WIRELESS SENSORS EMBEDDED IN CONCRETE

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ABSTRACT

Efficient embedded antennas are needed for future wireless structural health monitoring. The properties of patch antennas with concrete are investigated at 860MHz. Simulations for different cases (different concrete permittivity and tangent loss) with and without the presence of steel reinforcements are performed using ANSYS HFSS software for 3-D full-wave electromagnetic field simulation and some experimental results are presented.

KEYWORDS : *Wireless sensor networks, concrete attenuation, embedded antenna, concrete characterization , reinforcement bars.*

INTRODUCTION

SHM (Structural Health Monitoring) is a system that diagnoses the condition of structures such as buildings, bridges, roads, and so on, to repair and prevent the potential danger of collapse by detecting it in advance. Current structural health monitoring systems are usually based on wired measurement equipment. The main drawback of such systems is that the number of sensors is limited, reducing the extensibility of the system significantly. Especially, wired systems require a non-trivial amount of time and cost for the initial deployment.

Recently there has been considerable interest among researchers on distributed wireless sensors to monitor the health of infrastructures. Of particular importance are embedded sensors which can be implemented during the construction phase of bridges and buildings.

The fundamental problems of any wireless sensor embedded in concrete are the wireless communication and power consumption. Electromagnetic waves suffer from attenuation in concrete depending on the moisture content [3], the heterogeneity of concrete, the presence of metal [4] and other factors. Efficient embedded antennas are needed for future wireless structural health monitoring. Since the integration of wireless communication removes the need for transmitting data from one point to another with cables, the lack of cables requires in situ power. Currently, batteries represent the most common portable power source for wireless sensor.

In this paper the characteristics of an embedded patch antenna is studied to investigate the data communication. Numerical simulations were conducted using HFSS to study the return loss and transmission loss of an embedded patch antenna within concrete.

1 DIELECTRIC PROPERTIES OF CONCRETE

To design efficient embedded antennas, we need to know the relative permittivity (dielectric constant) and conductivity of concrete. It is well known that the propagation of electromagnetic waves will be affected by the presence of moisture in the concrete. The real part of the complex permittivity and the effective conductivity of concrete have a fundamental role in assessing the ability of concrete to inhibit the propagation of electromagnetic waves.
The inherently lossy nature of concrete is taken into account by a complex permittivity (1):

$$\varepsilon^{*} = \varepsilon^{'} - j\varepsilon^{''} \tag{1}$$

Where $\varepsilon^{'}$ and $\varepsilon^{''}$ are the real and imaginary parts of the concrete dielectric constant, respectively. In general both $\varepsilon^{'}$ and $\varepsilon^{''}$ can depend on frequency in complicated ways and to some degree on moisture content.

The real part of the relative permittivity is presented in equation (2):

$$\varepsilon_{r}^{'}(\omega) = \varepsilon_{\infty} + \frac{\Delta\varepsilon}{1+\omega^{2}\tau^{2}} \tag{2}$$

Where $\Delta\varepsilon$ stands for the difference between the values of the real part of the relative permittivity at low and high frequencies, and τ is the relaxation time. The real part of the complex relative permittivity represents the ability of the medium to store electrical energy.

The imaginary part of the complex relative permittivity represents the energy losses due to dielectric relaxation as follows in equation (3):

$$\varepsilon_{r,eff}^{''}(\omega) = \frac{\omega\tau\Delta\varepsilon}{1+\omega^{2}\tau^{2}} + \frac{\sigma_{dc}}{\omega\varepsilon_{0}} = \frac{\sigma_{eff}(\omega)}{\omega\varepsilon_{0}} \tag{3}$$

Where σ_{dc} is the DC electrical conductivity of concrete and $\sigma_{eff}(\omega)$ is the effective conductivity.

2 CHOICE OF FREQUENCY AND ANTENNA TYPE

Attenuation in concrete increase with frequency [1]. Moisture and metal increases radio attenuation in concrete, an effect which is more pronounced at higher frequencies.

The 860MHz ISM band is chosen as the transmission frequency for sensors embedded in reinforcement concrete, since antennas working in this band are less sensitive to the effects of varying humidity as well as rebar configuration.

