Wireless Sensor Networks in Structural Health Monitoring: a Modular Approach

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***Abstract*—In this paper, we present the Modular Monitoring System (MMS), a low-power wireless architecture dedicated to Structural Health Monitoring (SHM) applications. Our solution features an easily customizable modular architecture, fulfilling the needs of many SHM applications. The MMS supports mesh network topology and offers excellent coverage and reliability, taking advantage of Wireless Sensor Networks (WSN) technology. In this preliminary work we show how the flexibility of our approach offers great advantages with respect to the current state-of-the-art systems dedicated to SHM.**

Keywords–Wireless Sensor Networks; Structural Health Monitoring; Modular Architecture; Wireless; Low-Power.

I. Introduction

Detecting damages to which civil and industrial structures, such as roads, bridges, canals, buildings and aerospace vehicles are subjected, is referred as SHM. It can prevent collapses and breaks, avoiding permanent damages to structures, thus simplifying their maintenance. Depending on application scenarios, SHM requires many different types of sensors, including pressure sensors, vibrating-wire strain gauges, inclinometers, crackmeters, etc. Most monitoring systems dedicated to SHM are wired but, deploying a wired system in a wide area or in a harsh environment, can pose both economical and practical limitations. For such reasons, WSNs were proposed as network infrastructure to support SHM, avoiding prohibitive costs of wired systems and easing the on-field deployment. Nowadays, SHM supported by WSN is an active and well-established research field and some wireless SHM systems are now entering the market. The preliminary work made in this paper introduces the MMS, a wireless, low-power, scalable architecture dedicated to SHM. The main strength point of MMS is its high modularity that allows easy customization of the platform depending on the number and the type of sensors required by the specific application scenario. In addition, MMS fully supports multi-hop wireless communication paradigm and mesh networks. The remainder of this paper is organized as follows: Section II is dedicated to both wired and wireless SHM state-of-the-art systems, in Section III we explain motivations supporting design choices made during the development of the MMS, while in Section IV we introduce the features characterizing our system from an high-level perspective. In Section V, we present the hardware prototype and the achieved results. Finally, in Section VI, we give conclusions and directions for the future.

II. State of the Art

Nowadays, most SHM systems available on the market, such as the Geomonitor by Solexperts [1], are wired. However, deploying those systems can be cumbersome: besides the installation costs, a detailed deployment plan is required to face evolving needs of different construction phases. Moreover, cables are subjected to accidental cuts and damages and, in some scenarios, their installation is unfeasible or inappropriate (e.g., historical buildings). Along with wired systems, some standalone data loggers dedicated to SHM are commercially available, among the others: Solexperts SDL [1], Geokon 8002-16-1 [2] and Keller GSM-2 [3]. Those systems are simpler to install, but they do not allow real-time remote monitoring and require frequent in-situ access by qualified personnel to collect data.

The introduction of wireless communications in SHM gives immediate advantages in terms of easier deployments and reduced maintenance and personnel costs. However, when monitoring devices are battery-powered, the employment of wireless communications is among the most energy demanding feature that can significantly limit the devices lifetime. Prominent examples of wireless monitoring systems are: National Instruments Wireless Data Acquisition (WiFi-DAQ) [4] and MicroStrain's wireless sensor network [5]. While the former supports IEEE 802.11 standard, the latter is compliant with IEEE 802.15.4. Both products adopt a conservative approach by limiting wireless communication to 1-hop. Supporting multi-hop wireless communications was investigated in several research papers in the last decade [6][7][8]. Multi-hop networking provides a number of advantages: scalability (larger areas can be covered), reliability (failure and multiple routing paths without single point of failure) and ease of deployments (the presence of multi-hop relay nodes allows to bypass obstacles like walls and metal structures). Recently, National Instruments presented the NI WSN [9]: a multi-hop battery-powered WSN supporting up to 36 nodes configured in a mesh network and up to 3 years node lifetime.

