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ARTICLE *in* STRUCTURAL CONTROL AND HEALTH MONITORING · AUGUST 2011

Impact Factor: 2.13 · DOI: 10.1002/stc.403

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STRUCTURAL CONTROL AND HEALTH MONITORING
Struct. Control Health Monit. (2010)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/stc.403

A multi-channel wireless connection system for structural health monitoring applications

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SUMMARY

To overcome the drawbacks related to a wired solution for structural health monitoring applications, many kinds of wireless sensors have been proposed and prototyped. Most of these sensors are of the single channel type. Multi-channel solutions also exist and they are mainly based on time-division multiplexing (TDM). Both these types of wireless communication systems cause large time delays when a large number of sensors nodes are deployed. In this paper, a different multi-channel wireless sensor solution, based on a mixed approach that exploits both TDM and frequency-division multiplexing (FDM), is introduced. As a result, the time delay is independent of the number of sensor nodes. The real-time multi-channel feature represents a key aspect of the proposed wireless sensing network. The wireless scheme is initially intended a simple solution for analog cable replacement and it is preliminarily tested in a laboratory environment. The powerful and flexible system-on-chip single-chip wireless transceiver, which can operate in the Industrial, scientific and medical (ISM) license-free frequency bands, is employed to perform both the control function and the wireless communication. The goal is to reach a good balance among communication range, power consumption, data rate, and link quality. The overall design, the implementation, and an experimental validation of the proposed multi-channel wireless sensor solution are presented. Copyright © 2010 John Wiley & Sons, Ltd.

Received 5 February 2010; Revised 9 May 2010; Accepted 14 May 2010

KEY WORDS: structural health monitoring; wireless connection; frequency-division multiplexing; multi-channel; real time

1. INTRODUCTION

Wireless connection has emerged in recent years as a promising technology that will greatly impact the field of structural health monitoring (SHM) and control, as the wired connection often suffers of various problems mainly related to the cabling which limits the applicability. These issues include the cost of cables, their difficulty of installation, their invasive effect on the monitored structure, their vulnerability to mechanical damage, and the high cost of their maintenance. All these disadvantages urge the need for wireless connections.

Although many wireless sensors for SHM have been proposed [1], including experimental prototypes (such as the Stanford Unit developed by Wang, Lynch *et al.* [2]) and commercial units (such as the Imote2 produced by Intel [3–5]), wired monitoring systems are still extensively adopted in most practical applications of structural monitoring due to their availability, high performance, stability, and reliability. Therefore, to overcome the present state-of-the-art, it

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would be desirable to use the recent wireless communication technology to develop a simple but practical wireless update solution, which can achieve a similar performance without much more cost and significant changes with respect to the existing analog cables. In developing such a solution, the features of real-time, multi-channel, low-cost, and low-power wireless communication are the priorities to be addressed.

To date, several types of standard wireless communication systems are in use, such as the cellular phone standards (GSM, 3G, etc.), WiFi (IEEE802.11), Bluetooth, and ZigBee (IEEE802.15.4) [6]. Other ones are currently emerging, such as WiMax and UWB. Moreover, many non-standard wireless modules and single-chip radio-frequency (RF) wireless transceivers are commonly available on the market. Based on the overall considerations of cost, power consumption, and required performance, among the above-mentioned wireless technologies, the ZigBee and the non-standard RF transceivers are considered as the most suitable for applications in wireless SHM systems, where low power consumption is necessary and relatively low speed is acceptable. In particular, the ZigBee is tailored to flexible and versatile wireless sensing networks and its potential to be deployed in large-scale densely distributed wireless monitoring systems is currently under investigation [3–5]. However, in comparison to the complexity of the ZigBee protocol, the non-standard single-chip RF transceivers, which can operate in a large range of the Industrial, scientific and medical (ISM) license-free frequency bands, are more efficient and suitable when pursuing a simple wireless connection as the replacement of an analog cable. The wireless connection task is to obtain an optimized balance among communication range, power consumption, data rate, and link quality.

A solution in which the RF transceiver CC1020 and an integration design approach were adopted was initially proposed by the authors [7,8]. To further reduce the cost and the risk of an analog cable replacement, and to increase the performance and the flexibility of the wireless transmission, a newly designed solution is originally proposed in this paper and the details of its implementation are provided. In the latter solution, the recently developed system-on-chip (SoC) wireless transceivers, CC1110 and CC2510, are used and a modular design approach [9] is adopted. To guarantee a real-time multi-channel transmission, this solution employs the frequency-division multiplexing instead of the commonly adopted time-division multiplexing (TDM). The features of the selected wireless transceivers are discussed, the hardware architecture is described, and an experimental validation of the wireless connection is performed.

