route discovery; node A is the source and I is the destination[10].

2.8 Environmental monitoring

Structures are exposed to diverse environmental changes including temperature, humidity and light, which may affect on the structural behavior, accelerating deterioration, consequently the health of structures. In addition, the performance of the energy harvesting system heavily relies on the environmental conditions. Hence, to monitor the environmental changes and their effects on a structure is an important task. The SHM-A sensorboard contains a temperature/humidity sensor (SHT11, Sensirion) and a light sensor (TSL2561, Taos). And the PMIC (DA9030, Dialog semiconductor) of Imote2 provides the information about powering condition of the sensor. The utility commands of ISHMP Services Toolsuite like *Vbat*, *ReadTemp*, *ReadHumidity* and *ChargeStatus* are available for this purpose, and the *AutoUtilsCommand* enables the autonomous tracking of the temperature, light, battery voltage and charging status in schedule base.

2.9 Wind monitoring and Data acquisition board (SHM-DAQ board)

The test bed structure for this study is located in coastal windy area, in particular, on the way of typhoon path, which is supposed to experience several typhoons every year. Considering that the wind loading is one of the most critical loadings on a cable-stayed bridge, the wind loading monitoring is an indispensable option for the SHM system for a cable-stayed bridge. Ultra-sonic anemometers (Model 81000, RM Young) are used to get high-precision wind information of wind speed, wind directions (horizontal/vertical) in this study. To collect wind information from the anemometer into the WSSN, the data acquisition board (SHM-DAQ board, see Figure 5) is used, instead of SHM-A board. The SHM-DAQ board for Imote2 platform has been designed to interface with external analog sensors (0 ~ 5V or -5 ~ 5V outputs, up to four channels) and digital sensors of I2C or SPI interface. It uses same ADC (QF4A512) and opens all the four channels of the ADC to external sensors; which makes synchronized sensing with SHM-A boards possible. The three-channel signals (wind speed, horizontal & vertical wind directions) from the ultra-sonic anemometer are linked to the first three channels of the ADC through the terminal blocks on the top of the board and measured together with accelerations from other SHM-A boards using the *RemoteSensing*.

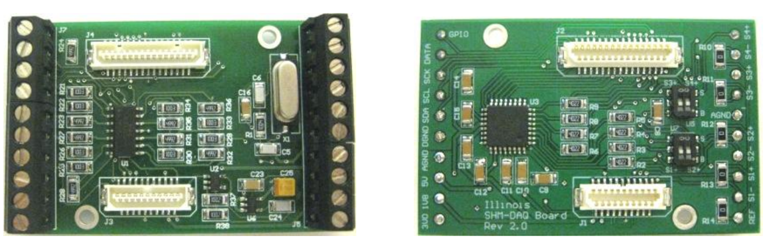


Figure 5. SHM Data acquisition board (SHM-DAQ board): top (left) and bottom (right)

2.10 High-sensitivity sensor board (SHM-H sensor board)

Even many attractive features of low cost MEMS accelerometers (cheap, small, power efficient etc.), the resolution of the MEMS accelerometers may be still insufficient for low-level ambient vibration. The high-sensitivity sensorboard for

Imote2 platform (SHM-H sensorboard, see Figure 6) has been developed for measuring low-level vibration less than 1.0mg. It uses a low noise accelerometer (SD1221-002L, Silicon Designs) having the noise density of 5.0µg/√Hz and contains a signal conditioning circuit to better fit the signal to the input range of the ADC and not to add unnecessary noise to the signal[16]. The resulting noise level of the SHM-H board at 20Hz bandwidth is 0.05mg (even less at lower bandwidth), which would be enough for measuring the ambient vibration of civil infrastructure. Another application of this kind of high-sensitivity sensorboard is to use it as a reference sensor in a sensor network[17]. Taking the cross-correlation (or cross spectrum) of a low-noise sensor data with low-cost sensor data can lower down the noise levels; small number of high-sensitivity sensors as reference sensor can improve the correlation function estimation of whole sensor network. In this study, the SHM-H boards are used as the cluster heads of the *DDA*.

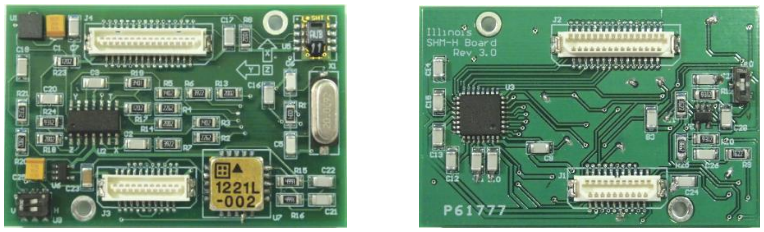


Figure 6. SHM High-sensitivity sensorboard (SHM-H board): top (left) and bottom (right)

2.11 Autonomous monitoring of hybrid WSSN

To effectively manage all these features mentioned above, well-organized management software is required. The *AutoMonitor* of ISHMP Services Toolsuite had been designed for autonomous operation of a full-scale WSSN; which incorporates with *ThresholdSentry* and *SnoozeAlarm* and consequently enables the power-efficient and continuous management of the WSSN[12]. In this study, the *AutoMonitor* has been upgraded for the hybrid operation of the *CTE*, *DDA*, multi-hop communication, *AutoUtilsCommand* and *RemoteSensing* as well as *ThresholdSentry* and *SnoozeAlarm*. With carefully designed scheduler, all the applications are performed without any conflict.

