Project ANR McBIM

Deliverable 2.3
Antenna Design and Optimization

Alassane Sidibé, Gaël Loubet, Alexandru Takacs, Daniela Dragomirescu

Context

In the McBIM project and in order to implement a complete wireless sensor network embedded in a reinforced concrete element linked to a digital twin through the Internet, several kinds of antenna are required for two different applications. Indeed, both the wireless communications and the far-field radiofrequency wireless power transmission (or the ambient radiofrequency energy harvesting) need antennas. Moreover, there is a least three kinds of wireless communication with the framework of the wireless sensor network: from the sensing nodes to the communicating nodes, between the communicating nodes and from the communicating nodes to the Internet and/or the stakeholders.

This report concerns specifically the antennas dedicated to the far-field radiofrequency wireless power transmission from the communicating nodes to the sensing nodes and to the wireless data transmission from the sensing nodes to the communicating nodes. Thus, the antennas needed by the bidirectional communication between the communicating nodes and between the communicating nodes and the Internet are out of the scope of this report. Nevertheless, the optimization of these other antennas could follow the same process.

Specifications

Some parameters should be taken into consideration in order to choose or design an antenna. For the McBIM project, a compromise between the volume, the gain, the radiation pattern and the polarization of the antenna has been sought. Indeed, in order to have a low impact in the physical and mechanical properties of a reinforced concrete element, the volume of the sensing node (which is in part dependent of the size of the antenna) must be as low as possible; in order to have sufficient range of use (especially for the far-field radiofrequency wireless power transmission), the gain of the antenna must be as high as possible; and as the relative location and orientation of the sensing nodes in relation to the communicating nodes are random, a radiation pattern as isotropic as possible is wished and a non-linear polarization is preferred.

Far-field radiofrequency wireless power transmission

Regarding the far-field radiofrequency wireless power transmission, the choice of the frequency of use was preponderant. Indeed, this frequency is closely linked to the size of the antenna (whose its maximal length is generally closely related to the wavelength) and 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). Moreover, the maximal equivalent isotropically radiated power allowed is function of the geographical area and the frequency of use [1-2]. 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). It has to be noted that ambient radiofrequency energy is not taken into consideration into the different bands because of its very low power level [3].

Data transmission from sensing nodes to communicating nodes

Regarding the data transmission from sensing nodes to communicating nodes, the choice of the wireless communication technology of use was preponderant. Indeed, each communication protocol have specific needs in terms of antenna according to the central frequency and the bandwidth they use as presented in Table II.

Table II: Comparison of the targeted radiofrequency wireless communication technologies

Technology	IEEE 1902.1 (RuBee) [4]	LoRa [5]	IEEE 802.15.1 (Bluetooth Low Energy) [6]
Electromagnetic wave type	Inductive	Radiative	Radiative
Central frequency	131 kHz	868 MHz	2.45 GHz
Bandwidth	/	Up to 500 kHz	2 MHz
Link budget	/	Up to 170 dB	Up to 105 dB

The optimization process of antennas was firstly achieved for the LoRa radiofrequency wireless communication technology.

Sensing nodes

The sensing nodes must both be able to harvest the radiative power transmitted by the communicating nodes and be able to wirelessly transmit the collected data to the communicating nodes, both through an antenna. As the frequency chosen for the far-field radiofrequency wireless power transmission and the one used by the LoRa technology are similar (868 MHz) and as the downlink is for the power and the uplink for the data, it is possible to use a unique antenna with a radiofrequency circulator for these two assignments. In this way, the size of the sensing node can be minimized and the paradigm of simultaneous wireless power and information transmission is met. If the frequency chosen for the far-field radiofrequency wireless power transmission and the one used by the wireless communication technology are different, the use of a unique antenna with a radiofrequency circulator is always possible if the antenna is bi-band and if the radiofrequency circulator covers the two bands. Anyhow, this kind of antenna is more complex to design and the characteristics in each band will differ. For the sensing nodes, the antenna must allow to receive the maximum radiofrequency power and to transmit the data with the highest power. Lastly, the choice of using the ground plan of the printed circuit board of the sensing node as a reflector plan was made. In this way, the gain of the antenna could almost be double at the price of the modification of the radiation pattern whose a half is deleted (the ‘bottom’ side of the radiation pattern is translated and added to the ‘front’ side).

