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# Autonomous Wireless Sensors Network for the Implementation of a Cyber-Physical System Monitoring Reinforced Concrete Civil Engineering Structures

Gaël LOUBET\*, Alassane SIDIBE\*\*, Alexandru TAKACS\*\*\*, Daniela DRAGOMIRESCU\*\*\*\*

\* LAAS-CNRS, INSA Toulouse, Université de Toulouse, CNRS, Toulouse, FRANCE  
(e-mail: [gael.loubet@laas.fr](mailto:gael.loubet@laas.fr)).

\*\* LAAS-CNRS, UWINLOC, Université de Toulouse, CNRS, Toulouse, FRANCE  
(e-mail: [alessane.sidibe@laas.fr](mailto:alessane.sidibe@laas.fr)).

\*\*\* LAAS-CNRS, UPS, Université de Toulouse, CNRS, Toulouse, FRANCE  
(e-mail: [alexandru.takacs@laas.fr](mailto:alexandru.takacs@laas.fr)).

\*\*\*\* LAAS-CNRS, INSA Toulouse, Université de Toulouse, CNRS, Toulouse, FRANCE  
(e-mail: [daniela.dragomirescu@laas.fr](mailto:daniela.dragomirescu@laas.fr)).

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**Abstract:** This paper presents an autonomous Wireless Sensors Network as the hardware basis for implementing a Cyber-Physical System. The Wireless Sensors Network is composed of Sensing Nodes and Communicating Nodes. The Sensing Nodes can wirelessly transmit data measured in reinforced concrete using Non-Destructive Testing methods over several tens of meters. These are battery-free, and are powered and controlled wirelessly and remotely by a radiative electromagnetic Wireless Power Transfer system tuned by the Communicating Nodes. Each Communicating Node covers a volume of at least 11 meters in all directions for the Wireless Power Transfer. The Wireless Sensors Network meets the requirements of the Simultaneous Wireless Information and Power Transmission paradigm by using a single antenna in the Sensing Nodes (concurrently for power harvesting and data transmission). The proposed system is designed for the Structural Health Monitoring of reinforced concrete civil engineering structures, but can be adapted to other applications, especially in harsh environments.

*Keywords:* Wireless Sensors Network (WSN); Wireless Power Transfer (WPT); Cyber-Physical System (CPS); Internet of Things (IoT); Simultaneous Wireless Information and Power Transmission (SWIPT); Structural Health Monitoring (SHM); Non-Destructive Testing (NDT).

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## 1. INTRODUCTION

Wireless Sensors Networks (WSN) have rapidly become common thanks to the rise of: wireless communication technologies, including machine-to-machine (M2M), enabled by the digitization and miniaturization of electronics and the huge availability of embedded systems; and of the Internet of Things (IoT) paradigm. The WSN can be used as the hardware basis for Cyber-Physical Systems (CPS), as these can both monitor and control the physical world, and connect it to the digital world and its digital twins (such as Building Information Modelling (BIM)).

Cyber-Physical Systems are particularly suited for Structural Health Monitoring (SHM) applications in various fields, including civil engineering. These allow to permanently monitor the evolution of the state of structures in order to make possible preventive treatments and to avoid irreversible failures such as collapse, thus ensuring their proper use and ageing. These use Non-Destructive Testing (NDT) methods to perform the measurements because these latter do not alter the structure under test (Darwin et al., 2016; Taheri, 2019).

To date, the main restriction to the long-term deployment of Wireless Sensor Networks is their energy autonomy, which is usually ensured by the use of batteries. To override this constraint, ambient energy harvesting and Wireless Power Transfer (WPT) solutions are being investigated (Peruzzi and Pozzebon, 2020). Also, by considering conjointly Wireless

Power Transfer and wireless communication, both using the same propagation support (e.g. electromagnetic waves), Wireless Sensors Networks can meet the Simultaneous Wireless Information and Power Transmission (SWIPT) paradigm (Costanzo et al., 2021; Ponnimbaduge Perera et al., 2018).

