Design of Smart Bridge based on WSN for efficient measuring of Temperature, Strain and Humidity

Mohamed. Bouyahi, Houria. Rezig, and Tahar. Ezzedine

***Abstract*—**This paper presents the development of an automatic wireless sensor monitoring system for civil engineering structures. The objective is to provide a solution to measure temperature, humidity and strain inside a concrete structure. The research has been focused in the early age and curing phase period. Two sensors have been used. The first sensor fiber optic Brillouin Strain and temperature, the second is the sensor fiber optic Bragg of Temperature and Humidity. The two sensors used with Zolertia mote MSP430F2617 microcontroller allowing for the creation of an IEEE 802.15.4 network.

***Keywords*—** Structural Health Monitoring (SHM); Optic Fiber Sensor (OFS); Wireless Sensor Network (WSN).

I. Introduction

SHM is a new concept of civil engineering, it is able to monitor the structure on real time and evaluate the performance under many loads and determine the damage of structure. The goal of the monitoring is understand the structure and prevent the damage and prepares to repair it before the catastrophe failure. Many systems based maintenance are implemented in many structure and many sensors used. [2] Explain the SHM for Yongjong Grand Bridge (a long span Bridge such as Yongjong Grand Bridge). It contains a technology called MBM (Monitoring Based Maintenance), the sensors installed on cables vibration of stiffening stress, inclination and vibration of pylon, seismic acceleration, main cable temperature and wind direction/velocity. [9] implements 800 sensors in the super-tall, the 400 sensors vibrating strain gauges installed in different heights, the displacements and tilts sensors installed on the structure top under normal and typhoon conditions. [3] Use in the railway structure these sensors; the strain gages sensor, a distributed fiber optic strain sensor based on Rayleigh backscatter and embedded the long gage sensor in the concrete slabs, these sensors are used to measure the strain of structure.

This work was supported in part by the SysCom Laboratory. Communication System Laboratory Sys'Com, National Engineering School of Tunis, University Tunis El Manar, BP 37, belvedere 1002 Tunis, Tunisia

M. B. Author is with the National Engineering School of Tunis, University Tunis El Manar, BP 37, belvedere 1002 Tunis, Tunisia; (e-mail: mohamed.bouyahi@enit.rnu.tn).

H. R. Author is with the National Engineering School of Tunis, University Tunis El Manar, BP 37, belvedere 1002 Tunis, Tunisia; (e-mail: houria.rezig@enit.rnu.tn).

T. E. Author is with the National Engineering School of Tunis, University Tunis El Manar, BP 37, belvedere 1002 Tunis, Tunisia; (e-mail: tahar.ezzedine@enit.rnu.tn).

SHM enables the measurement of structural safety and integrity and ensure integration with bridge maintenance and management to contribute to bridge management plan. The long term loads will suffer damage, the loads result the variation of structure. Therefore, regularly testing the bridge during construction and operation to ensure its safety.

To evaluate the health of bridge structure and transmit the data with wired solution or optical cable, this method wills costs lots of manpower and material resources, and also cause measurement inefficiency, maintenance difficulty, and even causes unreliability of data transmission. The advancement in wireless technology has provided motives to the authors to develop the wireless network-based bridge health monitoring system.

Wireless Sensor Networks (WSNs) integrated with sensor technology, embedded computing technology, modern networking and wireless communications technologies, and distributed information processing technology can monitor, perceive and acquire various environmental or object information [7].

This paper presents a prototype of wireless sensor network system for a structure health monitoring. Sensor devices such as fiber optic Bragg of Humidity and Temperature and fiber optic Brillouin of Temperature and Strain and ZigBee modules are combined to implement the System Hardware. The Collect Tree Protocol (CTP) is tested to send the data to gateway. The collected data sent to database for SHM and the application software view the result [2].

This article opens with motivation and objectives carried out on objective to used the Wireless Sensor Network which shall be introduced in Section 2. Next section will present the system architecture. Then, in section 4 a sensor selection along with our installation. While Section 5 will include system hardware, Section 6 presents the system software. Last section 7 concludes the paper.

II. Motivation and Objectives

The objective of this researcher is to develop a prototype of Wireless Sensor Networks for Remotely Monitoring Bridge. WSN is formed by tiny devices; the tiny device is the mote as composed by microcontroller, sensors, memory, power unit and a communication module. They are able to sense the value of sensors and communicate with the base station as a wireless links. These sensors are reading the physical parameters of the structure at a given location, detecting of events and the signal as processing from the structure to the application. The WSNs are useful in situation where the structure is required. The research work was focused on detecting the structure parameter based on temperature, strain and humidity of the Bridge. This is accomplished by using the 802.15.4

ISBN: 978-1-61804-351-1

communication enabling a significant reduction of the installation time and costs.