2.12 Fault tolerant WSSN

In a full-scale implementation of WSSN, diverse fault tolerant features should be taken into account to make the WSSN robust and stable. Even though some of nodes sometime have problems, it should not affect the stability of entire network. The fault tolerant features considered in this WSSN, particularly, for the long-term operation, contain follows;

- Skipping unresponsive nodes: sensing is initiated for the only woken-up sensor nodes. However, some nodes can be unresponsive with low-power, bad communication or hardware malfunction before or after sensing, even if they notify that they were awaken. In that case, the unresponsive nodes are excluded in the network to avoid the unnecessary waiting time and excessive use of power.
- Cluster head change in *DDA*: the cluster head is most important node in a local group when using *DDA*. If the cluster head has problem, the DDA finds another cluster head in the group. Otherwise, the whole data from the local group is lost though the other sensor nodes are responsive in the local group.
- Exclusion of low-power sensor nodes before sensing start: sensing is one of the main sources of power consumption. Even if a sensor node is woken up, it can be powered off during sensing or after sensing if the battery voltage is not sufficient. Once power off, it cannot be recharged.
- Watchdog timer: when sensor nodes being in stuck for unexpected reasons and do nothing for a while, the watchdog timer in sensor nodes or gateway nodes reset the nodes.

For the full-scale deployment, tremendous amount of efforts were poured into making a fault tolerant WSSN with numerous trial-errors, lab-scale and full-scale tests and updates. Though the detail of all the endeavors cannot be shown here, the fault tolerant features of the WSSN are the key components of this SHM system.

3. FULL-SCALE DEPLOYMENT ON A CABLE-STAYED BRIDGE

The 1st year's deployment in the Jindo Bridge focused on demonstrating the performance and applicability of the Imote2 sensor platform and the ISHMP software in the full-scale test bed in a harsh environment. The research effort has been continued to the second year to realize a larger, autonomous, power-harvesting network of multimetric sensors with decentralized data processing strategies as well as the centralized data acquisition. Following a brief description of the

Jindo Bridge, an overview of this deployment will be provided in detail.

3.1 Bridge description

All the software and hardware developed and upgraded in this study have been validated on a cable-stayed bridge (the 2nd Jindo Bridge) in South Korea. The Jindo Bridges are twin cable-stayed bridges, which connect Jindo Island and the southwestern tip of Korean Peninsula near the town of Haenam. The subject of this study is the 2nd Jindo Bridge that is newer one constructed in 2006 (left of Figure 7). The bridge is a three-span steel-box girder cable-stayed bridge; which are 344m of main span and 70m of side spans. The streamlined steel-box girder is supported by the sixty stay cables connected the two A-shaped steel pylons on concrete piers.

Figure 7. The Jindo Bridges

3.2 Sensor topology & network division

In this deployment, total 669 channels with 113 sensor nodes have been installed on the bridge. To efficiently operate the large sensor network, the WSSN is divided into four subnetworks, considering the functionalities, network size, communication range, and communication protocol of each network. All four subnetworks share a common software configuration that includes autonomous operation by *AutoMonitor*, power harvesting by *ChargerControl*, sleep-cycling by *SnoozeAlarm*, monitoring of the network status by *AutoUtilCommand*, and centralized data acquisition by *RemoteSensing*. In addition to these common features, the subnetworks have their own unique software applications: deck networks employ *DecentralizedDataAggregation* to efficiently utilize limited bandwidth by condensing sensor data, while cable networks can obtain tension forces of cables by the *CableTensionEstimation* application. Furthermore, the cable network on the Jindo side features multi-hop communication. The description of each network is summarized see Figure 8 and Table 1.

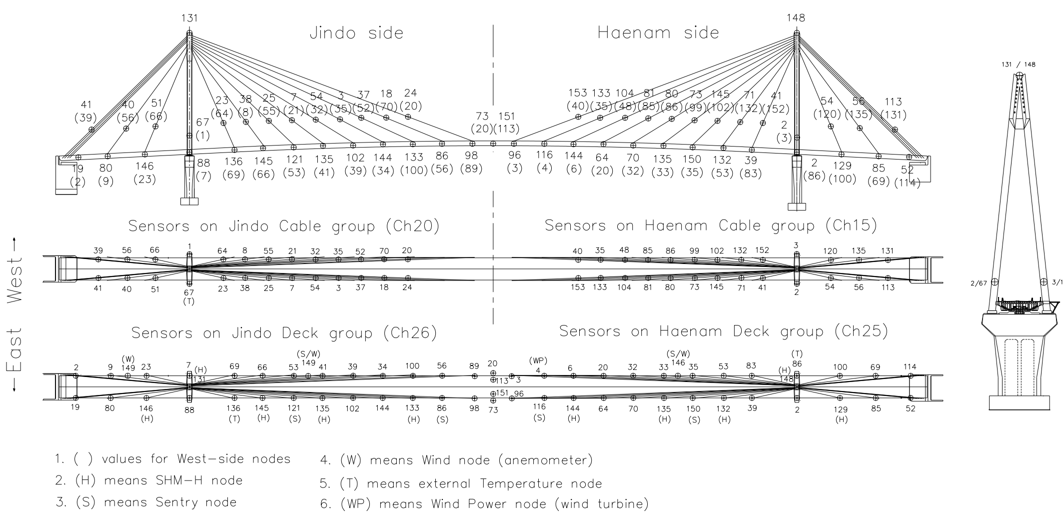


Figure 8. Sensor topology with node IDs (2011 deployment on the 2nd Jindo Bridge)

