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► **To cite this version:**

Vincent Le Cam, Louis-Marie Cottineau, Frédéric Bourquin. A WIRELESS SENSOR NETWORK FOR DAMAGE DETECTION AND HEALTH MONITORING OF CABLES. Third European Conference on Structural Control, 3ECSC,, Vienna University of Technology, Jul 2004, Vienne, Austria. hal-04465752

**HAL Id: hal-04465752**

**<https://hal.science/hal-04465752>**

Submitted on 22 Feb 2024

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# A WIRELESS SENSOR NETWORK FOR DAMAGE DETECTION AND HEALTH MONITORING OF CABLES

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Acoustic emission emerges as one of the reliable methods for cable health monitoring. Practical implementation involves numerous acoustic sensors to be placed along cables, as well as a supervising system. The Public Works Laboratory has developed such a platform. One version has been produced, and actually equips several bridges (Tancarville bridge, Iseron bridge, Aquitaine bridge,...). The system provided reliable results and was able to warn on-time bridge operators in case of critical health state. This article aims at presenting recent progresses towards better reliability of break detection by means of DSP, and increased flexibility provided by a TCP/IP - WIFI wireless implementation.

## 1 Introduction

In view of safety, structure durability and cost efficiency, detection of wire breaks is a strategic component of cable monitoring. Knowing the number of breaks and their location contributes to understand the health state of the structure. Acoustic emission emerges as one of the favourite non-destructive evaluation techniques. A great challenge is to develop reliable and versatile systems. This article especially describes the wire breaks detection by an acoustic emission method and the use made of emergent technologies such as the WIFI and Digital Signal Processing.

## 2 Principle of the acoustic emission

### 2.1 Acoustic wave in cables

The configuration of pre-stressed internal and external cables as well as those in bracing cables or suspension bridges implies that when a wire breaks, its two ends re-anchor close to the crack location. At this moment, an acoustic wave is generated in two opposite directions in the corresponding strand and neighbouring ones. Multistrand configurations may lead to the problem of detecting ruptures in internal strands. Fortunately, since corrosion and fatigue coupled to corrosion are major causes of ruptures, internal strands should undergo much less ruptures than external ones.

### 2.2 Rupture detection

Detection of a wave by means of acoustic sensors that transmit this information to a supervisor means that a rupture occurred in the cable. Sensor detection consists of recording the amplitude of the wave and the time to arrival at sensor location.



Figure 1: Rupture detection by acoustic sensors

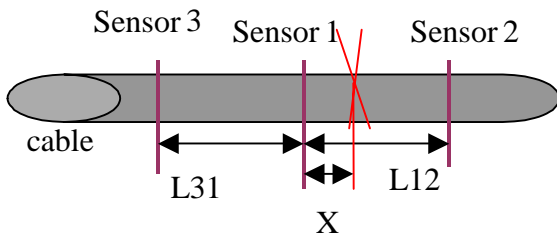
### 2.3 Rupture location

Each sensor that has detected the event sends its amplitude and time to a supervisor that “knows” all sensor relative locations (L12, L23,...). Then by a simple calculation the supervisor can determine the point of rupture.

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**Figure 2:** Rupture location by acoustic sensors

First, the supervisor identifies sensors 1, 2 and 3. Sensors 1 and 2 are the two sensors that received the wave first. The break thus occurred between these two sensors. Sensor 3 and sensor 1 enable one to compute the speed "V" of the wave. From these data it determines "X" as follows :

$$V = L31 / \Delta t31 \quad (1)$$

$$X = \frac{1}{2} * (L12 - v * \Delta t12) \quad (2)$$

Where  $\Delta t_{ij}$  denotes the delay in event detection between sensor i and sensor j.

This principle not only enables one to detect wire breaks but it also yields their location along the cable. The wave amplitude sent by each sensor provides information on the energy released during rupture.

### 3 First implementation of the system

#### 3.1 Description

A first generation system has been designed and produced. It now equips several french civil engineering constructions such as Aquitaine Bridge in Bordeaux, Tancarville bridge, Normandie bridge.