Communicating nodes

The communicating nodes must both be able to transmit the radiative power needed to wirelessly power the sensing nodes and be able to wirelessly receive the collected and transmitted data from the sensing nodes, both through an antenna. As the frequency chosen for the far-field radiofrequency wireless power transmission and the one used by the LoRa technology are similar (868 MHz) and as the downlink is for the power and the uplink for the data, it is possible to use a unique antenna with a radiofrequency circulator for these two assignments.

In this way, the size of the communicating node can be minimized and the paradigm of simultaneous wireless power and information transmission is again met. If the frequency chosen for the far-field radiofrequency wireless power transmission and the one used by the wireless communication technology are different, the use of a unique antenna with a radiofrequency circulator is always possible if the antenna is bi-band and if the radiofrequency circulator covers the two bands. Anyhow, this kind of antenna is more complex to design and the characteristics in each band will differ. For the communicating nodes, the antenna must allow to transmit the maximal equivalent isotropically radiated power and to receive the data with the lowest sensitivity.

General constraints

The current solution is mainly constrained by the far-field radiofrequency wireless power transmission, which has a useful range of few meters, and not by the radiofrequency wireless communication technology, LoRa, which could transmit data over kilometers even in non-optimal configuration. In that way, the design and choice of an antenna were done in order to optimize far-field radiofrequency wireless power transmission (in fact, the rectifier associated to this antenna to get a rectenna must also be designed in parallel in order to optimize far-field radiofrequency wireless power transmission). Thanks to the use of the radiofrequency circulators (in the sensing nodes and in the communicating nodes), the discrimination between the the far-field radiofrequency wireless power transmission and the radiofrequency wireless communication is effective without interference problem. Thus, and simultaneously, the sensing nodes can be wirelessly powered by the communicating nodes and the communicating nodes can successfully receive all the data send by the sensing nodes.

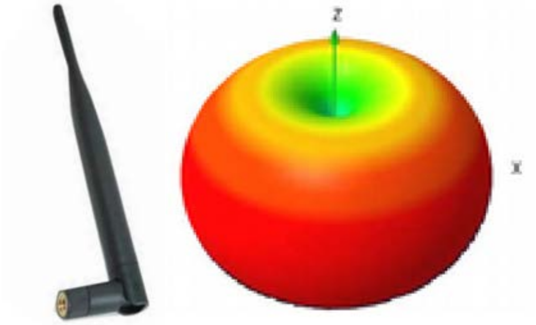
Used antennas

During the McBIM project, several antennas were designed, tested or used, sometimes for the communication, sometimes for the far-field radiofrequency wireless power transmission, and sometimes for the two.

Half-wavelength and quart-wavelength whip antenna

Only two commercial antennas were used during the McBIM project.

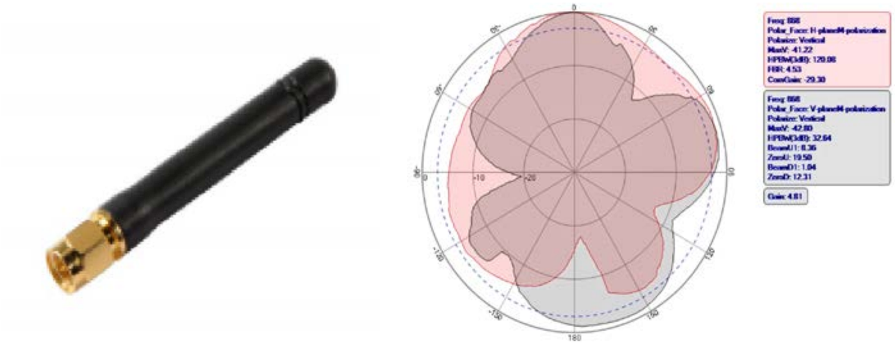
The IMST iC880A LoRaWAN gateway includes a RF Solutions ANT-8WHIP3H half-length whip antenna [7]. This is an almost omnidirectional antenna with a vertical polarization, a center frequency of 868 MHz and a theoretical gain of +3 dBi at 868 MHz. This one was firstly used for the LoRaWAN gateway as a part of the exploded communicating node. Currently, this is used as the unique antenna of the exploded communicating node, connected to the port 1 of an Aerotek C11-1FFF/OPT.N circulator (with the port 2 used by the LoRaWAN gateway and the port 3 by the radiofrequency power source). Indeed, regarding the far-field radiofrequency wireless power transmission, its almost omnidirectionality allows to irradiated a large volume and its gain of +3 dBi allows to transmit a +33 dBm of radiofrequency power without the use of an attenuator (the radiofrequency power source provides a +30 dBm of radiofrequency power at the port 1 of the circulator). Regarding the communication aspect, its almost omnidirectionality allows to receive at least all the data send by the sensing nodes located in its area covered by the the far-field radiofrequency wireless power transmission.