The WSN using by the civil engineering is able to accommodate the large number of sensor, depending of needs, the small cost, sharing the information using the network. For the context the remote agents can collect the information and storage in the database through base station Gateway. The gateway has an interface of ZigBee module and another interface module 3G that is connected to a PC. The Fig. 1. Resume the system architecture.

Temperature is an important parameter, if the temperature decreases the hydration reaction slow down, if the temperature of concrete increase the hydration reaction accelerates. Result the differential of temperature within the concrete causing the lead to the fissuring.

The life cycle of the concrete bridge and her development linked with rate of hydration. It is important to study the impact of the temperature increase caused by the occurrence of the hydration reaction. A structural health monitoring is an important field of application for WSNs. Since with traditional wired-based solutions present the many problems like installation and maintenance cost. A WSN was created to collect the data from a sensor which facilitates the monitoring.

The properties of civil structure involve an important quantity of uncertainties in several parameters, this parameter like temperature, strain and humidity. In the ages of structure the temperature, strain and humidity can caused the most factors of deterioration of structure and can plays an important role to during of the concrete, and have a long-term consequence [1].

III. System Architecture

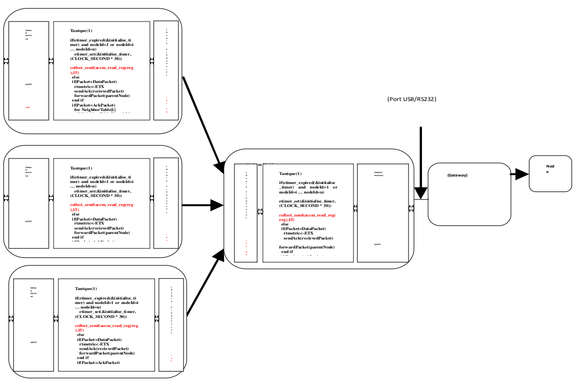

Fig. 1 System Design

The system is designed based on the wireless sensor network principles and we adopt the ZigBee communication inter-nodes. We have the central station like base station and many sensors in the Structure. The node data is transmitted in the 250 kbps radio channel. The Fig. 1. is shown the system design. The frequency to send packet from node to another is deferent when the frequency of the sensor fiber optic is deferent the frequency to send packet is deferent.

A wireless communication between the mote and the Gateway; the data request is transmitted to the Gateway after the sensor is detected the measurement to the Bridge, the Gateway is connected to the server when to store the data in the database server via the module 3G. The Gateway transmits the data to the server. The data is sent after the moment of temp, this temp depends on the sensors and the variation of these parameters [7].

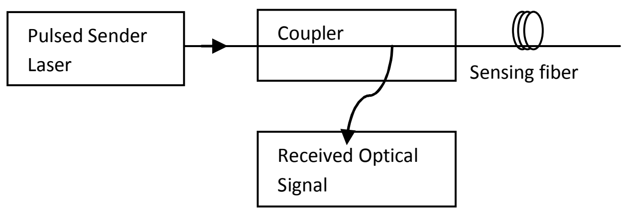

Fig. 2 Optical Time Domain Reflectometer functional schematic.

IV. Sensor Selection

In this section, we present the sensors are used in the structure. The Fiber Optic Sensor based on Stimulated Brillouin Scattering (SBS) for measuring the Temperature and Strain and the Fiber Bragg (FBG) for measuring the Temperature and Humidity. The installation model of sensor when the sensor is used for backscattering optic signal present on Fig. 2.

A. Sensor Fiber Brillouin

The physical parameters of optical fiber can be affected by temperature and strain. So the fiber sensors are able to detect the variation of temperature and strain over long distances.

These parameters have becoming the essence of distributed fiber optic sensing. The Rayleigh, Raman, and Brillouin scattering represent the basic scattering mechanism of the distributed sensing techniques which commonly occurred inside the fiber. The distributed fiber sensing is a really attractive technique for structural health monitoring (SHM). While it provide information of strain and temperature about a section or the complete structure with durability, robustness and measurement reliability. The distributed optical fiber sensing systems give us the opportunity to determine physical parameters, when large structures are to be monitored, such as bridges, dams and tunnels so this mechanism is suitable.