Our objective is to design and develop an antenna embedded in concrete in the 860MHz band that can support the functions of data communication. Since the dielectric constant and loss tangent of concrete vary depending on the moisture content we investigate the characteristics of a patch antenna as function of those parameters. Patch or printed antenna is a type of antenna which can be used for transmitting and receiving signals. They are low profile, small size and light weight. In this paper, the prototype patch antennas were simulated, designed, fabricated and tested within concrete.

3 ANTENNA CONCEPTION

Efficient embedded antennas are needed for future wireless structural health monitoring. The input return loss and transmission losses of a patch antenna are studied at around 860 MHz when these antennas are embedded inside a concrete box. The return loss S_{11} is the loss of signal power resulting from the reflection caused at a discontinuity in a transmission line. Usually expressed in decibels (dB), it is a measure of how well devices are matched. A match is good if the return loss is low [2]. The transmission coefficient S_{21} is the forward gain or loss.

Antenna performance is investigated in free-space, in air dried concrete and in saturated concrete without the presence of steel reinforcements. A probe-fed patch antenna measuring 7.014cm by 7.11cm by 2.8 mm was designed on Taconic RF-60(tm) substrate (ε_{r} =6.15 and $\tan\delta$=0.0028).

3.1 Model setup:

Two pairs of probe-fed patch antennas were buried in (40x60x100cm^3) boxes of: free space, dry and saturated concrete respectively with a distance of D=20cm between the two antennas for each case. In Free space: ε_{r} =1 and $\tan\delta$=0, Dry concrete: ε_{r} =4.5 and $\tan\delta$=0.0111, Saturated concrete:

ε_r =7.5 and $\tan\delta$=0.133. Similar geometries are used for all three cases. Experimentally, the sensor has a center frequency at 860 MHz when matched to a 50 ohm transmission line. The electromagnetic properties of concrete a t different relative permittivity determine the power loss level of the electromagnetic wave and the performance of the antenna buried inside it.

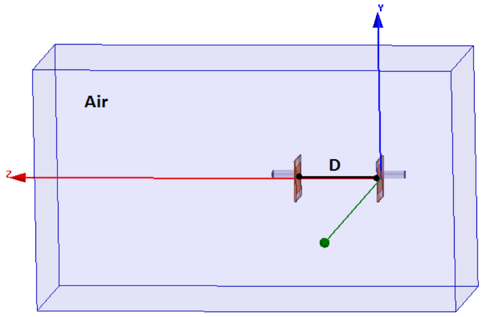

Figure 1: HFSS geometric configurations of 2 patch antennas in free space

3.2 Simulations:

Simulated return loss S_{11} and transmission S_{21} plots are shown in figure 2, 3 and 4. As seen in figure 2 and 3; the increase in loss tangent and permittivity degrades the reflection coefficient from S_{11} = -23.18 dB in free space to S_{11} = -16.62dB in dry concrete and S_{11} = -13.55dB in saturated concrete. When the loss tangent is increased while keeping the same relative permittivity, there is a shift in the center frequency and the antennas are less matched. When embedded in concrete the resonant frequencies decreased from their free space values of 860MHz to 857.5MHz in dried concrete to 859MHz in saturated concrete.

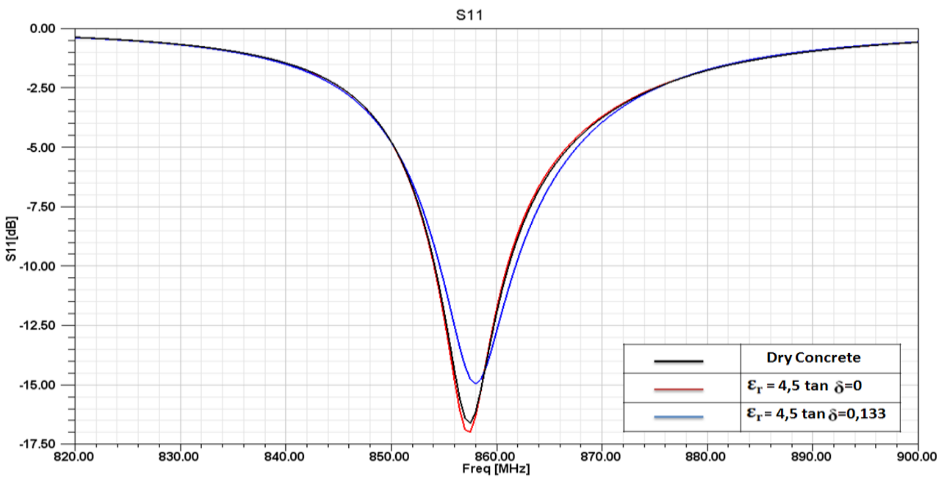

Figure 2: Return loss of patch antennas embedded in dried concrete by varying the loss tangent