III. Motivations

As seen in the previous section, WSNs are slowly entering the market of SHM applications. An attempt to develop a robust solution and to test it in realistic application scenarios was made in the GENESI Project [10]. The main goal of this project was to design and implement a "novel generation of green wireless sensor networks which can be embedded in buildings and infrastructures at the time of construction and be able to provide a monitoring and control intelligence over the whole structure lifetime". The project involved the monitoring of a bridge construction site in Fribourg [11] and the construction of a tunnel for the B1 underground line in Rome [12], by means of WSNs. The outcomes highlighted the advantages of WSN technology described in Section II compared to old monitoring techniques. According to the application requirements provided by the SHM experts, GENESI nodes can support a number of heterogeneous sensors.

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However, a GENESI node can manage only a single sensor per type, while there are some applications in which multiple instances of the same sensor are needed. As an example, in a 3-axis deformation analysis, a single wireless node may need to interface with three instances of a vibrating-wire strain gauge while to monitor a concrete junction the node may need to interface a current-loop inclinometer sensor and a resistive displacement sensor. Other commercial solutions, such as the NI WSN described in Section II, can handle multiple instances of the same sensor but can not support different sensor families simultaneously. In general, we observed that developing a hardware platform flexible enough to handle a high number of sensor combinations required by SHM applications is not practical both in terms of size and costs. In the specific, such solution would require additional hardware and connectors that could remain unused during deployments. This brought us to propose a novel low-power slotted modular system made by a set of modules connected through an internal communication bus. This solution features one wireless-capable master module managing a group of extension modules, each one designed to interface a specific sensor setup. The flexibility of the proposed architecture, named MMS, allows to support a vast number of SHM applications by simply plugging into each node the required extension modules. Another important advantage given by MMS is the possibility to easily swap between wireless technologies by replacing the master module. This characteristic allows to preserve the required level of wireless performance in both indoor and outdoor scenarios, further increasing the flexibility of our system.

IV. System Architecture

The MMS architecture is based on a master/slave communication abstraction: a *master module*, provided with radio capability and responsible for most of computational tasks, communicates through a *low-power shared bus* with a maximum of four *extension modules* (slaves). All modules are interconnected through a backplane following Figure 1.

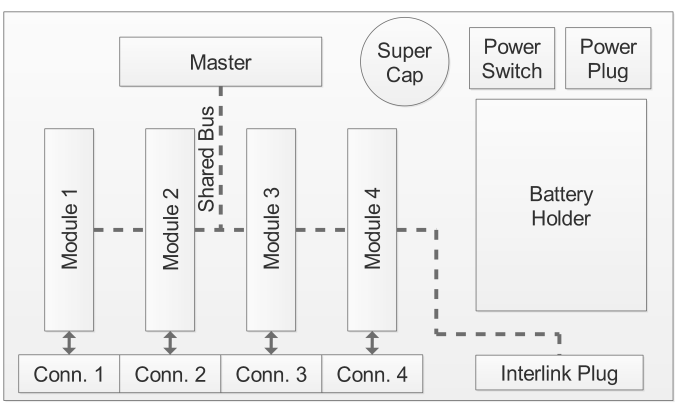

Figure 1. Modular Architecture

The backplane also offers 12 external pins per module to attach external sensors and a battery plug for different kind of power supplies.

A. Low-Power Shared Bus

The low-power shared bus was designed to optimize the energy consumption of the whole system. For this reason, it uses a communication principle based on Serial Peripheral Interface (SPI) with dedicated chip-selects, interrupts and power lines for each extension module. This enables the master to communicate in an exclusive way with each module, without spurious wake-up of slave modules not involved in the communication (as opposed to other shared bus communication interfaces, i.e., the Two-Wire Interface). The drawback of this approach is a high number of additional lines required, with a subsequent limited number of supported extension modules. Please refer to Section IV-D for a solution to this known limitation.

