Smart Structures and Systems, Vol. 6, No. 8 (2010) 939-951
DOI: http://dx.doi.org/10.12989/sss.2010.6.8.939

Design of wireless sensor network and its application for structural health monitoring of cable-stayed bridge

H.R. Lin[1], C.S. Chen*[2], P.Y. Chen[3], F.J. Tsai[1], J.D. Huang[1], J.F. Li[2], C.T. Lin[4] and W.J. Wu[3]

[1]Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan
[2]Department of Civil Engineering, National Taiwan University, Taipei, Taiwan
[3]Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei, Taiwan
[4]Graduate Institute of Electronics Engineering, National Taiwan University, Taipei, Taiwan

(Received November 18, 2009, Accepted March 8, 2010)

Abstract. A low-cost wireless sensor network (WSN) solution with highly expandable super and simple nodes was developed. The super node was designed as a sensing unit as well as a receiving terminal with low energy consumption. The simple node was designed to serve as a cheaper alternative for large-scale deployment. A 12-bit ADC inputs and DAC outputs were reserved for sensor boards to ease the sensing integration. Vibration and thermal field tests of the Chi-Lu Bridge were conducted to evaluate the WSN's performance. Integral acceleration, temperature and tilt sensing modules were constructed to simplify the task of long-term environmental monitoring on this bridge, while a star topology was used to avoid collisions and reduce power consumption. We showed that, given sufficient power and additional power amplifier, the WSN can successfully be active for more than 7 days and satisfy the half bridge 120-meter transmission requirement. The time and frequency responses of cables shocked by external force and temperature variations around cables in one day were recorded and analyzed. Finally, guidelines on power characterization of the WSN platform and selection of acceleration sensors for structural health monitoring applications were given.

Keywords: wireless sensor network (WSN); ZigBee; structural health monitoring (SHM); Chi-Lu cable-stayed bridge.

1. Introduction

A wireless sensor network (WSN) is an enabling technology for extracting various types of information about the environment. Applications of WSNs require an integration of multiple aspects of technology such as application-oriented hardware development and software programming. WSNs are a promising solution due to their compatibility with IEEE 802.15.4 or ZigBee, their low power consumption, and their network feasibility. Owing to the high level compatibility of such standards, large-scale deployment of WSNs for different application domains has been realized; for instance, structural health monitoring (SHM, Lee *et al*. 2006), medical services (Lin *et al*. 2006), smart homes (Lee *et al*. 2006, Huang *et al.* 2008), long-term wild life detection, traffic flow and the environmental conditions (Kohvakka *et al*. 2005, Suhonen *et al*. 2006). It appears that WSNs are becoming the basis for creating intelligent environments (Bonivento *et al*. 2006).

*Corresponding Author, Professor, E-mail: dchen@ntu.edu.tw

The idea of using an integrated wireless system to conduct SHM has increasingly been explored in recent years (Yuan *et al*. 2006, Lu *et al*. 2008, Meyer *et al.* 2010) and numerous research groups have developed similar wireless platforms for SHM (Fujino and Abe 2004). However, most of these studies were restricted to lab-scale applications and small structures due to the dimensional limit of sensing elements and the lack of affordable wireless systems. Besides, there was no uniform rule explicated when specifications were built to facilitate wireless network application and integration (Lynch and Loh 2006). To address these limitations, a low-cost, flexible and compatible solution is required for large-scale engineering structures such as highways, buildings and bridges.

The impact of environmental factors on bridges has been studied. In particular, it has been reported in analytical and empirical terms that temperature variation can induce thermal displacements and stresses in curved or skewed bridges and therefore, making them susceptible to damage (Moorty and Roeder 1992). In the early 90s, only thermal couples and wired systems were available for the manual recording of temperature variations. Since then, several tests have been applied to verify the thermal effects over cable-stayed bridges. According to Zhang *et al.* (2003), the main tower of cable-stayed bridge would rotate periodically in synch with the incident angle of solar radiation. The temperature changed rapidly during the periods from 7 am to 11 am and from 4 pm to 7 pm. Apart from this rotation issue, cable-force variation was related to the positioning of cables (Hou *et al*. 2002). As cable-stayed bridges have been increasingly constructed worldwide, it is important to thoroughly understand the structural behaviors of such bridges.

The Chi-Lu Bridge, a cable-stayed bridge in southern Taiwan, was devastated by a massive earthquake in 1999 (famously known as the 921 Earthquake). As of 2004, and after a series of reconstruction and loading tests, the bridge re-opened for public transportation. To ensure the security of this bridge, continuous monitoring is necessary. A forced-vibration test and a 24-hour temperature monitoring routine have been scheduled since 2008 to detect the responses of cables under external shock and temperature variation around cables, respectively.

The objective of this paper is to study and develop a low-cost, flexible and compatible WSN solution for large-scale engineering structures. The WSN module set is then adopted to meet the sensing acceleration and temperature requirements for SHM of the Chi-Lu Bridge. The WSN platform, which includes the related design of the modules, the measurement results and implementation concerns are discussed.

