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Gael Loubet, Ethan Gardner, Alexandru Takacs, Andrea de Luca, Florin
Udrea, Daniela Dragomirescu

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COVER SHEET

Title:

Wirelessly Powered and Battery-Free LoRaWAN Wireless Sensing Nodes Designed for Communicating Reinforced Concrete

Authors:

Gaël LOUBET

Ethan GARDNER

Alexandru TAKACS

Andrea DE LUCA

Florin UDREA

Daniela DRAGOMIRESCU

ABSTRACT

A Wireless Sensor Network dedicated to Structural Health Monitoring applications in harsh environments, which is the basis for the design of a communicating reinforced concrete, is presented. An autonomous wirelessly powered and battery-free LoRaWAN Sensing Node is highlighted here. The presented system measures temperature and humidity from its environment and transmits the recovered data to a Communicating Node, which interconnects the physical and digital worlds whilst simultaneously powering the Sensing Nodes *via* a far-field Wireless Power Transmission interface.

INTRODUCTION

To implement Cyber-Physical Systems (CPS) responding to the needs of Structural Health Monitoring (SHM) applications, e.g. for buildings and civil infrastructures, Internet of Thing (IoT) technologies can be used [1,2]. In parallel, the concept of ‘communicating material’ has emerged [3]. It is a material able intrinsically to collect, process, store and share data from itself with digital systems and other elements made of ‘communicating materials’. The McBIM (Material communicating with the Building Information Modeling) project targets to develop a communicating reinforced concrete to offer new solutions in the construction domain (e.g. for SHM) [4].

A successful implementation of a Sensing Nodes (SN) network designed with the final objective of being embedded in reinforced concrete elements to provide a communicating reinforced concrete is provided. The SNs are battery-free and wirelessly powered through a far-field Wireless Power Transmission (WPT) system. They can measure the temperature and relative humidity of their environment and communicate the collected data by a wireless unidirectional transmission based on LoRa technology and LoRaWAN protocol. The SN prototypes were characterized in various configurations and it has been proved that the periodicity of measurement and data transmission (uplink) can be controlled wirelessly by the WPT (downlink).

Gaël LOUBET, Alexandru TAKACS, Daniela DRAGOMIRESCU; LAAS-CNRS, Université de Toulouse, CNRS, UPS, INSA; 7, Avenue du Colonel Roche, 31400 Toulouse, France.
Ethan GARDNER, Andrea DE LUCA, Florin UDREA; Department of Engineering, University of Cambridge; 9 JJ Thomson Avenue, Cambridge CB3 0FA, United Kingdom.

This paper introduces our first contribution in the McBIM project. It presents the proposed architectures of the mesh Wireless Sensor Network (WSN) and the designs of the Communicating Nodes (CN) and of the Sensing Nodes, which must be the hardware elements allowing the implementation of a communicating reinforced concrete. Next, the implementation and functionalities of the wirelessly powered and battery-free LoRaWAN Sensing Node are discussed. Finally, similar state-of-the-art research is highlighted and compared, as well as the limitations and future works on the prototype, namely the integration of a low-power, low-cost temperature sensor developed at the University of Cambridge and experiments to perform in the targeted material.

WIRELESS SENSOR NETWORK DESIGNED IN THE VIEW OF THE COMMUNICATING REINFORCED CONCRETE IMPLEMENTATION

Objectives and Positioning in the McBIM Project

Within the scope of the McBIM project -funded by the French National Research Agency (ANR), composed of three French laboratories (CRAN, LAAS and LEI) and a company (FINAO SAS / 360SmartConnect)- communicating reinforced concrete must be implemented [4]. This one must be able to generate, process, store and exchange data with other structural elements whilst also relaying with Building Information Modeling (BIM) to keep updated [5]. This CPS must be used in the manufacturing, construction and exploitation phases of civil infrastructures for, among others, SHM applications.

This contribution concerns the hardware implementation of the communicating reinforced concrete, in other words the hardware and low-level software needed to make and use the communicating reinforced concrete, on which high-level and application software must be developed.

