16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 981

Registration Code: S-F1461773343

INTELLIGENT POWER MANAGEMENT SYSTEM FOR WIRELESS SHM THAT INTEGRATES A RADIO-TRIGGERING FUNCTION

Shih-Lin Hung [(1)], Chun-Ting Ding[(2)]

[(1)] *Professor, Department of Civil Engineering, National Chiao Tung University, Hsinchu, Taiwan, slhung@mail.nctu.edu.tw*

[(2)] *Ph.D. Student, Department of Computer Science, National Chiao Tung University, Hsinchu, Taiwan, chunting.cs03g@g2.nctu.edu.tw*

Abstract

Characterized by its low manufacturing costs, low power requirements, miniaturize size, and the lack of any cables, the wireless sensor network (WSN) is an attractive sensing technology for structural health monitoring (SHM). The conventional sources of energy for sensing nodes in wireless sensors networks (WSN) that are utilized to monitor the health of structures are lithium-ion batteries. Improving the stability and durability of the energy supply for the sensing nodes in a WSN is an important goal in the field of SHM. The periodic entering of control sensors into a low-power mode or sleep state is frequently used to reduce their energy consumption. However, the need for faultless time synchronization makes implementation in large-scale WSNs difficult. If a node receives a sampling command but is in the listening-time cycle, then the sampling process is delayed. In that case, a radio triggering function can improve the stability and durability of a sensing node when it is integrated with an external low-power circuit that is attached to a sensing node. Wirelessly transmitting a wake-up command when particular start-up conditions are met to awaken wireless sampling nodes is effective. This work proposes a dual radio cooperation scheme that is based on the wake-on-radio (WOR) method to construct an intelligent, energy-saving WSN. Four testing cases are investigated and the power consumptions are measured and compared. The intelligent sensor is a more effective conventional sensor than traditional always-on sensing nodes in measuring structural responses to an earthquake, as it has a longer sleeping time, saves energy and extends the lifetime of the associated wireless sensing system.

Keywords: Structural Health Monitoring (SHM), Wireless Sensor Network (WSN), Wake-On-Radio (WOR)

1. Introduction

A building structure may be damaged either when subjected to severe loading such as during a strong earthquake or when its material degrades. Accordingly, monitoring the structural health of buildings and civil infrastructure has attracted considerable interest in the last decade [1, 2]. Approaches to structural health monitoring (SHM) can be classified as local and global monitoring methods. Non-destructive evaluation (NDE) techniques are the most commonly used for local health monitoring. Global structural health monitoring (SHM) has conventionally been performed using vibration-based (acceleration-based) methods. These methods identify structural damage by detecting modal property change, such as natural frequencies, modal damping, or mode shape; these methods are economical and convenient means of evaluating damage to structures. Densely distributed sensors are critical to ensuring the efficiency of vibration-based damage identification. However, a conventional wired sensing system for this purpose is expensive and not feasible. Characterized by its low manufacturing costs, low power requirements, miniaturize size, and lack of cables, the wireless sensor network (WSN) is an attractive sensing technology in which densely distributed sensors are deployed to measure structural responses and external excitations. However, measuring a structure’s response to earthquake excitation is very difficult owing to its unpredictable behavior. However, an earthquake early warning (EEW) system helps to mitigate uncertainty in event detection.

A power supply is typically not an issue in traditional wired sensing systems and sensor implementations. Sensors can always be working or can be triggered by the meeting of low-latency requirements to acquire structural response data. Lithium-ion batteries are the typical energy source for sensing nodes in a WSN-based system so the fact that the supplied energy in a WSN-based system is severely limited poses a serious problem. This energy constraint problem can be mitigated by developing new energy-harvesting systems and power management, which is highly practical.

Power management for a WSN platform typically utilizes several states. Deep sleep or “hibernation” has the lowest power consumption and this mode can be activated by a hardware reset, or General Purpose I/O (GPIO) event such as triggered by an internal wakeup timers and external interrupt. Large amounts of energy can be saved when sensor nodes are in deep sleep. Causing control sensors periodically to enter low-power mode or the sleep state by duty cycling the radio is a common method of reducing energy consumption [3]. However, deep sleep mode has a shortcoming: the radio in the wireless sensor is usually turned off in deep sleep so it cannot communicate with the outside world and cannot receive a sampling command.