B. Master Module

The master module is responsible for keeping wireless connectivity with the WSN and manages extension modules. When switched on, the master performs a discovery routine on the low-power shared bus to detect extension modules and their slot locations. For each discovered module, the master retrieves its configuration information and computes the sensing schedule. The master can also update the configuration depending on the user needs. When asking for sensor data, the master has different ways to interact with the extension modules based on power requirements, scheduling and module type. The typical interaction protocol of the master module follows the steps:

1) *Optional:* It enables the power line of the extension module
2) It pulls down the corresponding chip-select line
3) It sends a *Data Request* command with all the required information
4) *Optional:* It pulls up the chip-select line and perform other tasks or goes to sleep
5) It waits for an interrupt from the module
6) *Optional:* It pulls down the chip select line
7) It sends a *Data Read* command and retrieves the response
8) It pulls up the chip select line
9) *Optional:* It disables the power line of the corresponding module

C. Extension Modules

The extension modules provide the hardware interface to external sensors. Each module communicates over the low-power shared bus with the master by means of an SPI-capable microcontroller. They also feature an interrupt pin for chip-select detection and a general-purpose I/O pin to signal the interrupt to the master. In addition, a power pin allows the master to power-down the whole extension module. This power line gives to the system the maximum flexibility in terms of energy management: the module can be switched off or simply kept in a sleep state by the master. This choice varies according to the sampling period, the start-up time and the sleep power consumption of the extension module. The hardware interface provided by each module depends on sensors it supports: it can be fully digital, e.g., to interface RS-232 or RS-485 peripherals, or analog, to connect sensors such as current-loop, vibrating wire strain gauges, resistive etc. Each extension module can support different kinds of sensor or several sensors of the same type.

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D. Additional Features

Interlink Bus: As pointed out in Section IV the low-power shared bus cannot interface more than four extension modules, which in some rare cases might represent a limitation. To overcome this issue, we introduced the interlink bus which enables the MMS to support a virtually unlimited number of extension modules. In the specific, it connects the master modules of different MMS creating a tree structure where the parent MMS acts as master for its children.

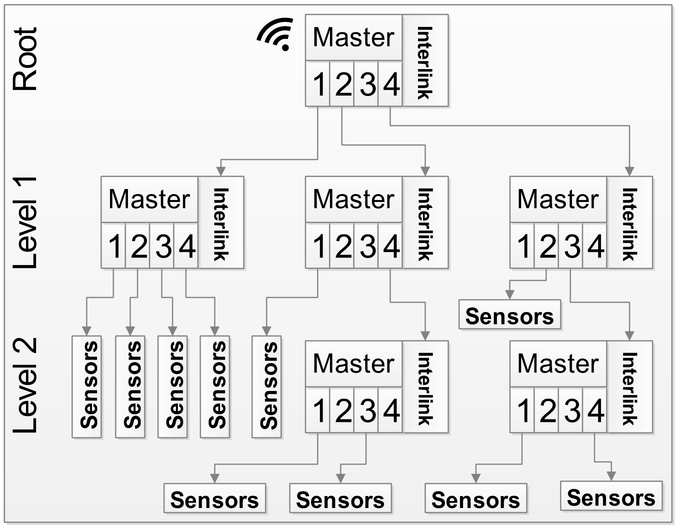

Figure 2. Interlink connections

To do so, the parent MMS uses the extension slots to make a connection through the interlink plugs of its children (see Figure 2). Hence, the parent sees its children as enhanced extension modules. This mechanism can be replicated at each level of the tree to support an unlimited number of sensors. Each leaf node advertises the connected sensors together with its identification number to its parent which aggregates the received information and forwards it to the upper level. This procedure is iterated until the root MMS is reached. The root MMS is the only one which manages wireless communications. From a WSN perspective, this makes the whole tree resulting as a single wireless node.