In this context, the McBIM project (Material communicating with the Building Information Modelling) (Derigent et al., 2019) proposes an implementation of the communicating material paradigm (Kubler et al., 2010) in the case of reinforced concrete, to ensure its Structural Health Monitoring through the use of a Cyber-Physical System. This one is based on a Wireless Sensors Network using Non-Destructive Testing methods, and meeting the requirements of the Simultaneous Wireless Information and Power Transmission paradigm by employing a radiative electromagnetic Wireless Power Transfer solution to achieve its long-term energy autonomy, and a wireless communication solution to transmit measured data.

This paper presents the design, implementation and test of a Wireless Sensors Network based on battery-free Sensing Nodes (SN), which are powered and controlled wirelessly and remotely. Subsequently, the architecture and implementation of the Sensing Nodes and of the Cyber-Physical System are presented. Then, the experimental results obtained so far are introduced. Before concluding, a critical analysis and perspectives are proposed.

## 2. DESIGN AND IMPLEMENTATION OF A CYBER-PHYSICAL SYSTEM BASED ON AN AUTONOMOUS WIRELESS SENSORS NETWORK

The communicating reinforced concrete should be intrinsically capable of: (1) generate (locally); (2) process (locally and/or remotely); (3) store (locally and/or remotely); and (4) share data (from its own state and/or from its environment), (i) with other communicating elements in the physical world, and (ii) with digital twins *via* the Internet in the digital world. This behavior must be verified throughout its life, *i.e.* for decades, in order to keep its digital model(s) up-to-date, and to make it and its history available to the different users. It is therefore a CPS. In order to implement it, it was decided in the McBIM project to embed a WSN into the reinforced concrete (Derigent et al., 2019; Loubet et al., 2019; Loubet et al., 2020; Loubet, 2021).

### 2.1 Architecture of the Cyber-Physical System

The architecture of the designed, implemented and tested CPS is presented in Fig. 1. It is based on a WSN, composed of: Sensing Nodes (SN) and Communicating Nodes (CN). The number of nodes in the network depends on the structure to be monitored and the requirements in terms of measurements (*e.g.* sensors to be used, spatial precision sought, etc.).

The SN are used to (1) make measurements, (2) format, and then (3) wirelessly transmit the measured data to the CN. These must be wireless, battery-free and energy autonomous, but also resilient and reliable throughout their life. These are powered by the CN through radiative electromagnetic WPT. This solution eliminates the dependence on ambient energy sources

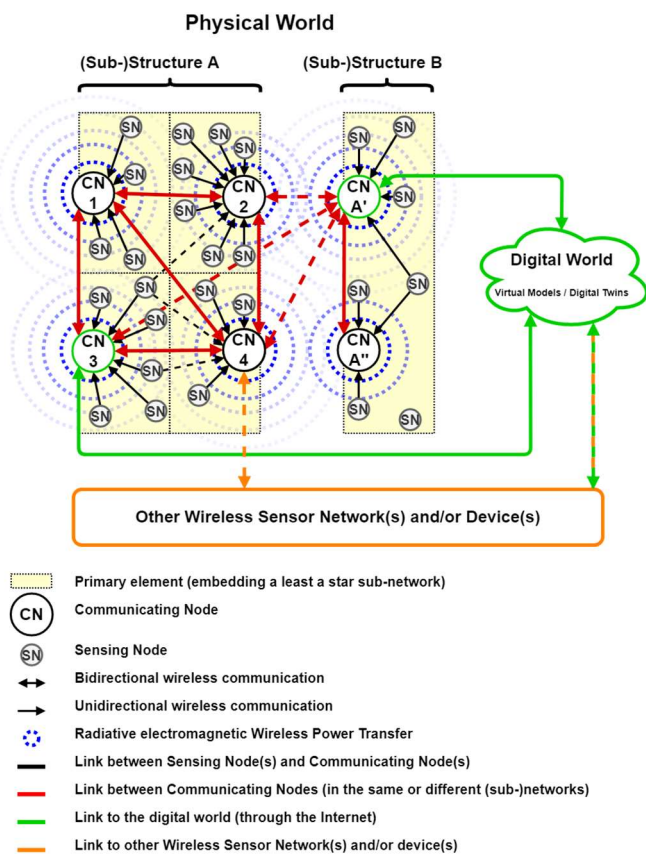


Figure 1. Bloc diagram of the Cyber-Physical System.

