Project ANR McBIM

Deliverable 2.4
Energy Harvesting Design

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Context

In the McBIM project and in order to implement a complete wireless sensor network embedded in a reinforced concrete element and autonomous in terms of energy for its entire lifetime, the solutions of ambient energy harvesting or of wireless power transmission were studied. This report will justify the choice of the far-field radiofrequency wireless power transmission and will explicit the choice of the different components of its interface: from the radiofrequency power source in the communicating nodes to the rectenna, as well as the strategy of management, storage and use of the collected energy in the sensing nodes.

Specifications

Some parameters should be taken into consideration in order to choose the best way to power the wireless sensor network once randomly deployed in a reinforced concrete element. Indeed, for the McBIM project, the sensing nodes must be embedded in a reinforced concrete element for its entire lifetime and also must be powered during all this time, without being accessible. These sensing nodes must be as compact as possible, must sense physical parameters, preprocess and then wirelessly broadcast the collected data to the communicating nodes. To date, less than 150 mJ is needed to measure the temperature and the relative humidity and send these collected data thanks to the LoRa technology and the LoRaWAN protocol to the communicating nodes as presented in Figure 1 [1]. This amount of energy is used as a reference for the design of the energy management and storage parts of the sensing nodes. It has to be noted that it is possible to reduce this needed energy by using less consuming sensor and wireless technology. Nevertheless, by beginning by the worst case, it is always possible to validate the concept for better cases. In order to release the constraints of a full energy autonomy for the wireless sensor network, the communicating nodes are considered as accessible and continuously powered (by the main power or a battery regularly recharged). Moreover, the distance between each component could be up to several meters.

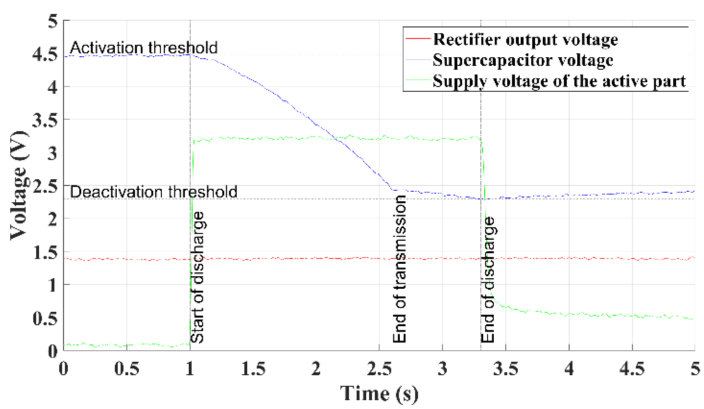

Fig 1. Use of the stored energy by the sensing nodes with a +10 dBm radiofrequency power available at the input of the rectifier.

Power sources

In order to release the constraints of a full energy autonomy for the wireless sensor network, the communicating nodes are considered as accessible and continuously powered (by the main power or a battery regularly recharged).

Concerning the sensing nodes, as they are fully embedded in reinforced concrete elements which composed buildings or engineering structures, the common ambient energy harvesting solutions are not conceivable: there is no light radiation for the photovoltaic solutions, the thermal gradient is locally too low for the thermal energy harvesting solutions, mechanical waves and vibrations are too weak and low frequencies for mechanical energy harvesting solution, and ambient radiofrequency energy is too low for ambient radiofrequency energy harvesting solution. More, solutions based on multiple sources are not relevant either. Moreover, the real backscattering solutions are appropriate in terms of communication but they do not intrinsically allow getting energy to use active sensors. Thus, the wireless power transmission solutions seem more suitable as they are no more dependent of the availability of ambient energy sources and, by controlling the emitted power, it is conceivable to wirelessly control of the behavior of the sensing nodes (as the periodicity of activation (measurement and transmission)) without needing to change or update the software or hardware. There are two kind of wireless power transmission: the inductive or nearfield wireless power transmission which is short range, and the radiative or far-field wireless power transmission which is medium to long range. In order to achieve the powering of the sensing nodes several meters around the communicating nodes, the radiative or far-field wireless power transmission was chosen.