Table 1. Functionalities of four sub-networks

		Haenam side		Jindo side	
		Deck	Cable	Deck	Cable
Communication channel		Ch 25	Ch 15	Ch 26	Ch 20
Network size		30 nodes	26 nodes	31 nodes	26 nodes
SHM-H board (cluster head)		5 nodes	-	5 nodes	-
SHM-DAQ board (wind)		1 nodes	-	2 nodes	-
Sentry node		3 nodes	2 nodes	3 nodes	2 nodes
Temperature node (exposed)		1 nodes	-	1 nodes	1 nodes
Functionalities	Common	*RemoteSensing*, *AutoUtilsCommand*, *ChargerControl*, *ThresholdSentry* and *SnoozeAlarm*			
	Particular	*DDA*	*CTE*	*DDA*	*CTE*
Communication protocol		Single-hop	Single-hop	Single-hop	Multi-hop

3.3 Energy harvesting

A noticeable enhancement for this deployment, compared with the 1st year deployment[6~8], all the sensor nodes are self-powered with energy harvesting devices. Even though the battery life could be extended by efficient power management strategies and data condensation using in-network processing, the use of ordinary batteries implies the inconvenience of regular battery replacement. In the 1st year deployment, 8 nodes of 70 nodes were equipped with solar panels and rechargeable batteries for testing purpose. The size and type of the energy harvesting devices used in the 1st year deployment have been shown to be adequate for the WSSN. Thus, the power harvesting is expanded to entire network in this deployment. Power harvesting device in this deployment include SCM-3.3W from SolarCenter (9V-370mA) shown in Figure 9 (left) for solar panels and the ainsys lithium-polymer rechargeable battery (3.7V-10,000mAh). In addition, a prototype wind turbine (HR-W35V, Hankukrelay), shown in Figure 9 (right), is used to power a sensor node underneath the deck.

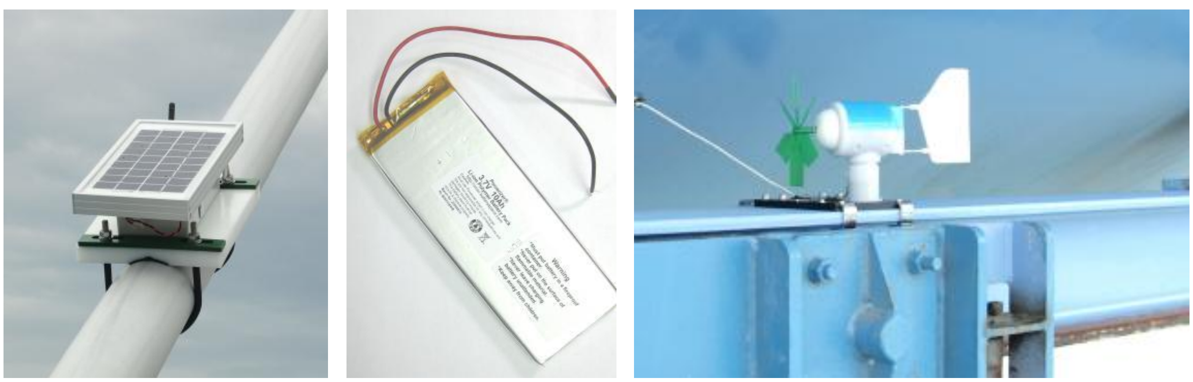


Figure 9. Rechargeable battery (middle) and energy harvesters; solar panel (left) and wind turbine (right)

3.4 Environmental hardening and sensor installation

Sensor nodes should be protected from environmental effects that can cause the electrical or mechanical malfunctioning. PVC enclosures are used for all the leaf nodes, which has silicon packing for water-proofing, a hinge-latch type cover for easy opening and closing and sufficient space that can accommodate a battery, sensor module, cables and accessories (Figure 10, left). A sensor module (combined set of battery board, Imote2 and sensorboard) is bolted to an acrylic base plate boned on the bottom of the enclosure (Figure 10, middle). The enclosures are mounted on the bottom plate of the deck using magnets shown in Figure 10 (right), and a specially designed PVC plate and U-shaped screws are used for cable nodes installation (Figure 9, left).