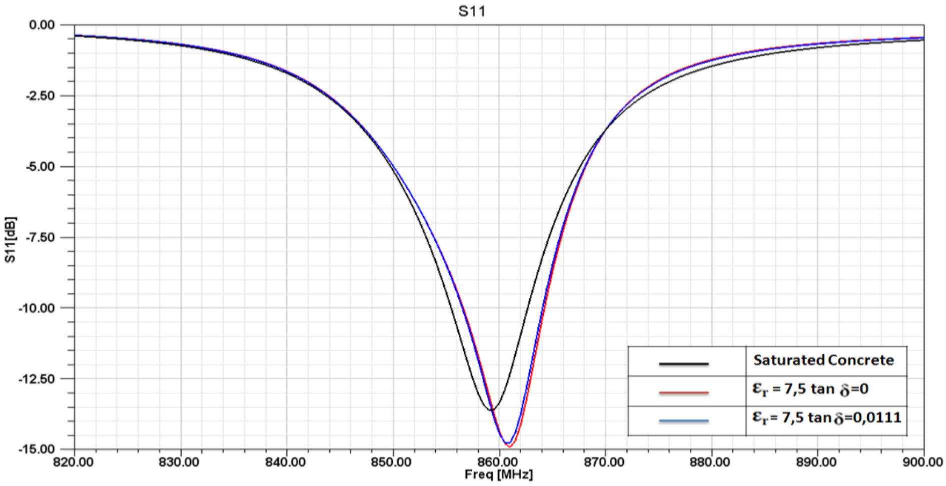

Figure 3: Return loss of patch antennas embedded in saturated concrete by varying the loss tangent

As shown in figure 4, the transmission coefficients S_{21} varied from -12.86 dB for saturated concrete to -10.26 dB for dried concrete and to -10.14 dB for vacuum. We can say that the transmission loss for saturated concrete is 2 dB less than the transmission loss for dry concrete.

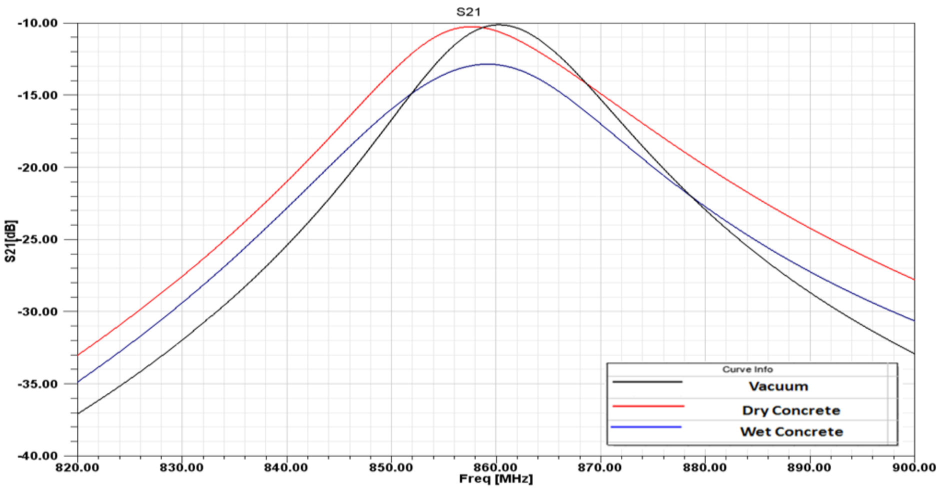

Figure 4: Transmission coefficient of patch antennas embedded in vacuum, dry and saturated concrete

4 ANTENNA REALIZATION

Measurements have been performed using Agilent Network Analyzer. The antennas were placed on a polystyrene box to protect the antennas from harsh environmental condition.
The outer dimensions of the polystyrene box are 15x15x3.5cm³. The measured reflection coefficients of antenna in free space is S_{11} =-20.99dB.