(a) (b)

Fig 1. (a) Photograph and (b) theoretical radiation pattern of the RF Solutions ANT-8WHIP3H at 868 MHz

The ST B-L072Z-LRWAN1 includes a LPSR ANT-SS900 compressed (quart-wavelength) whip antenna [8]. This is an almost omnidirectional antenna with a vertical polarization, usable at 868 MHz and 915 MHz and with a theoretical gain of +2 dBi at 868 MHz. This one was only used for the communication part of the first exploded prototype of the sensing node.

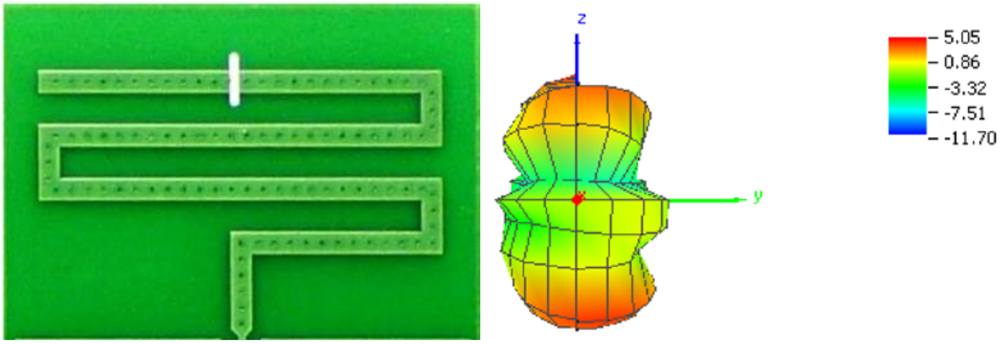


(a) (b)

Fig 2. (a) Photograph and (b) radiation pattern of the LPSR ANT-SS900 at 868 MHz

Printed quart-wavelength meandered monopole antenna

A printed on 1.6 mm FR4 substrate quart-wavelength meandered monopole antenna whose the design is provided by TI was used for the communication part of the first integrated prototype of the sensing node [9]. This is an almost omnidirectional antenna with a vertical polarization, usable at 868 MHz and 915 MHz and with a theoretical gain of +5.05 dBi at 868 MHz.

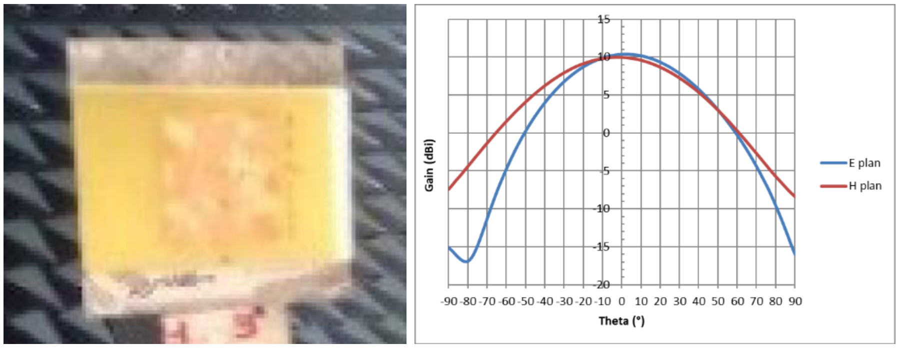


(a) (b)

Fig 3. (a) Photograph and (b) radiation pattern of the TI printed meandered monopole at 868 MHz

Printed half-wavelength patch antenna

In order to have a reference antenna for the measurement in the anechoic chamber, a printed on 1.6 mm FR4 substrate half-wavelength patch antenna was designed, manufactured and characterized. This is a directional antenna with a vertical polarization, usable between 859.5 and 886 MHz and with a gain of +10.35 dBi at 868 MHz. This one was used for the far-field radiofrequency wireless power transmission part of the first exploded prototype of the communicating node. It was also connected to radiofrequency power synthesizer which could generate a wave at 868 MHz with a maximal power of +24 dBm. Thus, with this patch antenna and by taking into consideration the loses induced by the connectors, this first radiofrequency power source could provide a measured +31.9 dBm radiofrequency wave at 868 MHz.