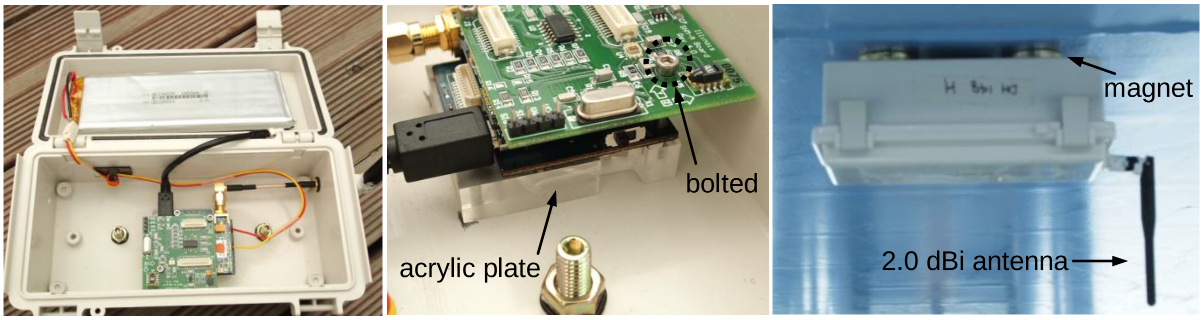


Figure 10. Enclosure assembly (left), sensor module mounting (middle) and installation using magnet (right)

3.5 Environmental monitoring

Environmental monitoring of this deployment includes temperature and wind speed. To track temperature change, the temperature sensors (SHT11, Sensirion) on SHM-A board are utilized. As the SHM-A board is placed inside the enclosure, the temperature sensors of several nodes are pulled out and placed below the cover of the enclosure to be able to measure outside temperature through a hole shown in Figure 11 (left, middle).

The 3D ultra-sonic anemometer (Model 81000, RM Young) used in this deployment can measure wind speed of 0 ~ 40m/s range at 0.01m/s resolution and wind direction of 0~360 degrees (-60~60 degrees for elevation). In total three anemometers are installed with 5m-length stainless poles (Figure 11, right) on the bridge, two in the center span and the other in the side span (see Figure 8). The SHM-DAQ board takes analog voltage signals from the anemometer for synchronized sensing with acceleration measurement.

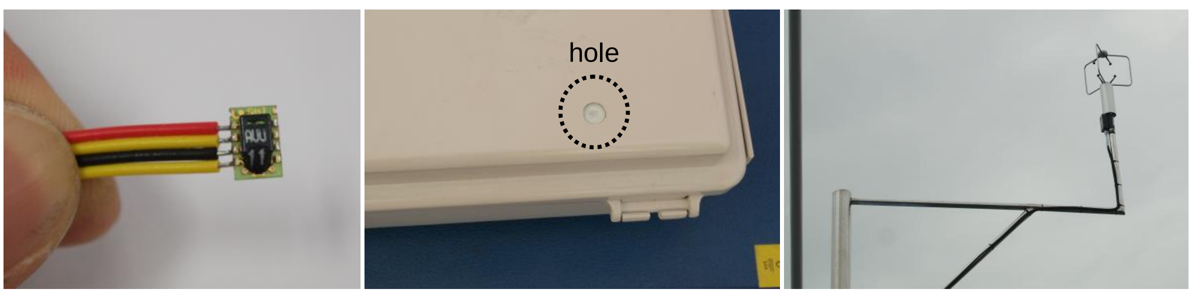


Figure 11. Temperature sensor (left), exposed outside enclosure (middle) and 3D ultra-sonic anemometer (right)

3.6 Base station

The base station provides access to the entire WSSN; hence, the base station is a critical component in the WSSN. For the long-term monitoring, the base stations are carefully designed to endure the harsh environment in the Jindo Bridge. A temperature and humidity durable industrial-grade PC (AEC-6905, AAEON) is selected as the base station. The UPS backup (ES550, APC) is supplemented to protect the PC from unexpected electric surges and outages. In this deployment, two base stations are installed on each pylon pier of Jindo and Haenam sides. The base stations are environmentally protected with water-proof PVC enclosures (Figure 12, left) and have two gateway nodes that control deck and cable subnetworks. A wired internet line is installed to the base station, and the PC is remotely controlled with TeamViewer that is a screen-sharing and file-transfer application[19]. For the single-hop networks, a 8 dBi antenna (PM-0M07 8dB Volcano, Daeheung) with a noise compensator (SLIM54M-500mW, Daeheung) is used for each gateway node (Figure 12, right), while 2 dBi smaller antenna (PM-DI02A, Daeheung) is used for the gateway node of the multi-hop network (Jindo side cable network) to make optimal condition for multi-hop communication.

