Wireless sensor network developments for physical prototype testing

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ABSTRACT
Measurement data play a critical role on each level of the mechanical engineering development process, in product benchmarking, target setting, model verification, load analysis, hybrid model building to product qualification and performance monitoring. This paper investigates how recent evolutions in the field of Wireless Sensor Networks (WSN) have the potential to dramatically change the way physical prototype testing is performed. The envisaged application involve multi-channel high-speed sensor data acquisition combined with advanced signal processing for the purpose of fast physical prototype refinement (in the design stage) as well as life-cycle product integrity and performance monitoring. Considered prototypes are cars, aircraft or civil engineering structures such as bridges equipped with monitoring systems. This paper presents a prototype WSN development that uses wireless communication protocols and digital sensors to perform vibration-based physical prototype testing. Migration to MEMS sensor reduces the size and prices of the sensors and at the same time increases the possibilities of electronic integration. Wireless technology reduces also the price of the final system, eliminating the wires, and expands the possibilities of measurement performance. The architecture of the system will be described as well as some extensive validation tests.

1 INTRODUCTION
The goal of the European, MEDEA+ research project “SWANS” (Silicon platforms for Wireless Advanced Networks of Sensors) is to define a generic silicon platform aiming at integrating analogue and digital IP blocks for future wireless sensor nodes. This platform will be used to demonstrate functional IP blocks, macrocells and chipsets for 5 application classes: aeronautic, health/fitness, homeland security, automotive and environmental monitoring. The consortium gathers 28 actors from 6 countries among which two of the world leading semiconductor manufacturers, leading integrators and end users in the various application field as well as research institutes and SMEs bringing to the project state of the art expertise.

LMS International was one of the end-users in this project and mainly cooperated with IMEC, which is Europe’s largest independent research centre in nano-electronics and nano-technology. This cooperation within SWANS resulted in a prototype Wireless Sensor Network (WSN) that was validated for applications involving multi-channel high-speed sensor data acquisition combined with advanced signal processing for the purpose of fast physical prototype refinement (in the design stage) as well as life-cycle product integrity and performance monitoring.

Current high-quality Noise and Vibration (N&V) measurement systems are (still) built up by means of analog sensors, connected by wires to a single, but multichannel, data acquisition system, which is interfaced to a workstation or PC by a high-transfer rate communication bus [1][2][3]. Advances in sensor and sensor-interfacing technologies explored in other (mostly low-frequency and low-resolution) applications (biomedical, in-vehicle systems like airbag sensors, …) have not yet entered this type of instrumentation-grade noise and vibration measurement systems. This is due to a multitude of reasons such as required data resolution and quality, data integrity, frequency range, data transfer rates, but also because of a certain conservatism in the concerned sectors (equipment investments in the automotive and aerospace labs, compatibility with existing sensor platforms, lab environment robustness, …) and the rather limited scale of the addressed market (in the order of thousands of systems, making large-scale IC integration very costly).
However, it is expected that this N&V measurement systems scene will change considerably, due to the advances in technology fields like microsystem sensors, integrated sensor-acquisition nodes and advanced data communication as well as in the field of lower-cost processes for limited-series microsystem and IC development. All this may lead to a disruptive (r)evolution in test instrumentation, data collection and even test concepts in fields such as automotive, aerospace or production or construction monitoring.

The traditional approach to physical prototype testing consists of wired sensors (e.g. piezoelectric accelerometers) connected to an acquisition system that is managed via a PC (Figure 1). The main disadvantages of this system are (a) high cost of sensors and wires, (b) difficult installation of the sensors (sometimes as many as thousand) or (c) some measurement conditions, like rotations or large displacement, are difficult for wired systems. Therefore, significant research is conducted to overcome these drawbacks in two different directions: MEMS sensors and Wireless Sensor Networks [4].