Figure 5: Realized Patch antenna

A concrete mold of size (55x36x20) cm ^{3} (LxWxH) was then used, the two patch antenna were placed in the center of the mold and the concrete has been added. The antennas matching is degradated in concrete with a return loss S_{11} = -10.1819dB.

Figure 6: Experimental setup for two patch antenna embedded in concrete slab L=55cm, W=36cm, H=20cm

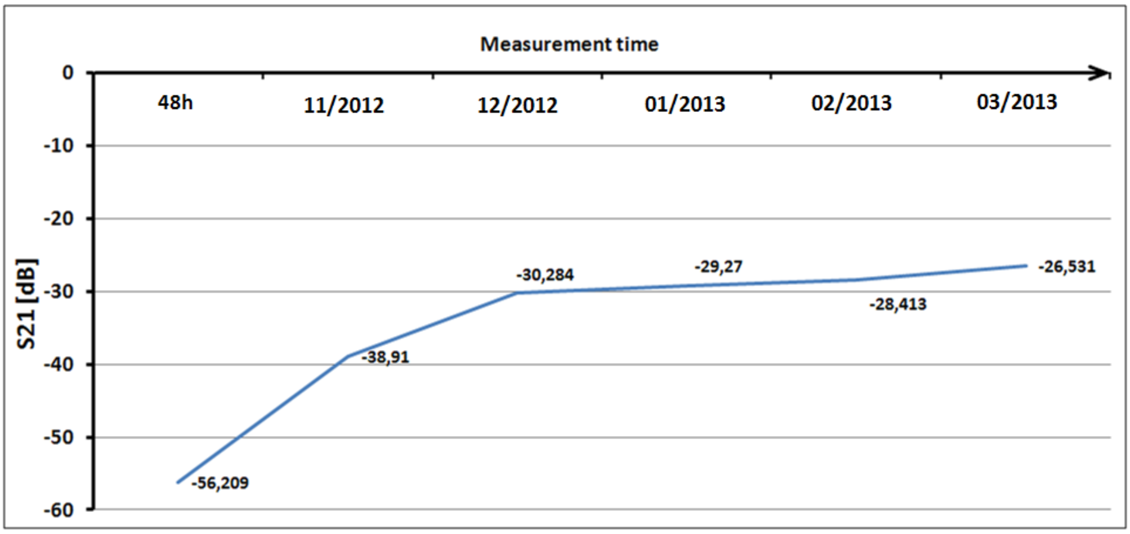

Figure 7: Transmission Loss S_{21} (dB) after placing Concrete

After adding the concrete, the transmission coefficient increases with the progression of time with S_{21} =-53.34dB immediately after the concrete has been poured and S_{21} =-26.531dB after four month of concrete curing. These results confirm the effect of humidity on concrete attenuation. Water content decreases over the concrete curing cycle (weeks or even months).

5 CONCRETE CHARACTERIZATION

By varying the relative permittivity without dielectric losses we obtain a central frequency of 855MHz with ε_r =5 as shown in figure 8. We can see in Figure 9 that a compatible simulated S_{21} plot and experimental S_{21} plot are obtained with $\tan\delta$=0.4.