2. MIXED APPROACH OF TIME AND FREQUENCY-DIVISION MULTIPLEXING

TDM is a physical layer multiplexing approach in which two or more signals are apparently transferred simultaneously as sub-channels into a single frequency channel, but they are physically taking turns on the channel. The time domain is divided into several recurrent timeslots of fixed length, one for each sub-channel. A data block of sub-channel 1 is transmitted during timeslot 1, and then a data block of sub-channel 2 is transmitted during timeslot 2, and so on. A single TDM frame consists of one timeslot per sub-channel. After the last sub-channel is transferred, the cycle starts all over again with a new frame and the data block of sub-channel 1.

Frequency-division multiplexing (FDM) is another kind of physical layer multiplexing approach where the available total frequency bandwidth is divided into several separate frequency slots, which correspond to different frequency channels dedicated to the transmission of different signals. As the occupied frequency bands of different slots are non-overlapping, the signals of different channels can really be transmitted simultaneously without introducing any delay due to the transmission in series of the other signals. To implement an FDM approach, a transceiver equipped with a programmable frequency synthesizer and a bandwidth-programmable band-pass channel filter is usually required. The programmable frequency synthesizer is used to produce different carrier frequencies for different channels, while the channel filter is used to filter the undesired signals from other channels. A schematic representation of the two physical layers multiplexing methods is provided in Figure 1.

DOI: 10.1002/stc

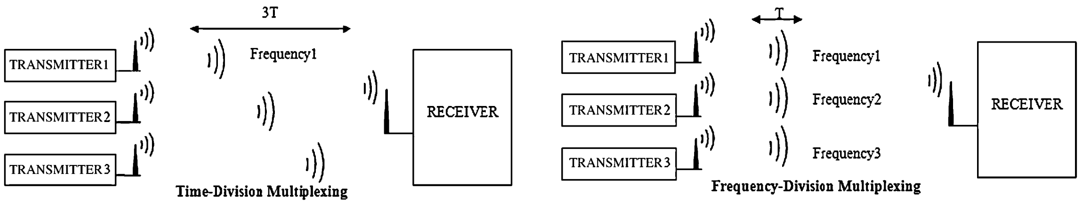

Figure 1. Time-division (left) and frequency-division (right) multiplexing methods.

In the proposed solution for analog cable replacement, both the TDM and FDM approaches are adopted. A single sensing unit mounting a wireless transceiver integrates three analog channels that employ the TDM to share the same wireless frequency channel, while different sensing units operate on different frequency channels by employing the FDM.

3. THE EVOLUTION OF WIRELESS TRANSCEIVERS

The adoption of a single-chip wireless transceiver greatly facilitates the design of a wireless system, as the transceiver has integrated most of the relevant functional modules and it only requires few simple external components. Therefore, in order to meet the requirements inherent to the replacement of an analog cable (mainly concerning the low-cost, low-power, multi-channel, and real-time features of the wireless connection), the authors directly resorted to the custom single-chip transceivers, which operate in the ISM license-free frequency band. However, it was chosen not to employ the associated easy-to-use commercial unit, because it limits the capability of achieving an optimized solution for the envisioned application.

With the rapid development of the mixed signal integrated-chip (IC), the wireless transceivers also experienced a fast evolution of their digital baseband processing capability, which mainly developed in three stages. First, they were equipped only with a little relevant hardware, then a powerful digital baseband processing hardware was introduced, and eventually a microprocessor core was integrated. Considering as examples the products of Texas Instrument [10–13], the RF transceivers which are representative of these three stages of evolution can be identified with the CC1020 (which was adopted by the authors in their previous wireless prototype), the CC1101, and the CC1110 and/or CC2510 (which are selected for implementation in the current wireless solution). A brief comparison of the main features of these RF transceivers is provided in Table I.

The CC1020 belongs to the earliest generation of single-chip transceivers. It has most of the function modules integrated into one chip and it only needs few external passive components for its application circuit. Its main operating parameters can be programmed digitally via a serial bus, so that the CC1020 is flexible and easy to use. However, its baseband processing capability is limited. As the CC1020 is not equipped with a packet handle hardware, it can only receive and transmit serial data stream. Therefore, all the data processing tasks, including the packing and serialization of the transmitted data and the de-serialization and unpacking of the received data, must be performed by an external microcontroller. As a consequence, the adoption of this transceiver implies the additional burden of an external microcontroller and a delay in the wireless communication.

In comparison with the CC1020, the newer transceiver CC1101 features a powerful baseband processing hardware, which can be used to perform the aforementioned data processing tasks. In this case, the external microcontroller is needed only to transfer the data between the internal memory and the data buffer of CC1101 through the high-speed SPI interface.

The SoC transceiver CC1110 has an integrated microcontroller core, which consists of an enhanced 8051 microcontroller. The interface of the CC1101 RF transceiver is mapped as the internal memory addresses of the microcontroller. Therefore, the communication delay between the transceiver and the microcontroller is very small. It is also worth mentioning that the

DOI: 10.1002/stc

Table I. Comparison of different generations of wireless transceivers.