The radio-triggering technique is performed using an external low-power circuit that is attached to sensing nodes. The radio-triggered circuit is operated by the main processor when sensor nodes switch to deep sleep mode. When specific start conditions are met (such as when a wake-up command is wirelessly transmitted by a remote node), the radio-triggered circuit issues interrupt signals to the main processer, and then sensor nodes rapidly and wirelessly awaken into the full function stage. This method causes the main components in the sensor nodes to consume less power than that for periodically awaking or always-on nodes, and enables the sensor nodes to wake up at critical times. Therefore, the objective of this work is to combine the radio-triggering technique with a reliable earthquake early warning (EEW) system to construct an intelligent energy-economizing WSN. A p-wave detector, a wakeup-radio transmitter and a data sink radio are integrated into the gateway unit of a WSN. All WSN nodes are designed to provide a dual-radio architecture, in which one radio is responsible for data communication and the other one is responsible for monitoring radio-wakeup events. In this mode, a sensor will exhibit increased effectiveness in measuring structural responses for an earthquake, have longer sleep time, and save energy than traditional always-on nodes, so the life of the wireless sensing system will be extended.

2. EEW and Radio Trigger

EEW technology has been developed and tested in several countries [4, 5, 6]. Its main purpose is to assess the difference between the velocity of a p-wave and that of an s-wave that are generated by an earthquake. Accordingly, the EEW system can be used for regional and on-site warnings. The regional warning is based on networks of seismic stations that typically estimate multi-seismic source parameters. On-site warning is based on single sensor evaluations and the beginning of ground motion at a particular site.

The predictive accuracy of regional warnings exceeds that of on-site warnings owing to the analysis of multiple ranges of data and ranges of hyperdense data. However, the regional warning method takes considerable time in data processing and communication. Therefore, it cannot be used to provide immediate warnings in areas that are close to an earthquake's epicenter. In this "blind zone" of current regional warning systems, the p-wave method must be used. The on-site p-wave method typically uses real-time strong-motion data to evaluate an earthquake's magnitude and other parameters. Wu *et al.* [7] utilized this method to estimate earthquake magnitude using the first 3 s of p-wave data. This method can also be used to estimate the location of the epicenter as part of a rapid assessment. The threshold-based approach sets a vertical displacement threshold (such as 0.35 cm), calculated by a regression analysis based on historical earthquake data. The above methods generally provide 2-4 s of lead time, depending on the relative positions of the sensor and the epicenter. This information from a p-wave detector can improve the robustness of a WSN-based SHM system.

Two common methods of improving the energy-efficiency of sensor nodes are the duty cycle method and the event-driven method. The duty cycle method uses an internal timer in a microcontroller to activate sensor nodes periodically to monitor a radio channel for communication. When no wake-up signal is received, the sensor node switches back into the sleep mode. This method limits the ability of the transmitting nodes to access the network at any time. An alternative to duty-cycle-based control is the event-driven method. In this method, a particular threshold value for measurement is typically established by using a sensor or radio. An external low power circuit, called a wake-up receiver, is added to each node. The wake-up receiver module wirelessly detects wake-up signals from a transmitting node, and immediately sends an interrupt signal to the main microcontroller. Therefore, the deep sleep mode can be excited by a GPIO event in each node, and then the node can immediately join to a WSN to perform other tasks. Since the wake-up receiver module continuously monitors the radio, its active power consumption must be very low [8].

Various researchers have developed low-power wireless wake-up receivers. Van der Doorn *et al.* [9] designed a sensor node that was equipped with a wake-up circuit that operated at a frequency of 862MHz. When a wake-up signal was detected, the wake-up circuit could interrupt its main microcontroller from its deep sleep mode. The power consumption in wake-up mode was 819W and the achieved wake-up range was 2-3 m. Gamm *et al.* [10] utilized a low-frequency wake-up signal (125kHz) that was modulated on a high-frequency (868MHz) carrier in the main radio of the transmitting node. The transmitting node sent a wake-up signal by the main radio at +10 dBm output power, and its wake-up distance was almost 40m . Since low latency in the sampling process is also important in vibration-based approaches, this result should attract more interest in the field of WSN-based SHM.

This work proposes a prototype dual-radio wireless sensor node that can operate at 868MHz and 2.4GHz. The main communication component operates on IEEE 802.15.4 and performs advanced information transmission. The 868MHz module is used only as a wake-up receiver for the node. An interrupt signal is issued when the wake-up receiver detects specific start conditions. The main microprocessor wakes up when the interrupt signal is received. Following, the wake-up receiver switches to sleep mode again to save power. The purpose is to reduce power consumption and shorten the delay time of the wake-up receiver. The following section will introduce the architecture in detail.

3. Proposed novel intelligent power management architecture

The duty cycle method makes an obvious trade-off between energy efficiency and latency. A low duty cycle is energy-efficient, because the power is off most of the time, but it also results in high latency in data transmission and vice versa. The proposed intelligent power management architecture consists of two major parts: dual-radio wireless sensor node and on-site EEW integrated wireless gateway

The dual-radio wireless sensor node builds two radios; one radio performs partial duty cycling in an energy-efficient way with short delay and the other performs advanced data transmission and system management. The on-site EEW integrated wireless gateway provides a smart preamble, in the form of the so-called wake-up command, based on the EEW's reliable event trigger.

