Battery-free Bluetooth Low Energy Sensing Nodes for Structural Health Monitoring of Concretes

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HAL Id: hal-03648201
https://laas.hal.science/hal-03648201

Submitted on 21 Apr 2022

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ABSTRACT

This paper presents a Bluetooth Low Energy sensing node, part of a wireless sensor network dedicated to the deployment of a cyber-physical system for the structural health monitoring of reinforced concretes throughout their life. This fully wireless sensing node is designed to measure temperature and relative humidity, and wirelessly transmit the collected data in its network, as well as to be energy autonomous. For that, it is battery-free, able to cold-start, and wirelessly and remotely powered -and controlled- over several meters by communicating nodes (other part of the network, assuring the connection to the digital world) *via* a radiative electromagnetic power transfer system.

INTRODUCTION

For several years, electronic embedded systems have played an increasingly important role in our societies. Numerous and always more diversified wireless communication technologies have been developed with various features and performances, both for human-to-human and machine-to-machine (M2M) communications. These technologies are employed to deploy Wireless Sensor Networks (WSN) for different applications, such as Structural Health Monitoring (SHM) of various structures (e.g. vehicles, buildings, etc.).

Nevertheless, one of the main limitations to the deployment of WSN is their energy need. To date, these are essentially powered by the use of the mains supply or batteries. But these two solutions are expensive, required a lot of maintenance, and limit the mobility and the scalability. To assure the energy autonomy of the WSN, both the ambient energy harvesting and the Wireless Power Transfer (WPT) solutions are investigated [1]. However, these latter are highly dependent on the deployment environment and on the targeted application.

In this context, and in the framework of the McBIM project (Material communicating with the Building Information Modelling (BIM)) [2], wireless, battery-free and wirelessly powered sensing nodes (SN) based on the Bluetooth Low Energy

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(BLE) technology have been developed, implemented and tested. These SN are devoted to the design and implementation of a WSN embedded in a reinforced concrete to make it communicating and thus, to obtain a Cyber-Physical System (CPS) dedicated to the SHM in the civil engineering industry [3, 4].

In this paper, the design and implementation of the BLE battery-free and wirelessly powered SN will be presented. Then, their characterization and some experimental results will be provided and discussed. Next, the positioning, the current limitations and perspectives will be explained. Before concluding, a comparison with similar SN based on the LoRaWAN wireless communication technology will be carried out.

DESIGN AND IMPLEMENTATION OF THE SENSING NODES

The McBIM project targets the design and implementation of a communicating reinforced concrete, according to the 'Communicating Materials' paradigm [5], and dedicated to the SHM of concrete structures throughout their life. To achieve this objective, we choose to embed a WSN inside the reinforced concrete, which must be able to sense various parameters (from the reinforced concrete itself and/or from its environment), to process, store and share wirelessly the collected data with the physical and digital worlds [3,4]. This WSN is composed of a meshed network of communicating nodes (CN) gathering information from a star network of SN fully embedded in the reinforced concrete (used to generate, pre-process and transmit data). This paper is focused on the SN based on the BLE. Complementary information is available in [2-4].

Architecture of the Sensing Nodes

The SN will be embedded into the reinforced concrete, and thus, become inaccessible. Thus, two main constraints must be overcome in their design:
- these must be able to wirelessly transmit the measured data to the CN through the reinforced concrete.
- their energy autonomy and reconfigurability must be ensured during all their lifespan.

To meet these requirements, the architecture presented in Fig. 1 has been chosen. It is composed of two distinct but interconnected parts, respectively dedicated to the data and the uplink, and to the energy and the downlink.

A specific package must be considered for the deployment in order to protect the electronics from the concrete, while allowing accurate measurements. The current prototype of the SN is presented in Fig. 2.

Data Measurement, Pre-Processing and Transmission

In order to assure the SHM of the reinforced concrete throughout its lifetime (expressed in decades), the SN must measure relevant data from the monitored structure and/or its environment such as temperature, relative humidity, mechanical deformations, corrosion rate, etc. The collected data can be formatted before being wirelessly transmitted to the CN and becoming accessible for the whole CPS.