Main features	CC1020	CC1101	CC1110	CC2510
Frequency range	402–470 MHz 804–940 MHz	387–464 MHz 779–928 MHz	300–348 MHz 391–464 MHz 782–928 MHz	2400–2483.5 MHz
Data rate	Up to 153.6 kbaud	Up to 500 kBaud	Up to 500 kBaud	Up to 500 kBaud
Output power	Up to 10 dBm/5 dBm at 433/868 MHz	Up to 10 dBm	Up to 10 dBm	Up to 1.26 dBm
Sensitivity	–118 dBm for a 12.5 kHz channel	–111 dBm at 1.2 kBaud	−110 dBm at 1.2 kBaud	−103 dBm at 2.4 kbaud
Power consumption	Voltage: 2.3–3.6 V Current: RX, 19.9 mA; TX, 21 mA at 0 dBm and 868 MHz	Voltage: 2.3–3.6 V Current: RX, 14.7 mA; TX, 16.9 mA at 0 dBm and 868 MHz	Voltage: 2.3–3.6 V Current: RX, 16.2 mA; TX, 21 mA at 0 dBm and 868 MHz	Voltage: 2.3–3.6 V Current: RX, 17.1 mA; TX, 26 mA at 0 dBm and 868 MHz
Microcontroller core	No	No	Yes	Yes
Packet handling hardware	No	Yes	Yes	Yes

integrated microcontroller has a Direct Memory Access controller, which can transfer data from a peripheral unit, such as the ADC or the RF transceiver, to its internal memory with a minimum burden on the CPU. These features enable the CC1110 to operate with high efficiency and low delay. The CC2510 and CC1110 transceivers feature very similar architectures and the main difference between them is the operating frequency range. The CC2510 operates in the global license-free frequency band of 2.4 GHz, whereas the CC1110 operates in the regional license-free frequency band below 1 GHz.

4. IMPLEMENTATION OF A MULTI-CHANNEL COMMUNICATION SYSTEM

The RF characteristic of CC1110 and CC2510 are suitable to the envisioned application, because both of them can operate in a large frequency range covering most of the ISM/short range device frequency bands. Moreover, they have a programmable channel filter and a frequency synthesizer, which support the multi-channel application. As shown in Table I, the CC1110 can operate in the frequency range below 1 GHz (namely, in the ranges of 300–348 MHz, 391–464 MHz, and 782–928 MHz) and the CC2510 can operate in the frequency range of 2.4 GHz (from 2400 to 2483.5 MHz).

To design a system complying with the current legal regulations, the wireless transceivers should operate within the limited license-free frequency bands enforced in each geographical area. In particular, while the 2.4 GHz frequency band is globally license-free, the license-free frequency band below 1 GHz is regionally dependent. For example, in Europe, the license-free frequency bands below 1 GHz include the ranges of 433.05–434.79 MHz and 863–870 MHz, whereas in U.S.A., the range is 902–928 MHz. The advantages and disadvantages of either adopting the globally accepted 2.4 GHz frequency band or the regionally limited sub 1 GHz frequency band are summarized in Table II [14,15].

To cover most of the license-free frequency bands and to optimize the communication performance, both the RF transceivers CC1110 and CC2510 are used. Although the hardware is different, the CC1110 and CC2510 modules have the same hardware interface and the same embedded software, which is tailored to different frequency configurations. Owing to their similarities, the design of their modules can be unified.

The resulting number of channels that can be used for wireless data transmission is calculated by dividing the total available bandwidth (TB) by the channel bandwidth (CB). To achieve the best performance, it is recommended that the necessary CB must occupy at most 80% of the

DOI: 10.1002/stc

Table II. Comparison between the available licence-free frequency bands.

Frequency bands	Advantages	Drawbacks
2.4 GHz	Same solution worldwide Large bandwidth 100% duty cycle allowed	Shorter range Crowded
Below 1 GHz	Better range Less crowded	Custom solutions Limitations in 'performance' Duty cycle restrictions

actually configured TB [10]. Therefore, the number of channels, N, is determined as:

$$N = \frac{80\% \times \mathrm{TB}}{\mathrm{CB}} \tag{1}$$

When either the modulation approach of FSK (frequency shift keying) or GFSK (Gauss frequency shift keying) is adopted, the necessary CB is given by

$$\mathrm{CB} = \mathrm{DR}+\mathrm{FS}+4 \times X \times F \tag{2}$$

where DR indicates the data rate, FS is the frequency separation value, X is the tolerance of the crystal oscillator, and F is the average frequency of the carrier.

As the 2.4-GHz frequency band is globally license-free and it has loose limitations, the calculation of the available number of channels is performed in this bandwidth to provide an example. The following values are assumed for the parameters in Equation (2): $X = \pm 20$ ppm, DR = 100 kHz, FS = 130 kHz, and the carrier frequency is 2441.7 MHz, which is the center of the 2.4 GHz frequency band. Using Equation (2), the CB is calculated to be equal to 536 KHz. The nearest channel filter bandwidth configuration available in CC2510 is 541 kHz. From Equation (2), the corresponding number of channels, N, is 154 when a total bandwidth of 83.5 MHz is considered. However, guard bands between two adjacent channels are required due to the imperfect filters and the interference. Therefore, the resulting number of the actually available channels is less than its theoretical value. Furthermore, as many devices are working on the 2.4-GHz frequency band, particularly the WiFi, the number of usable channels also depends on the specific occasion.