**Figure 1: Synchronized multi-channel data acquisition: typical cabling situation.**

Wireless sensors are applied to modal analysis in [5]. The potential for wireless sensor and data acquisition methods to mitigate some of the inherent problems associated with experimental modal analysis as it is currently performed with “hard wire” technology is examined. Approaches to wireless hardware and software are suggested that could parallel calculations and thus reduce calculation time and improve data quality by elimination of interconnecting wires. A wireless instrument for providing long-term structural dynamics measurements of the International Space Station (ISS) Solar Array Trusses while deployed on-orbit, was introduced in [6]. The data acquisition units will acquire synchronized micro-g measurements from 10 triaxial accelerometers distributed along the truss and forward this information via Radio Frequency communication into the ISS, where it will be downlinked to controllers at Mission Control.

In [7] and [8], commercially available MEMS (Microelectromechanical systems) accelerometers are discussed from a high-end instrumentation point of view and with modal testing or structural health monitoring applications in mind. These papers contain a complete mechanical characterization of some MEMS sensors in comparison with other traditional accelerometers, piezoelectric and servo ones. Obtained results allow concluding that the quality/cost ratio of this kind of sensors is very high. They can be tens times cheaper than traditional accelerometers and performances can be compared, even if final user has to take care to some fundamental aspects, such as signal-to-noise ratio, low frequency response, temperature influence and transverse sensitivity.

A machinery condition monitoring application using wireless self-powered sensor nodes is discussed in [9]. The sensor node scavenges energy from machinery vibration and uses this energy to power an embedded processor, sensors, and radio. This overcomes a major drawback to low-cost wireless sensor nodes, namely the need to regularly replace batteries.
A lot of WSN research is performed in the context of Structural Health Monitoring of civil Structures. The drawbacks of the traditional approach to (vibration-based) monitoring include (1) the high cost of installation and disturbance of the normal operation of the construction due to wires having to run all over the structure, (2) the high cost of equipment; and (3) cost of maintenance [10]. Therefore, significant research is conducted to overcome these drawbacks. Often, this research goes into the direction of Wireless Sensor Networks (WSN). Compared to the conventional methods, WSN provide comparable functionality at a much lower price, which permits a higher spatial density of sensors. Compared to the wired network, installation and maintenance are easy and inexpensive in a WSN, and disruption of the operation of the structure is minimal. In [11] a low-cost solar and wind powered wireless sensor node called DuraNode and a highly cost-effective sensor network system with real-time wireless communication capability in practical ranges of transmission distance over several miles is discussed. The network systems are used for Caltrans’ bridges in Orange County, California. The development and deployment of low-cost wireless sensor prototypes for the Geumdang Bridge in Korea is described in [12]. In [13] distributed data processing architectures for wireless SHM systems are discussed. The design, implementation, deployment and testing of a 64-node Wireless Sensor Network installed at the Golden Gate Bridge is discussed in [10]. Finally, [14] describes a recently developed WSN that was installed on the Wanda Bridge over the Vistula River in Poland. Ambient vibration data of such a system was used to illustrate Operational Modal Analysis, a technique that allows for an optimal information extraction from such data.

As a starting point for the work presented in this paper, it is interesting to consider nowadays N&V instrumentation requirements:

- Support of wide variety of transducers: accelerometers, microphones, strain gauges, temperature sensors;
- Low noise level and high dynamic range (contrary to in-vehicle and biomedical sensors);
- Typical sensor size: 1 cm³;
- Frequency range: DC – 20 kHz;
- Multi-channel data acquisition: 4 – 1000 channels;
- Very strict synchronization requirements;
- Covering large measuring area: Range = 300 m;
- Real-time measurements.

These quite general requirements are met with current modern digital front-ends such as the LMS Scadas III or Scadas Mobile [2], but it is clear that in case of wireless sensors, the system has to be tuned to a more specific application within the N&V measurement scene, such as, for instance, Ride & Handling measurements, Road Load Data Acquisition or Ground Vibration Testing of aircraft.

This paper presents a wireless measurement system designed by IMEC and LMS. It is organized as follows. First, the developed WSN is described, emphasizing the system architecture, MEMS accelerometers, and the wireless communication and synchronisation. Afterwards some validation studies are performed using a bridge scale model and a Ground Vibration Test of an aircraft.