**Figure 3:** Iseron and Tancarville bridges

Main features :

- Sensors are linked by an RS485 serial wire,
- The physical measure is performed by an accelerometer,
- Supervisor is a central PC to watch the serial link is connected,
- Sensors use an accelerometer and detection is made by permanent comparison of the signals to a pre-determined threshold (around 0.8g),

- An alarm device using telephone modems warns the bridge operator,
- Sensors are placed 10 m apart from one another

### 3.2 Results

Clear-cut results have been obtained with this system. First, laboratory tests show an accuracy of the order of  $\pm 15$ cm for crack location when sensors are located 10m apart from one another. *In situ*, the system provided with strategic informations that justified the cable replacement of Aquitaine bridge. Once took down, cables have been analyzed; the actual number and location of ruptures proved to be in agreement with those detected by the acoustic system [1]. Therefore this system in its wire version proves reliable in delivering critical internal informations on cable health in full scale real life applications

## 4 A wireless and smart sensor network

### 4.1 Motivations

Even if the first generation gives useful informations for crack detection, two main evolutions are being added to the acoustic system :

- In view of flexibility, cost efficiency, wireless sensors have been designed,
- In view of increased reliability in wire breaks detection, sensors are made "intelligent".

### 4.2 Wireless TCP/IP (WIFI) solution

More than only wireless sensors, the goal is to obtain the capabilities offered by sensor networks.

Sensor network architectures are more and more appropriate in many cases. Sensor network topologies allow to organize the monitoring in a way that complies with the nature of what should be measured and the final goal of the monitoring. For example, variable sensor density as well as heterogeneous or combined measures are easily supported.

Moreover, "network" means that entities could exchange data between each other. Sensor data don't have inevitably to go through a supervisor. Sensors can be grouped in sub-networks that take care of only part of the monitoring. Computation and analysis can be decentralized through the sensor network. A hierarchy can be implemented : one sensor can supervise a group of sensors that measure temperature, whereas another manages strain measurements... Thus only relevant informations are furnished to the main supervisor.

For many years, as a consequence of the exponential computer science development, the TCP/IP protocol has emerged. It has now become a world wide standard protocol. It appears very interesting to implement this protocol in sensors not only because of its perennity but also because TCP/IP can transit now through a new wireless standard called WIFI (standards 802.11a, b, and g, 802.16 coming) [6].

TCP/IP protocol has often been cited as a "heavy protocol" [5]. But thanks to new electrical components (micro-controller, DSP, processor, memory storage...) this protocol can easily be embedded in the memory space of a processor. The TCP/IP software stack code can be optimized and customized to minimize its size and its CPU needs.

Without a standard communication protocol, wireless sensors are often dedicated to only one kind of measurement and systems are usually in a "star topology" around a supervisor (each sensor doesn't know the other ones). Moreover, sensor evolution is then more difficult because the protocol has to be rewritten according to the new type of data whereas TCP/IP offers a standard pipe between entities.

That problem is well underlined by the example of the MEMs inexpensive wireless sensor accelerometers [2] that the Intel's EcoSense research project [3] tries to connect while maintaining a high level of network performance and using the wireless TCP/IP.

Nevertheless, in case of very local and dedicated measures such as seismic instrumentation, specific development could be more suitable [4].

#### 4.3 Smart sensors - Use of a DSP core

The waves produced by wire breaks have a velocity of about 5000 m/s and a frequency band under 30kHz. In order to have a good resolution, waves are sampled at 300kHz by sensors.

With such a sampling frequency, the first generation of sensors (using Motorola 68hc11 micro-controller) was only able to record a threshold value exceed and its moment. Then those two datas are sent to the supervisor.

Thanks to electronic evolutions and especially in signal processing, DSPs (Digital Signal Processors) allow high speed sampling and simultaneous "high level" treatment : numerical filtering, FFT,... The DSP family is large and subject to permanent evolution (integration, low power consumption...).

L.C.P.C. retained DSPs that embed a TCP/IP stack, a large memory storage, and an Analog to Digital Converter.

### 5 Platform development

The new health monitoring platform integrates the wireless TCP/IP protocol (802.11b) for communication between network nodes. Each entity (supervisor, sensors) is viewed as in a classical office data network.