Another aspect relevant for the application of wireless communication in the monitoring of large-scale structures is the communication range. In the ideal free space, where there are no obstacles between the transmitter and the receiver and the signal can propagate along a straight line between the two, the path gain P_G [6] is given by

$$P_{\mathrm{G}} = 10\,\mathrm{Log}_{10}\frac{P_{\mathrm{r}}}{P_{\mathrm{t}}} = 10\,\mathrm{Log}_{10}\frac{G_{\mathrm{l}}\lambda^2}{(4\pi d)^2} \tag{3}$$

where P_{r} is the power of the received signal, P_{t} is the power of the transmitted signal, G_{l} is the product of the antenna gains of the transmitter and the receiver in the direction of the line of sight, d is the distance between the transmitter and the receiver, and λ is the wave length of the signal.

Equation (3) shows that the power of the received signal is inversely proportional to the square of the distance and directly proportional to the square of the wavelength. Therefore, operating in the frequency band sub-1 GHz results into a better communication range than the one that can be achieved in the 2.4-GHz band. Another problem encountered in the implementation of wireless communication systems is the conflict between the receiver sensitivity and its bandwidth; indeed, a large bandwidth decreases the sensitivity. For example, the receiver sensitivity of CC1110 at 433 MHz is equal to: –110 dBm with a data rate of 1.2 kBaud, −102 dBm with 38.4 kBaud, and −95 dBm with 250 kBaud. Therefore, reducing the data rate can increase the communication range, but the communication delay and the power consumption are also consequently increased. In the proposed wireless system, when the data rate is set to 100 kBaud, a stable communication range can be up to 150 m. Neverthless,

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a more accurate estimate of the actual range can be formulated only at the end of the testing process, when in-field applications are implemented.

5. HARDWARE DESIGN AND IMPLEMENTATION

The proposed multi-channel wireless data transmission system is shown in Figure 2 and it consists of several components including the wireless sensing unit, the receiver unit, the UART to USB convertor, and an USB2.0 hub. The wireless unit connected to the sensing device (such as an accelerometer) is supposed to be powered by batteries when applications that require a completely wireless solution are considered. This unit performs the tasks of powering the sensor, sampling its signal, and then transmitting the data to the receiver unit by a wireless connection.

To implement FDM, each channel requires a pair of wireless transceivers operating in the same frequency range: a transceiver is mounted on the sensing unit and the other on the receiver unit. The receiver unit accomplishes the tasks of receiving the data from the sensing unit, reconstructing the analog signal by DAC and/or sending it to the computer via an RS232 serial port. As the number of RS232 ports in the computer is very limited, while the USB interface is very popular and easy to be extended, the authors employed the UART-USB convertor to implement a virtual RS232 interface in the computer via the USB connection. As shown in the Figure 2, it is easy to extend the number of USB interfaces (the maximum number is 127) by introducing an USB2.0 hub, which can be cascaded.

To reduce the design risk, to increase the flexibility, and to facilitate the future maintenance, a modular approach is adopted in the design of both the sensing unit and the receiver unit. Furthermore, as the functions of the two units are symmetrical, their design can be unified as schematized in Figure 3, where the analog signal reconstruction is assumed to be performed in the receiving unit. A picture of the implemented wireless sensing unit is shown in Figure 4.

The unified architecture mainly includes the CC1110 board, the AD/DA main board, a power management board, two signal-conditioning boards, and a filter board. The CC1110 board mounts the CC1110 chip and other few necessary components, leaving some pins available for connection. The AD/DA main board mainly consists of a four-channels ADC chip, a four-channels DAC chip, and some interfaces for connection with the other boards. The analog filter board provides three fourth-order Bessel filters to perform anti-aliasing before ADC and after DAC and to remove other undesired noise. When the anti-aliasing is not required, the presence of the filter board is optional, because the other noise can also be digitally filtered inside the microcontroller. The signal conditioning board 'Module 1' in Figure 3 is dedicated to the sensor. It has four signal attenuation options (namely, attenuation equal to 1,