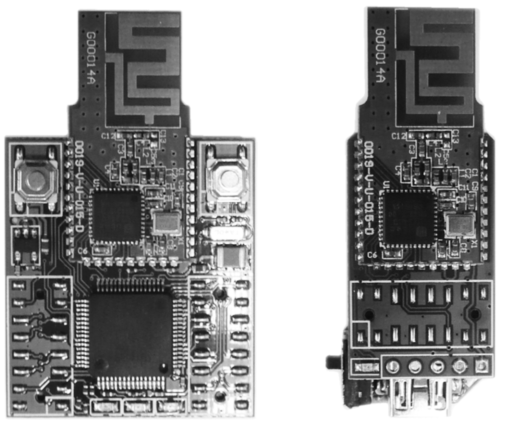
2. Design of WSN platform

Hardware costs and incompatibility are the main disadvantages of traditional sensors and data acquisition systems for SHM, where the cost of servo velocity seismometers is much higher than the cost of chip MEMS accelerometers. Although it is believed that a servo velocity seismometer could meet almost all kinds of field requirements, cheap and newly designed MEMS sensors are needed to reduce the cost of macro-scale deployment. Fortunately, MEMS sensors are increasingly able to meet the requirements of SHM, for example, in cable forced-vibration testing. If WSNs with MEMS sensors are adopted in SHM, the number of sensing points, which can be modified according to the experiment schedule, is highly flexible and active. The design concepts of such an integrative system are shown in following sections.

2.1 Adaptive module design

To simplify the installation of the WSN platform and help researchers overcome technical barriers, modularity and flexibility are considered herein. In this paper, the WSN platform for SHM system follows the IEEE802.15.4 standard and is divided into the communication and computation core, the sensor board, and the power board. Each part of the platform can be modified and replaced according to specific requirements and budget.

The core for networking and computing includes the *simple node* and the *super node*, each of which is designed for a specific purpose. The super node provides better hardware performance and consumes less energy compared to current commercial network coordinators or routers. It also serves as a sensing node if higher computing power and sampling rate are required. The computational



(a) (b)