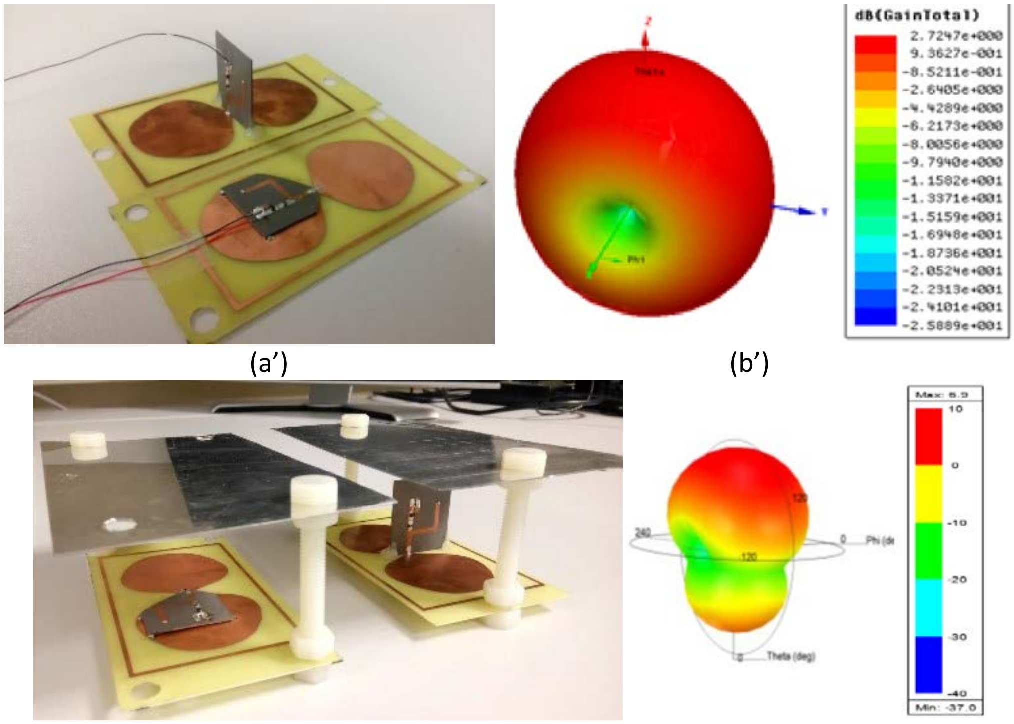


(a) (b)

Fig 4. (a) Photograph and (b) radiation pattern of the patch antenna at 868 MHz

Printed rounded quart-wavelength dipole antenna with resonant rectangular ring

A printed on 1.6 mm FR4 substrate rounded quart-wavelength dipole antenna with resonant rectangular ring was designed, manufacturer, characterized and well highlighted in [10-11-12-13]. This is an almost omnidirectional antenna with a vertical polarization, usable between 850 and 910 MHz and with a gain of +2.64 dBi at 868 MHz. A reflector plan was added at 6 cm from this antenna in order to emulate the ground plan of the printed circuit board of the sensing nodes. By that way, the gain was increased up to +6.8 dBi at the cost of the increase of the directionality and the rise of the volume. This antenna was used in the rectenna of the exploded prototypes and of the first integrated prototypes of the sensing nodes, and several topologies were tested.