The key component in a partial-duty-cycling radio is called the Wake-on-Radio (WoR). WoR is a hardware that is used for Low-Power Listening (LPL). It allows the main processor to go completely to sleep, or "hibernate", enabling the radio to wake up periodically from sleep mode and listen for incoming packets without interacting with the processor. WoR reduces the energy cost during idle listening, and so saves power relative to the traditional IEEE 802.15.4-based protocol. Figure 1 compares general idle listening to the integrated WoR scheme.

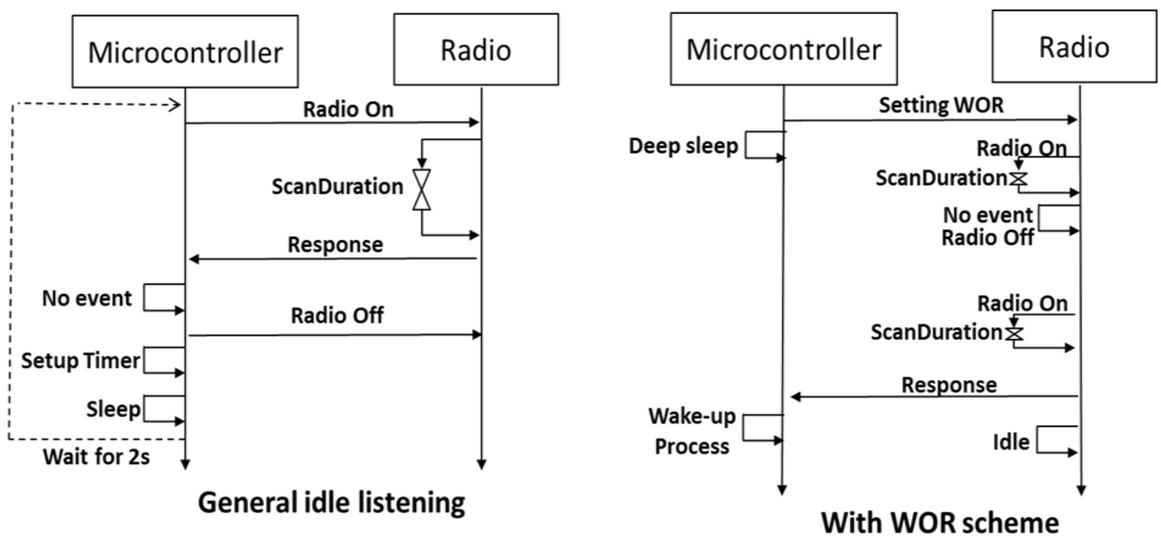

Fig. 1– Comparison of general idle listening and integrated WoR scheme.

Using WoR as the wake-up source rather than using an event-driven Wake-up Receiver (WuR) or a traditional IEEE 802.15.4 radio has the following advantages and disadvantages.

- The scan duration, channel and interrupt condition are all settable in WoR, so WoR is more flexible than WuR.
- For WoR, the ranges of radio communication and interference resistance are better than those for WuR.
- The scan period is shorter than that of IEEE 802.15.4 radio so the use of WoR as a wake-up source saves power.
- The latency is longer than that of WuR but shorter than that of IEEE 802.15.4 radio.
- The system is easier to duplicate and integrate than WuR, because the WoR chip module can be purchased.

The hardware architecture comprises two parts. The first part is the secondary radio, which monitors the wake-up event using the WoR. The second part is the main board, which contains an IEEE 802.15.4 standard radio, a micro-processor and an accelerometer. The main board handles such processes as sampling, power management, secondary radio configuration and data transmission.

WoR chips that are currently available in the marketplace were studied and compared in terms of functionality and features for potential use in a prototype. WoR chips include the CC1101/CC2500 series from Texas Instruments, TRX2 from Quasar and ATmega128RF from Atmel. CC1101 was used herein because it integrates adaptive wake-up with a received signal strength indicator (RSSI). The chip checks that the signal strength exceeds a preset threshold before switching into sleep mode or remaining in receiver mode to listen for a wake-up event and is therefore more energy-efficient in idle listening than the others. Figure 2 presents the architecture of the dual-radio.