Fig. 1 The WSN modules: (a) super node and (b) simple node

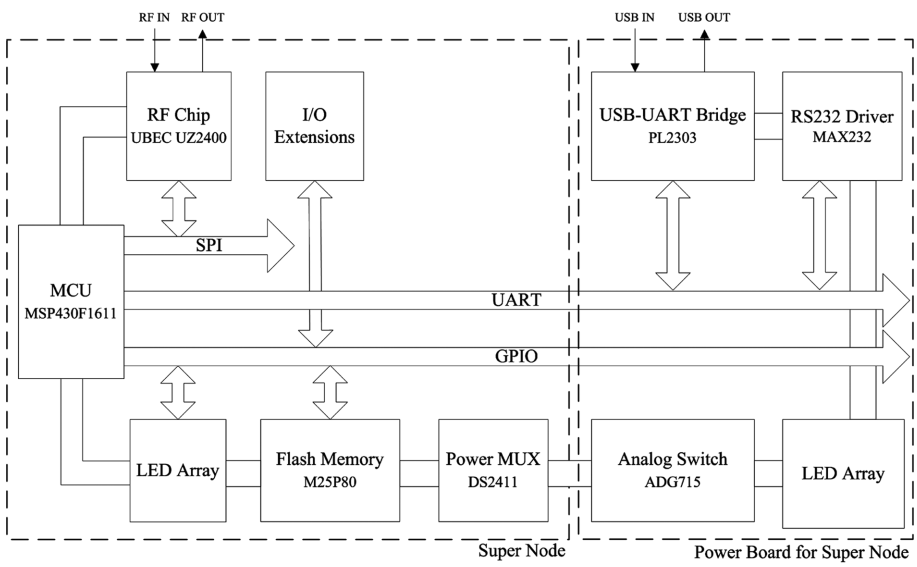


Fig. 2 Super node system architecture

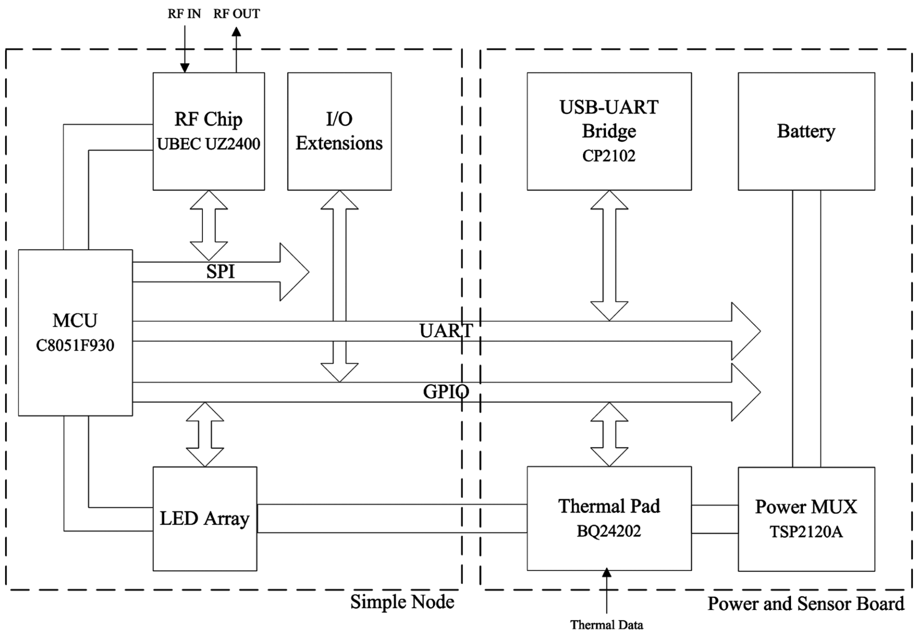


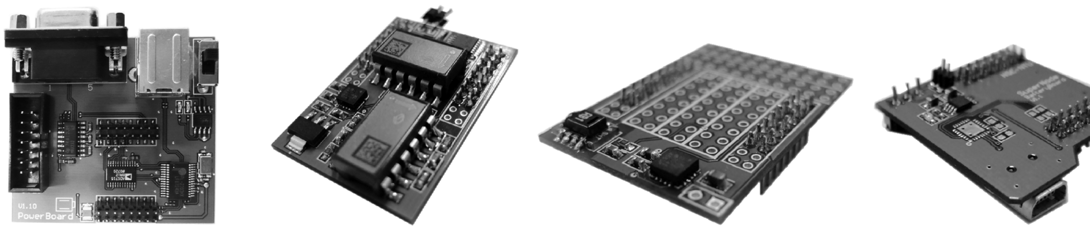
Fig. 3 Simple node system architecture

Table 1 Comparison of the Super Node, Simple Node and IMOTE2

	Super node	Simple node	IMOTE2
CPU			
Processor	TI MSP430F1611	Silicon Lab C8051F411	Intel PXA271
SRAM memory	10 KB	2 KB	256 KB
SDRAM memory	n/A	n/A	32 MB
FLASH memory	48 KB	32 KB	32 MB
POWER CONSUMPTION			
Current draw in deep sleep mode	42 μA	80 μA	390 μA
Current draw in active mode	29 mA	32 mA	66 mA
RADIO			
Transceiver	UBEC UZ2400	UBEC UZ2400	TI CC2420
Data rate	625 kb/s (Burst Mode)	625 kb/s (Burst Mode)	250 kb/s
Tx power	-30 - 0 dBm	-30 - 0 dBm	-24 - 0 dBm
Rx sensitivity	-95 dBm	-95 dBm	-94 dBm
Range	~30 m	~30 m	~30 m
I/O			
	UART, GPIO, I^2C, SPI, 12-bits ADC/DAC	UART, GPIO, I^2C, SPI, 12-bits ADC/DAC	UART, GPIO, I^2C, SDI0, SPI, I^2S, AC97, Camera
MECHANICAL			
Dimensions	29 mm × 47 mm × 7 mm	16 mm × 41 mm× 7 mm	36 mm × 48 mm × 9 mm
Weight	5g	3g	12g
PRICE			
	USD. 20.00	USD. 8.00	USD. 299.00

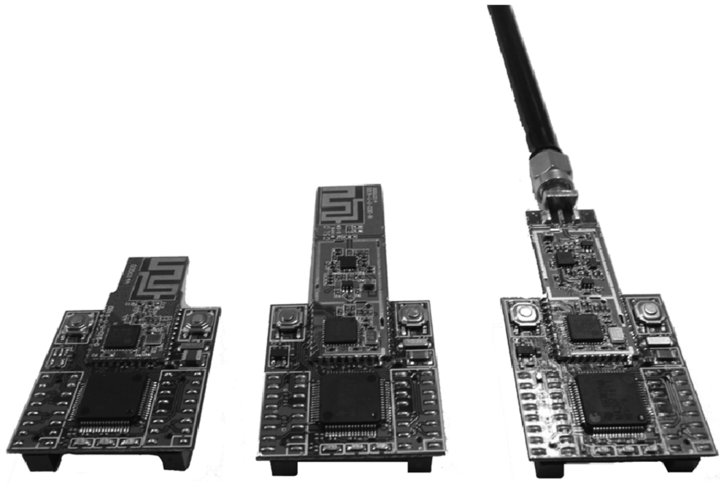
capability of the simple node is less than that of the super node but it is a cheaper alternative for macro-scale deployment. To reduce the cost of this experiment, super nodes were adopted as the network gateway to sink all information from a large number of simple nodes. Fig. 1 shows the top-side views of the super node and simple node. Figs. 2 and 3 depict the system architecture of super node and simple node respectively. Table 1 shows a comparison of IMOTE2, a commercial WSN module designed by Crossbow and Intel, and the WSN module designed herein. Compared with IMOTE2, the WSN modules developed in this work are considered to be a cheaper and lighter solution for SHM.

Other than the core, this research also developed power and sensor boards for specific applications. Many I/O ports, such as universal asynchronous receiver/transmitters (UARTs), serial peripheral interface buses (SPIs), I^2C buses, general purpose I/O's (GPIOs), 12-bit ADC inputs and DAC outputs in super or simple node are reserved for sensor boards, to make integration easier. Fig. 4 shows four different supplementary sensor boards and power boards. It can be noted that such power boards not only provide energy for nodes and sensor boards but also various communication interfaces for WSN modules and computers. Through this interconnection between a super node and a computer, node programming is made possible. As well as the sensor boards and the power boards, there are



(a) (b) (c) (d)

Fig. 4 Super node compatible modules: (a) power board, (b) tilter and accelerometer board, (c) humidity, temperature, and acceleration board and (d) battery board



(a) (b) (c)

Fig. 5 Three different compatible RF modules of the WSN platform: (a) short range RF module, (b) middle range RF module and (c) long range RF module three radio frequency (RF) modules (Fig. 5) used to meet different transmission range requirements: 30 meters, 100 meters and greater than 100 meters. Taking the forced-vibration test conducted herein for example, the half bridge is 120 meters long. To meet the transmission requirement of at least 60 meters, the middle-range RF module was used instead of the standard ZigBee module (range of 30 meters), to overcome the distance barrier.