Proposed Architecture of the Mesh Wireless Sensor Network

To implement the communicating reinforced concrete an embedded mesh WSN is proposed [6]. This WSN illustrated in Fig. 1 is composed of Sensing Nodes and Communicating Nodes. Each communicating reinforced concrete element hosts one or more CNs on its surface and several SNs located inside. Their number must be a function of the needs of the different end-user applications. Each SN communicates its collected data to its neighbor CN(s) through a unidirectional star network topology. The CNs wirelessly power the near SNs and exchange and store their data within a mesh network. One or more reprogrammable interfaces between this mesh network and the Internet are available and allow the communication with the BIM.

Design of the Communicating Node

The Communicating Nodes presented in Fig. 2 B) must receive from SNs, process and exchange wirelessly data with other CNs and also with the BIM through the Internet whilst storing the relevant data. In addition, they must power smartly and wirelessly the associated SNs to allow them to be completely autonomous. They are accessible and can be powered by conventional energy sources due to their availability in each stage of the life cycle of the monitored structure (e.g. mains supply, batteries, etc.).

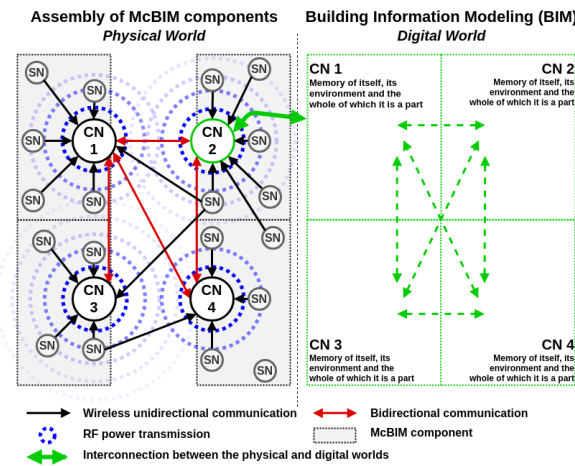


Figure 1. Suggested architecture of the McBIM Cyber-Physical System.

Design of the Sensing Node

The Sensing Nodes presented in Fig. 2 A) must measure relevant information from the monitored structure (e.g. temperature, humidity, mechanical stress, corrosion, etc.) and then process and transmit the collected data to the CNs. Once installed, they become inaccessible and must therefore operate reliably for the entire life of the monitored concrete structure, i.e. for decades. To meet these requirements, the SNs must be simple, battery-free, wirelessly powered and must wirelessly communicate with the CNs.

PROTOTYPE OF THE SENSING NODES

Implementation of the Sensing Nodes

Due to their inaccessibility and long operation requirements, the SN must be low power, reliable, maintenance-free, as simple as possible (e.g. store no data), battery-free and wirelessly powered. According to the architecture highlighted in Fig. 2 A), SNs have been implemented [6], as shown in Fig. 3 A). These prototypes are composed of:

(i) a temperature and humidity sensor (Adafruit DHT22) to quantify these values in the monitored structure. Each is coded on 2 bytes with a resolution of 0.1 °C and 0.1 %.

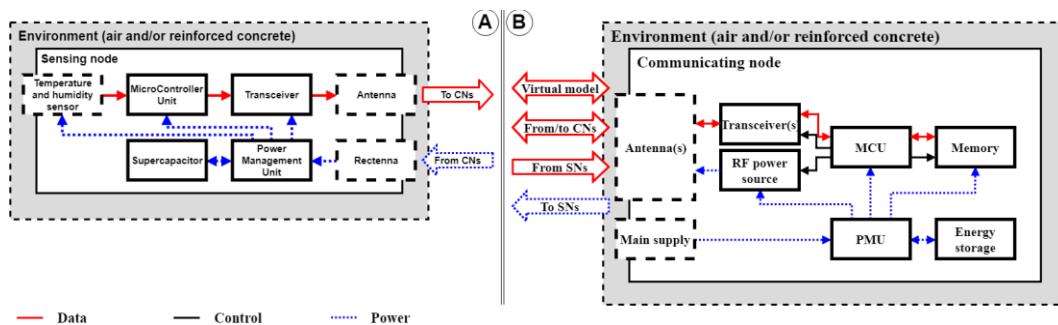


Figure 2. Schematic diagrams of: A) the battery-free and wirelessly powered wireless Sensing Node; B) the suggested Communicating Node.