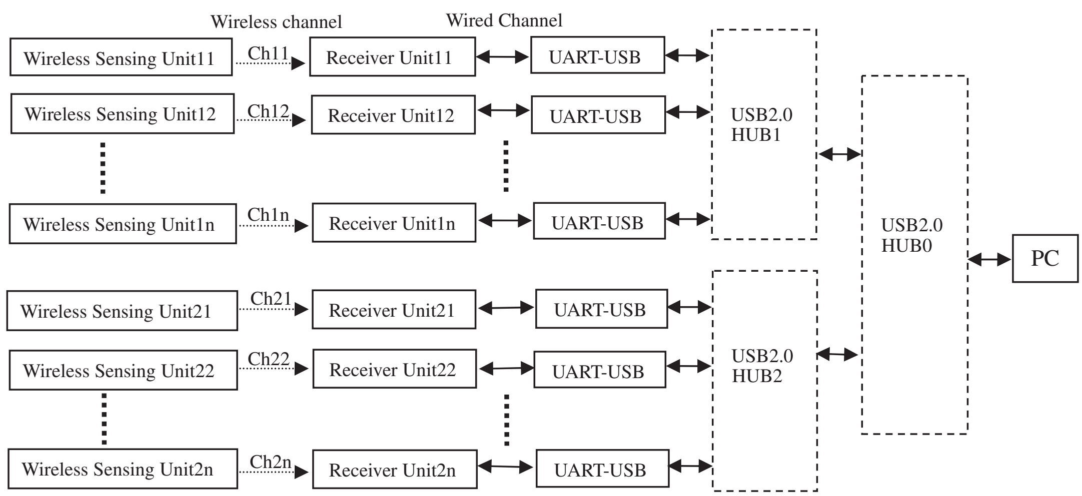

Figure 2. Communication topology between the receivers and the central computer.

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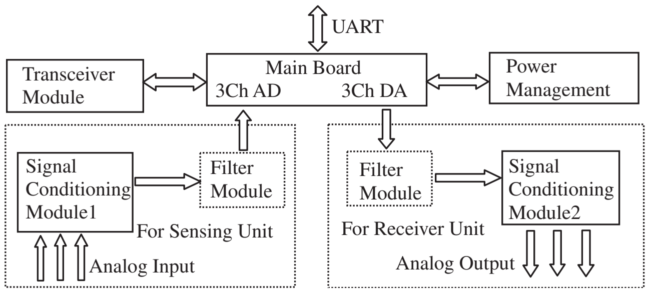

Figure 3. Unified block diagram of the wireless sensing unit and the receiver unit.

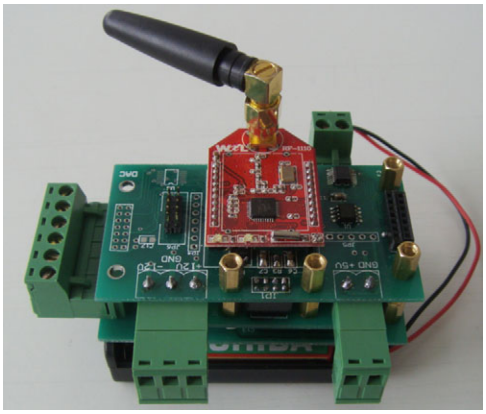

Figure 4. Wireless sensing unit as implemented in the authors' laboratory.

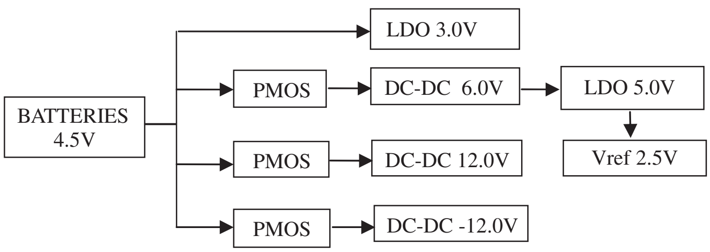

Figure 5. Block diagram of the power management module.

1/2, 1/4, and 1/8), which are programmable by an electronic switch for application to different inputs. Its tasks include transforming the differential signals into single end signal, setting the signal offset, and adjusting the amplitude by an operational amplifier instrument. The signal conditioning board 'Module 2' in Figure 3 is dedicated to the analog output, and it is also used to set the signal offset and to adjust the signal amplitude by an operational amplifier instrument.

To operate by consuming as low power as possible, thus enabling the feasibility of batteries-supply, the wireless sensor requires a flexible and highly efficient power management unit. As shown in Figure 5, the overall strategy adopted in this design is based on the use of high-efficiency switching regulators and on the capability to shut down the power supply of the unused modules by a PMOS (p-type metal-oxide-semiconductor) power transistor when it is set in sleeping mode. In the authors' envisioned application, two power sources of 12 and -12 V are needed by the sensor and by the signal conditioning modules, 5 V power is used by the AD/DA and the filter modules, and 3 V power is required by the CC1110 module. The 12 V, -12 V, and 5 V power supplies can be shut down by the microcontroller of CC1110, while the 3 V power supply is always active. To reduce the noise, the 5-V power source is filtered by the LDO (low drop-out regulator). Therefore, when the sensor unit is set in sleeping mode, it can only consume

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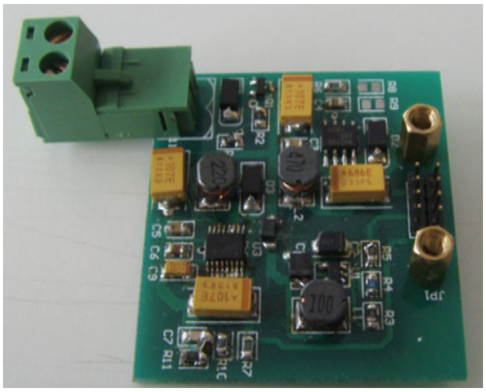

Figure 6. The power management module as implemented in the authors' laboratory.

a current of few micro Amperes. Instead, during operating mode, it uses the power efficiently. Moreover, if the specific application requires a lower voltage supply, the power consumption can be reduced accordingly. A picture of the implemented power management unit is shown in Figure 6. The feasibility of power harvesting techniques has also been investigated by the authors [16,17] and it is currently under development.