2.2 Reliable WSN control software

Due to a lack of a power supply on the bridge, wireless communication is imperative for each of the tasks and therefore batteries and power boards are integrated with the nodes. A preliminary version of the wireless communication software was used for the forced-vibration tests. With evolving user requirements, a more inclusive and reliable version, called UNET was used for temperature monitoring.

In the first forced-vibration test, a 24-to-4 preliminary star topology was used to leverage the loading of the huge data flow produced by the high 64 Hz acceleration sampling rate. The advantage of this topology is a reduction in the number of collisions between nodes. There are four central nodes and each leads six sub-nodes in a separate channel. Since sub-nodes only listen to the broadcasting

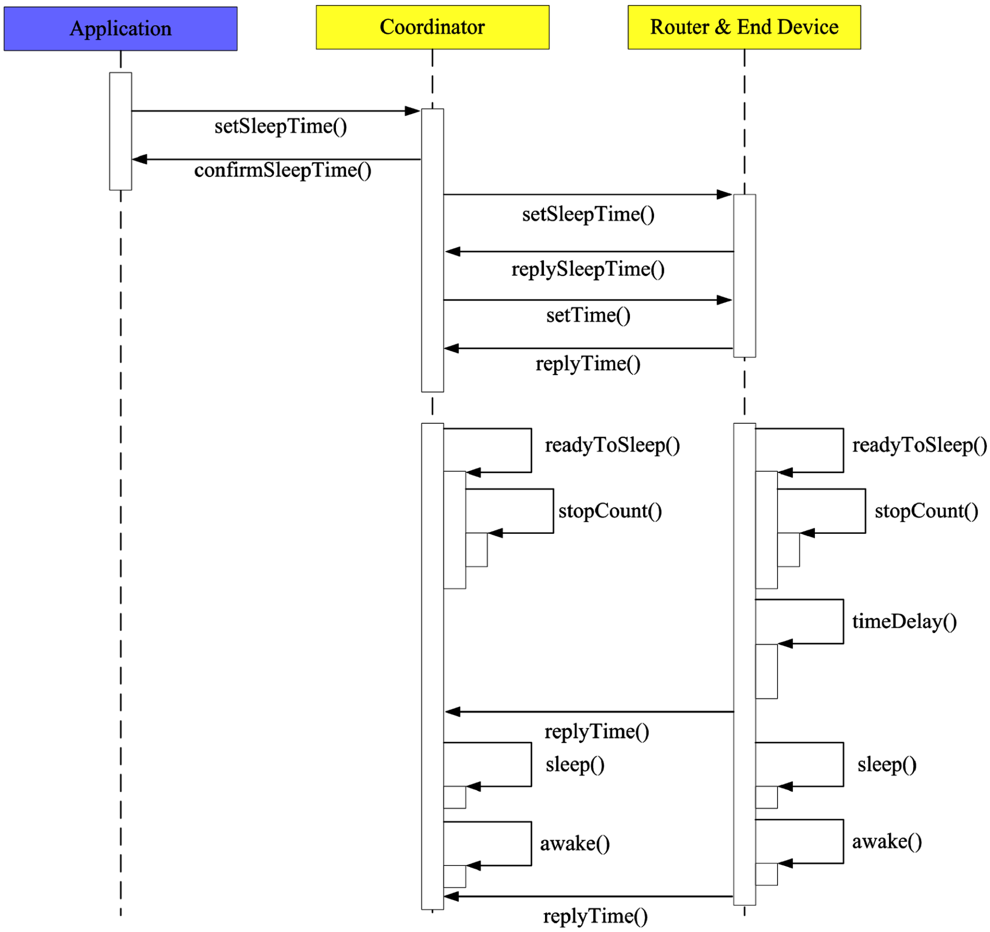


Fig. 6 Sequence diagram for UNET synchronization and sleeping procedure for platform power saving

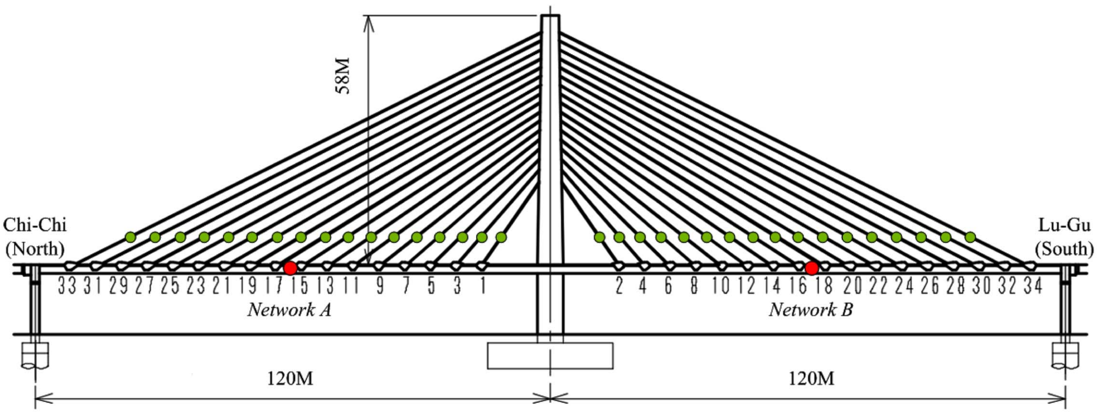


Fig. 7 The deployment of sensor and coordinator modules on the Chi-Lu Bridge

of respective central nodes, implementing the synchronization and sleep-mode functions became relatively easier. Meanwhile, only one chief central node controlled the remainder of the central nodes. To save time and energy, autonomous ID distribution and multiple routing of packets were not used.