(insufficient or unavailable, fluctuating, unpredictable and uncontrollable), and is independent of the targeted application and deployment environment.

The CN are used to (1) aggregate the data measured and sent by the SN, then (2) process them, (3) store them locally and/or on remote servers, and (4) exchange them locally and/or remotely (i) with other CN composing an *ad-hoc* mesh network, (ii) possibly with other communicating elements, and (iii) with its virtual model(s) *via* the Internet in the digital world. Moreover, by tuning their electromagnetic power source, the CN can adjust the periodicity of operation of the SN.

### 2.2 Architecture and Implementation of the Sensing Nodes

The architecture of the designed, implemented and tested SN is shown in Fig. 2, while photographs of some SN and experimental setups are shown in Fig. 3. The implementation of each part of the SN is detailed in the next paragraphs. As the SN are intended to be deployed and buried in reinforced concrete, and thus become inaccessible in a direct way, they must be reliable and usable over the long term. They are therefore as simple as possible, fully wireless, battery-free, remotely powered and controlled.

Some sensors are particularly relevant for the SHM of reinforced concrete according to (Taheri, 2019). Thus, some of these are implemented in the proposed solution to perform the measurements (Loubet et al., 2019; Loubet et al., 2020; Loubet, 2021). These include: (1) a thermodiodes-based temperature sensor from the University of Cambridge (De Luca et al., 2015); (2) an HDC2010 temperature and relative humidity sensor from Texas Instruments; (3) a mechanical deformation sensor (strain gauge); and (4) a Wenner-configured electrical resistivity sensor from the Laboratory for Materials and Sustainability in Construction (LMDC) in Toulouse (Badr, 2019).

For the data processing and wireless transmission, a Murata CMWX1ZZABZ-091 all-in-one module (microcontroller unit and transceiver) is used. This allows to format on 4 bytes and to wirelessly transmit the measured data *via* a 17-byte LoRaWAN frame to the CN. LoRaWAN technology was chosen for its low power consumption and range (regardless of its configuration) even through reinforced concrete, a very restrictive propagation medium for electromagnetic waves. Two configurations were studied for wireless communication in the 868 MHz ISM frequency band: (1) the most reliable which allows the longest ranges (transmission power of +14 dBm and data rate of 250 bps); and (2) the most energy-efficient one which offers ranges of at least several tens of meters from a reinforced concrete beam (transmission power of +4 dBm and data rate of 5470 bps).

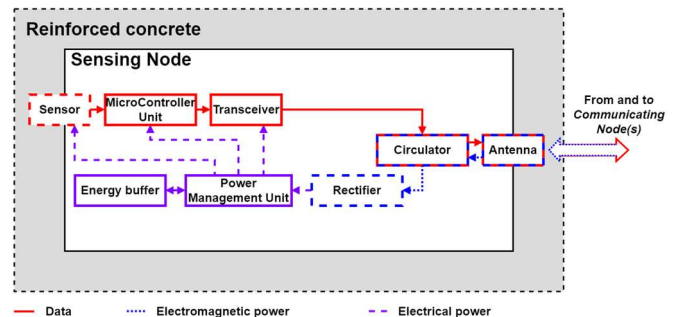


Figure 2. Bloc diagram of the Sensing Node

For the energy autonomy through a WPT solution, an energy harvesting and management system is used. In practice, a Skyworks SMS7630 Schottky diode-based doubler rectifier is used, along with a Texas Instruments BQ25504 Power Management Unit (PMU) and a Texas Instruments TPS63031 buck-boost DC/DC converter to provide a 3.3 V voltage to the active components whenever enough stored energy is available. The recovered energy is stored in a 2.2 mF supercapacitor for the most energy-efficient configuration, or in a 22 mF supercapacitor for the most reliable one.