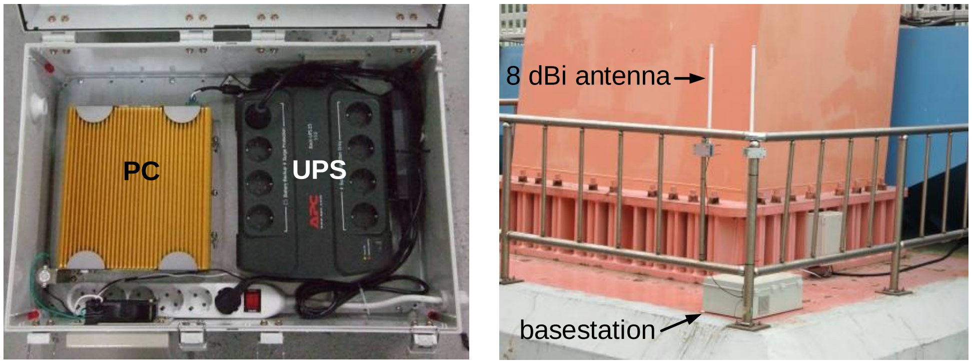


Figure 12. Basestation with PVC enclosure (left) and 8 dBi antenna for single-hop gateway node (right)

The WSSN deployed on the Jindo Bridge were described in detail, focusing on the unique features of this deployment such as network topology, power harvesting, environmental monitoring, and environmentally hardened base stations and sensor nodes for long-term monitoring. The following section presents analyses of the bridge using the collected data.

4. EVALUATION OF THE SHM SYSTEM

The hybrid WSSN described in the previous section provides a wide variety of valuable information in assessing the state of the Jindo Bridge. This section focuses on describing wind monitoring, performance of power harvesting, and centralized/decentralized data processing for modal analysis and cable tension monitoring.

4.1 Wind monitoring

The Jindo Bridge has experienced a Typhoon having the 960 hPa of central pressure and 40m/s of max wind speed, named Kompasu, after the deployment (Aug.31th ~ Sep.2nd, 2010). The typhoon passed the bridge quite closely shown in Figure 13. Based on the Korea Meteorological Administration (KMA) records, the wind speed was 14~20 m/s (green line, Figure 14) and the wind was blowing from the southeast, which is the orange dots in Figure 12 (left) and reproduced with an arrow in Figure 14 (right), in the Jindo area around 9pm on Sep.1st, 2010. The measurements from the 3D ultra-sonic anemometer installed on the bridge, which were collected by the SHM-DAQ board, showed the 15~25 m/s of wind speed (Figure 15, left) and 170~200 degree of wind direction (Figure 15, middle); the anemometer was installed in perpendicular direction to the bridge axis and the wind direction is calculated in clockwise from the anemometer axis (Figure 14, right). Considering that the KMA record is from a mountain (Cheomchal-san) in Jindo Island, not from the Jindo Bridge, the wind data measurements are acceptable.

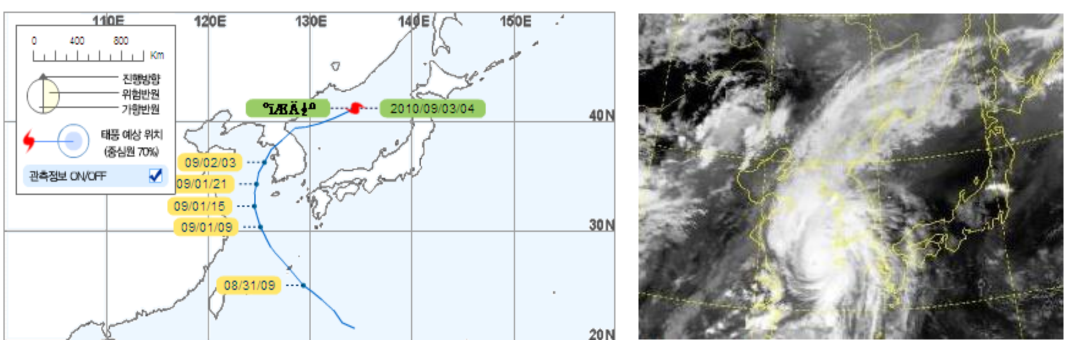


Figure 13. Typhoon Kompasu route (left) and satellite picture at 5:30pm in Sep.1st, 2010 (right)

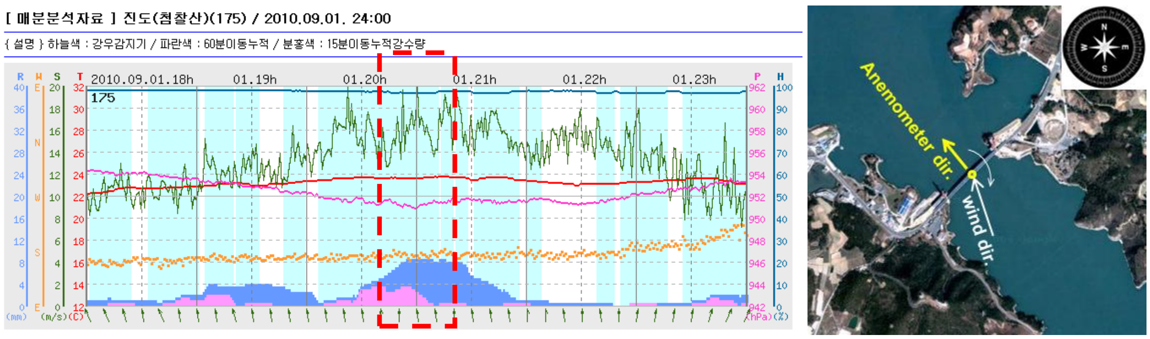


Figure 14. KMA record (left), anemometer and wind direction in Sep.1st, 2010 (right)