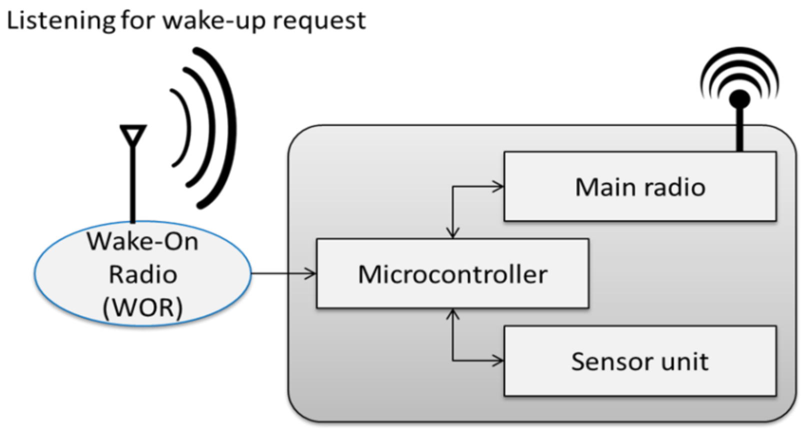

Fig. 2 – Hardware diagram of dual-radio.

In this work, the wireless sensor node is composed of a Jennic microprocessor, an MPU6050 6-axis (Gyro/ Accelerometer) Micro Electro Mechanical Systems (MEMS) chip, and a micro SD card slot. The Jennic microprocessor has an enhanced 32-bit reduced instruction set computing (RISC) processor and a fully compliant 2.4GHz IEEE802.15.4 transceiver (SoC) with 128 KB RAM and 512 KB flash memory. The USB host interface of Jennic platform facilitates firmware upgrades by users and firmware development by users. The microcontroller accesses the MPU6050 6-axis chip through a two-wire serial interface (I2C interface). The SD card is added to store measured acceleration data with high sampling rate. A sensor board reserves the expansion interface, allowing users to customize sensor board to their application. This interface is integrated with an ultra-low power transceiver, called the TI CC1101. The main operating parameters can be controlled using the Serial Peripheral Interface (SPI) bus. The TI CC1101 has a sleep mode (14.7mA in RX) that consumes 200nA of current and takes 240μs to switch from sleep to receiver mode (RX). It provides extensive hardware support, such as wake-on-radio (WOR) and functionality for automatic low-power RX polling, and has been used in many wireless alarm and security systems owing to its very low power consumption. In this work, the TI CC1101 is utilized as a secondary radio to monitor the wake-up event. The main radio is based on the IEEE 802.15.4 standard and used to manage all wireless sensor nodes in a WSN. In the proposed scheme, the main radio can be staged in hibernation mode and cooperate with a secondary WOR to achieve low power listening.

Notably, WSN gateways coordinate a wireless network and aggregate data from distributed wireless sensor nodes. The proposed wireless gateway integrates a Boarder Router Node (BRN) and a p-wave detector. It accesses the BRN and p-wave detector through a USB serial port, as presented at Fig. 3. The BRN has the same hardware design as the wireless sensor node but different firmware runs into it. It communicates with up to 500 sensor nodes in a star topology. In addition to aggregating data, the gateway filters, compresses, and transmits measured data to the remote server via the Internet.

In the proposed architecture, the wake-up mechanism is based on a radio trigger. First, a wireless gateway receives an event from p-wave detector, and then it immediately begins the wake-up procedure and sends the wake-up message to a boarder router node. The boarder router node starts to transmit a “smart preamble” message, based on the B-MAC protocol. Long-format packets, including preamble packets, synchronization packets, and payload, are sent, and all packets must be long enough to match the channel checking period at the receiver side. The long preamble is a minimalistic method, as presented at Fig. 4, which requires no explicit synchronization, is highly scalable and checks packets with little noise.

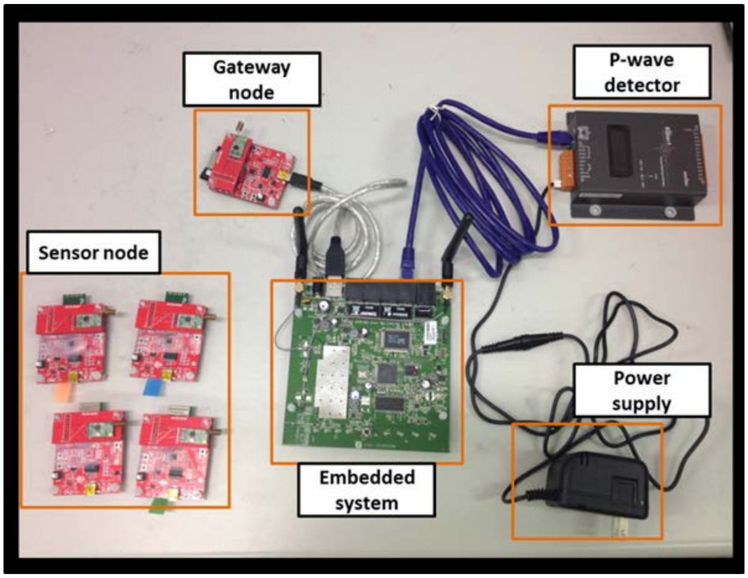

Fig. 3 – A new wireless gateway environment, integrating p-wave detector and radio trigger.