The requirements are less strict for temperature monitoring: a low sampling rate is acceptable and only one physical parameter is needed. UNET provides several functionalities such as power-saving profiles, data security, routing and robust network construction. In the power-saving profiles, UNET uses node sleeping procedure with time synchronization to awake the nodes upon request just-in-time. The power-saving operation sequence is depicted in Fig. 6. For data security, UNET uses a light weighed Advanced Encryption Standard (AES) as its encryption methodology. In its encryption procedure, UNET uses the preloaded key set by the users. The key size varies from 32 to 128 bits.

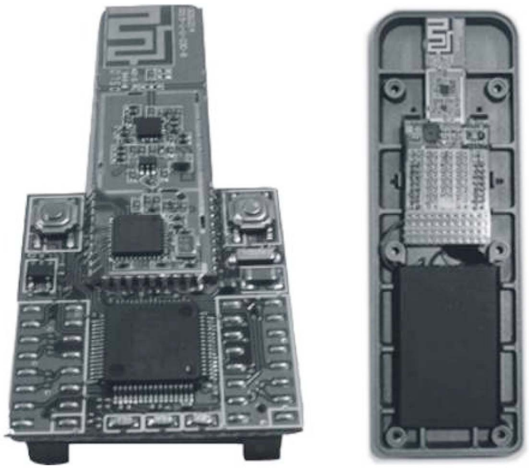
UNET is divided into three levels: coordinators, routers and end devices. A coordinator controls the entire network including the network joining mechanism, the routing protocol and network topologies. Routers are responsible for routing mechanisms and end devices are typically sensors or actuators. With UNET, the network of WSN modules is configured automatically by the software. As such, manual setting of individual modules is not necessary. General star and tree topologies are available for different experiments. With these advantages, UNET is able to better ensure a reliable network than the previous preliminary software with respect to reducing the errors caused by human factors.

As shown in Fig. 7, two groups of nodes were arranged on both sides of the bridge for temperature monitoring. The red spots represent coordinators and the green spots show the location sensing nodes. In other words, each network contained one coordinator and several sensing nodes. The sensing nodes report the data directly to the coordinator, without going through the routing protocol.

3. Field tests and experiment results

3.1 Forced-vibration tests of cables on the Chi-Lu Bridge

In the first field test, the compact WSN package, as shown in Fig. 8, was implemented to detect the forced-vibration responses of cables suspending the Chi-Lu Bridge, as shown in Fig. 9. In this



(a) (b)

Fig. 8 The sensing module system of the forced-vibration experiment: (a) a bird's-eye view of the super node with a middle range RF module and (b) a top view of the combination within the housing

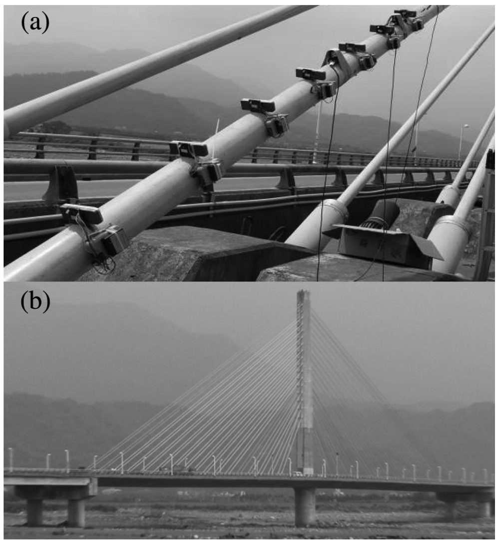


Fig. 9 WSN modules implemented on Chi-Lu Bridge: (a) super node platforms located on a cable and (b) the panorama of the Chi-Lu Bridge

test, the transient responses of the cables were measured from which the respective spectrum analyses were derived. This is one of several methods that can be used to compare the actual cable force with the designed force.

With the aid of the WSN system integrated with a ADXL322 2-axis accelerometer, the transient responses and frequency spectrum of a cable can be obtained as shown in Figs. 10 and 11. Although the noise performance is not as good as that when traditional seismometers are used, the readings from the accelerometer would still meet the sensitivity requirement of forced-vibration of the cables.

