Wireless interfaces for sensor networks embedded in tough environments

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Abstract—The paper introduces an efficient procedure that allows the design of low cost magnetic antennas with arbitrary shape and extremely reduced dimensions. The technique is mainly analytical, with a simple and fast optimization procedure and it can be applied to any magnetic antenna, even with very complex geometry, e.g., with fractal shape. Simulations have been compared to measurements, proving an excellent agreement. The chosen configuration is implemented in planar geometry, where the transceiver and the matching circuit can be inserted within the antenna perimeter, allowing the realization of compact devices. For this reason, the device can be efficiently proposed for the realization of the terminal unit in wireless sensor networks. A first prototype has been constructed and tested and the results showed an excellent range.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) represent an efficient instrument for a detailed analysis of a general set of physical parameters, even in complex environments. Several examples of application can be found in the literature [1], [2] for a huge variety of cases. Each of those requires a dedicated design, for the construction of the physical sensor, the definition of the electronics circuitry, the realization of an efficient ad-hoc network, based on the configuration of the scenario to which the device should be applied. In many cases, the electromagnetic front-end (antenna, matching circuits, connecting cables) is designed by means a standard design procedure. Many times, radiofrequency (RF) components are chosen from a set of available commercial ones. When the device must be inserted in environments with extreme complexity, a dedicated design procedure should be introduced. In some cases, different RF configurations must be adopted, depending on the geometrical and physical characteristics of the application point [3]. Since an essential characteristic of WSNs, and in particular WSN terminal nodes, is the minimization of the manufacturing costs, the RF design must be simple, repeatable and controllable.

II. AD-HOC ANTENNAS IN TOUGH ENVIRONMENTS

In the recent past we have designed and realized wireless sensor networks with the sensing unit embedded in harsh environments. I.e., within water conduits, to monitor the characteristics of the pipeline [4], or more recently, inside glaciers and snowfields, to monitor the wateriness and forecast avalanche events [5]. We are now evaluating the possibility to use wireless sensors to monitor the humidity content of the roots, to better estimate the physical parameters that govern the growth of the trees and the production of the fruits.

In all mentioned scenarios, the wireless node is embedded in a dissipative medium, and the design of its RF part must take into account the electromagnetic characteristics of the surrounding environment, as well as its dimensions. The nodes require low energy consumption. They must communicate trough relatively short distances, with presence of several obstacles that make the propagation highly dissipative.

To achieve adequate performance, very low frequencies should be used, leading to the exploitation of antennas with large dimensions. Furthermore, the presence of a medium with low propagation impedance suggests the use of magnetic antennas, preferably short ones. In this way, the coupling between the radiator and the environment is optimized, the losses are minimized, and smaller dimensions are necessary for the RF components. Furthermore the use of magnetic antennas allows the adoption of circuitual configurations where the matching circuit and the transceiver can be mounted on the plane containing the radiator. In particular, those circuits can be hosted on the surface inside the antenna perimeter, guaranteeing the absence of any coupling with the radiator itself, avoiding any further increment of the dimension of the device.

The chosen frequency for this project is the Industrial Scientific Medical (ISM) 433MHz which has a wavelength in the free space $\lambda = 693\text{mm}$.

III. ANTENNA TYPOLgy AND DESIGN CONSTRAINTS

We have been working on the definition of a suitable antenna geometry based on the previous research of the iXem lab [6], as well as the identification of a procedure for the design of radiators in lossy media [7]. Moreover we have adopted an efficient design model that allows to synthesize magnetic antennas in very few steps. It introduces an extremely compact and efficient configuration, and it reduces the use of optimization process for its definition.

The magnetic antenna is printed in the form of a loop on a dielectric sheet that stands as support. For our first trials, we have used a a standard dielectric sheet for printed circuits with dielectric permittivity $\epsilon_r = 4.5$. The height of the sheet...
is about 1.6 mm. The radiating element is realized by means of a metalization printed over a dielectric, one be referred in the following as radiating line. The matching elements have been realized by means of stubs hosted on the same portion of the board. We have chosen to implement those reactances by means of stubs, instead of lumped elements, for more flexibility and to enforce the bidimensional shape of the device. In the following, these stubs are referred as matching lines.

In Fig. 1, real and imaginary parts of the loop impedance are reported as a function of the ratio between the loop circumference and the wavelength. Assuming that a 50 Ω matching is required, according to those curves, it is sufficient to choose the radius for which the real part of the loop impedance is equal to 50 Ω, and cancel its imaginary part by dimensioning the reactances of the circuit shown in Fig. 2 in order to satisfy the rule \[ X_{m1} + X_{m2} + X_{ant} = 0. \] Depending on the application, \( X_{m1} \) and \( X_{m2} \) can be equal, one of the two can be equal to zero, or it may be necessary to realize a non-symmetric configuration.

Figure 3 shows the variation in frequency of the real part (continuous blue line) and imaginary part (dashed green line) of the impedance of a standard loop with radius 55 mm. The two solutions at the left part of the curve correspond to short antennas while the two points to the right of the curve are the one used for self resonant antennas. The first and third solution are preferable, since the antenna reactance variation in frequency is smoother than the one characterizing the second and fourth points. As one can notice, both the chosen options are characterized by a positive reactance. Hence, the matching requires the realization of capacitive stubs, with open-circuited terminations, in order to minimize the dimensions.