Extension Module Configuration Advertisement: Thanks to the discovery procedure performed by the master during the boot phase, extension modules attached to the backplane exchange configuration information. Hence, an operator can add an extension module at any time by just power-cycling the MMS, without the need of an in-situ reprogramming. This feature eases the effort required by operators and qualified personnel. Based on our on-field experience, this functionality is often required in evolving environments, such as (but not limited to) SHM scenarios.

V. Preliminary Work

A. Prototype development

We developed and assembled the first prototype of the MMS at the Department of Computer, Control and Management Engineering of the University of Rome ”La Sapienza”. The prototype includes a master module, a Resistance Temperature Detector (RTD) extension module and a backplane. The modules are plugged into the backplane by a standard Peripheral Component Interconnect Express (PCIe) edge connector.

The master module is responsible for radio communication and for managing the extension modules. It is based on the MagoNode OEM [13], a wireless hardware platform specifically designed for WSN applications. The MagoNode is based on the Atmel Atmega128RFA1 (RFA1) System-On-Chip micro-controller equipped with 128KB of ROM (Read Only Memory), 16KB of RAM (Random Access Memory) and an embedded 2.4Ghz radio transceiver fully compliant with the 802.15.4 standard. The radio range is extended through a power efficient RF (Radio Frequency) front-end which enhances radio performance while keeping the power consumption low. The main figure in terms of power consumption are: radio transmission 27.7mA @+10dBm, radio reception 14.5mA and $<2\mu$A in sleep. The master module is equipped with a NOR flash for persistent data storage, three status leds, a micro-usb plug and an RP-SMA (Reverse Polarity SubMiniature version A) antenna connector.

The RTD module is the first extension module developed for the MMS node. It is a hardware interface made for reading up to four PT-100 or PT-1000 RTD temperature sensors. Two accurate 24-bit ADCs (Analog-to-Digital converter), together with a finely tuned filtering circuit, provides sensor readings in 50ms with a maximum error of $\pm$0,1°C. An Atmel 8-bit AVR micro-controller manages the communication with the two ADCs and with the master module over the low-power shared bus. The power consumption is 2μA in sleep and less than 500nA when powered off.

The backplane hosts the low-power shared bus that connects the master and up to four extension modules through PCIe connectors (see Figure 3). It provides the interlink bus header (see Section IV-D) and 12 pins per extension modules to plug external sensors. The backplane also supplies the system through different battery types. It supports battery holders for 2xAA, 1xC or 1xD thionyl chloride batteries (3.6V) and an external power supply for other power sources (3 to 5.5V).

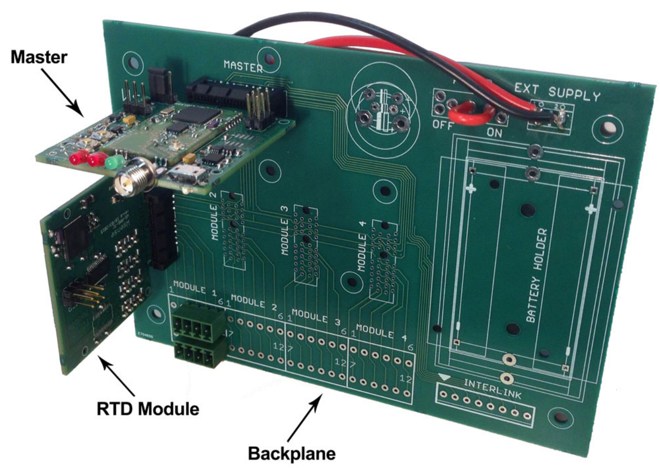

Figure 3. The MMS: master, RTD module, backplane

We developed drivers and firmware for the MMS in compliance with TinyOS [14], an event-driven, open-source operating system (OS) dedicated to Wireless Sensor Networks. TinyOS is designed to cope with typical constraints imposed by WSNs hardware: low computational capabilities, limited memories and scarce energy resources.