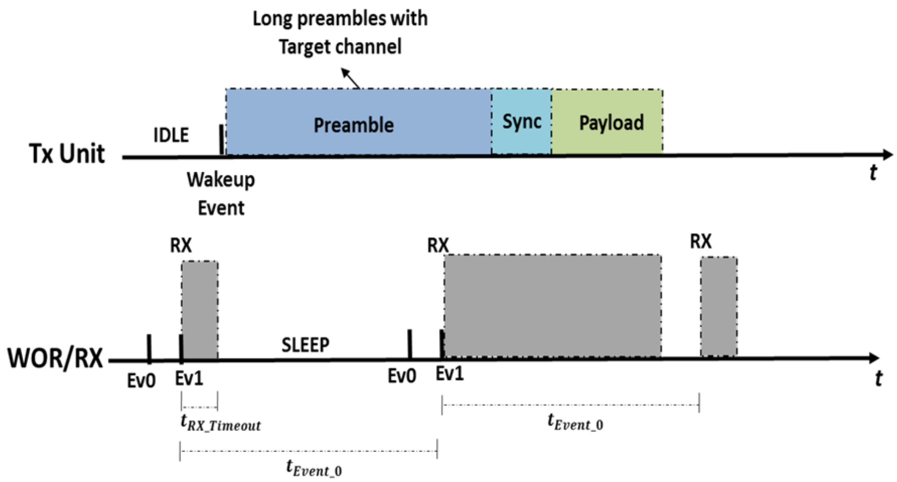

Fig. 4 – Wake-up command: long preamble packets

4. Verification

When the p-wave detection and wireless trigger mechanics are complete, preliminary tests are performed to confirm the power consumption of the wireless sensor nodes and the wake-up latency of the proposed architecture.

Figure 5 displays the p-wave detector and radio trigger-based protocol with the WSN-Based SHM system. Initially, the sensing node is in deep sleep mode. When the p-wave (Pd) detector of the WSN gateway detects an earthquake event, it instantly sends a particular wake-up command to the sensing node. Each node is then awakened and begins initializing the hardware and network parameters (such as node address and PAN address). It then joins the network and sends a “start” message to the gateway. The gateway node counts the number of received “start” messages and ensures that all nodes are ready. During the second phase, the sensing node waits for the fire command from the gateway node. The gateway node broadcasts a packet with a fire command to the sensing nodes. Finally, data are sampled at all sensing nodes and written to an SD card. Relevant parameters, such as sampling rate, data type, and data length, are chosen before sampling begins.