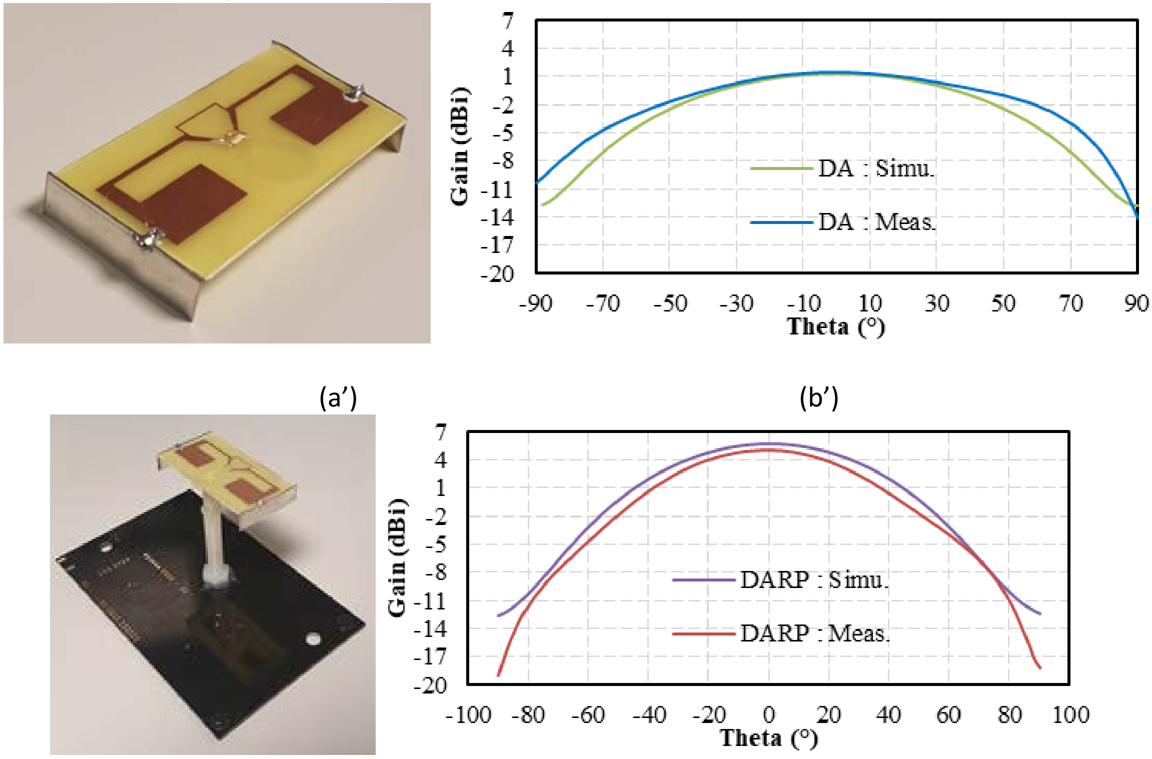
(a’) (b’)

(a’’) (b’’)

Fig 5. (a) Photograph and (b) radiation pattern of the rounded dipole with resonant ring at 868 MHz (‘) without and (’’) with a reflector plan

Printed folded quart-wavelength dipole antenna with capacitive arms

A printed on 1.6 mm FR4 substrate folded quart-wavelength dipole antenna with capacitive arms was designed, manufacturer, characterized and well highlighted in [14-15-16]. This is an almost omnidirectional antenna with a vertical polarization, usable between 848 and 886 MHz and with a gain of +1.54 dBi at 868 MHz. A reflector plan was added at 5 cm from this antenna in order to emulate the ground plan of the printed circuit board of the sensing nodes. By that way, the gain was increased up to +5.0 dBi at the cost of the increase of the directionality and the rise of the volume. This antenna was used as the unique antenna for the integrated prototypes of the sensing nodes using a circulator.



(a') (b')

(a'') (b'')

Fig 6. (a) Photograph and (b) radiation pattern of the folded dipole with capacitive arms at 868 MHz (') without and ('') with a reflector plan