B. Test Results

During our preliminary tests, we evaluated the MMS energy consumption while performing different activities. The MMS hardware configuration used during tests consisted of a master module interconnected through a backplane to an RTD module, which acquires samples from a temperature probe simulated by a 100 Ohm resistor. In order to measure current consumption, the device was powered by a 3.6V external supply and connected to a Rigol DM3068 digital multimeter sampling at a 10KHz rate. The prototype was programmed to wake-up from sleep state, perform a sensor reading (involving ADC initialization, data conversion and retrieval), send acquired data over the wireless medium and go back to sleep. Figure 4 shows the current measurements of the previously cited activities while in Table I significant current values corresponding to different MMS states are summarized.

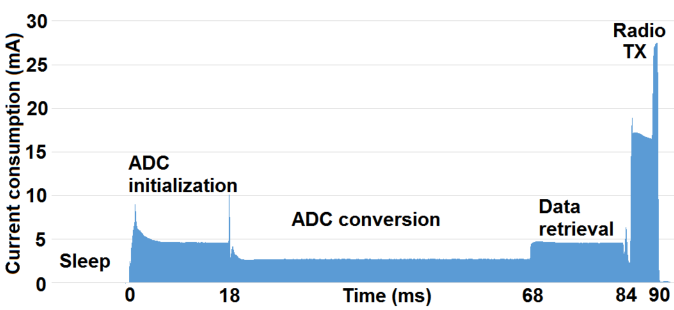

Figure 4. MMS Current Consumption

As expected, Table I shows how the low consumption in sleep state of both master and RTD modules allows the MMS to draw a negligible amount of current (4.5μA). Such a low value would allow the system to last in this state for more than most batteries self-discharge time. The MMS sleep current can be further reduced by allowing the Master to power off the RTD module. This feature, which is irrelevant in this case, becomes important whenever there is the need to deal with extension modules with a high sleep current consumption.

TABLE I. MMS CURRENT CONSUMPTION

State	*Description*	*Current (mA)*
Sleep	Baseline consumption	0.0045
Radio TX	Master radio transmitting	27.7
Radio LISTEN	Master radio idle listening	14.4
Radio RX	Master radio receiving	16.9
Data acquisition	RTD module ADC conversion	2.8

The radio power consumption of the MMS are strictly related to the MagoNode platform, this is why the same values measured in [13] are reported in Table I. Finally, the ADC of the RTD module performs a single conversion in 50ms by generating two 1mA bias current over the RTD sensor that, summed with the 800μA power consumption of the chip, gives an overall consumption of 2.8mA.

VI. CONCLUSION AND FUTURE WORK

In this work, we presented a novel low-power wireless modular architecture designed for SHM applications. Our platform, the MMS, takes advantage of a low-power shared bus connecting slotted extension modules that interact with a master in a master/slave communication abstraction. The extension modules, which can be combined as needed, allows the MMS to face the continuously evolving needs of most SHM scenarios. Thanks to its peculiar characteristics, the MMS overcomes commercial state-of-the-art WSN solutions for SHM, like the NI WSN, which do not offer enough flexibility to fulfill requirements of many application contexts in a both cost-effective and efficient way.

The preliminary work done toward the implementation of this novel architecture consists of the design and the assembly of a master module, a first RTD extension module and a interconnection backplane. The master module, based on the MagoNode platform, makes the MMS a powerful wireless node fully supporting multi-hop communications. The RTD module gives low-power readings from up to 4 PT100 or PT1000 temperature probes with a precision of $\pm$0,1°C. In the near future, we plan the develop several additional extension modules able to support all kinds of sensors dedicated to SHM, such as strain wire gauges, crack meters, inclinometers, displacement sensors, etc. Furthermore, additional Master modules will be designed to support different wireless frequencies (e.g., 433Mhz, 868Mhz, 915Mhz) and certified industrial wireless protocols like Wireless Hart.

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