The choice of the frequency of use was important in the case of the far-field radiofrequency wireless power transmission because it is related to the range of use. Indeed, this frequency is closely linked to the free space losses (more the frequency is high, more the free space losses are high, and less the useful distance of use is high) and to the size of the antenna (whose its maximal length is generally closely related to the wavelength) which will constraint the overall size of the sensing nodes. Moreover, the maximal equivalent isotropically radiated power allowed is function of the geographical area and the frequency of use [2-3]. Finally, the industrial, scientific and medical radiofrequency bands are privileged. The Table I summarize some relevant information leading up to a decision. The free space loses and the range to a defined power are calculated thanks to Equation 1 and Equation 2.

$$free\_space\_losses = 20 \cdot log\left(\frac{4 \cdot \pi \cdot d \cdot f}{c}\right) \quad (1)$$

with d the distance, f the frequency and c the celerity of light.

$$range = \sqrt{\frac{\lambda^2}{4 \cdot \pi} \cdot \frac{P_{EIRP}}{3600 \cdot \pi \cdot P_{RF}}} \quad (2)$$

with λ the wavelength, P_{EIRP} the maximal equivalent isotropically radiated power and P_{RF} the targeted power.

Table I: Comparison of the main industrial, scientific and medical band for far-field radiofrequency wireless power transmission

Main frequency	13.56 MHz	433 MHz	868 MHz	2.45 GHz	5.8 GHz
Wavelength	22.1 m	69.2 cm	34.4 cm	12.2 cm	5.2 cm
Bandwidth	14 kHz	1.74 MHz	5 MHz	100 MHz	150 MHz
Maximal equivalent isotropically radiated power	/	10 mW / +10 dBm	2 W / + 33 dBm	100 mW / +20 dBm	200 mW / +23 dBm / 1 W / +30 dBm
Free space losses at 1 m	/	25.17 dBm	31.21 dBm	40.23 dBm	47.71 dBm
Free space losses at 5 m	/	39.15 dBm	45.19 dBm	54.20 dBm	61.69 dBm
Range to +0 dBm	/	/	123 cm	9 cm	6 cm / 13 cm
Range to -14 dBm	/	87 cm	615 cm	49 cm	29 cm / 65 cm

Thus, the choice of the 868 MHz industrial, scientific and medical radiofrequency band was made because of being the best compromise between antenna size (linked to wavelength) and the theoretical useful range of use (linked to the maximal equivalent isotropically radiated power and the free space losses).

Finally, a radiofrequency power source was designed in order to emit an almost omni-directional +33 dBm radiofrequency continuous wave at 868 MHz. This radiofrequency power source is a part of the communicating nodes which would control it.

<u>Harvesting, management and storage of the radiofrequency energy</u>

Rectenna

A rectenna (rectifying antenna) is used to scavenge and convert into DC the radiofrequency power. It is composed of an antenna and a rectifier.

The choice of the antenna is detailed in the "Optimization of the antennas" report and met as well as possible the compromise between volume (as low as possible) and radiation pattern (high gain, large directivity and non-linear polarization). Thus, a printed on 1.6 mm FR4 folded dipole with capacitive arms is simultaneous used in the rectenna (for the far-field radiofrequency wireless power transmission) and for the wireless communication, thanks to the use of a radiofrequency circulator [4-5-6].

Concerning the rectifier, two main topologies were tested with various antennas in order to obtain the best performances [1]. A doubler radiofrequency rectifier manufactured on 0.8 mm thick FR4 substrate and a serial half-wave radiofrequency rectifier manufactured on 0.8 mm thick Rogers Duroid 5870 substrate -all based on Schottky diodes- were studied and compared for powering the sensing nodes. Figure 2 shows the times needed for each rectifier to achieve a first charge and recharges (in other words, the times needed to have the first measurement and transmission, and between each next ones), as well as their available output voltage, in function of the available radiofrequency input power at 868 MHz. These rectifiers are characterized at 868 MHz which is within a few MHz of their optimum use value. Concerning the output voltages: the doubler rectifier ones are the highest whatever the input radiofrequency power, but the Schottky diodes saturate for powers higher than +6 dBm. During the cold-start procedure (the main part of the first charge duration), a less than 400 mV voltage is imposed by the power management unit, that why serial rectifier is faster than doubler rectifier (which is more efficient for higher voltages) for the first charge. In contrary, when the cold-start procedure is achieved, the doubler rectifier is faster than serial rectifier for highest radiofrequency input powers, but the two rectifiers are close similar for lowest radiofrequency input powers. Regardless of the chosen rectifier, the sensing nodes have a periodicity of measurement and transmission which variate between few minutes to hours in function of the available power. Thus, by controlling the radiofrequency power source (in terms of transmitted power or duty cycle) it is possible to control wirelessly this periodicity without alter the sensing nodes software or hardware parts.