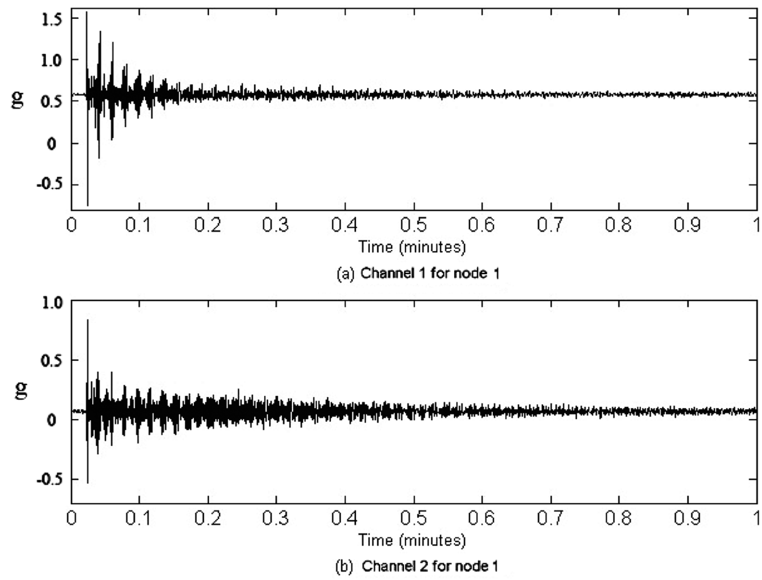


Fig. 10 Signal responses of 2-axis acceleration in time domains measured by the WSN platform: (a) the time evolution of channel 1(first axis) of one node and (b) the time evolution of channel 2(second axis) of the node

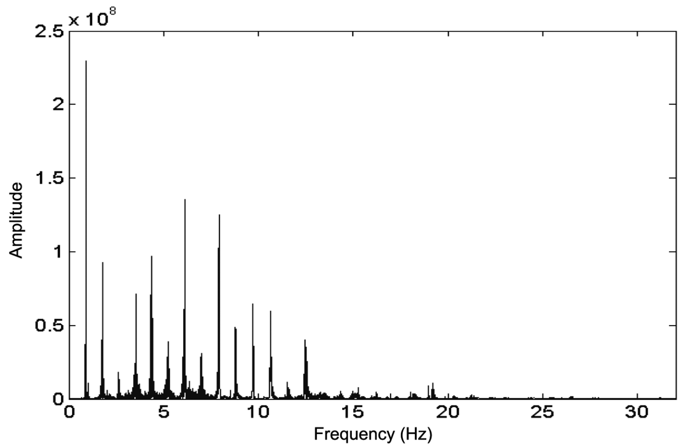


Fig. 11 Signal responses, for channel 1 of the node, in the frequency domain measured by the WSN platform

3.2 Twenty-four hour temperature monitoring on Chi-Lu Bridge

As previous studies have shown there exists a thermal effect of solar radiation on the bridges' structural displacement and cable force. Therefore, the temperature of cables on the bridge should be measured. A 24-hour experiment was scheduled to monitor the temperature of the bridge's cables. A chip temperature sensor was applied instead of a thermal couple. The simple node was adopted as the sensing node for macro-scale deployment. To conserve more energy, the sample interval was set to 4 seconds. The arrangement of temperature monitoring is shown in Fig. 7.

From the experimental results shown in Fig. 12, it is noted that the spatial difference of neighboring

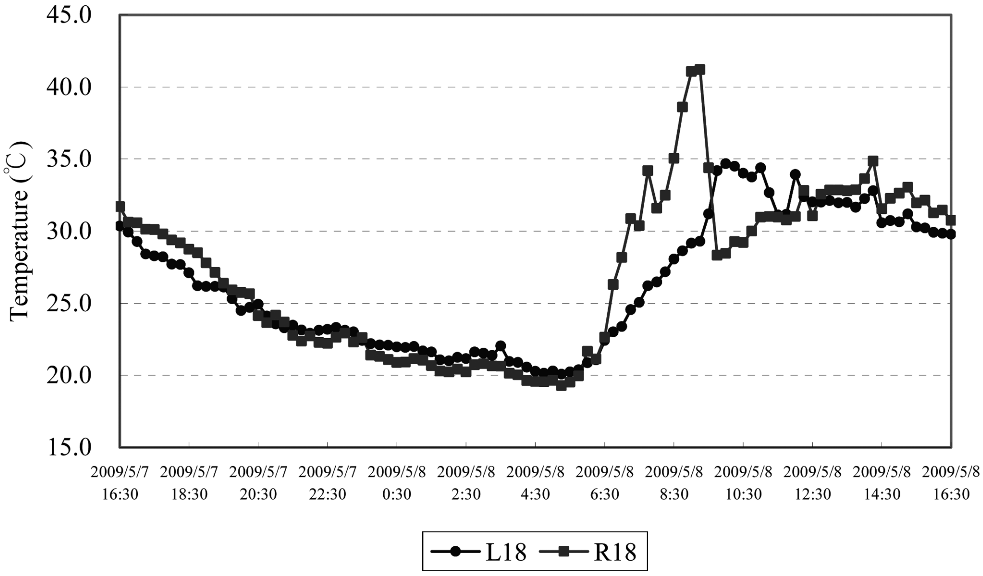


Fig. 12 Temperature variations of L18 and R18 cables on Chi-Lu Bridge from 16:30 7 May to 16:30 8 May, 2009. The square and circle denote the data from R18 and L18, respectively

cables is about 2 to 3 ºC at night. After sunrise, the temperature difference increased due to the incident angle of sunlight and shadow of cables on the sensors. Over one day, the temperature of a single cable varied as much as 20 ºC. Accordingly, this would result in 5 to 6% variation in cable force (Wong 2009). Apart from this, the temperature increased rapidly during the period between 6 am and 10 am and went down gradually from 2 pm to 8 pm.