2 WIRELESS SENSOR NETWORK DESCRIPTION

2.1 System architecture

The system is divided in three different modules (Figure 2): (a) sensor module and wireless transmitter, where the data is acquired and then codified and modulated to be sent via radio; (b) wireless receiver, where the data is received and de-codified and (c) and data post processing controlled by a PC and software [15].

IMEC’s processing and wireless platform (Figure 3 – Left) is used to handle the control of the data acquisition and the wireless communication. It is a layered, modular system containing in the top layer a low-power radio with integrated antenna, in the second layer a low power microcontroller, and in the subsequent layers application-specific functionality and power. The prototype system development described here uses connectors for the vertical interconnect. A much more compact implementation can be made using solder ball interconnect technology. Both stacking options are represented in Figure 3 (Right). The envisaged measurement scenarios
required accelerometers sensing in all three axes. The selected MEMS accelerometers will be discussed in Section 2.2. In case an accelerometer is selected that also includes analog-to-digital converter (ADC), the data is provided digitally to the controller. If the accelerometer has analog outputs, the internal 12-bit ADC of the microcontroller layer is used. The system is powered by a compact and light rechargeable Li-ion battery (150 mAh, 25x20x4 mm³, 3.7 g), with an included overcharging/overdischarging protection chip. The fourth layer in the stack implements the voltage regulation from the battery voltage to 3.0 V, as well as a power on/off switch. When the data acquisition software is not active, the sensor nodes go in a sleeping mode. The autonomy of the system (continuous measurement mode) is about 8 hours.

Figure 2: Wireless Sensor Network consisting of 4 sensor node and 1 USB receiver.

2.2 MEMS sensors

Nowadays, MEMS accelerometers are quickly replacing conventional accelerometers for crash air-bag deployment systems in automobiles. The conventional approach uses several bulky accelerometers made of discrete components mounted in the front of the car with separate electronics near the air-bag; this approach costs over $50 per automobile. MEMS and Nanotechnology has made it possible to integrate the accelerometer and electronics onto a single silicon chip at a cost between $5 and $10. These MEMS accelerometers are much smaller, more functional, lighter, more reliable, and are produced for a fraction of the cost of the conventional macro-scale accelerometer elements. In addition, the low power consumption is one of the strong points of MEMS so that they are good candidates for wireless applications. However, the evolution in MEMS is not driven by the relatively low-volume instrumentation market needs and, for instance, the noise floor of commercially available MEMS is much higher than of classical piezoelectric sensors (Table 1).

It was the intention to develop a WSN that was suited for low-g applications (e.g. ambient vibration testing of civil structures) as well as higher-g application (e.g. laboratory or road tests of a car). Two different MEMS accelerometers have been selected:
• Kionix KXP84-2050 (Figure 4 – Top) for applications till 2 g. This is a tri-axial accelerometer with integrated ADC. The output data is digitally provided to the microcontroller at the sensor node.
• Freescale MMA6233Q for applications till 10 g. This is a two-axis sensor; therefore two sensors are placed perpendicularly in order to get a three axes sensor (Figure 4 – Bottom). This accelerometer has analog outputs, so the internal 12-bit ADC on the microcontroller layer is used in this case.

Table 1 compares some key specifications of the sensors. For comparison, the same table also shows a classical piezo-electrical sensor which is typically used in civil engineering vibration testing (PCB 393B12).

Table 1: Comparison between MEMS and seismic piezo-electrical sensor.

<table>
<thead>
<tr>
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<th>KIONIX KXP84-2050</th>
<th>FREESCALE MMA6233Q</th>
<th>PCB 393B12</th>
</tr>
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<tbody>
<tr>
<td>Measurement range</td>
<td>2 g</td>
<td>10 g</td>
<td>0.5 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>819 counts/g, 12 bits</td>
<td>120 mV/g</td>
<td>10 V/g</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1.7 kHz</td>
<td>0.9 kHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Voltage supplier</td>
<td>3 V</td>
<td>3 V</td>
<td>5 V</td>
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<tr>
<td>Current supplier</td>
<td>1 mA</td>
<td>2 to 20 mA</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>175 µg/√Hz</td>
<td>30 µg/√Hz</td>
<td>1.3 µg/√Hz</td>
</tr>
<tr>
<td>Number of axes</td>
<td>3</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Dimensions</td>
<td>5x5x1.2 mm³</td>
<td>6x6x1.98 mm³</td>
<td>30.2 mm, h= 55.6 mm</td>
</tr>
</tbody>
</table>