To achieve ranges of several meters, radiative electromagnetic WPT (far-field) solutions are preferred over near-field solutions (capacitive and/or inductive). The 868 MHz ISM band was chosen as the best trade-off between antenna size and range. Thus, the CN use a radiated electromagnetic power source providing a +33 dBm EIRP continuous wave in the 868 MHz ISM band in accordance with the regulations (European Union, 2017) to wirelessly power the SN. The SN use a folded quarter-wave dipole antenna with capacitive arms (metallic and orthogonal to the plane of the dipole) (Sidibe et al., 2021) to harvest the transmitted power. This antenna measures 5.6 cm x 3.2 cm x 1.0 cm, has linear polarization, is usable between 848 MHz and 886 MHz, has a measured gain of +1.54 dBi at 868 MHz, and is nearly omnidirectional with a -3 dB aperture angle of 110° in the E plane. By adding an 8 cm by 6 cm metal reflector plane 5 cm behind, the gain increases to +5.00 dBi at the cost of greater directivity (the -3 dB aperture angle decreases to 70° in the E-plane) and an increase in total volume. This antenna appears to be a good trade-off between size and radiation performance in the target frequency band.

Since only one frequency band is used for wireless communication and WPT, it is possible to use a single antenna in combination with a circulator (with low insertion losses and high isolation). This works because there is only one data uplink and one power downlink. In addition, this trick reduces the overall size of the SN. Thus, simultaneously, the electromagnetic power received by the antenna is transmitted to the

rectifier *via* the circulator, forming a *quasi*-rectenna, and the data to be sent from the transceiver is transmitted to the antenna *via* the circulator. Furthermore, there is no significant connection between the rectifier and the transceiver, nor interference between the data and power transfers. Finally, the requirements of the SWIPT paradigm are met by discriminating data uplink and power downlink, *i.e.* without time, frequency or spatial multiplexing, nor power splitting.

As the desired periodicity of measurement depends on the step of the life cycle, the SN must be reconfigurable. But, these are inaccessible in a direct way, both in hardware (no physical access) and software (no data downlink). Therefore, the CN can only control the periodicity of operation of the SN -wirelessly and remotely- *via* the power downlink, *i.e.* by adjusting their power source in terms of waveform, transmitted power and/or activation periodicity. Thus, this periodicity is not dictated by the hardware or software of the SN, and can be reconfigured.

### 3. EXPERIMENTAL RESULTS

Several implementations of the CPS have been carried out as proofs-of-concept using LoRaWAN wireless communication technology (Loubet et al., 2019; Loubet et al., 2020; Loubet, 2021). Also, first works using Bluetooth Low Energy (BLE) wireless communication technology have been done (Loubet, 2021; Sidibe et al., 2021). SN can measure various parameters from the reinforced concrete (temperature, relative humidity, mechanical deformation, electrical resistivity), and then wirelessly format and transmit the measured data over at least several tens of meters from the reinforced concrete to the CN.

The most reliable LoRaWAN configuration requires 250 mJ of energy (*i.e.* 62.5 mJ per byte of data, or 14.71 mJ per byte transmitted, or 1.84 mJ per bit transmitted) to complete a full process: the measurement regardless of the sensor used, and the full transmission of a 17-byte LoRaWAN frame with 4 bytes of payload. The most energy-efficient LoRaWAN configuration requires 21 mJ of energy (*i.e.* 5.25 mJ per byte of data, or 309 mJ per byte transmitted, or 39  $\mu$ J per bit transmitted), which is more than 10 times less. Whereas using BLE technology requires 1.2 mJ of energy (*i.e.* 400  $\mu$ J per data byte, or 63  $\mu$ J per transmitted byte, or 7.9  $\mu$ J per transmitted bit), which is almost 20 times less for a complete process: temperature and humidity measurement, and transmission at +0 dBm and 1 Mbps of 4 *advertising* frames of 19 bytes with 3 bytes of payload. These energy quantities are overestimated by +20% compared to the average needs to certify a proper operation despite the variability of the components and their ageing.

The duration of the first charge (from an empty energy buffer) and recharges (after another full charge) gives relevant information on the smallest periodicity of operation of the SN as a function of the available electromagnetic power, as shown in Fig. 4. In the most reliable LoRaWAN configuration, the SN can operate between -14 dBm and up to at least +15 dBm, resulting in first charge times between about 34 hours and 36 minutes, and about 1 minute and 10 seconds, and recharge times between about 14 hours and 38 minutes, and about 33 seconds. In the most energy-efficient LoRaWAN configuration, these times are respectively between about 17 hours and 21 minutes, and about 30 seconds, and between 7 hours and 59 minutes, and



Figure 3. Photographs of: (top) Sensing Nodes, using (right) or not (left) the electronic Printed Circuit Board as a 6 cm x 8 cm metallic reflector plane located 5 cm behind the single antenna; and (bottom) experimental setups of the Cyber-Physical System (left) indoors and (right) with Sensing Nodes embedded in a reinforced concrete beam.