(ii) a MicroController Unit (MCU) (STMicroelectronics STM32L072CZ) to collect and process the measured data, to drive the other active components and to manage the LoRaWAN protocol stack and the application software.

(iii) a LoRa transceiver with an antenna (Semtech SX1276) to operate a long-range unidirectional wireless LoRa communication with the CN connected to the digital world through the Internet. It works in the ISM 868 MHz band.

(iv) a rectenna [7] (rectifying antenna) to scavenge the far-field power density generated by a dedicated radiofrequency (RF) source and convert it in a DC signal. This rectenna is tuned to work in the ISM 868 MHz band.

(v) a Power Management Unit (PMU) (Texas Instruments bq25504) to harvest the DC power provided by the rectenna, to store it efficiently in a storage element and to supply the active components each time enough stored energy is available.

(vi) a 22 mF (C) supercapacitor (AVX BZ01CA223ZSB) to store the scavenged energy with low losses (10 μ A). The energy (E in J) it can store can be estimated as:

$$E = C \cdot (V_{\max}^2 - V_{\min}^2) / 2 \quad (1)$$

where V_{\max} (5.25 V) and V_{\min} (2.30 V) are the selected thresholds which limit the charges and discharges of the supercapacitor. By using (1), E is estimated to 245 mJ.

The MCU and LoRa transceiver are implemented in an all-in-one module Murata CMWX1ZZABZ-091 used in the board STMicroelectronics B-L072Z-LRWAN1.

Experimental Results

OPERATION OF THE SENSING NODES

The SNs harvest energy until they have collected a sufficient amount and then supply all the active components. At each iteration -supercapacitor discharges-, the software initializes the MCU, the sensor and the LoRa transceiver. Then a temperature and humidity measurement is performed and the collected data are transmitted in a 17-bytes LoRaWAN data frame. The SNs are deactivated and powered-off until enough energy is scavenged again -supercapacitor charges-. This treatment lasts about 2.13 s (830 ms to the initialization and measurement and 1.30 s to the transmission of a frame). The system needs 214 mJ to work properly, where 64 mJ are needed for the sensor.

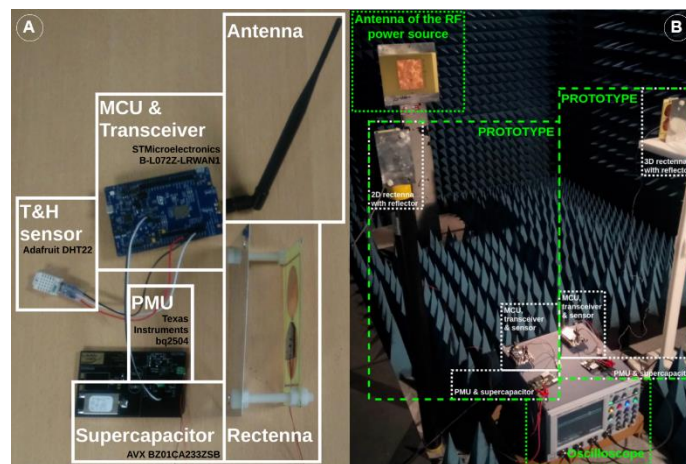


Figure 3. Photographs of: A) the Sensing Node prototype; B) the experimental setup for a network of two prototypes powered by using a far-field RF Wireless Power Transmission system in an anechoic chamber.

EXPERIMENTATIONS AND RESULTS

Three types of experiments were conducted to characterize the SN prototypes [6]: (i) with a well-defined RF input power feeding the rectifier (not a WPT system) and in an anechoic chamber with the WPT system (ii) for a prototype and (iii) a network of two prototypes as presented in Fig. 3 B). The evolution of the measurement and communication periodicity and the output voltage of the rectifier as function of the RF power at the input of the rectifier are plotted in Fig. 4 as summary of the obtained results.

As the CNs are not yet designed, a LoRa gateway is used to collect the data transmitted by the SNs and to route them *via* the TheThingsNetwork network up to servers, where they can be recovered and processed; as well; a RF power source (RF power synthesiser Anritsu MG3694B and a patch antenna operating at 868 MHz) is used to illuminate the SNs with a well-defined power density to power them.