6. EXPERIMENTAL VALIDATION

To validate the developed wireless sensing network platform, a laboratorial test is conducted using a reduced-scale, three-storey steel frame mounted on a shaking table. A mono-axial accelerometer FBA-11 is installed on each floor of the structure. The shaking table is configured to move in a sinusoidal mode with a frequency of 1 Hz and an amplitude of 2 mm. The acceleration response of the third floor are simultaneously acquired, with a sampling rate of 250 Hz, via two wireless sensing units and a wired DAQ system serving as reference.

In Figures 7–9, the acquired data are plotted together and aligned using MATLAB. The data from the wireless sensing units 1 and 2 are labeled as 'WSU1' and 'WSU2', respectively, and they are compared with the ones obtained from the wired DAQ system. From Figure 7, the waveforms resulting from the two wireless sensing units are basically consistent between each other and with the waveform from the wired system. From the enlargements in Figures 8 and 9, the waveforms from the wired DAQ are characterized by a 'saw-tooth' trend, because the corresponding ADC is 12 bit and the reference voltage is 10 V, thus resulting in a sampling resolution of 0.00488 V. Instead, the ADC on the wireless sensing unit is 16 bit and its reference voltage is 2.5 V, resulting in a sampling resolution of 0.0000763 V. Therefore, its waveform is very smooth even when the signal amplitude is very small. The slight differences in the signal amplitudes are mainly due to small errors in the circuit parameters, such as the gain and the reference voltage.

The phase consistency is another important aspect to be analyzed. In Figure 8, the initial phases of the three signals are exactly the same. In Figure 9, where only the ending part of the waveform is plotted, a small phase difference between the wireless sensing units and the wired DAQ system is observed, while the phases between the two wireless units are still exactly the same. The detected phase discrepancy between the two kinds of communication systems can be justified by a small error in the sampling rate. To confirm this motivation, another experiment is carried out.

In the new experiment, the wired DAQ system still operates with a sampling rate of 250 Hz, while the wireless system is intentionally adjusted to sample the data at about 249 Hz so that the resulting sampling rate is not exactly equal to 250 Hz. Only one wireless unit is deployed in this second experiment, as no phase difference is observed between different wireless units. The operating parameters of the shaking table are the same as the ones adopted for the previous

DOI: 10.1002/stc

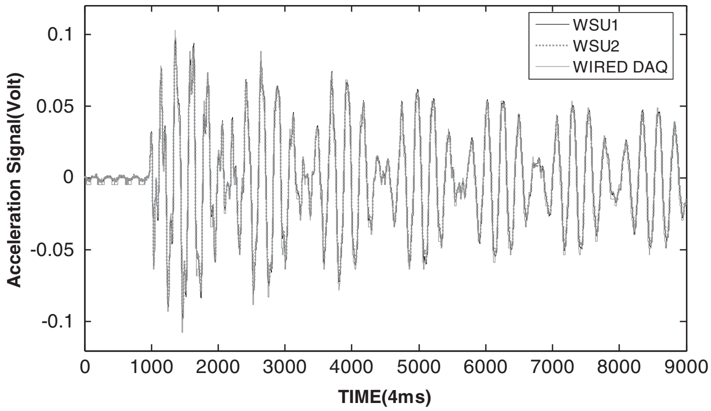

Figure 7. The complete waveforms acquired from 'experiment 1'.

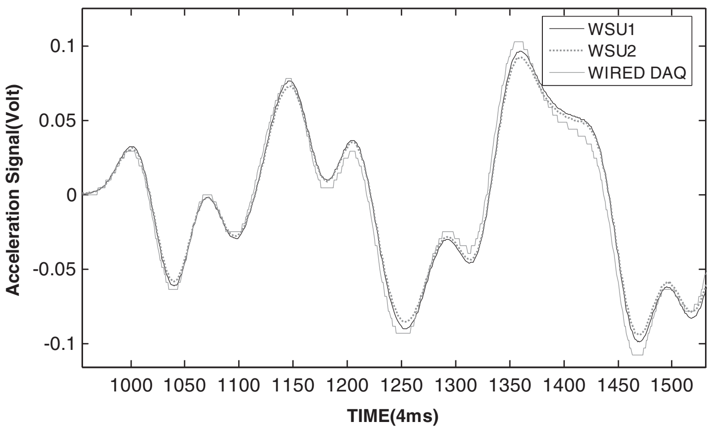

Figure 8. Enlargement of the initial part of Figure 7.