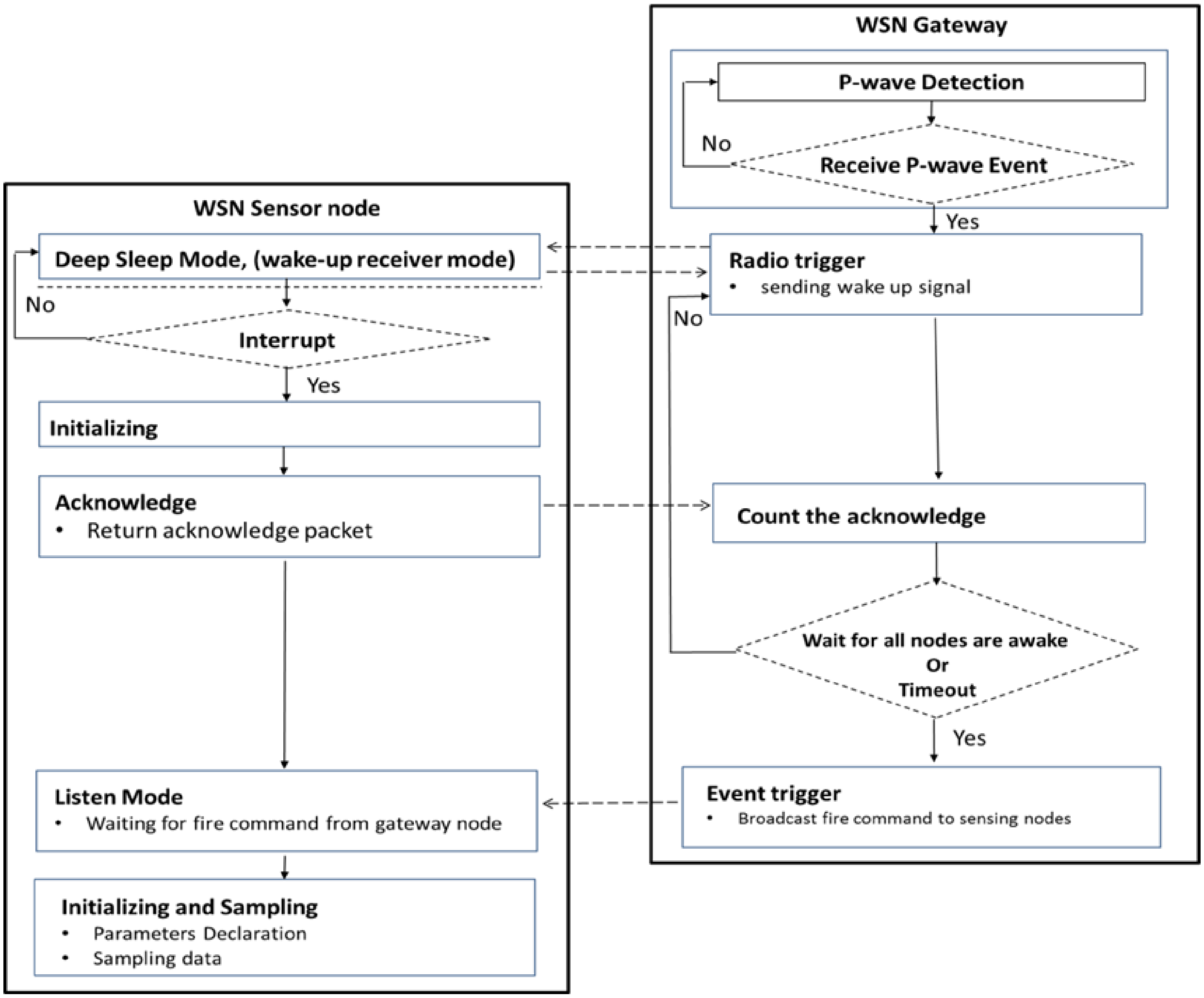

Fig. 5 – Data flowchart for p-wave detector and radio trigger-based protocol

Four testing cases are employed to elucidates the measurement of power consumption under several testing conditions using a Monsoon Power Monitor. Energy savings in four testing cases are compared, as the nodes use a fixed voltage and thus the power consumed can be measured based off of the current. Case A is the always-on case; case B involves single IEEE 802.15.4 radio that is based on a Beacon Order of three and a Superframe Order (SO) of two; case C is similar to case B but with the BO changed to one and the SO changed to zero. Case D involves the proposed dual-radio cooperation model.

Table 1 – The testing cases

Case	Descriptions
A	Always-on
B	Beacon-mode of IEEE 802.15.4 (BO=3, SO=2, listening period 2s)
C	Beacon-mode of IEEE 802.15.4 (BO=1, SO=0, listening period 2s)
D	Our purposed dual-radio cooperation model

In the always-on testing case, the mean current (power consumed) was measured at 28.21mA. Case A was taken as the benchmark in determining power savings. Figure 6 illustrates the measured average current consumed in the testing case A. The listening periods in case B and case C were equal: woke up every 2s, but had different listening times. In case B, sensor nodes listened for 220 ms when BO was set to 3 and SO was set to 2; in case C, sensor nodes listened for 130 ms when BO was set to 1 and SO was set to 0. The average current consumed was measured at 2.51 mA in case B and 1.43 mA in case C. Finally, the listening time, listening period, and current of the dual-radio model (case D) are verified. The listening time of the WoR module is 2.87 ms and the listening period is 130 ms. Clearly, the latency of case D is lower than in cases B and C (2s). The current consumed was measured at 350 µA and that is much less than that of cases A, B, and C. Figure 7 displays the measured average current consumed in the testing case A. The consumed current value reveals that the dual-radio cooperation scheme can be used to save power with low latency. Figure 8 presents all measurements.