From the experiments with a controlled RF power at the input of the rectifier, the following features have been obtained: (i) the cold-start procedure (350 mV and 15 μ W required) can be achieved from an input of -10 dBm, (ii) the time needed to the cold-start procedure can be controlled between 17 min 51 s (for an input of +0 dBm) and 3 h 33 min (-8 dBm), (iii) the time needed to the first charge can be controlled between 29 min 04 s (+0 dBm) and 5 h 16 min (-8 dBm); and (iv) the periodicity of measurement and communication can be controlled between 1 min 24 s (+10 dBm) and 4 h (-10 dBm).

For the prototype characterization with the WPT system in an anechoic chamber, the SN was located in the far-field region of the RF power source (150 cm). The RF power density illuminating the rectenna (S in W/m^2) is computed as:

$$S = P_T / (4 \cdot \pi \cdot d^2) \quad (2)$$

P_T is the power generated by the RF source and d the distance between the power source and the rectenna. The power collected by the rectenna (P_{RF} in W) is computed as:

$$P_{RF} = G_R \cdot S \cdot \lambda^2 / (4 \cdot \pi) \quad (3)$$

G_R is the gain of the antenna of the rectenna and λ the wavelength. According to these experiments, the periodicity of measurement and communication can be tuned by the power density illuminating the rectenna between 5 min 41 s (4.16 μ W/cm² of power density, +2.56 dBm estimated at the input of the rectifier) and 1 h 43 min (0.52 μ W/cm², -6.43 dBm). Despite the consistency, the differences with the previous results are mainly

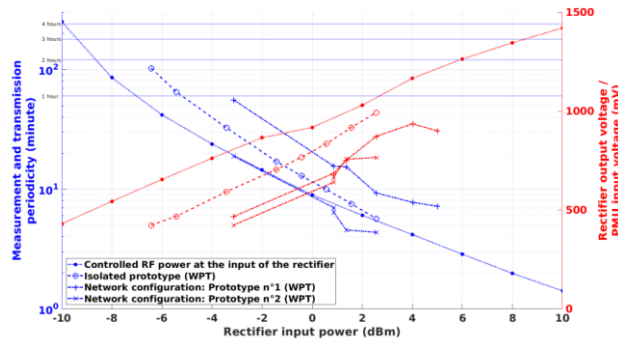


Figure 4. Measurement and communication periodicity (blue) and rectifier output voltage (red) as function of the rectifier RF input power: for the SN prototype supplied by a controlled RF power at the input of the rectifier (\bullet , continuous line); by a controlled power density illuminating the rectenna in an anechoic chamber (\circ , dashed line) and for the network of two SN prototypes in diverse configurations in a 60° angular area over several meters (dotted and dashed lines - Prototype 1: + and Prototype 2: x).

due to the errors in the computation of the RF power densities and the RF powers at the input of the rectifier as well as errors during experimentations and measurements.

By deploying the network of two SNs, consistent results were provided again. Some various configurations were studied: (i) the two SNs were tested alone in the same configuration, (ii) the two SNs were illuminated with the same power density and (iii) the two SNs were illuminated with different power densities. The differences with the previous results are mainly due to the errors in the computation of the RF power densities and the RF powers at the input of the rectifier as well as the diversity in the components and the multipath effects and coupling interferences between the SNs.

IMPLEMENTED FUNCTIONALITIES

A simple battery-free and wirelessly powered (by a far-field WPT system) LoRaWAN wireless Sensing Node were developed and tested. By tuning the generated power density, the CNs can power wirelessly and manage the periodicity of measurement and communication of multiple SNs located in their neighborhood for periods between minutes and hours (for input powers currently higher than -10 dBm or power densities higher than $0.52 \mu\text{W}/\text{cm}^2$). Today, it is the regulations and not the technology that limits the capabilities of the far-field WPT system: the maximum Effective Isotropic Radiated Power (EIRP) that can be radiated in the ISM 868 MHz band is limited at +33 dBm or 2 W [8]. By following (2) and (3) a $0.5 \mu\text{W}/\text{cm}^2$ power density can be generated at nearly 550 cm away from a source. As communication and WPT bands are the same (ISM 868 MHz), antennas operating with orthogonal polarizations are used to discriminate these two uses.

