Sensitivity Analysis for Wireless Dielectric Reflectometry with Modulated Scatterers

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Abstract

Load-modulated scattering antenna technology has been very efficiently developed these last decades. Low-cost RFID tags for identification and low-invasive Modulated Scattered Technique (MST) probes for EM field measurements constitute two relevant examples. More recently, remote sensing applications of modulated scatterers have been considered. In such applications, the general objective is to remotely retrieve some local property of a material or environment under test via its impact on a modulated scattering probe. This paper is more particularly focused on the case where the sensing mechanism is expected to result from the change of the probe impedance, due to variations of the refractive index in its close vicinity. This problem is usually addressed under empirical and global viewpoints, by combining numerical modeling and optimization. Often, such a blind approach may result in some disappointment. This paper aims to develop a more comprehensive analytical-based approach, thanks to a general reciprocity-based formulation. Inspired from standard reflectometer techniques, the ternary load modulation scheme is shown to remove specific difficulties inherent to wireless reflectometry such as propagation effects or misalignment between the probe and the reader antennas. The test case of center-loaded dipoles is considered for the sake of illustration.

1. Introduction

This paper deals with wireless dielectric reflectometry. Taking inspiration of the technology developed for RFID tags or MST probes [e.g. 1,2,3,4,5], the idea is to investigate how modulated scatterers can be used for non-invasively and wirelessly measuring the dielectric constant of Materials Under Test (MUT). A further step, not considered here, may be to retrieve some local property of this material from its dependence with respect to its refractive index. Water content, temperature, composition, etc. constitute some examples of such quantities, which have been demonstrated to be accessible by means of microwave sensors [e.g. 6,7]. Dielectric measurement via reflectometry is a well-documented area. Standard systems involve measurement probes (open coaxial or waveguide, patch antennas, cells, etc.) which are connected to a Vector Network Analyzer (VNA) to measure their reflection or/and transmission coefficient when the probes are placed in front of or in close contact with the MUT. The dielectric constant, and hence the refractive index, are retrieved from analytical or numerical models reproducing the probe arrangement. In this paper, one considers that the VNA is changed for a reader, which interrogates a remote scattering probe. Dissociating the probe from the measurement setup poses additional specific difficulties such as the removal of the impact of mutual reader antenna probe position and orientation. In addition, the probe response at the reader must provide an unambiguous correlation with surrounding index, via its input impedance. The measurement of antenna impedance from RCS measurement has been already covered [8,9,10]. However, while previous studies are mostly concerned with reducing errors in RCS-based impedance measurement, this paper is more particularly considering the sensitivity of the probe response with respect to the refractive index, in arbitrarily complex environment and not only under far-field / free-space conditions. The paper is organized as follows. In a first time, a general reciprocity-based formulation allows to obtain the wireless reflectometer equation relating the modulated reflection factor viewed by the reader to the differential complex reflection factor viewed by the probe when modulated by a binary load. Secondly, after discussing the possible impact of refractive index changes on the probe response in a binary load modulation scheme, the case of ternary load modulation is considered. Some guidelines are provided for the selection of the loads. Thirdly, the simple test case of the center loaded dipole antenna is considered for the sake of illustration of the analytical formulation previously developed. Approximate formulas are provided to quickly obtain an explicit solution to the index sensitivity issue.

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2. Wireless Reflectometer Equation

Figure 1.a shows the principle of a wireless reflectometer using a modulated scatterer probe. In this monostatic arrangement, the wave radiated by the reader is scattered by the probe toward the reader back. The probe has an input impedance $Z_T = R_T + jX_T$ and is activated according to the Modulated Scattering Technique (MST) by periodically switching the load impedance Z_L from $Z_{L,1}$ to $Z_{L,2}$. In the case of RFID tags such impedances could correspond to different states of the RFID Chip [11], that can be obtained by measurements. More generally some chip manufacturers provide these impedances.