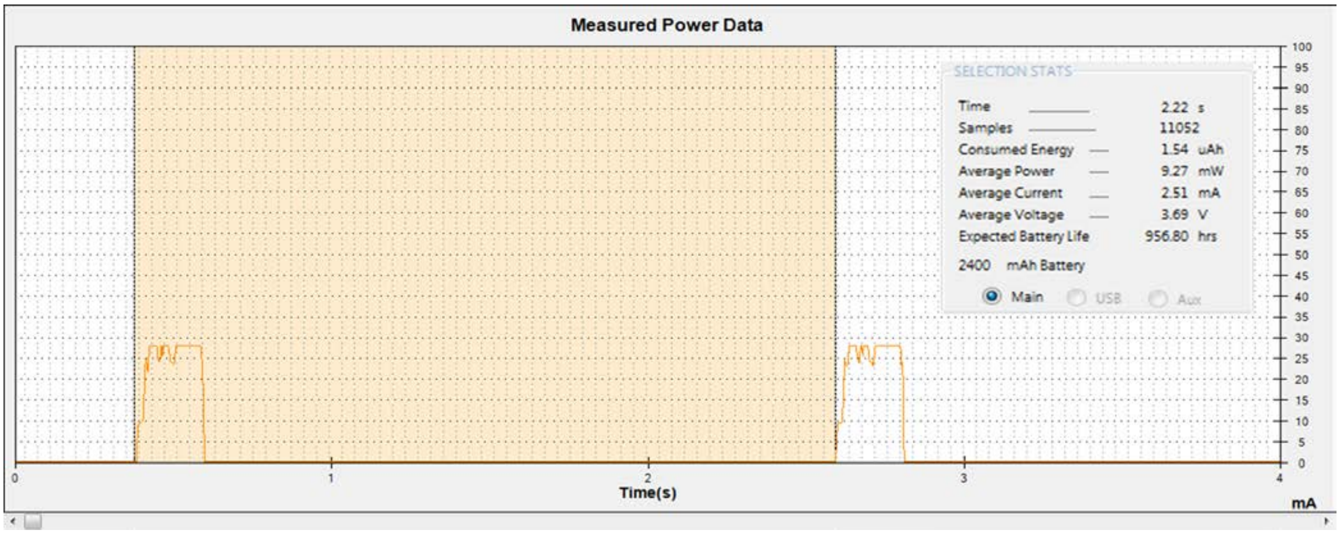

Fig. 6 – Measured average current consumed of testing case A

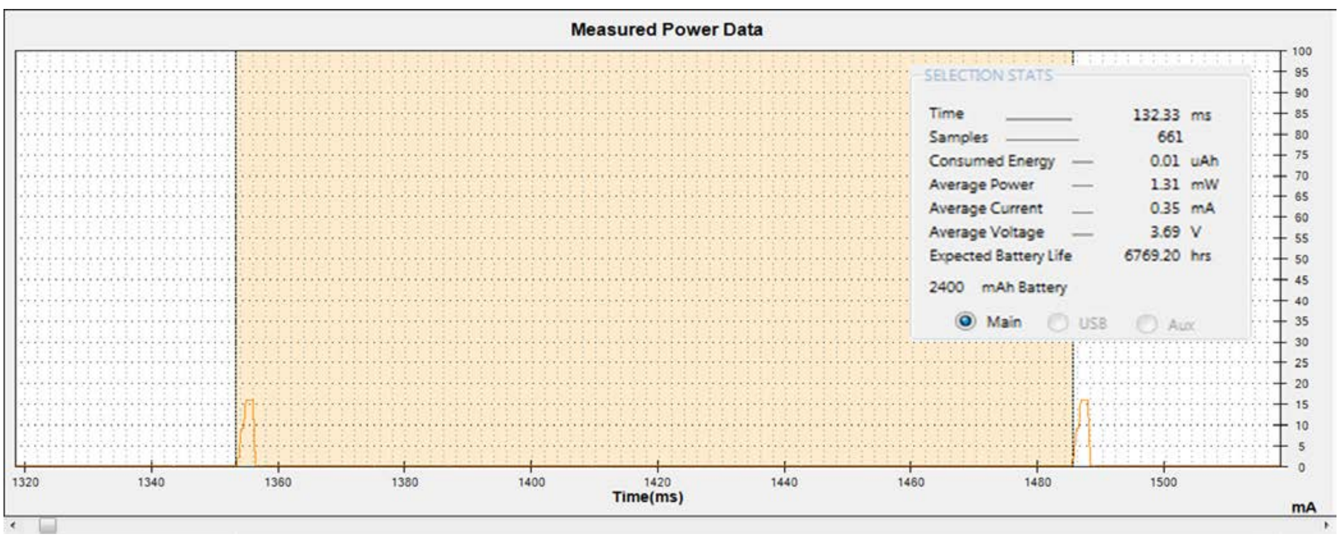

Fig. 7 – Measured average current consumed of testing case D (this work)