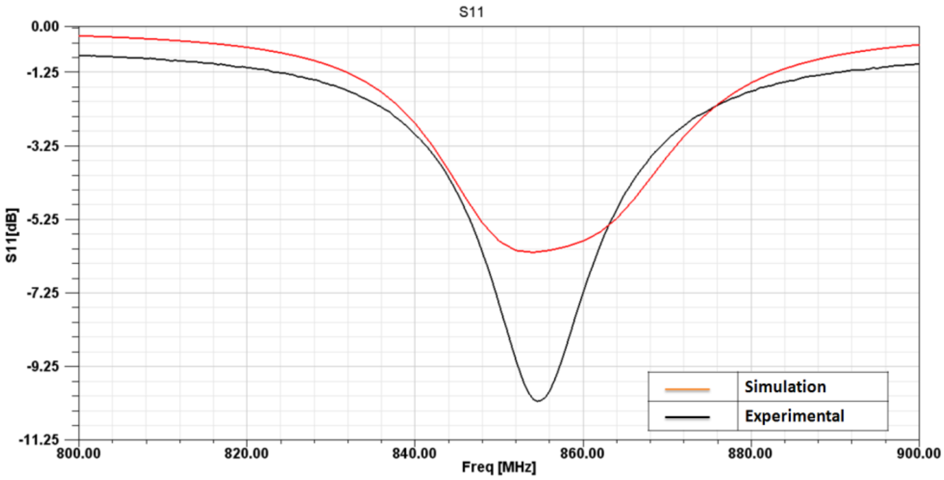

Figure 8: Return loss of 2 patch antennas in simulation and experimentation

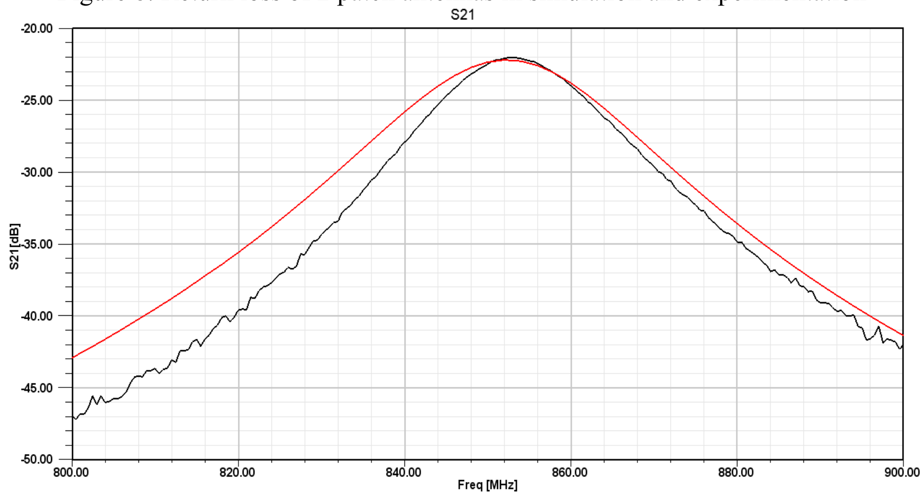

Figure 9: Transmission coefficient of 2 patch antennas in simulation and experimentation

6 EFFECT OF REINFORCEMENT BARS

The main impediment to radio waves is the use of rebar in the concrete. The nature of propagation loss is affected by the width of a reinforcement bar lattice and diameter of steel elements. In this section, we have studied the influence of these critical parameters on the transmission characteristics of the antennas.

6.1 Positioning of reinforcement bars:

Patch antenna is positioned below, between and above reinforcement bars in order to identify the best position in concrete box. The results are shown in figure 11. We can see that positioning the patch antenna between or above the rebar layers provide better signal transmission.

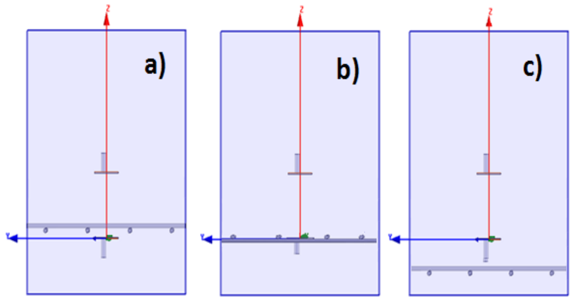

Figure 10: HFSS geometric configuration of patch antenna positioned a) below, b) between and c) above reinforcement bars