DISCUSSIONS

Battery-Free Sensing Nodes dedicated to Structural Health Monitoring

Some implementations of battery-free LoRaWAN Sensing Nodes have been developed in past years. They used ambient energy harvesting (e.g. solar [9], mechanical [10], etc.) or backscattering [11] techniques. Nevertheless, until [6] no implementation of the WPT approach was proposed to the authors' best knowledge, although its feasibility has been demonstrated theoretically in [12]. Using WPT avoids the dependency of ambient energy sources, which fluctuate continuously, and allows the control of the power transmitted to the SNs and thus their measurement and communication periodicity. The far-field WPT approach allows an increase of the distance of use compared to the near-field WPT solution proposed for instance in [13]. Other projects of wirelessly powered Sensing Nodes are based on far-field WPT as [14,15] which use Bluetooth technology for the wireless communication.

Current Limitations and Perspectives

The current prototypes present some limitations, they: (i) are composed of bulky independent blocks, (ii) use a power intensive temperature and humidity sensor, (iii) can measure only temperature and humidity, (iv) use LoRaWAN protocol and LoRa technology which require high power and are long range, (iv) need a specific power

source generating a power density higher than $0.52 \mu\text{W}/\text{cm}^2$ to work whilst only $1.69 \text{ pW}/\text{cm}^2$ is available in buildings in the ISM 2.45 GHz band and $57.37 \text{ nW}/\text{cm}^2$ in the GSM 900 MHz band according to [16] and (v) are only tested and validated in the air and not in the target medium that is more constraining for RF propagation.

Thus, the next improvements consist of: (i) the integration, miniaturization and optimization of the SNs, (ii) the use of various low-power sensors (e.g. temperature, humidity, corrosion or mechanical stress), (iii) the test of other communication technologies as BLE or RFID for middle- and short-ranges, (iv) the development of the CNs and (v) the experimentation in real harsh environments with the SNs embedded in reinforced concrete. As presented in Fig. 5, a reinforced concrete beam has been manufactured to test the WPT and wireless transmission of the SNs once embedded.

Regarding the temperature and humidity sensor choice, it is pertinent to optimize its power consumption. Currently, 64 mJ, i.e. 30 % of the used energy, is consumed by the Adafruit DHT22 sensor. This can be replaced with ultra-low power temperature and humidity sensor, e.g. the Texas Instruments HDC2010 which can measure in isolation these parameters with higher accuracies, less time and the same ranges. The estimated reduction factor of the power consumption is around 100. In addition to this an in-house developed CMOS-MEMS thermodiode can be another solution to sense temperature owing to its ultra-low power, ultra-wide range, long-term stability and linearity [17].

CONCLUSION

Several prototypes have been implemented as a proof-of-concept of wirelessly powered battery-free wireless Sensing Nodes for SHM application. The energy autonomy is available through a far-field Wireless Power Transmission, which can be tuned to control the periodicity of temperature and relative humidity measurement and long-range LoRaWAN communication. This successful proof-of-concept is a first necessary step before the implementation of a communicating reinforced concrete.

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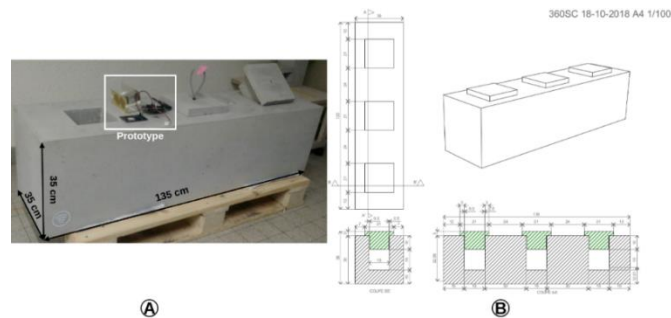


Figure 5. A) Photograph and B) Design of the reinforced concrete beam, which will be used for characterization of the Sensing Node prototype in the targeted medium.

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