Thus, and to date, the choose rectenna is composed of a printed on 1.6 mm FR4 folded dipole with capacitive arms antenna and a doubler radiofrequency rectifier manufactured on 1.6 mm thick FR4 substrate and based on a Schottky diode. This topology allows the best compromise between volume of the sensing nodes and radiation patterns properties.

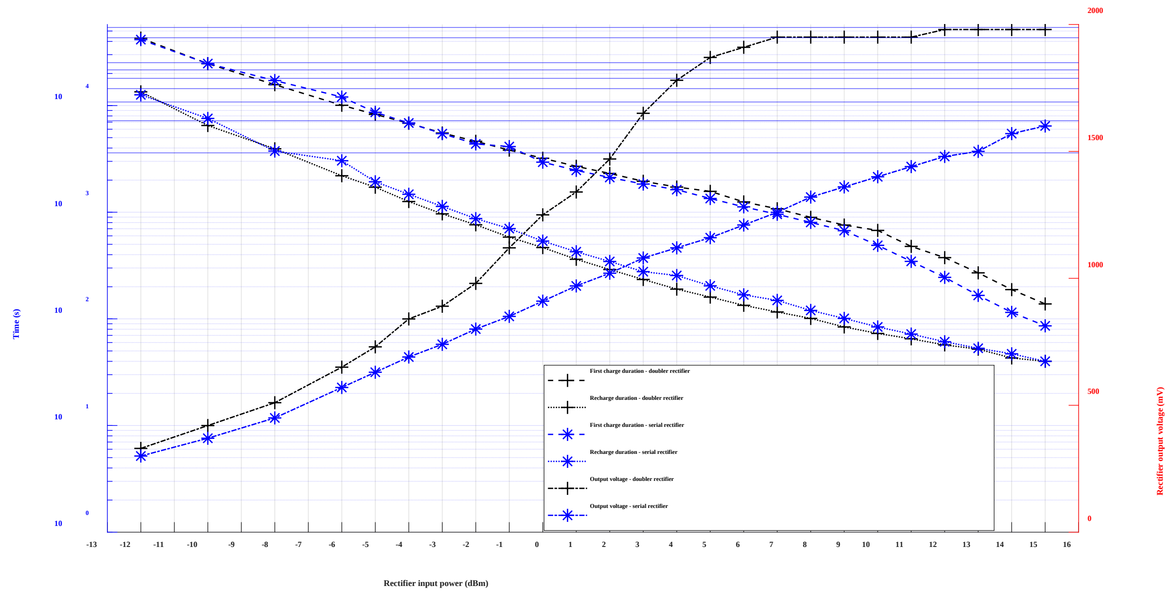

Fig 2. Durations of the first charge (dashed lines, left) and recharges (dotted lines, left) and rectifier output voltages (dotted and dashed lines, right) as function of the controlled radiofrequency power at 868 MHz applied at the input of the rectifier of the sensing nodes for the various rectifiers under test: doubler rectifier (+) and serial rectifier (*).