The BLE technology is interesting for our application as it provides the next specifications:
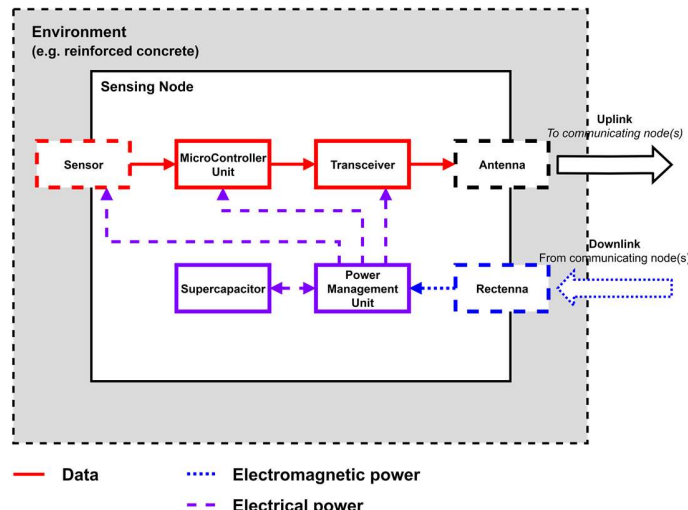
Figure 1. Bloc diagram of the architecture of the sensing nodes.

- unidirectional communications without connection or acknowledgement, due to the notification mode in the broadcaster/observer configuration;
- low power consumption;
- low to medium data-rate;
- medium range of use: at least ten meters from a reinforced concrete element;
- large availability and included in all general-purpose wireless devices.

The data acquisition and transmission part of the SN is printed or soldered on a 0.8 mm FR4 substrate and is composed of:

- a low-power temperature and relative humidity sensor (Texas Instruments HDC2080 [6]) with accuracies of respectively 0.2 °C and 2 %, and ranges of -40 °C to +125 °C, and of 0 to 100 %;
- a low-power BLE transceiver embedding a microcontroller unit (NXP QN9080 [7]) which will drive the sensor, collect and format the measured data, and manage the BLE stack. The 3 bytes data will be wirelessly transmitted in an advertising broadcasting frame of 19 bytes. To assure the reliability, this frame will be transmitted 4 times on 3 different 2 MHz-channels on the 2.45 GHz ISM frequency band;
- a printed meandered inverted-f antenna (MIFA) [8].

The data downlink is not implemented, and even not desired, for reasons of hardware security and power consumption. The power consumption is reduced by deleting the time dedicated to the listening of the medium for receiving acknowledgement, data or firmware update. The security is increased by imposing a fixed firmware and by blocking all accesses required to alter or update it.

Power Harvesting and Energy Management for Long-Term Autonomy, and Reconfigurability

In order to assure their energy autonomy for reliable long-term operations and because inaccessible once installed, the SN have been designed as simple as possible, low-power battery-free, able to cold-start, wirelessly powered and remotely controlled, over several meters even through the reinforced concrete.

A radiative electromagnetic WPT system controlled by the CN has been chosen to power the SN. This provides a generic long-term solution, for all possible use cases, and
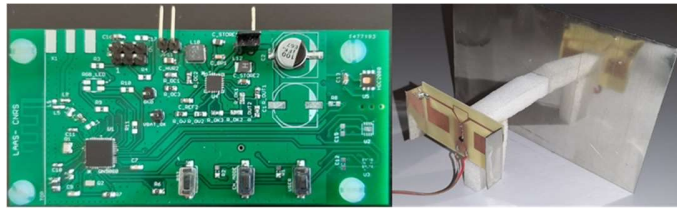
Figure 2. Photograph of a prototype of the sensing nodes.

independent of the targeted environment, structure and/or application. The choice of the ISM 868 MHz frequency band for the WPT is based on the best trade-off between the range of use and the size of the SN antenna.

The energy part of the SN is composed of:
- a rectenna (rectifying antenna): a printed folded quart-wavelength dipole antenna with capacitive arms, connected to a full-wave RF-to-DC rectifier, with a 14 cm x 9 cm metallic reflector plane located at 6 cm achieving a good trade-off between compactness and radiation efficiency [9]. It will harvest the +33 dBm (or 2 W) radiative electromagnetic power generated by the CN through a continuous wave in the ISM 868 MHz frequency band and convert it in DC power;
- a Power Management Unit (PMU) (Texas Instruments bq25570 [10]) to store efficiently the energy in a supercapacitor and to supply the data part of the SN each time enough energy is available;
- a 100 µF aluminum electrolytic capacitor (Panasonic EEEFK0J101P 100 [11]) to store the scavenged energy with low losses.