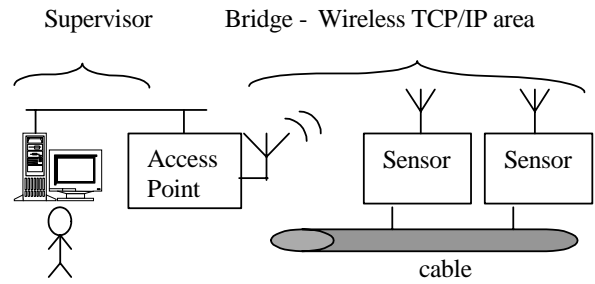


Figure 5: The wireless sensor network architecture

Sensor role is extended : waves are permanently compared to a threshold. If exceeded, the sensor records the complete signal on a 8ms period including a 1ms pre-trigger delay. Then it sends this temporal signal to the supervisor using its embedded TCP/IP wireless stack.

#### Wireless platform :



Figure 6: The wireless platform in development

The supervisor consists of a user-friendly interface software that computes messages from sensors to perform the rupture tracking. WIFI area is performed by a traditional Access Point. Sensors use an Analog Device BlackFin533 DSP (100MHz processor frequency) and an Intersil PCMCIA wifi board.

#### Preliminaries results

The laboratory wireless sensor network system has been developed and works fine : signals over the threshold are detected, wireless transmitted to the supervisor that analyses them for tracking wire breaks.

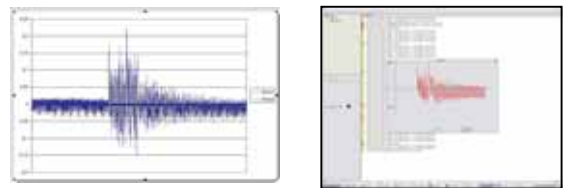


Figure 7: Sensor (oscilloscope snapshot) and supervisor measure of a shock

Amplitude distortion is less than 0.5% and the transmission delay of a signal from a sensor to supervisor is less than 10ms.

## Autonomy

Wireless sensor networks must ensure long-term monitoring. Thus, one of the challenges to reach in sensor development is to guaranty a sensor autonomy that allows suitable periods (from weeks to half a year at least).

In wireless sensors, the most demanding is the communication module that embeds an antenna and all the RF communication's components. In our Wifi case power consumption range is : 10mW to 400mW.

Consequently, sensor algorithms are developed with the following philosophy: "sensor permanently measure but seldom talk". The sensor is always the entity that decides when to transfer informations. Since ruptures are very rare events, the Wifi module is permanently OFF and only turned ON by the DSP when such an event occurred.

In addition, sensor is composed of very few low-power consumption electronic components : a piezzo-electric (0 mW), an ADC (< 5mW), a DSP AD-BF533 (< 43mW), the Wifi module (< 250mW when ON).

The above paragraph underlines a serious limitation of wireless systems : sensor autonomy. When sensor have to be permanently online (in real-time applications for example), this increases its power consumption and long monitoring periods are not possible. The ways that should be explored are low-power consumption and node exchange optimization.

## 6 Conclusion

Use of the TCP/IP protocol provides notable advantages : even if radio link is disturbed, typical rate remains equal to 1 Mb/s; a wifi area can easily be increased by adding other Access Points (in "roaming mode"); TCP/IP protocol is independent of the physical link, thus, sensors can be connected if a wire connection is more appropriate (in bridges for example). This world-wide protocol is "layer-level" designed, so any modification in data exchange (with supervisor, other sensors...) only consists of high-level software programming.

The initial platform and works in progress prove that cable health monitoring can be performed by a non destructive acoustic method. During the coming year, a first complete and industrial wireless platform will be designed and attached to real cables under real conditions in order to validate and improve the system.

Many ways have to be explored. First, DSP functionalities are under-used : a studied evolution is the frequential signature analysis to separate real ruptures detection from noise and to increase scientific knowledge in this domain. Another way is the development of the network capacities offered by the TCP/IP protocol : while paying attention to power consumption, sensors are able to communicate with each other and the sensor network could be hierarchized in agreement with instrumentation needs.

According to the number of industrialized sensors and selected technologies, the unit price should be included between a few tens and a few hundreds of dollars.

Due to its modularity, the wireless sensor network could equip smart structures and be used for other kinds of instrumentations such as vibration measurement using accelerometers, wind monitoring of bridges using pressure sensors, fatigue monitoring using deformation gauges, temperature measurement, or chemical measurement to quote a few .

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