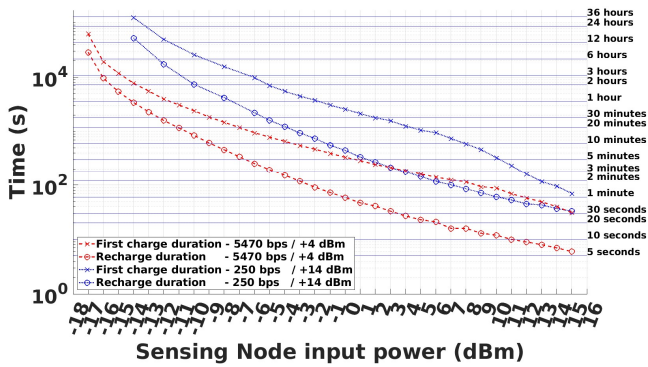


Figure 4. Durations of the first charge ('x') and recharges ('o') against the electromagnetic power applied at the input of the circulator of the Sensing Node, at 868 MHz, and for two configurations of the wireless communication: transmission power of +4 dBm and data rate of 5470 bps (red, dashed lines), and transmission power of +14 dBm and data rate of 250 bps (blue, dotted lines).

about 6 seconds, for an input power between -17 dBm and at least +15 dBm. Longer periodicities can obviously be achieved by the CN by controlling their power source in terms of transmitted power and of duration and periodicity of activation. Usually, the lower the energy to be stored and/or the higher the available input power, the faster the charge.

From the minimum power required at the input of the SN to operate, a maximum operating range can be estimated. This minimum input power is a function of the power required by the PMU to operate, but must also allow for compensation of the DC/DC converter and energy buffer losses. Experimentally, this power is measured at -14 dBm for the most reliable LoRaWAN configuration and at -17 dBm for the most energy-efficient one.

By applying the Friis equation, the distance between a CN (with a maximum allowed EIRP power of +33 dBm in the 868 MHz ISM band (European Union, 2017)) and a SN (with a +1.54 dBi gain antenna) can be estimated based on the minimum power required at the input of the SN. Thus, -17 dBm can be recovered at a distance of about 10.38 meters (*i.e.* a periodicity of about 7 hours and 59 minutes), -14 dBm at about 7.35 meters (*i.e.* a periodicity of about 14 hours and 38 minutes and about 57 minutes, respectively for the most reliable and energy-efficient LoRaWAN configurations), and about -10.6 dBm at a distance of 5 meters (*i.e.* a periodicity of about 3 hours and about 15 minutes, respectively). Using a metallic reflector plane to achieve a gain of +5.00 dBi, -17 dBm can be recovered at a distance of about 13.78 meters, -14 dBm at about 10.95 meters, and about -7.2 dBm at a distance of 5 meters (*i.e.* a periodicity of about 50 minutes and about 6 minutes, respectively for the most reliable and energy-efficient LoRaWAN configurations).

It should be noted that a minimum power requirement of -17 dBm at the input of the SN is one of the lowest found in the literature. To our knowledge, only (e-peas semiconductors) provides PMU that require -19 dBm in the 868 MHz ISM band. Usually, the lower the power required at the input of the SN, the greater the range.

The deployment volume of a star sub-network consisting of a CN and a multitude of SN is limited by the operating range of

the radiative electromagnetic WPT system and not by the range of the wireless communications. Its maximum tested range indoors, in any direction, is 11 meters, the longest tested to our knowledge. However, longer ranges appear to be achievable. In terms of deployment, this may seem sufficient to cover indoor use cases (*e.g.* office or residential buildings, structures such as bridges or tunnels, etc.): approximately as many CN would be needed as Wi-Fi access points in office buildings. Furthermore, although the wireless communication ranges are sufficient, deployments outdoors or in very large structures seem unviable due to the operation ranges of the WPT. Also, the targeted periodicity of measurement must be considered during the deployment. As in reinforced concrete the variations of the physical parameters are slow, the periodicity of measurement can be large, but this is not the case for all applications. Usually, the lower the available input power, the longer the periodicity.