Power management unit

A power management unit is used in order to efficiently store the harvested energy provided by the rectenna in an electrical energy storage element and used this stored energy to power the active elements of the sensing nodes when enough energy is available. Several power management units were tested [7]: Analog Devices/Linear Technology LTC3105 and LTC3108, and Texas Instruments bq25504 and bq25505. The last two were chosen because they require the lowest input power (15 µW) to work properly, even during the cold-start, they have a hardware maximal power point tracking system, and they are configurable for the ratio of input voltage on the open-circuit voltage and the minimal and maximal thresholds for controlling the charge and discharge of the electrical energy storage element (and even thresholds for over- and under-voltage protections). As presented in Figure 1, when the high threshold is reached the energy stored in the storage element is transferred to the active components of the sensing nodes; and when the low threshold is reached the active components of the sensing nodes are disconnected in order to prevent the deep discharge of the storage element. The charge process is also restarted once the low threshold voltage is reach. To date, during each discharge, the sensing nodes could measure the temperature and humidity, pre-process these data and transmit them to the communicating nodes thanks to LoRa wireless technology and LoRaWAN protocol. The E-PEAS AEM30940 is another power management unit which is under investigation because needing a lower input power to work properly.

More, a Texas Instruments TPS63031 DC-to-DC buck/boost converter is used at the output of the power management unit to provide a constant power voltage at the active components of the sensing nodes. In that way, the energy consumption of the sensing nodes is reduced by reducing the current loses due to higher voltages [1].

Electrical energy storage element

An electrical energy storage element is needed in order to store the energy provided by the power management unit until being used to power the active components of the sensing nodes. This electrical energy storage element must have a low energy density (only 150 mJ have to be stored in the worst case), a medium to large power density (all the stored energy is consumed in few seconds), few electrical losses and must be reliable for decades. Thus, primary and secondary batteries are not suitable (because of a high energy density, a low power density and a lifespan of only several years), as well as a conventional capacitor (because of a too low energy density and too high electrical losses, even if a high power density). Thus, the supercapacitors (with a medium energy density, a medium power density, few electrical losses and a long lifespan) are privileged. Several supercapacitors were tested [7] and the AVX BZ01CA223ZSB was chosen because of its lowest announced loss current (10 µA). Thus, with a capacitance (C) of 22 mF and the activation and deactivation thresholds (V_{max} and V_{min}) of the power management unit fixed at 4.45 V and 2.3 V respectively, the energy stored (E) could be approximated at 159 mJ by the Equation 3:

$$E = \frac{C}{2}.\left({V_{max}}^2 - {V_{min}}^2\right) \quad (3)$$

In that way, enough energy is stored in the supercapacitor to make a full process of the sensing nodes (measurement and transmission) and even spared energy is available to compensate disparity in the components and the capacitance losses due to the ageing. Thus, if the energy needed decrease (by optimizing the radiofrequency energy harvesting or minimizing the consumption of the sensing nodes (e.g. by changing the wireless communication technology, limiting the current losses, etc.)), the capacitance can be reduced and the activation and deactivation thresholds optimized.

Efficiency

With the current architecture (rectenna made of a a printed on 1.6 mm FR4 folded dipole with capacitive arms antenna and a doubler radiofrequency rectifier manufactured on 1.6 mm thick FR4 substrate and based on a Schottky diode, Texas Instruments bq25504/bq25505, and 22 mF AVX BZ01CA223ZSB supercapacitor), the sensing nodes could work with a radiofrequency power down to -14 dBm or 40 µW at the input of the rectifier, that says a theoretical maximal range in free space of nearly 11 m from a +33 dBm or 2 W maximal equivalent isotropically radiated power source [1].