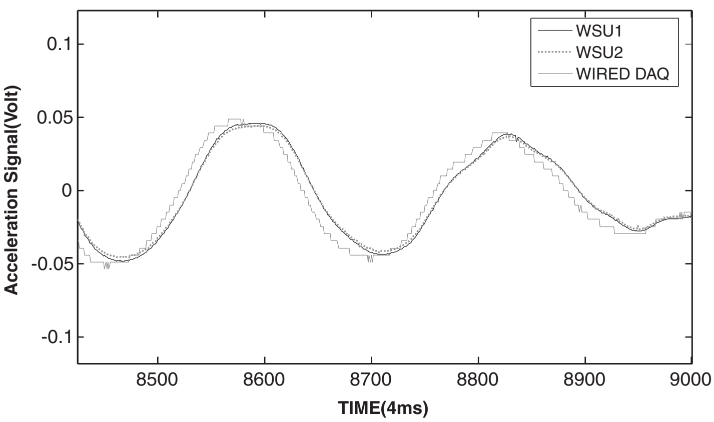

Figure 9. Enlargement of the ending part of Figure 7.

experiment. Similar figures are obtained by plotting the acquired data (Figures 10–12). By comparing the ending part of the waveform represented in Figure 12 with the one plotted in Figure 9, it can be observed that the phase difference between the signals from the wireless and wired systems is increased, as expected. This result demonstrates that errors in the sampling rates can result in a phase difference between the data transmitted to the central computer.

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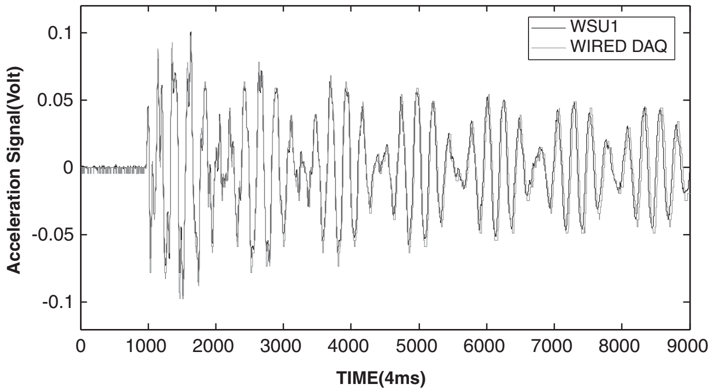

Figure 10. The complete waveforms acquired from ‘experiment 2’.

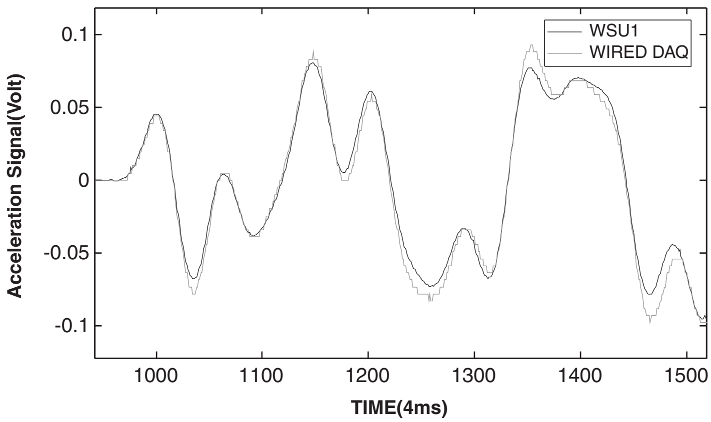

Figure 11. Enlargement of the initial part of Figure 10.

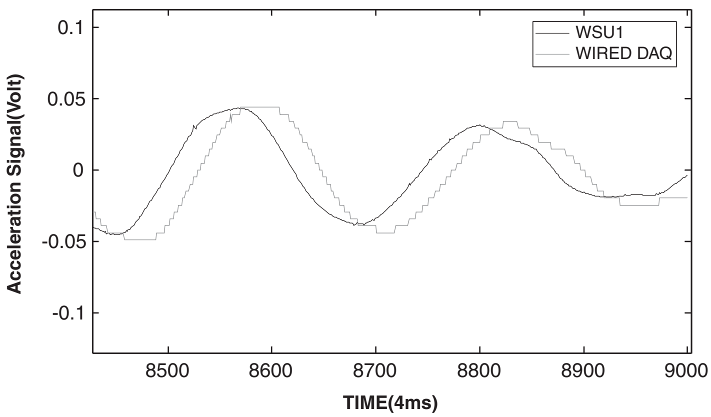

Figure 12. Enlargement of the ending part of Figure 10.

7. COMPARISON WITH OTHER SOLUTIONS

To date, many wireless sensors have been developed for structural monitoring applications. Their typical representatives can be identified with the academic unit of Stanford University (proposed by Wang, Lynch *et al*. [2]) and the commercial unit of Crossbow named Imote2 (used in [3–5]). A brief comparison of these solutions with the one proposed by the authors is outlined in this Section.