4. Discussion

4.1 Power characterization of WSN platform

Power consumption is critical to the life span of a WSN. Table 2 shows the relation between current consumption of super node and RF power under a 3.3 V supply voltage. Although the current consumption reaches as high as 46 mA at 0 dBm transmitting power, the duty ratio could be lowered to a reasonable percentage to extend the lifetime of the Li-ion battery. In this case, 1900 mAh Li-ion batteries were adopted. It has been shown that the super node could survive for at least seven days with a high loading of 64 Hz sampling rate at 7% duty ratio.

Theoretically, the radio range of the receiver would be related to the transmission power. For a signal traveling at 2 GHz with 0 dBm power, the ambient transmission range would be 37 m long (Otis and Rabaey 2007). Although this frequency is slightly different from the ZigBee standard frequency, similar relationships can be found in the modules developed in this study. The relationship between the transmission range and data loss rate of the short-range module is shown in Fig. 13. Considering Fig. 13 and Table 2, it may be concluded that short-range module demonstrates better RF transmission capacity at the same transmission power. But, it should be noted that this is due to the polarization field of this RF module, which needs careful antenna alignment between

Table 2 Current consumption versus RF operating conditions (the unit of current is mA)

	RF power					
	10 dBm	0 dBm	-10 dBm	-20 dBm	-30 dBm	RF Off
Tx	51	46	45	43	43	0.35
Rx	29	29	29	29	29	

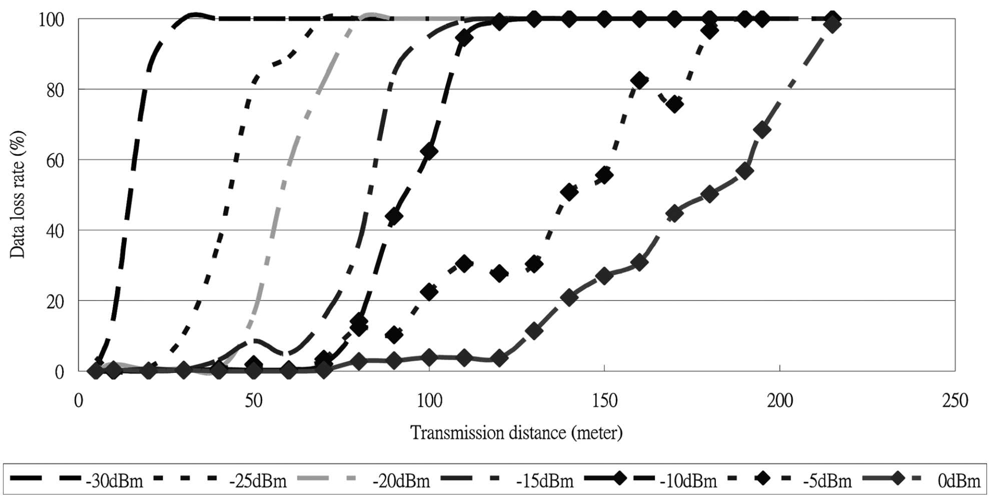


Fig. 13 The relationship between transmission distance and data loss rate of short-range module

modules when setting up the module in the field.

4.2 Selection of acceleration sensors

When selecting accelerometers for vibration sensing, there are several concerns for current commercial sensors. The noise performance and measurement frequency range need to be considered first. Typically, the structural response frequency is low and therefore, supporting frequency of sensors higher than 1 KHz is not necessary. Traditional servo velocity seismometers and piezoelectric accelerometers are such examples in which the application frequency range could be as low as 100 Hz.

Once the frequency range has been determined, the comparison of noise density (also called broadband resolution) of sensors becomes relevant. In this forced-vibration test, an mg-level sensing ability is derived and meets the requirement. However, if an ambient-vibration test is implemented, μg-level sensing ability is required. To date, resolutions of servo velocity seismometers, piezoelectric seismic accelerometers and MEMS accelerometers are 0.01 μg, 1 μg, 1mg, respectively. This parameter is affected by the noise performance. To further enhance the noise performance of monolithic MEMS accelerometers, the noise of the transducer itself and the integral circuit inside the package need to be improved. The electrical-thermal noise of transducers and flicker noise of FET circuit predominate most of the noise sources at low frequencies of 50 Hz and under (Levinzon 2005). It is suggested that the resolution of such accelerometers could be greatly improved if the noise source in CMOS and MEMS processes is suppressed.

For the scenarios where the noise performance is sufficient, the combination of sensor sensitivity and ADC resolution bit number needs to be considered, especially for MEMS sensors. Given a

MEMS accelerometer with sensitivity fixed as S_{ax}, it can be associated with the required g-value G_{req}, supply voltage V_{DD} and bit number, r_{ADC}, of ADC as

$$S_{ax} \geq \frac{V_{DD}}{2^{r_{ADC}} \times G_{req}} \tag{1}$$

If the ADC supply voltage is 3 V, bit number is 12 and required sensitivity is 3 mg, then the accelerometer sensitivity should be at least 244 mV/g. Similarly, if the accelerometer sensitivity is fixed, the requirement of ADC could be obtained from this equation.