The energy efficiency of the sensing nodes (here defined as the ratio of the energy available at the input of the rectifier (i.e. the integrated available radiofrequency input power over the period of interest) to the energy needed for a measurement and transmission) is rather low for the first charge (between 3.4% and 9.2% for the doubler rectifier and 4.7% and 9.2% for the serial rectifier) and recharges (between 13.1% and 36.4% for the doubler and 13.1% and 31.0% for the serial rectifier), as shown respectively in Figure 3 and Figure 4. As said earlier, the serial rectifier is more efficient than the doubler rectifier during the first charge whilst this is the opposite during the recharges. For all the rectifiers, the lowest efficiencies during the first charges are for input powers higher than +4 dBm. Only the serial rectifier sees this efficiency re-increasing for input powers higher than +12 dBm. Moreover, the lowest efficiencies during the recharges are for lowest and highest input powers. To improve this energy efficiency, the electrical losses and the needs in terms of energy must be limited. For instance, the used supercapacitor has losses up to 11.5 µW for a 2.30 V voltage and up to 22.3 µW for a 4.45 V voltage. As well, the needed energy by the sensing nodes can be minimized by optimizing the software to shorten process time, by choosing low consumption sensors and transceivers, etc. In this way, the capacity could be reduced, as well as activation and deactivation threshold voltage, and so the losses could be again limited. Also, developing specific and well-defined components could improve the efficiency by reducing the needed energy: for instance, the power management unit used needs at least 15 µW just to work. Last but not least, the development of high efficiency rectifier (or radiofrequency-to-DC converter) has a large impact on the energy efficiency. In spite of these weak efficiencies, the sensing nodes are usable thanks to the data that can be generated and transmitted periodically, nevertheless this criterium has to be take in consideration to provide a sustainable system.

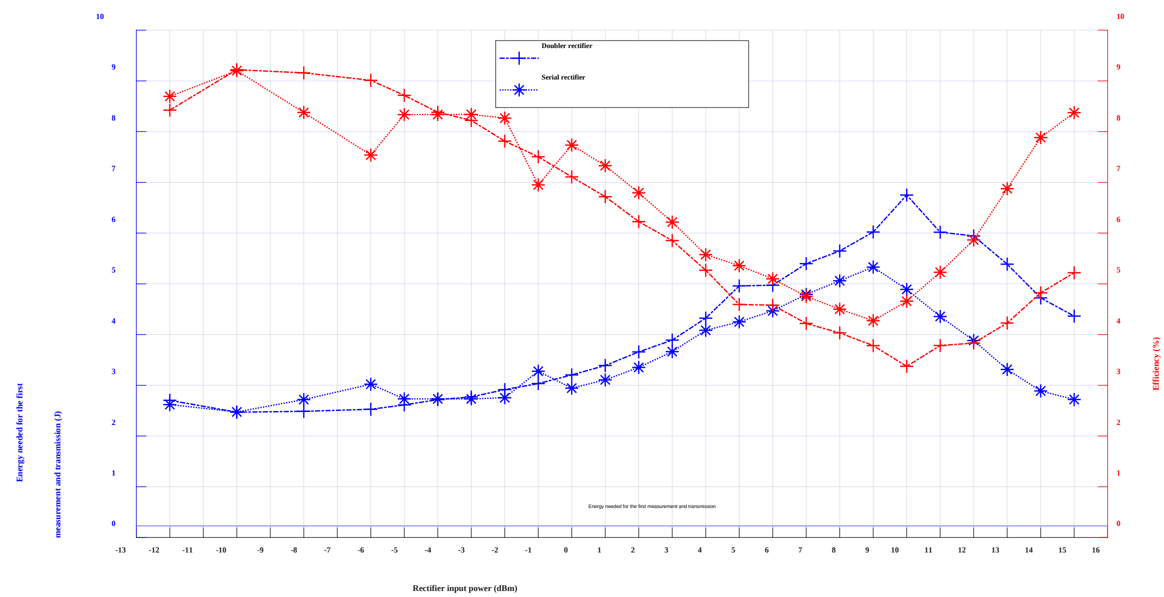

Fig. 3 Energy needed for the first charge (blue) and the energy efficiency of the sensing nodes during this first charge (red) as function of the controlled radiofrequency power at 868 MHz applied at the input of the rectifier of the sensing nodes for the various rectifiers under test: doubler rectifier (+) and serial rectifier (*).