When applicable, the symmetric solution (Fig. 4.a) is preferred. Alternatively, a single stub solution can be implemented (Fig. 4.b). Sometimes, if the reactance of the antennas is too small, a longer stub would be required. To make it shorter, the configuration reported in Fig. 5 is implemented: one of the stubs is capacitive, the second inductive, and the desired value is obtained from the difference between the two reactances. To maintain the symmetry, the stubs reactance is varied by playing with the stub characteristic impedance, rather than the stub length.

The design procedure requires the adoption of an iterative process, or an optimization procedure, in order to compensate the coupling effect between the loop and the stubs. The optimization is necessarily needed when more complex geometries
are adopted, e.g. a loop with non constant radius.

As stated before, two antenna typologies have been chosen for the mentioned application: a short antenna and a self resonant one. The first case has a reduced bandwidth but a very small dimension, while the second case has a larger bandwidth but a bigger dimension. For sensing applications, the limitation in bandwidth does not affect the performance of the system, as monitored data are typically characterized by an extremely limited data rate.

The chip used has a balanced connector which impedance changes with the working frequency (it can work in several bands such as 315/433/868/915 MHz).

IV. IMPROVED GEOMETRY FOR ANTENNA SIZE REDUCTION

It is evident that a variation of the radius with the angle generates a longer path for the current, lowering down in frequency its radiation behavior. For this reason, the standard loop geometry has been modified by adopting a flower shape, where the radius of the loop is a function of the polar coordinates \( \theta \).

\[
R = \delta \rho \cos(N.\theta)
\]

where \( \rho \) is the original loop radius, \( \delta \) and \( N \) are parameters, describing the height of the petals and their number (see Fig. 5 for reference).

To synthesize the radiating line, and maintain a constant distance between the radiating line borders, the following Cartesian expressions have been deduced for the outer and inner borders:

\[
\begin{align*}
    x_{up} &= x_{old} + \delta \cos(\beta)(1 + \cos(N.\theta + \phi)) \\
    y_{up} &= y_{old} + \delta \sin(\beta)(1 + \cos(N.\theta + \phi)) \\
    x_{down} &= x_{old} - \delta \cos(\beta)(1 - \cos(N.\theta + \phi)) \\
    y_{down} &= y_{old} - \delta \sin(\beta)(1 - \cos(N.\theta + \phi))
\end{align*}
\]

where \( \beta \) is the angle of the normal to the perimeter of the flower.

V. SYNTHESIS PROCEDURE VALIDATION

The synthesis procedure has been implemented and validated by realizing a first prototype working at 868 MHz. This choice is originated by the availability of a transceiver, which has been implemented on the board to analyze any electromagnetic compatibility issue. The transceiver is a Ciseco XRF, based on the Texas Instruments CC1110 chip with an SMA connector of 50\( \Omega \) at 868 MHz.

For the validation of the method, we have chosen to synthesize a self-resonant antenna, comparing the measured results to a traditional self-resonant loop with lumped matching circuit. In particular, we have added an additional design parameter: the width of the radiating line. By increasing the width, the antenna reactance decreases, until the point where it is equal to zero. In this way, it has been possible to avoid the presence of the matching circuit.

The antenna has been synthesized with the following parameters: \( R_{int} = 16 \text{mm}, \ N=12, \ \delta \rho = 0.42 \), external radius 39 mm, which represents a 30% reduction with respect to a normal self-resonant loop radiator. Fig. 6 shows the realized prototype.

The antenna impedance and the performance of the matching circuit has been measured by means of a network analyzer (Agilent technologies model E8361A). The antenna has been inserted in an anechoic chamber, with dimensions 25 m x 5 m x 3 m working in the frequency range 700 MHz - 40 GHz. Radiation pattern measurements have been done in the same environment, along the three main Cartesian planes.

The antenna has been measured and results are represented in Fig. 7, showing a matching in terms of input impedance. The radiation pattern is reported in Fig. 8, where it is possible to appreciate the value and the efficiency. The characteristics have been verified in presence of the XRF board getting excellent results.
VI. LOW FREQUENCY ANTENNA

Once the model has been validated, a 433MHz antenna has been synthesized. The radiating line width has been reduced to ψ = 1mm and the number of petals has been increased from 12 to 20.

Two antennas have been designed, a self-resonant and a short one. The solutions with positive reactance have been chosen, to obtain a larger bandwidth. The short one has been synthesised with the following parameters \( R_{int} = 12\text{mm} \), \( N=20 \), \( \delta \rho = 0.17 \). The self-resonant one has been synthesized with \( R_{int} = 12\text{mm} \), \( N=20 \), \( \delta \rho = 0.5 \).

Figure 9 shows the two antennas compared to a short magnetic loop, synthesized with the same technique.

The short antennas is characterized by a high reactance, hence its cancellation can be obtained by using two small symmetric matching lines. As shown in Fig. 10, the obtained bandwidth is small, and the result appears to be shifted in frequency. This is mainly due to the selective dependency of the lines dimensions, and it can be reduced by increasing the printing definition.

The self-resonant antenna is characterized by a small inductive impedance. In this specific case, we have decided to avoid compensating it by the line width: this action is not compatible with the chosen number of petals. Since the reactance is small, longer stubs are required. The asymmetric solution with one stub is preferred, but the optimum one is represented by the use of one opened and one shorted stub (Fig. 5). With this technique the two stubs are shorter, and it has the advantage to maintain the antenna more or less symmetric. Both antennas have been synthesized, obtaining good performance as shown in Fig. ??

VII. CONCLUSION

The paper presents an improved technique for the synthesis of magnetic antennas with modified loop perimeter, obtaining devices with extremely compact dimensions. The synthesis procedure has been validated. It is applicable to realize any kind of matching, independently on the characteristics of the transceiver.

REFERENCES