2.3 Wireless transmission and receiver
IMEC’s processing and wireless platform makes use of the Nordic nRF2401A 2.4 GHz radio transceiver. The maximum data rate is 1 Mbit/s, but in the application it is limited to 250 kbit/s. The reduced bit rate allows better receiver sensitivity and therefore better link robustness in the face of interfering metal objects etc. expected to be present in an automotive environment. For a single-sensor three-axis sensor node, a sampling rate of 2500 Hz for each axis could be achieved. In case of a 4-sensor network (Figure 2 – Right), the sampling rate was restricted to 512 Hz for each of the 12 axes.

The receiver emits periodic synchronization beacons, every 7.8 ms. The sensor nodes listen for these beacons and use it to synchronize their timing (Figure 5). Using this method the sample moments are synchronized across the network to ±30 µs accuracy (compared to the sample period of 1.95 ms). Even if sporadically beacons are missed (not picked up by the receiver), the nodes’ internal time schedulers will continue to run accurately from a watch crystal oscillator and data will continue to be transmitted at the expected times. Figure 5 (Right) shows the “perfect” synchronization between the four wireless sensors during a shaker sine vibration test. A time-division multiple-access (TDMA) principle is used to share the radio channel between the different nodes. Between the beacons, each node is assigned a timeslot during which it will transmit a packet of sample data. Meanwhile, the sampling process runs continuously in the background. A possible extension to frequency-division multi-access (FDMA) could be used in order to provide more channels. The receiver module dictates the master clock for the whole network by sending out the periodic beacons described above. Besides their timing purpose, these beacons are also used to upload commands or parameters, either addressed to a specific sensor node or broadcast to the entire network. The receiver outputs the received data over a USB communication interface to the PC.
3 PHYSICAL PROTOTYPE TESTING

3.1 WSN validation on a bridge scale model

A scale model of a bridge was used as an object to validate the developed WSN; see also [16]. The bridge model is located in the Active Structures Laboratory at the Université Libre de Bruxelles (ULB); see [17] for more details. This cable-stayed bridge (Figure 6) can be divided in different elements: the supporting pillar (made of steel), the bridge deck, the eight stay cables (made of steel) and the slab (made of concrete), supporting the pillar. Some masses were added in the deck of the bridge to shift the resonance frequency to a real bridge range.

Vibration-based Structural Health Monitoring consists of tracking the evolution of the modal parameters of the structure over time. Usually ambient sources like wind and traffic are exciting the bridge, but in lab conditions, shaker excitation is used. In order to perform this test, the bridge is equipped with two different kinds of excitations (Figure 7):

- A shaker at the base of the bridge to simulate earthquake excitation.
- Four APA 100M cable shakers in each corner of the bridge deck, that can be used to excite the bridge deck though originally they were used for active control of each cable.
In order to measure the modes and resonant frequencies of the bridge, a four wireless sensor network was used. Two sensors were placed in each end of the bridge to measure the vibrations on the four corners of the deck (Figure 6 – Right). In order to control the proper operation of the wireless sensors, four classical wired sensors were placed close to them to compare the measured data. At the same time, more classical sensors were placed along the deck and in the tower to scan the bridge structure more in detail. In the bridge test, band-limited (2 – 30 Hz) random noise was used. In Figure 8 (Left) it is possible to see how the wireless time domain data acquired match very well with the classical wired sensor data. In Figure 8 (Right) the averaged power spectra of the bridge accelerations are represented. Better than the time-domain representation of the signals, these frequency-domain functions are able to highlight small differences between the wired and wireless sensors. The main difference comes from a clearly visible noise floor in the wireless data. Further investigation revealed that this noise floor can be completely attributed to the sensing element (MEMS accelerometer). When the signal exceeds the noise floor, however, both signals match very well.