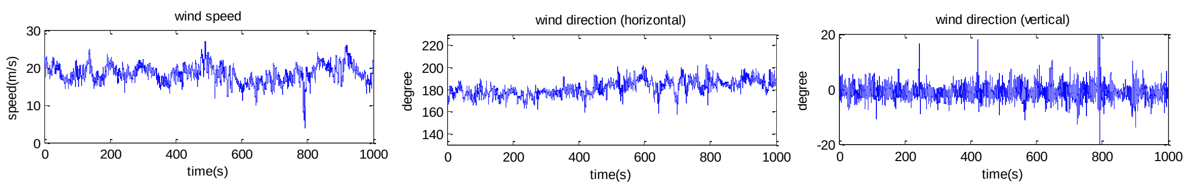


Figure 15. Wind measurements from Haenam side anemometer (9pm, Sep. 1st, 2010)

4.2 Power harvesting

Figure 16 shows a typical charging status monitoring example for two days (Sep. 11~12th, 2010) using *AutoUtilsCommands*. The first day was sunny and the second day was rainy. In this deployment, the default checking cycle is 1 hour for the charging currents and battery voltages of all sensor nodes. As shows in the Figure 14 (bottom), the charging starts around 6~7AM, then keep the average charging current of 140mA during daytime and stop charging in the night in the Sep. 1st. The battery voltages (Figure 16, top) were little pulled up (from 4.08V to 4.17V in average) for fast charging by PMIC charger controller, and went back to the actual battery voltages after charging mode off. The actual voltage increase of the 10,000mAh Li-ion battery with one day charging was about only 0.02~0.04V around 4.1V level at that time; this is because the battery was in almost fully charged status. As the charging level goes up, the charging speed becomes slower for safe charging[14]. The second day was rainy, and the average charging current was around 70mA. However, some of them (node 150, 116 and 85) showed higher charging current of about 130mA, because the sensor nodes are sentry nodes and two solar panels were used for the sentry nodes which are supposed to consume more power due to periodic sensing with *ThresholdSentry*.

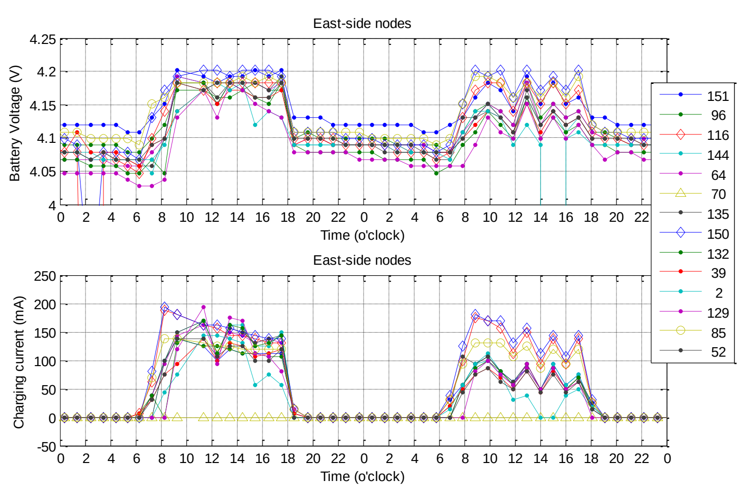


Figure 16. Example of charging status monitoring using *AutoUtilsCommand* (Sep. 11~12th, 2010)

4.3 Centralized data acquisition and processing

Each sensor node equipped with SHM-A or SHM-H sensor board provides 3-axes accelerations at given sampling rate of 25Hz (user selectable among 25, 50, 100 and 280Hz). Figure 17 shows the example acceleration time histories measured at the center span of Jindo-side deck (z-axis) during the typhoon Kompasu. The acceleration levels were about 20mg in average at that time and quite evenly distributed over the period. Figure 18 shows the power spectral densities (PSD) for the z-axis acceleration of Jino-side deck.

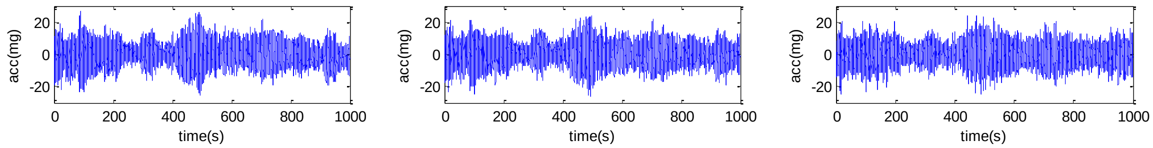


Figure 17. Example time histories; vertical acceleration of Jindo-side deck at node 20 (left), 89(middle), 25(right)

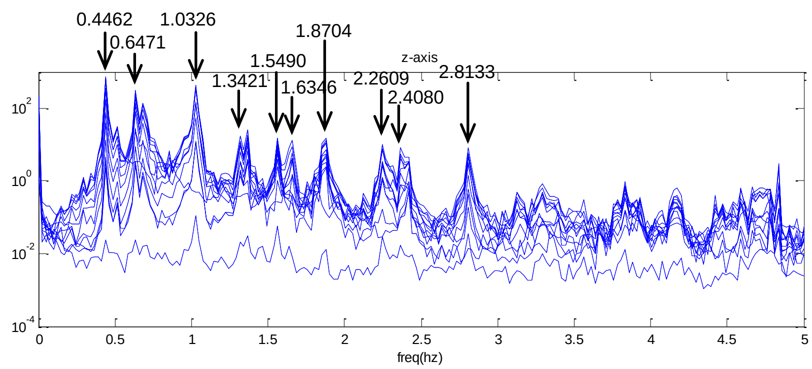


Figure 18. Example power spectral densities (PSD) for vertical accelerations of Jindo-side deck