Comparison

Antenna	RF Solutions ANT-8WHIP3H	LPSR ANT-SS900	Meandered monopole	Patch	Rounded dipole with resonant ring	Rounded dipole with resonant ring and reflector	Folded dipole with capacitive arms	Folded dipole with capacitive arms and reflector
Type	Whip antenna	Compressed whip antenna	Printed meandered monopole	Printed patch with reflector plan	Printed rounded dipole with resonant rectangular ring	Printed rounded dipole with resonant rectangular ring and reflector	Printed folded dipole with capacitive arms	Printed folded dipole with capacitive arms and reflector
Frequency band	868 MHz	868 MHz – 915 MHz	825 to 913 MHz	859.5 to 886 MHz	850 to 910 MHz	850 to 910 MHz	848 to 886 MHz	848 to 886 MHz
Gain at 868 MHz	+3 dBi	+2 dBi	+ 5.05 dBi	+10.35 dBi	+2.64 dBi	+ 6.8 dBi	+1.54 dBi	+5 dBi
Volume / Size	≈ 31.87 cm^3 / ⌀ 14 mm x 207 mm	≈ 2.56 cm^3 / ⌀ 8 mm x 51 mm	≈ 1.52 cm^3 / 38 mm x 25 mm x 1.6 mm	≈ 600 cm^3 / 300 mm x 200 mm x 10 mm	≈ 198 cm^3 / 110 mm x 60 mm x 30 mm	≈ 756 cm^3 / 140 mm x 90 mm x 60 mm	≈ 17.92 cm^3 / 56 mm x 32 mm x 10 mm	≈ 240 cm^3 / 80 mm x 60 mm x 50 mm
Impedance	50 Ω	50 Ω	50 Ω	50 Ω	50 Ω	50 Ω	50 Ω	50 Ω
Radiation pattern	Almost omni-directional	Almost omni-directional	Almost omni-directional	Directional	Almost omni-directional	Directional	Almost omni-directional	Directional
Polarization	Linear (vertical)	Linear (vertical)	Linear (vertical)	Linear (vertical)	Linear (vertical)	Linear (vertical)	Linear (vertical)	Linear (vertical)

Discussion and choice

In order to minimize the volume of the communicating nodes and the sensing nodes, the use of a unique antenna for the far-field radiofrequency wireless power transmission and the wireless communication is privileged. As previously said, it is the far-field radiofrequency wireless power transmission which would be limiting in terms of range of use. To meet these requirements, this antenna must be coplanar to the printed circuit board in order to use it as a reflector plan and increase its gain.

Regarding the antennas designed around the McBIM project, an evolution to a compromise between size (as small as possible) and gain (as high as possible) was driven. Thus, the volume of the antenna with the reflector plan (in other words, the printed circuit board) was reduced between the patch antenna to the folded dipole with capacitive arms, through the rounded dipole with resonant ring. The gain was also reduced but to a lesser extent and stays high enough to conserve to interesting range of use (few meters).

Even if the meandered monopole seems to have equivalent or even better characteristics than the folded dipole with capacitive arms, these were obtained in optimal conditions (specifically with a large ground plan) and thus it seems unrealistic to get a same behavior in complex environments (specifically with some electronic in its neighborhood).

Finally, and to date, the choice of the folded dipole with capacitive arms has been made to be used as the unique antenna of the sensing node for the far-field radiofrequency wireless power transmission and the wireless communication [17]. Because of the size of the printed circuit board, it was easy to adapt it to become a reflector plan and thus, the volume of the sensing nodes stays modest enough and the characteristics are sufficient (bandwidth, gain and directionality large enough).

Moreover, the choice of the RF Solutions ANT-8WHIP3H has been made to be used as the unique antenna of the communicating node for the far-field radiofrequency wireless power transmission and the wireless communication. Indeed, the volume of the communicating nodes are not yet constraints and the directivity and the gain of this antenna are particularly adapted to the needs of the radiofrequency power source (the +3 dBi of gain allows to transmit +33 dBm of radiofrequency power without using an attenuator, and the omnidirectionality allows to cover a large area/volume. For a updated version of the communicating nodes, there is a good chance that a specifically designed antenna would be used.

Conclusion

To date, several antennas were investigated and tested in the framework of the McBIM project. Even if a commercial solution is currently used for the communicating nodes, a specifically designed state of the art antenna is used for the sensing nodes. Obviously, the search of the best compromise between volume and radiation pattern (gain, directivity and polarization) is always under investigations. More, first designs of folded dipole with capacitive arms on a flexible substrate (Kapton) were leaded and, even if some manufacturing problems were highlighted, the preliminary results are encouraging. In that way, it becomes conceivable to design a sensing node fully on a flexible substrate, that could suffer from mechanical constraints and adapt itself without cracking. Lastly, the designed and used antennas were tested into a reinforced concrete beam and both the far-field radiofrequency wireless power transmission and the wireless communication work properly. Nevertheless, the sensing nodes are not in a direct contact with the reinforced concrete (there is an air gap), so, it is strongly possible that an impedance mismatch occurs and that a new design must be provided to compensate these effects [18].

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