When the CN transmit radiative electromagnetic power, the rectenna of each SN located around converts the available RF power in DC power and provides it to the PMU; this stores it in the capacitor, thanks to its cold-start ability if this one is completely empty, and in an MPPT optimized way when enough energy is available to power this hardware function; once enough energy is stored, the PMU discharges the capacitor to power the data part of the SN; once a full process is achieved (*id est* when the energy stored for it is fully consumed), this cycle begin again (with a capacitor not empty) as long as the CN provide a radiative electromagnetic power. Thus, a "store then use" strategy is employed.

By tuning the radiative electromagnetic power source of the CN in terms of output power, waveform or duty cycle, it is possible to wirelessly and remotely control the behavior of the SN in terms of periodicity of data measurement and transmission without altering either their hardware or software. This power approach is the only way to reconfigure the current SN for which no data downlink is available.

CHARACTERIZATION AND EXPERIMENTAL RESULTS

Characterization of the Power Consumption

As shown in Fig. 3, nearly 1 second is required by the SN to achieve a full process: power-up, initialization, temperature and relative humidity measurement, and 4 times frame transmission (frame length: 19 bytes including 3 data bytes) with a +0 dBm power and to be powered-off again. 780 ms are needed for frame transmission. The broadcasting frames are separate by 250 ms period of deep-sleep mode. Around 920 µJ

are required with a 3 V supply voltage, which means around 1.5 µJ is consumed per transmitted bit (for the 4 iterations) and 38 µJ per data bit (or 307 µJ per data byte).

In order to store enough energy in the 100 µF capacitor, the activation threshold voltage is set to 5.3 V and the deactivation one to 2.2 V, that allows to store around 1.16 mJ, enough for a full process and for the compensation of the disparity and ageing of the components.

Temporal Characterization of the First Charges and the Recharges

The periodicity of measurement and transmission of the SN are wirelessly and remotely controlled by the CN through the WPT. Thus, the characterization of the times required for a first charge (from an empty capacitor) and for recharges (between two process, with the same input power) in function of the input radiative electromagnetic power is a relevant information, and gives an important information of the possible ranges of use and frequencies of data collection. For an input power of the rectifier of +1 dBm, around 17 s are required for the first charge, and around 4 s for a recharge. For an input power of the rectifier of -16 dBm, 28 min and 17 s are necessary for the first charge, and 3 min 15 s for a recharge.

Wireless Communication Performances and Qualitative Tests

Several qualitative tests have been achieved in several configurations, in the air and/or from a reinforced concrete beam (with at least 10 cm of reinforced concrete around the SN). A unique CN can wirelessly power and collect data of several SN in its neighborhood (tested for 3 SN). If the SN are embedded in a reinforced concrete beam, the maximal range tested if 2 meters. If the SN is not embedded (only the sensor will be embedded) the maximal transmission range tested goes up to 7 meters in the air. In the both cases, the communication and power transmission work in almost omnidirectional way, no need of directive antennas. Moreover, by tuning their power source, the CN can remotely control the periodicity of functioning of the SN.

The impact of the reinforced concrete is highly visible in the performances of both the WPT and wireless communications. For one SN embedded in reinforced concrete powered wirelessly by an electromagnetic power of + 33 dBm at a distance of 2 m the first-time charge is of 1 min 15 s and the recharge time is 33 s. For the same SN placed outside the concrete beam powered by the same source of +33 dBm at 2 m distance the first-time charge is only 17 s and the recharge time goes down to only 4 s. For the wireless communications, the first packet losses appear for distance around 11 m for a SN embedded in the reinforced concrete beam, against more than 20 m for the SN placed on the concrete beam.
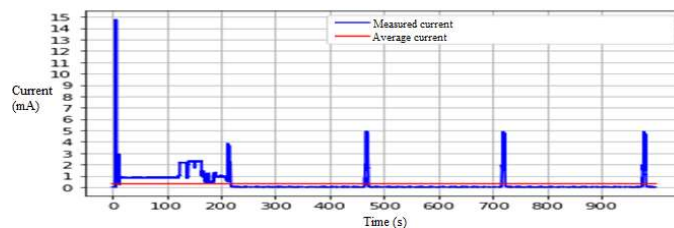

Figure 3. Power consumption of the sensing nodes powered by a 3 V supply voltage.

Moreover, it must be noted that the WPT and the wireless communications have a similar range of use, expressed in meters and with expected maximum ranges over 10 m.