The centrally collected acceleration responses are used in the Natural Excitation Technique[20] in conjunction with Eigensystem Realization Algorithm[21] to identify natural modes as shown in Table 3 and Figure 13. The modal properties from two deck networks are combined to provide the global information. To construct the global mode shapes, least-square method is applied to link the modes together at the four overlapped sensor nodes at the center of the deck (node 20, 73, 113 and 151, see Figure 8). The estimated modal properties are consistent with those from the wired sensor system[8].

Table 2. Identified natural frequencies and comparisons

Mode	NExT/ERA (Haenam)	NExT/ERA (Jindo)	from Wired SHM[8]
Deck **V**ertical -1	0.4462	0.4462	0.4395
DV 2	0.6454	0.6471	0.6592
DV 3	1.0331	1.0326	1.0498
DV 4	1.3559	1.3421	1.3672
DV 5	1.5549	1.5490	1.5869
DV 6	1.6528	1.6346	1.6602
Deck **T**orsion -1	1.7977	1.8022	-
DV 7	1.8710	1.8704	1.8555
DV 8	2.2594	2.2609	2.3193
DV 9	2.8121	2.8133	2.8076

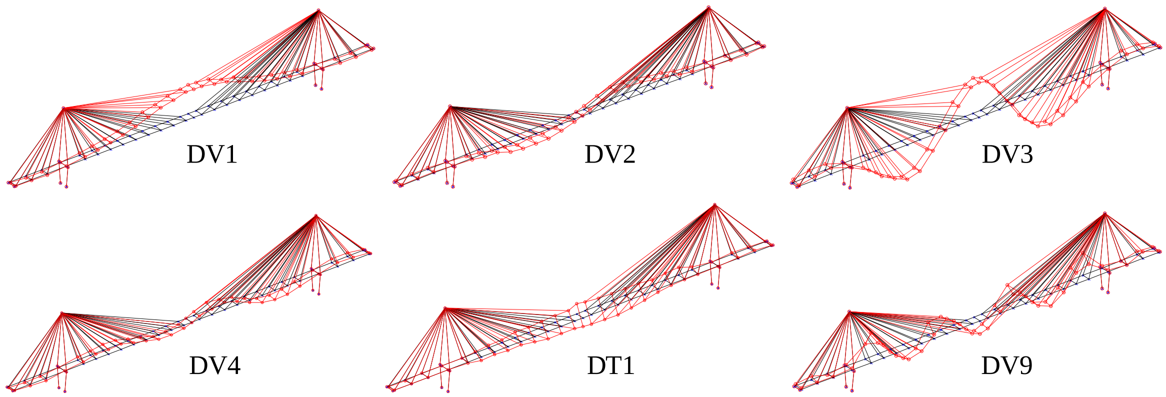


Figure 19. Identified mode shapes using NExT/ERA

4.4 Decentralized cable tension monitoring

The tension forces of the cables are estimated on the sensor nodes shown in Figure 20 (left) using the *CableTensionEstimation* application. Because the Jindo Bridge deployment is currently in the debugging phase, only the sensor nodes located on the Haenam side network are utilized in estimating cable tensions. The sensor node C10 is excluded from the network due to hardware malfunctioning. *AutoMonitor* at the gateway node runs *CableTensionEstimation* on a regular basis with the predefined time interval (24 hours), saving the retrieved cable tension values in the base station. In this debugging phase, cable tensions are estimated from September 21, 2010 to September 26, 2010 and compared to two references: (1) estimated tension by Park et al.[22] and (2) design tension; mean tension values from CableTensionEstimation in Figure 20 (right) are consistent with the references.

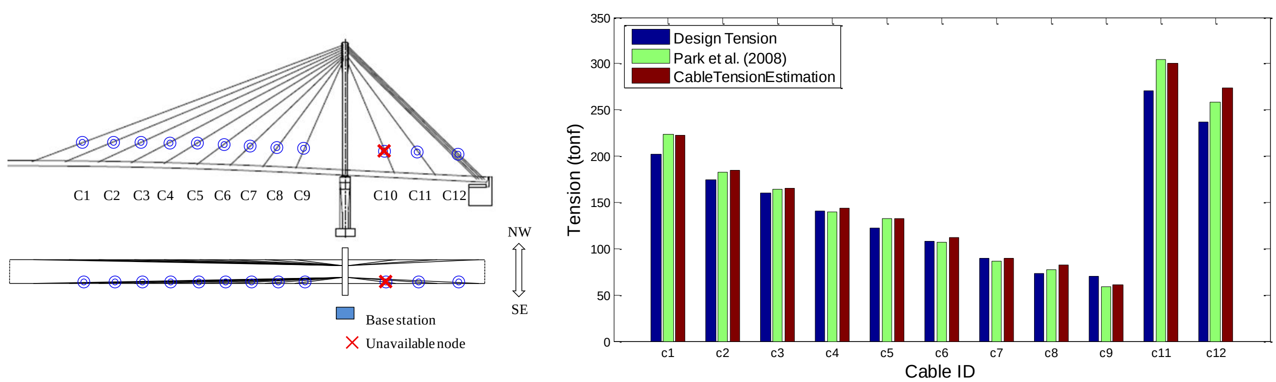


Figure 20. Cable nodes at the Cable-Haenam network (left) and Estimated cable tensions using *CTE* and comparisons (right).