Figure 8: Time series (Left) and averaged power spectrum (Right) comparison between wireless (green) and wired (red) sensors.

Figure 9 represents the FRFs and coherences measured using both systems. Again, in frequency ranges where the excitation level is such that the bridge response exceeds the MEMS noise floor, both systems agree very well. For illustration purposes, Figure 10 shows experimentally determined mode shapes of the bridge scale model using the more complete wired sensor data. However, similar results could be expected using purely wireless data, since modal parameters are obtained by curve-fitting FRFs.
The results prove that, in spite of the current performance limitations of commercially available MEMS accelerometers – when compared with state of the art analog sensors – accurate Experimental Modal Analysis can be carried out.

![Graph](image1.png)

**Figure 9:** Comparison between FRF of the system with a wireless sensor (green) and wired sensor (red) with the base shaker. Also the coherences (blue and pink) are shown.

![Graph](image2.png)

**Figure 10:** Bridge mode shapes estimated from the FRFs.

3.2 Ground Vibration Testing using the WSN.

A Ground Vibration Test (GVT) was performed on a laboratory scale model of an aircraft. To define a set-up, fourteen classical wired sensors were place along the wings of the aircraft and 4 wireless sensors were placed on the sides of the wings (positions 1, 7, 8, 14); see set-up in Figure 11. At the same time, two shakers provide random noise excitation to the plane from 0 to 200 Hz. In this validation case, the importance of synchronisation between wireless and classical wired data will be highlighted. The force signals and the “wired” accelerations were acquired using a classical data acquisition system [2][3]. The WSN discussed in Section 2 was also used to measure the accelerations at 4 locations close to a classical sensor. In order to compute the Frequency Response Functions (FRFs), the “wireless” accelerations need to be referenced to the “wired” force signals. The difficulty was that they were acquired using 2 different unsynchronised acquisition systems. In order to synchronise them, the cross-correlation between a wireless acceleration signal and the wired acceleration signal from the nearby sensor was calculated. The time lag at maximum correlation value determines the time shift between both acceleration signals. Figure 12 compares both signals after time-shifting.

The same time shift was applied to align the wired force signal with the wireless acceleration signal, but when the FRF is processed, the result looks very noisy above 50 Hz, although the “wired” FRF is of high quality till above 200 Hz (Figure 13). This is due to a slight difference in the sampling clocks. Every system has it is own main clock, and due to the tolerances – 50 parts per million (ppm) on the wireless receiver (Figure 2) and 5 ppm on the Scadas [2] – a sampling frequency of 512 Hz on the Scadas may correspond to a sampling frequency of 512.025 Hz on the wireless receiver. Although this difference seems to be very small, the effect on the FRF quality is dramatic. Therefore, the wireless time series was resampled to the Scadas clock and a new FRF computed (Figure 14), which is now very close to the wired FRF. As a conclusion it can be stated that the wireless sensors are able to generate high-quality FRFs in the whole available bandwidth.
Figure 11: GVT of an aircraft scale model. Classical wired and wireless sensor locations.

Figure 12: Time series comparison between wireless and nearby wired accelerometer after time-shifting.

Figure 13: Comparison between “wired” FRF (blue) and “wireless” FRF (green) after time-shifting.
4 CONCLUSIONS

The developed Wireless Sensor Network for physical prototype testing combines measurement precision, low power consumption, wireless communication and low cost equipment. This paper discussed the building blocks of the WSN and included some experimental validation studies using real-life laboratory set-ups. In these validation studies, the performance of the WSN was compared with a classical wired measurement chain. It can be concluded that accurate modal testing can be carried out with wireless technology and MEMS sensors. It is however evident that currently available WSN and MEMS technology do not yet have the same specifications as piezo-electric sensors combined with a modern digital front-end concerning noise floor, number of channels, sampling frequency, measurement distance. Wireless sensors may become successful when they are designed to meet the requirements of a specific measurement application, such as for instance Ride & Handling, rather than trying to develop a very general system.

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