5. Conclusions

In this paper, low-cost, highly expandable, and ZigBee-compatible WSN modules have been designed and applied for the SHM of the Chi-Lu cable-stayed bridge in Taiwan. The super node has been designed as a sensing unit as well as a receiving terminal with low energy consumption. The simple node has been designed to serve as a cheaper alternative for large-scale deployment. A 12-bit ADC inputs and DAC outputs have been reserved for sensor boards to ease the sensing integration.

Measurements obtained from the WSN show that temperature variations over 24 hours on the bridge are high enough to induce a change in cable force. In addition, WSN platforms have been successfully applied to monitor the transient and frequency responses of cables shocked by an external stimulus. From the data obtained, a further analysis to check whether the cable force meets the original design is possible. For further exploration, it is recommended that the noise problems need to be improved in both transducers and circuits when applying MEMS sensors in ambient vibration experiments. In addition, the sensitivity of the sensor and the resolution of the ADC need to be carefully considered in advance.

Acknowledgements

We would like to thank Prof. K-C Chang and his associates at the National Center for Research on Earthquake Engineering (NCREE) for the technical advice and support. The project is funded by the National Science Council (NSC) in Taiwan under the grant number NSC97-2218-E-002-005. We are grateful to the National Center for High-performance Computing for providing the computational resources.

References

Bonivento, A., Carloni, L.P. and Sangiovanni-Vincentelli, A. (2006), “Platform based design for wireless sensor networks”, *Mobile Netw. Appl.*, **11**(4), 469-485.

Fujino, Y. and Abe, M. (2004), “Structural health monitoring - Current status and future”, *Proceedings of the 2nd European Workshop on Structural Health Monitoring*, Munich, Germany, July.

Hou, J.M., Peng, X.B. and Ye, F.C. (2002), “Temperature effect on cable’s forces controlling of cable-stayed bridge”, *J. Chang'an Univ.,* **22**(4), 34-36.

Huang, J.D., Yeh, C.S., Chen, C.S., Lee, C.K. and Wu, W.J. (2008), “Design and implementation of a wireless

sensor network for smart living space", *Proc. SPIE*, **6932**, 69323P1-69323P9.
Kohvakka, M., Hännikäinen, M. and Hämäläinen, T.D. (2005), "Ultra low energy wireless temperature sensor network implementation", *Proceedings of the 2005 IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications*, Berlin, Germany, September.
Lee, R.G., Chen, K.C., Chiang, S.S., Lai, C.C., Liu, H.S. and Wei, M.S. (2006), "A backup routing with wireless sensor network for bridge monitoring system", *Proceedings of the 4th Annual Conference on Communication Networks and Services Research (CNSR 2006)*, Moncton, NB, Canada, May.
Lee, R.G., Lai, C.C., Chiang, S.S., Liu, H.S., Chen, C.C. and Hsieh, G.Y. (2006), "Design and implementation of a mobile-care system over wireless sensor network for home healthcare applications", *Proceedings of the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS '06)*, New York, USA, August-September.
Levinzon, F.A. (2005), "Noise of piezoelectric accelerometer with integral FET amplifier", *IEEE Sens. J.,* **5**(6), 1235-1242.
Lin, J.L., Liu, H.C., Tai, Y.T., Wu, H.H., Hsu, S.J., Jaw, F.S. and Chen, Y.Y. (2006), "The development of wireless sensor network for ECG monitoring", *Proceedings of the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS '06)*, New York, USA, August-September.
Lu, K.C., Loh, C.H., Yang, Y.S., Lynch, J.P. and Law, K.H. (2008), "Real-time structural damage detection using wireless sensing and monitoring system", *Smart Struct. Syst.*, **4**(6), 759-777.
Lynch, J.P. and Loh, K.J. (2006), "A summary review of wireless sensors and sensor networks for structural health monitoring", *Shock Vib. Digest*, **38**(2), 91-128.
Meyer, J., Bischoff, R., Feltrin, G. and Motavalli, M. (2010), "Wireless sensor networks for long-term structural health monitoring", *Smart Struct. Syst.*, **6**(3), 263-275.
Moorty, S. and Roeder, C.W. (1992), "Temperature-dependent bridge movements", *J. Struct. Eng.-ASCE,* **118**(4), 1090-1105.
Otis, B. and Rabaey, J. (2007), *Ultra-Low Power Wireless Technologies for Sensor Network*, Springer.
Suhonen, J., Kohvakka, M., Hännikäinen, M. and Hämäläinen, T.D. (2006), "Design, implementation, and experiments on outdoor deployment of wireless sensor network for environmental monitoring", *Lect. Notes Comput. Sci.*, **4017**, 109-121.
Wong, S.C. (2009), *The Study of Innovation Sensor Networks for Bridge Monitoring Application*, Master thesis, Taipei.
Yuan, S.F., Lai, X.S., Zhao, X., Xu, X. and Zhang, L. (2006), "Distributed structural health monitoring system based on smart wireless sensor and multi-agent technology", *Smart Mater. Struct.*, **15**(1), 1-8.
Zhang, H.L., Li, J., Liu, C.G., Jiang, T.H. and Wei, J. (2003), "Thermal effect of the cable-stayed bridge tower", *Wuhan Univ. J. Natural Sci.*, **8**(4), 1121-1125.

CC