DOI: 10.1002/stc

From an applicative point of view, the proposed solution is intended and optimized for the replacement of existing analog cables. Its goal is to achieve a multi-channel and real-time transmission of the raw sensor data. As, at present, the traditional wired monitoring systems are still the most commonly deployed during in-field operations, the development of a simple and practical wireless update solution can provide an important support to the spread of wireless technology in the context of structural monitoring. The already existing wireless solutions are advanced in pursuing a decentralized and mobile computing capability and they focus on the autonomy of the wireless sensor. However, their ability of multi-channel and real-time data transmission is limited due to the delay of the wireless communication intrinsic to the adoption of a TDM approach. In contrast, the originally proposed wireless solution exploits the recent advances in RF IC technology to support the implementation of the FDM method, which is used to ensure an optimal performance of the multi-channel real-time transmission.

The motivations for this study also include the requirement of a low-cost solution that provides an alternative to the expensive plug-and-go wireless modules when simple-sensing applications that do not rely on distributed computational capabilities are needed. An optimized custom wireless solution is, therefore, developed in the attempt of minimizing the cost of the hardware components. In particular, the recent highly integrated, SoC wireless transceivers CC1110 and/or CC2510 of Texas Instrument are selected to achieve a reliable FDM wireless connection at a low cost. To ensure the compatibility with different types of sensors, a flexible and transparent sensor interface is implemented. It can provide the various sensors with their typical voltages (such as +12, −12, and 5 V), and it features a large input signal range (from −12 to +12 V). To improve the efficiency of the power consumption, low quiescent current and highly efficient switching regulators are used. They can be switched off by the microprocessor while they are not operating.

In conclusion, four main aspects are identified for comparison between the present wireless solution and the two mentioned existing ones: the wireless technology, the processor, the ADC, and the RAM memory. Tables III–V are dedicated to their comparison. A general overview of

Table III. The main components of the three solutions.

Product	Wireless technology	Processor	ADC	RAM memory
Stanford	9XCite or 24XStream Non-standard	Atmeg128 L	ADS8341	4 kByte Internal SRAM 128 kByte External SRAM
Crossbow Imote2	CC2420 ZigBee	PXA270	Integrated in sensor	256 kB SRAM 32 MB SDRAM
Pavia	CC1110 or CC2510 Non-standard	Enhanced 8051 Core	ADS8343	4 kByte Internal SRAM Extendable by serial port

Table IV. Details of the different wireless technologies adopted in the three solutions.

Wireless technology	Operating frequency	Max. data rate	Max. RF power	Max. power consumption	Cost
9XCite	915 MHz	41.6 kbps	6 dBm(4 mW)	Voltage: 2.85–5.5 V Current: TX: 55 mA, RX: 35 mA	High
24Xsteam	2.4 GHz	20 kbps	17 dBm(50 mW)	Voltage: 5 V Current: TX: 150 mA, RX: 80 mA	High
CC2420	2.4 GHz	250 kbps	0 dBm(1 mW)	Voltage: 2.1–3.6 V Current: TX: 17.4 mA, RX: 18.8 mA	Low
CC1110	315/433/868/915 MHz	Up to 500 kbps	10 dBm(10 mW)	Voltage: 2.1–3.6 V Current: TX: 36.2 mA, RX: 20.5 mA	Low
CC2510	2.4 GHz	Up to 500 kbps	1 dBm(1.26 mW)	Voltage: 2.0–3.6 V Current: TX: 26 mA, RX: 22.9 mA	Low

DOI: 10.1002/stc

Table V. Comparison of the main features of the processors adopted in the three solutions.

Processor	Bus width and speed	Power consumption	Cost	Design complexity
Atmeg128	8 Bit and 0–16 MHz	Voltage: 4.5–5.5 V Current: 1.8 mA/MHz	Low	Low
PXA271	32 Bit and 13–416 MHz	Voltage: 0.85–1.45 V Current: 31 mA at 12 MHz	Expensive	High
Enhanced 8051 core	8 Bit and 0–26 MHz	Voltage: 2.0–3.6 V Current: 200 μA/MHz	Integrated in transceiver	Low

the main components of the three solutions is provided in Table III, while the details of the different wireless technologies and processors are reported in Tables IV and V, respectively. With respect to the other two solutions, the proposed scheme is expected to be lower cost, to offer higher compatibility, and to reach a good balance among power consumption, communication range, data rate and link quality.

8. CONCLUSIONS

In this paper, a wireless solution suitable to replace the existing analog cables of a monitoring system is originally presented. The details of the hardware implementation are provided. The results of a validation experiment are discussed to demonstrate that recently advanced SoC wireless transceivers are competent and suitable for the implementation of a low cost, FDM wireless connection. Compared with the other existing wireless solutions, the proposed system mainly features the capability of multi-channel and real-time data transmission based on FDM, lower cost, higher compatibility with various sensors, and better balance among power consumption, communication range, data rate, and link quality.

ACKNOWLEDGEMENTS

This research is supported by the Athenaeum Research Funds from both the University of Catania (PRA 2007) and the University of Pavia (FAR 2008).

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DOI: 10.1002/stc