In addition to the quantitative characterizations, many qualitative tests have been carried out to certify the proper functioning of the CPS and its SN. For example, a CPS consisting of a mesh network of 2 CN (one with an Internet connection) and 4 SN, 3 of which can be located in air cavities of a reinforced concrete beam, as shown in Fig. 3, has been successfully tested. Thus, the CN remotely powered and controlled the SN, and retrieved all the data sent over at least a few tens of meters indoors, to process, store and share these. A single CN can easily manage several SN located in its neighborhood, over several meters and in all the directions. The SN can be wirelessly powered over at least 3 meters (including at least 15 centimeters of reinforced concrete) when embedded in the reinforced concrete beam, but also over a distance of at least 11 meters indoors, and it seems possible to reach greater distances. It should be noted that this is the size of the experimental rooms that limits the distances tested.

Another relevant element to consider in order to achieve a sustainable system is its energy efficiency. It is defined as the ratio between the energy available at the input of the SN (*i.e.* the power harvested by the antenna integrated over the period of interest) and the energy required for a complete process. As presented in Fig. 5, the efficiency is rather low for the first

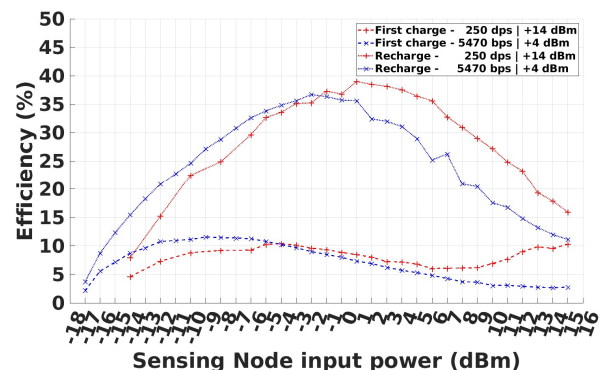


Figure 5. Energy efficiency of the Sensing Nodes during the first charge (dashed lines) and recharges (dotted lines) against the electromagnetic power applied at the input of the circulator of the Sensing Node, at 868 MHz, and for two configurations of the wireless communication: transmission power of +4 dBm and data rate of 5470 bps ('x', blue), and transmission power of +14 dBm and data rate of 250 bps (red, '+').

charge: between 2.16% and 11.54% for the most energy-efficient LoRaWAN configuration; and between 4.59% and 10.25% for the most reliable one. The efficiency increases in the case of the recharges, respectively: between 3.68% and 36.71%; and between 7.91% and 39.00%. The two configurations do not show their peak efficiency for the same input power. These are respectively reached at -9 dBm and -5 dBm for the first charge, and at -2 dBm and +1 dBm for the recharges. Moreover, the first configuration is more efficient for lower input powers, and the second for higher ones. Usually, the shorter the first charge and recharges, the higher the energy efficiency.

Another efficiency could be relevant to express: it is defined as the ratio between the energy transmitted by a CN to wirelessly power all the SN located in its neighborhood, and the sum of the energy consumed by each of the SN during a period of interest. Usually, the more SN there are and the higher the efficiency of each, the higher the overall efficiency.

#### 4. DISCUSSIONS AND PERSPECTIVES

Currently, and to our best knowledge, there is no CPS based on a WSN composed of battery-free, energy autonomous and fully wireless SN, which are designed to be fully embedded in reinforced concrete and to achieve its long-term SHM in an automatic manner. Indeed, the majority of existing nodes have a limited lifetime due to the use of batteries and are usually deployed on the surface of the structure to be monitored (or in some cases, at a limited depth in the concrete) (Loubet, 2021). The proposed solution can also be seen as a remotely powered WSN and can easily be adapted to other applications.

The implementation of the CPS and its SN is based solely on off-the-shelf components, with the exception of the rectenna for which no commercial solution is available. As the measured properties have slow variations in reinforced concrete, long periodicities of measurement are targeted. And, as the power available at the input of the SN is much lower than the power needed to run it continuously, the strategy of "store then use" the energy, with the ability of cold start, is employed. Also, as the SN are inaccessible in a direct way and deployed over the long term (*i.e.* several decades), the design provides for as few components and as little complexity as possible in order to minimize failure points.