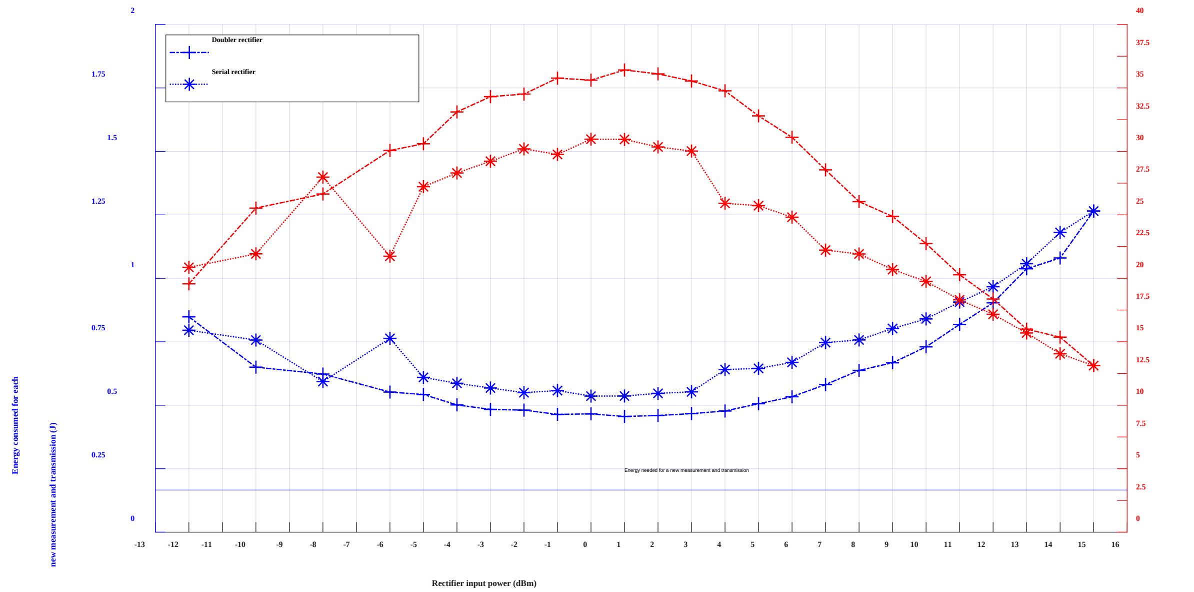

Fig. 4 Energy needed for recharges (blue) and the energy efficiency of the sensing nodes during recharges (red) as function of the controlled radiofrequency power at 868 MHz applied at the input of the rectifier of the sensing nodes for the various rectifiers under test: doubler rectifier (+) and serial rectifier (*).

Conclusion

To date, a first radiofrequency wireless power transmission system (a +33 dBm radiofrequency power source for the communicating nodes and a rectenna, a power management unit and a supercapacitor for the sensing nodes) was designed and tested, and is continuously updated to optimize it.

To complete the characterization of the sensing nodes with a controlled radiofrequency power at the input of the rectifier (which are some quantitative tests), several qualitative tests were achieved to have a full proof of concept of our wireless sensor network and to certificate that the system works properly even in a reinforced concrete beam. Thus, a sensing node has been wirelessly powered by a communicating node at a distance up to 550 cm in a complex environment (buildings subbasement) and in the air. A network architecture with a unique communicating node and multiple sensing nodes was tested in the air in order to certify that several sensing nodes can be powered by the same communicating node in a specified area (and that the data sent by each sensing nodes is well received and processed by the communicating node). A sensing node embedded in a reinforced concrete beam was successfully wirelessly powered by a communicating node located 170 cm away to which it sent successfully all the measured data. This 170 cm are composed of 15 cm of reinforced concrete and 155 cm of air. A specific air cavity was designed in the reinforced concrete beam to achieve these tests which are encouraging with the aim of provided a communicating reinforced concrete.

To go further and to upgrade the power efficiency of the radiofrequency wireless power transmission and the security, a learning period can be useful in order to characterize the environment of each communicating node*, id est* to discover the legal sensing nodes located in its neighborhood, to know their needs in terms of power to send for fully charging them (e.g. for a continuous wave at a specified transmitted radiofrequency power, the times need for the first charge and the recharges, etc.) or even their location by implementing beamforming solutions in the communicating nodes. It is even conceivable to make cohabite several fleets of sensing nodes (e.g. embedding different kinds of sensor) by dedicating a specific radiofrequency sub-band for the wireless powering to a kind of sensing nodes or even to a specific sensing node, or once more, by using beamforming solutions.

References

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