The Brillouin frequency shift has good linear relationship to the strain and temperature of the optical fiber, which can realize simultaneous temperature and strain measurement by using one optical fiber, with a lower accuracy [2] [5].

A pulse of laser is launched into the fiber, we amplify the input signal pulse in an optical fiber in a similar way as it undergoes in Erbium-Doped Fiber Amplifiers (EDFA). The directional coupler is backscattering the light to the same fiber to measure. The pulse propagates along the fiber to the receiver.

The backscattering of light is resumed of the scattering of incident photon in the fiber by the acoustic photon of the medium, this mechanism generate the frequency shift when we are measured the temperature and strain.

The backscattering signal refers to the Stokes frequency of the Stimulated Brillouin Scattering (SBS) and the occurrence of

ISBN: 978-1-61804-351-1

the bathochromic shift (the Stokes component) $w_s = w_p - w_{fa}$ with respect to the pumping beam, where w_{fa} denotes acoustic photon of the fiber. The fundamental difference from Brillouin and Raman scattering is the interaction of light photon with acoustic phonons in contrast to the Raman scattering where the interaction of light photons and molecular vibrations. The frequency of acoustic photon is lower than optical photon. The acoustic photon is determined by the following formula.

$$w_{fa} = \frac{4\pi n v_s}{\lambda} \tag{1}$$

v_s indicate the speed of sound in optical waveguide

n refraction index.

As a result of interaction between the matter and light photons the energy exchange occurs via acoustic photons leading to the third-order polarization of in medium.

$$p^{(3)} = \chi^{(3)}_{ijkl} E_j E_k E_l \tag{2}$$

$$\varepsilon_s = \frac{F}{E * A}(\cos^2\theta - \sin^2\theta) \tag{3}$$

The variation is detected by sensor Fiber Brillouin is ε_s focused by F is the force applied by concrete, A is the surface of optical fiber, E Young Module and θ the direction of light in the fiber [7].

The Brillouin Frequency Shift (BFS) of back scattering is linearly sensitive to strain and temperature.

It's expressed by:

$$\Delta V_B(T,\varepsilon) = C_T \Delta T + C_\varepsilon \varepsilon \tag{4}$$

B. Sensor Fiber Bragg

The sensor fiber optic is built to change their index of refraction periodically. The fiber Bragg grating is a linear superposition of temperature (T) and Humidity (RH) effects. In the presence of variations in relative temperature, ΔT, and humidity, ΔRH, the relative Bragg wavelength shift $\Delta\lambda / \lambda$ is therefore given by

$$\frac{\Delta\lambda}{\lambda} = S_{RH}\Delta RH + S_T \Delta T \tag{5}$$

When the S_T and S_{RH} are the sensor sensitivities to relative temperature and humidity, respectively. To relate the sensitivities to material properties, one many express S_{RH} as the sum of a mechanical, a strain-optic, and, for S_T only, a thermo-optic contribution [6].

$$S_{RH} = \beta_{cf} - P_e(\beta_{cf} - \beta_f)\left[\% RH^{-1}\right] \tag{6}$$

$$S_T = \alpha_{cf} - P_e(\alpha_{cf} - \alpha_f) + \xi\left[K^{-1}\right] \tag{7}$$

Where β_i is the hygroscopie longitudinal expansion coefficient, and α_i is the thermal longitudinal expansion coefficient The subscript stands for bare fiber (i=f), coating (i=c), and coated fiber (i=cf). $\hat{P}_e = n_{eff}^2\left[P_{12} + \varepsilon_{f,r} / \varepsilon_{f,z}(P_{11} + P_{12})\right]/2$ is the effective photoelastic coefficient of the coated fiber, where n_{eff} is the effective refractive index of the mode, P_{ij} are the coefficients of the strain-optic tensor, and $\varepsilon_{f,r}$ and $\varepsilon_{f,z}$ are the radial and axial elastic fiber strains, respectively. ξ is the thermo-optic coefficient of the fiber core [4] [8].

V. SYSTEM HARDWARE

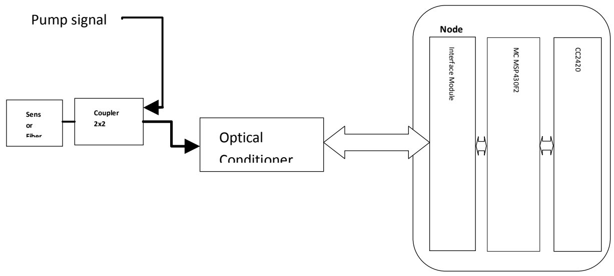

Fig. 3 Mote and Sensors.