4.5 Decentralized data aggregation

To validate the efficacy and scalability of the decentralized data aggregation approach, its implementation, DecentralizedDataAggregation application is used. The sensor topology with four local sensor communities shown in Figure 21 (left) is considered. Note that *DecentralizedDataAggregation* is performed only in the Haenam side network as the deployment is in the debugging phase. *DecentralizedDataAggregation* has successfully conducted the whole procedure, consisting of sensing, in-network processing, and collection of the processed data in the large-scale network of sensors distributed over the broad area (see Figure 21 (right) for sample correlation functions).

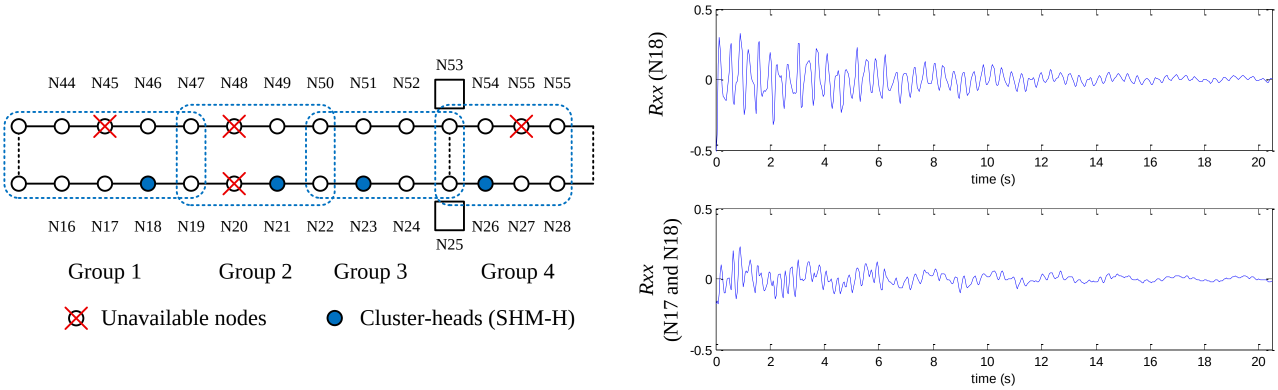
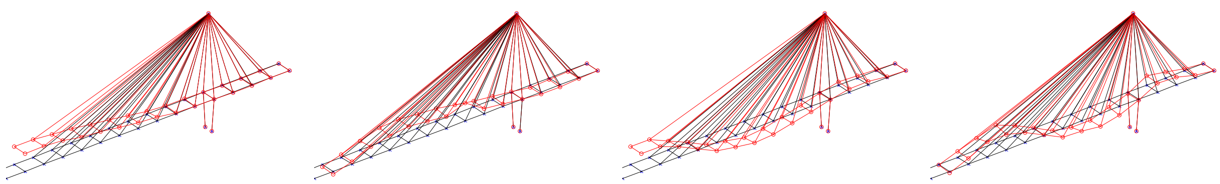


Figure 21. Sensor topology (left) and Auto- and cross-correlation functions estimated in Group 1(right).

To evaluate the obtained correlation functions, global modal properties are estimated. NExT/ERA is applied using each group's correlation functions to obtain local modal properties that are subsequently used to determine true modes and combine global mode shapes as found in Figure 22. These mode shapes are consistent with those obtained from the centralized approach previously described. As such, the performance of decentralized data aggregation is validated in the Jindo Bridge deployment.



(a) 0.4402 Hz (b) 0.6833 Hz (c) 1.0293 Hz (d) 1.3484 Hz

Figure 22. First four identified mode shapes using *DecentralizedDataAggregation*.

5. CONCLUSIONS

The hybrid SHM system using WSSNs has been proposed and experimentally validated through the long-term operation of full-scale deployment on a cable-stayed bridge. As the 2nd year deployment on the Jindo Bridge, in total, the 669 sensing channels with 113 sensor nodes have been installed; which would be the world largest WSSN for SHM application. Major updates, compared with the 1st deployment, are *RemoteSensing* using flash memory, energy harvesting system for all the sensor nodes, new hardware (SHM-H and SHM-DAQ board) implementation, use of multi-hop protocol, increased number of anemometer, specialized application for cable-stayed bridge (*CableTensionEstimation*), *DecentralizedDataAggregation*, autonomous environmental monitoring, and more fault tolerant features etc. All the hardware and software work well, and it showed the possibility of practical implementation of WSSN for long-term SHM system.

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