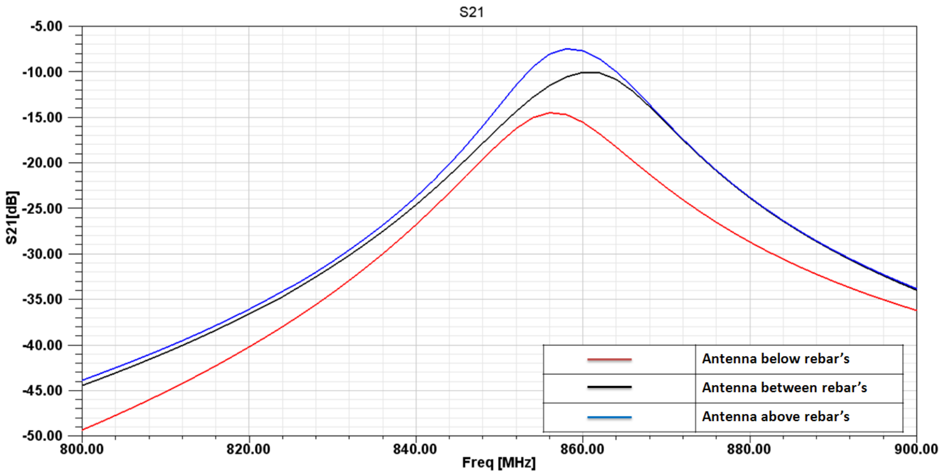

Figure 11: Transmission coefficients of patch antenna positioned below, between and above reinforcement bars

6.2 Square grid side length:

The transmitting antenna will be installed on the outside surface and the receiving antenna attached between two rebar layers. In practice, the rebar grid mesh and diameter in concrete slabs are always changing. Some of the effects of these rebar geometrical parameters are studied here and the results are shown in figure 12. The transmission coefficients are calculated for a mesh having a square side length varying between 11cm, 15cm and 20cm. This study is made at 860 MHz. The steel diameter is 10mm. Results are given in figure 12.We can see that the influence of the grid can never be negligible for the chosen dimension with S_{21} varying from -13dB for a side length of 11cm to -10.03dB for a side length of 15cm.

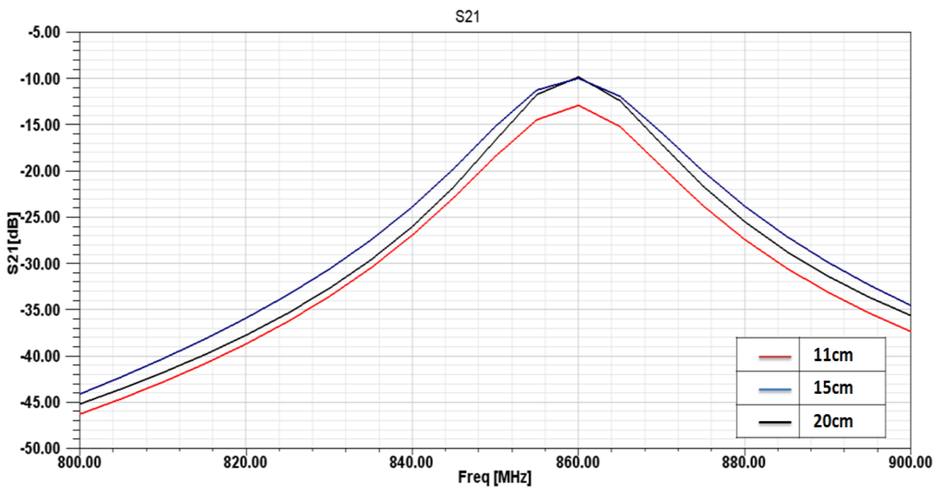

Figure 12: Transmission coefficients at 860MHz for a grid having a square side length of 11cm, 15cm, and 20cm

6.3 Steel diameter:

For a square grid of side length of 15cm, steel diameters of 4mm, 8mm, 12mm and 16mm are considered. The results obtained are shown in figure 14 and table I. We can see that the steel diameter has negligible affect at 860MHz.

Table I: Steel diameter effects on transmission coefficients

Steel diameter (mm)	S21 (dB)
4	-12.43
8	-12.41
12	-12.43
16	-12.37

CONCLUSION

SHM is a powerful tool to know the behavior of the structures over time. Conventional sensors are being used in a successfully way for ambient monitoring purposes. However, nowadays a new technology based on wireless systems is becoming interesting for SHM.

In this paper, we have expressed test result concerning the reflection and transmission coefficients in concrete. We have seen that the influence of the grid cannot be neglected. It was assumed that reinforcing bars will affect the communications distance in the same manner as the concrete. Further studies in hardware development and processing tools are also part of this work.

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