The node defined in Fig. 3. Correspond to a Pump laser, Sensor Fiber Optic, Coupler 2x2; Optical Conditioner, Interface Module and the wireless communication module are integrated in single unit. This unit transmits the signals with the digital format by wireless module and the development of unit combine the ADC coupling with ZigBee module.

The output from the optical sensor in a form of the impulsion of optical signal. The sensory output need to be converted to the electric by Optical Conditioner. The electric signal converts to the digital signal by interface module. After reading the data from the sensor and deliver to the ZigBee module. This sends the data to other ZigBee module wirelessly. The unit is powered by the battery [2].

A. Zolertia Mote microcontroller

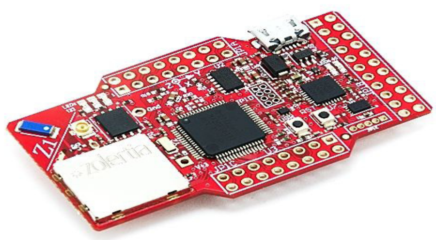

Fig. 4 Mote Zolertia.

The Z1 module Fig. 4. Developed by Zolertia, Z1 is a low power wireless module compliant with IEEE 802.15.4 and ZigBee protocols intended to help WSN developers to test and deploy their own applications and prototypes with the best tradeoff between time of development and hardware flexibility. Its core architecture is based upon the MSP430 and CC2420 family of microcontrollers and radio transceivers by Texas Instruments, which makes it compatible with motes based on this same architecture.

It has many port like UART, SPI, I2C, Phidgets, ADCs and DACs which facilitate the communication with external sensors, It is used in ultralow power consumption mode consist of several devices featuring different sets of peripherals targeted for various applications and allows its use for the high-frequency sampling required for dynamic structural monitoring. The architecture, combined with five low power modes is optimized to achieve extended battery life in portable measurement applications. It has the 16 MB Flash Memory, 8KB RAM [5] [7] [10].

B. Transceivers CC2430

The CC2420 is a true-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver designed for low-power and low-voltage wireless applications. CC2420 includes a digital direct sequence spread spectrum baseband modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps.

The CC2420 is a low-cost, highly integrated solution for robust wireless communication in the 2.4 GHz unlicensed ISM band [5] [7] [10].

C. Installation

The Mote is able to connect an Optical Conditioner with Universal Asynchronous Receiver Transmission (UART) [2] [5] [10].

The UART connection is embedded in the MSP430F2617. The resolution used in UART is 13-bit. The format of UART is a start bit, seven or eight bits of data, a parity bit, an address bit, and one or two stop bits. The baud rate of UART can detected automatically. The processor sends the value when it receives to the base station via radio [2].

VI. System Software

The system software includes the two parts, the embedded software of MSP430F2617 and the one of the Upper Machine.

A. Software of MSP430F2617

The main program flow of the proposed system is shown in Fig. 5. The MSP430F2617 will be initialized first, include the initialization time and when the time is expired the mote detect the signal from the optical conditioner, if the signal is defer then value registered by the mote can send a packet to the gateway.

If the signal is not defer then recent value the Mote can initialize the timer for new instance [10].

B. Development of sensor data management software

We can use the sensor Middleware to manage the sensor and reconfigured mote, the time of signal sends it is modified from user wirelessly [10].