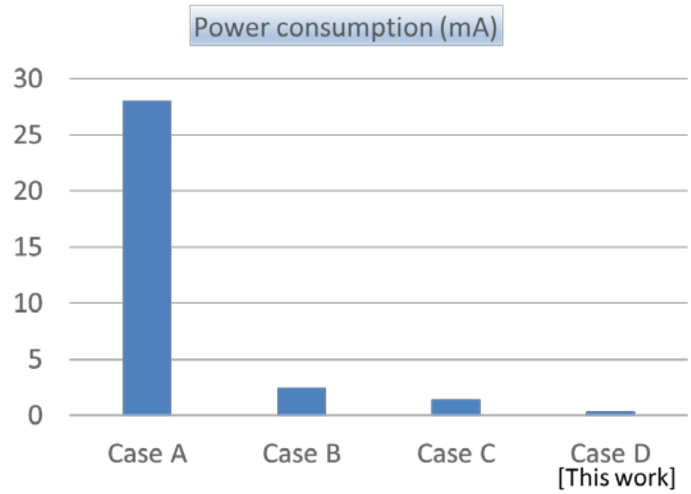

Fig. 8 – Measured power consumption of various testing cases

Finally, the communication latency among nodes with the one-layer star topology was measured and presented. The number of sensors is 20, and all nodes are connected to a boarder router node. The boarder router node is connected to a computer via a USB cable. A logging program runs on the computer to measure the latency time. The measurements begin when the wake-up command is broadcast and end when all nodes have responded to the "start" message. The results in Fig. 9 reveal that the latency of the first node is approximately 229 ms. The other nodes sequentially join the system with a delay of 9 ms between each consecutive pair. This delay time may comprise the node initialization period, the WoR listening period (130 ms) and the network joining time in IEEE 802.15.4. If the EEW provided a lead time of 2s, then it meets the low latency requirement for one-layer.

Fig. 9– Latency measurements with one-layer star topology

5. Concluding remarks

A novel method is utilized to evaluate the potential benefit of using the EEW system and the radio-trigger function to WSNs for SHM purpose. The EEW determines the trigger threshold for sensor nodes at various excitation levels of earthquake. The radio-trigger solution is a wireless method for waking up sensor nodes in a sensor network. The wake-up receiver module has potential to reduce the power consumption of sensor nodes. Four testing cases are employed to elucidate the measurement of power consumption under several testing conditions. The simulation results indicate that the power consumed of the proposed dual-trigger architecture outperforms the other three cases. An example with one-layer star topology WSN is performed herein to demonstrate how this radio trigger works in practice. This work focused only on wake-up performance. Optimization of the radio-trigger function is also required. The ultimate goal is to develop complete hardware and software to confirm the potential benefit of the proposed architecture. An advanced full-scale sensor network implementation and cross-layer system will be tested in the future.

6. Acknowledgements

The authors would like to thank the Ministry of Science and Technology (fomer National Science Council) of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 103-2625-M-009-003 and MOST 104-2221-E-009-049-MY2.

7. Copyrights

16WCEE-IAEE 2016 reserves the copyright for the published proceedings. Authors will have the right to use content of the published paper in part or in full for their own work. Authors who use previously published data and illustrations must acknowledge the source in the figure captions.

8. References

[1] Lynch, J.P. and Loh, K.J. (2006): A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock and Vibration Digest*.

[2] Jo, H., Rice, J. A., Spencer Jr., B. F. (2010): Development of high-sensitivity accelerometer board for structural health monitoring. *Proc. SPIE Smart Structures/NDE*.

[3] Rice, J. A., Mechitov, K. A., Spencer, B. F., and Agha, G. A. (2010): Autonomous smart sensor network for full-scale structural health monitoring. *Sensors and Smart Structures Technologies for Civil, Mechanical and Aerospace system*, 7647, .

[4] Horiuchi, S., Negishi, H., Abe, K., Kamimura, A., and Fujinawa, Y. (2005): An automatic processing system for broadcasting earthquake alarms. *Bulletin of the Seismological Society of America*, 95(2),708-718.

[5] Ionescu, C., Bose, M., Wenzel, F., Marmureanu, A., Grigore, A., and Marmureanu, G. (2007): An Early Warning System for Deep Vrancea (Romania) Earthquakes. *Earthquake Early Warning Systems*, 343-349, doi. 10.1007/978-3-540-72241-0_17.t

[6] Wu, Y. M. and Kanamori, H. (2005): Experiment on an onsite early warning method for the Taiwan early warning system. *Bulletin of the Seismological Society of America*, 95(1), 347-353.

[7] Yih-Min Wu and Hiroo Kanamori, (2008): Development of an Earthquake Early Warning System Using Real-Time Strong Motion Signals. *Sensors*, 8 ,1-9 .

[8] Matthias, V., Mirko, C., and Wolfram, H. (2012): Wake-Up-Receiver Concepts - Capabilities and Limitations. *Journal of Networks*, 7(1), 126-134.

[9] Langendoen. K., van der Doorn, B., and Kavelaars, W. (2009): A prototype low-cost wakeup radio for the 868 mhz band. *Intl. Journal of Sensor Networks*, 5(1), 22-32.

[10] Gamm, G. U., Matthias, S., Milos, K., and Leonhard, M. R. (2010): Low power wake-up receiver for wireless sensor nodes. *Sixth Int Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) Conf*, 121–126.