However, implementations of SN can be improved, both from a hardware and software perspective. For example, by reducing the minimum input power requirement of the SN, it is possible to increase the operating range of the radiative electromagnetic WPT system, which is currently limiting for large-volume deployment, in contrast to wireless communications which provide much greater ranges. Currently, the minimum input power of -17 dBm allows a range of at least 11 meters indoors. This reduction can be achieved by choosing a PMU that operates with less energy, and by limiting the DC/DC converter and energy buffer losses. In addition, by reducing the energy required to operate the SN, the time required for first charge and recharges can be reduced, regardless of the available input power. This can be achieved, for instance, by choosing an alternative wireless communication technology. The sensors can also be optimized to be more accurate and consume less energy, as well as other sensors can also be used. Moreover, the

efficiency of the SN can be enhanced by using a more efficient rectenna. This improvement concerns the antenna, the rectifier, but also their assembly. Finally, the overall efficiency of the radiative electromagnetic WPT system can be optimized by focusing the power transmitted by the CN on the SN with beamforming (Belo et al., 2019) or Frequency Diversity Arrays (Fazzini et al., 2021) techniques, or by using more efficient waveforms (Boaventura et al., 2015).

In fact, several trade-offs have to be considered. Firstly, between the volume of the SN, which we want to be as compact as possible, and the range of use, which we want to be as long as possible. These two considerations are correlated to the antenna and the chosen frequency. The volume of the SN is restricted by the size of the antenna, which is closely related to the wavelength. The range of use is restricted by the performances of the antenna in terms of radiation pattern, gain and polarization, which are closely related to its design. The chosen frequency also imposes regulations and propagation properties, especially with regard to losses. Secondly, between the power consumption of the SN and therefore the charging times, which we want to keep to a minimum, and the quality of wireless communications, which we want to be optimal in terms of range and reliability. The both are largely correlated to the chosen wireless communication technology and its configuration.

Other issues also need to be addressed. These include the design of the antenna, which must be able to operate effectively in direct contact with the reinforced concrete, both for radiative electromagnetic WPT and for wireless communication (Fraile-Garcia et al., 2017). The antenna can also be manufactured by three-dimensional (3D) or inkjet printing, or even by additive techniques, and on various (possibly flexible) substrates. Furthermore, the encapsulation of the SN should be considered in order to deploy them directly in the reinforced concrete as aggregates, *i.e.* randomly and no longer in air cavities, while allowing reliable measurements (Castorina et al., 2016).

Alternative strategies for deploying the SN in the reinforced concrete can be discussed. It is possible: (1) to deploy only the sensor(s) in the core of the concrete and the rest of the SN on the surface, so that measurements are made at the most relevant locations and the SN are accessible and thus replaceable and updatable; but also (2) to deploy the SN in the core of the concrete and the antenna on the surface, so that measurements are made at the most relevant locations and the SN are inaccessible, but the constraints of electromagnetic propagation through the reinforced concrete are relaxed. In both cases, the use of cables between the different parts can create weaknesses in the reinforced concrete and surface access is also an access point for pollutants and other contaminants, such as air and water, which can induce more rapid corrosion.

#### 5. CONCLUSION

This paper presents a Wireless Sensors Network dedicated to the Structural Health Monitoring of reinforced concrete structures as the hardware basis for the implementation of a Cyber-Physical System. The Wireless Sensors Network consists of generic wireless and battery-free Sensing Nodes, which are intended to be completely buried in the reinforced concrete. They are powered and controlled remotely over several meters

by a radiative electromagnetic Wireless Power Transfer system, controlled by the Communicating Nodes. The Sensing Nodes are, to our knowledge, the first to offer a solution to the paradigm of Simultaneous Wireless Information and Power Transmission based on the use of a single antenna. Experimental results show that the range of the radiative electromagnetic Wireless Power Transfer is at least 11 meters indoors, at a frequency of 868 MHz, while the range of the wireless communication can reach hundreds of meters using LoRaWAN technology. The successfully tested Cyber-Physical System allows data to be measured and shared from inside the reinforced concrete to the digital world *via* the Internet.

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