C. Flow Alarm circuit of Damage Detection

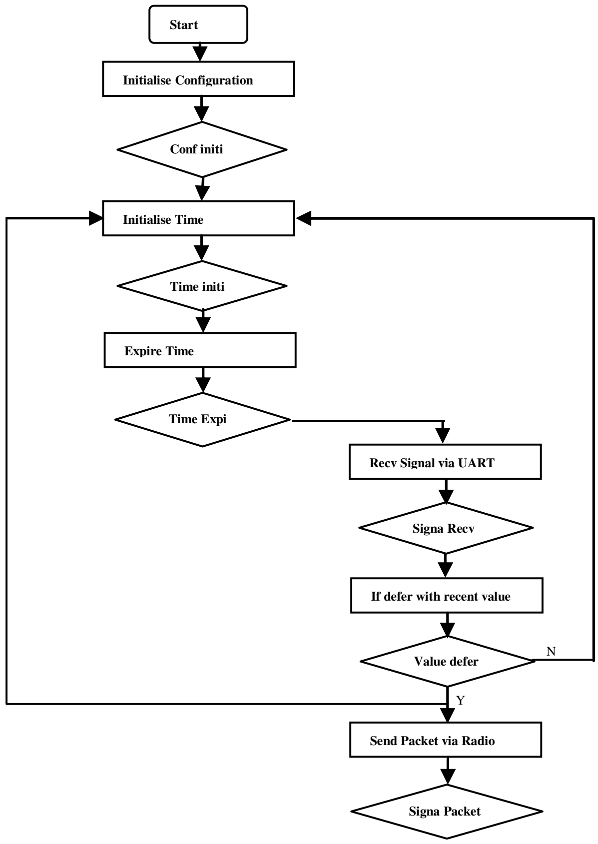

Fig. 5 Main Program Flow.

If the value of sensor measurement is equal or higher than the value of threshold memories in the mote the alarm is lunched [10].

D. Wireless communication protocol

In wireless sensor networks we can use the CTP protocol to achieve the destination of packet. We based on the Residual Energy and the Link Quality Indicator. The Link Quality Indicator and Energy Residual of the nodes can increase the performance of network. The link quality increases when the hop count decreases thus the node with high value of link quality will be chosen as the forwarding candidate. The threshold for the link quality can change the throughout, the lifetime of the network it makes more alive by selecting the longer routes with more energy. The optimal path will be chosen when the route has more Residual Energy or through Link Quality Indicator.

VII. Conclusion

This article developed a prototype of wireless sensor bridge health monitoring system. The wireless communication,

ISBN: 978-1-61804-351-1

the sensor and the node are used to make the system integration. Digital-Analogic and the electric to optical converters between module ZigBee and the optical sensors, the optical electric and the Analogic-Digital converters between sensors and module ZigBee.

This system able to detect any variation in the Bridge depends on the sensor parameters.

In addition, a protocol CTP can transmit the data between the sensors and Gateway. The sensors were installed on the Bridge.

REFERENCES

[1] Barroca N. Borges LM. Velez FJ. Monteiro F. Gorski M. Castro-Gomes J. "Wireless sensor networks for temperature and humidity monitoring within concrete structures", Construction and Building Materials, Vol. 40, pp. 1156–66, March 2013.

[2] Chae M.J. Yoo H.S. Kim J.Y. Cho M.Y. Development of a wireless sensor network system for suspension bridge health monitoring. Automation in Construction, Vol. 21, pp. 237-252, 2012.

[3] Chapeleau X. Sedran T. Cottineau L.-M. Cailliau J. Taillade F. Gueguen I. Henault J. Study of ballastless track structure monitoring by distributed optical fiber sensors on a real-scale mockup in laboratory, Engineering Structures, Vol. 56, pp.1751-1757, 2013.

[4] Chen Q. Lu P. Fiber Bragg Gratings and Their Applications as Temperature and Humidity Sensors. Advances In Atomic, Molecular, and Optical Physics, Vol. 56, pp. 235-260, 2008.

[5] Jafer E. Ibala CS. Harris J. Design and development of multi-node based wireless system for efficient measuring of resistive and capacitive sensors. Sensors and Actuators A: Physical, Vol. 189, pp. 276-287, 2013.

[6] Kronenberg P., Rastogi P.-K., Giaccari P., Limberger H.-G., Relative Humidity sensor with optical fiber bragg gratings. OPTICS LETTERS, Vol. 27, No. 16, pp. 1385-1387, 2002.

[7] Liu Z. Yu Y. Liu G. Wang J. Mao X. Design of wireless measurement system based on WSNs for large bridges. Measurement, Vol. 50, pp. 324-330, 2014.

[8] Sandra F.-H.-C., Paulo A., Edison P., Patrícia P.-L., Humberto V., Luis D.-C., Rute A.-S.-F., Paulo S.-A., Optical Fiber Relative Humidity Sensor Based on a FBG with a Di-Ureasil Coating. Sensors Vol. 12, pp. 8847-8860, 2012.

[9] Xia Y. Zhang P. Ni Y. Zhu H. Deformation monitoring of a super-tall structure using real-time strain data. Engineering Structures, Vol. 67, pp. 29-38, 2014.

[10] Yu Y. Zhao X. Shi Y. Ou J. Design of a real-time overload monitoring system for bridges and roads based on structural response. Measurement vol. 46, pp. 345-352, January 2013.