WORK IN PROGRESS ON THE BLE SENSING NODES

There are in the academic literature some recent works concerning the BLE nodes for WSN powered by the ambient energy harvesting or WPT. Some harvest ambient light [12, 13], mechanical vibrations [13, 14], temperature gradient [15], electromagnetic inductive field [16], electromagnetic radiative waves [17], or multiple sources [13], while others are based on the radiative electromagnetic WPT [18, 19], but all power a BLE node, battery-free [12, 14-19] or not [13, 16], and with [12-14, 16-19] or without sensor [15]. Those based on ambient energy harvesting are highly dependent of their environment and of their application, while those based on the WPT have limited range of use in the air (tested up to 2 m), are based on a "direct consumption" strategy, and their periodicity of data measurement and transmission is configured by software.

Our first BLE SN prototypes still have some limitations and some improvements (both hardware and software) can be carried out.

Concerning the data part, other low power sensors must be implemented with the aim of monitoring reinforced concretes and the data communication protocol can be optimized to further reduce the required energy, while ensuring reliable communications. It could be relevant to characterize the energy required and efficiency versus the supply voltage, the wireless communication transmitting power, the data-rate, the time intervals between advertising frames, the number of frames sent, the number of channels used, always by considering the impact on the reliability of the wireless communications. By reducing the needed energy, the times required for the first charge and recharges will be reduced too. The capacity of the storage element and the activation threshold of the PMU could also be decreased.

Concerning the energy part, its optimization must improve the energy efficiency of the SN and allow wider ranges of use for the WPT. This optimization concerns especially the reduction of the minimum required input power, which is highly correlated to the rectenna efficiency (related to both antenna and rectifier performances, especially with the reinforced concrete as propagation medium for the electromagnetic waves), the power required by the PMU and the losses of the capacitor.

Concerning the global implementation, its size is mainly constrained by the antenna, a specifically designed package must be used, and further tests and characterizations must be performed.

COMPARISON WITH SENSING NODES BASED ON THE LORAWAN WIRELESS COMMUNICATION TECHNOLOGY

The presented implementation of the SN based on the BLE technology can be compared with those described in [3, 4] and based on the LoRaWAN technology. However, these do not have the same maturity level.

The two are based on the same architecture, the same functioning in a "store then use" strategy (power-up, initialization, data measurement, formatting and wireless

transmission to the CN, power-off), and are dedicated to the same application: the design and implementation of a communicating reinforced concrete and its long-term SHM. Also, their energy parts are similar: the same rectenna is used (with different metallic reflector plane), the supercapacitor and capacitor have similar losses despite different capacities (2.2 mF for LoRaWAN SN versus 100 µF for BLE SN), and only the PMU are different, which allows minor improvements in the BLE version with theoretically a lower minimal required input power. Thus, their ranges of use for the WPT part are almost the same. These are battery-free, able to cold-start and wirelessly powered (and wirelessly and remotely controlled) by the CN through a radiative electromagnetic WPT.

The main differences are related to the available sensors, the energy required for the data part and the wireless communication performances. The LoRaWAN implementation provides a reliable medium to high range wireless communications even through the reinforced concrete, while the BLE one is limited to a ten of meters with a high impact due to the reinforced concrete and potential packet losses. Nevertheless, the BLE requires very little energy to operate, less than 1 mJ, while the LoRaWAN one needs at least 20 mJ. The lower the stored energy, the faster the time to a first charge or a recharge. The BLE is more efficient than the LoRaWAN one in terms of energy per byte of data transmitted, with 307 µJ per data byte against up to 5 mJ per data byte. Thus, a trade-off between the reliability of the wireless communications, its range and its energy consumption must be done.

These two implementations meet the requirements of the simultaneous wireless information and power transmission (SWIPT) paradigm, both without temporal multiplexing and power splitting; and without frequency and spatial multiplexing for the LoRaWAN one.

CONCLUSION

This paper proposes an innovative low-cost, low power, fully wireless, battery-free and wirelessly powered by radiative electromagnetic waves BLE sensing nodes embedded into reinforced concrete to ensure its SHM throughout its lifetime, but which can be easily employed for other applications. Due to its design, the BLE sensing node is reliable and completely autonomous for decades. It is wirelessly powered over 7 meters and it is able to transmit data with an energy efficiency of only 307 µJ per data byte for a range up to 7 meters. Moreover, by tuning the power source used by the WPT system, the BLE SN can be wirelessly and remotely reconfigured in terms of periodicity of use (temperature and relative measurement, and data wireless communication), without altering either its hardware or software.

ACKNOWLEDGMENT

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