The load modulation allows to discriminate the probe contribution form other non-relevant signals and to perform an efficient coherent detection at the modulation frequency [12]. Using a differential detection scheme, the structural mode of the probe is cancelled and only the antenna mode of the probe must be accounted for. Usually, Z_T is complex and, for a given load impedance Z_L, it is necessary to introduce the complex reflection factor:

$$\tilde{\rho}_L = \frac{Z_L - Z_T^*}{Z_L + Z_T} \tag{1}$$

The reciprocity theorem allows to simply relate, without constraining assumptions (such as free-space, far-field…), the modulated differential reflection factor $\Delta\rho$ viewed by the reader to the differential probe reflection factor $\Delta\tilde{\rho}_L = \tilde{\rho}_{L,2} - \tilde{\rho}_{L,1}$ [12]:

$$\Delta\rho = \frac{Z_{tr}}{2R_T}\Delta\tilde{\rho}_L \tag{2}$$

where $Z_{tr} = V_{OC}^2/(2R_T)$ is the so-called transfer impedance and V_{OC} the open circuit voltage at the probe port (Z_L infinite). Equation (2) offers a convenient basis for a parametric study of any modulated scatterer system. It constitutes the wireless reflectometer equation. In the case of electrically small antennas, it has been demonstrated that, for a given set of load impedances, there exists a probe impedance which maximizes $\Delta\tilde{\rho}_L$ and, hence, the modulated power budget. However, for a system operated around this optimized probe impedance, the power budget is rather insensitive to any variation of the probe impedance. In other words, such a power budget optimized system is not directly convenient for sensing purposes, when, on the contrary, one tries to obtain the largest sensitivity of the back-scattered signal with respect to environmental changes via the probe impedance. A wireless reflectometer requires specific performance optimization in view of sensing applications.

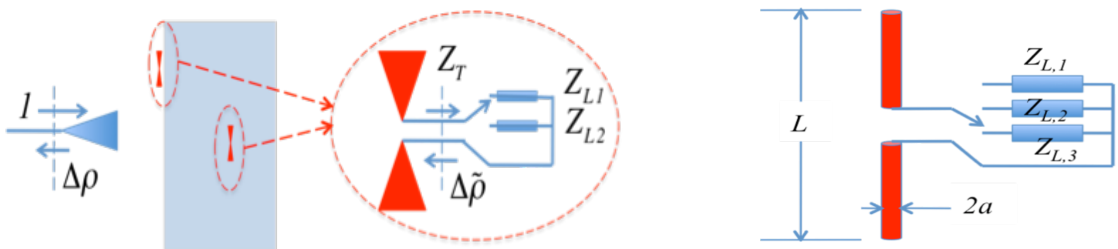

Figure 1 : Principle of a wireless reflectometer using a modulated scatterer probe loaded by a binary impedance (a), and a dipole probe loaded by a set of three impedances (b).

3. Sensitivity to Refractive Index

In the following, the attention is focused on sensing the refractive index $n = \sqrt{\varepsilon_r}$ (ε_r is the relative dielectric constant) of the MUT surrounding the probe. It is quite clear that n impacts directly Z_{tr} and Z_T and, hence, indirectly, $\Delta\tilde{\rho}_L$. However, is worth noting that Z_{tr} is mainly impacted by the propagation medium between the reader and the probe, while Z_T is only affected by the close surrounding of the probe. As a result, Equation (2) becomes a complicated function of n :

$$\Delta\rho(n) = \frac{Z_{tr}(n)}{2R_T(n)}\Delta\tilde{\rho}_L(n) \tag{3}$$

Consequently, the simple dual-load modulation is unable to isolate the effect of n on Z_T. Because one desires the sensing being localized to the probe surrounding, the influence of the transfer impedance must be removed. Another strong motivation is, more generally, to make the probe response independent of any propagation effects such as mutual reader/probe antennas position and orientation.

Various options have been proposed, either for antenna impedance measurement via RCS or for RFID-based sensors. They mainly consist in using either multi-loading of single-port sensors or single-loading of multi-port sensors [e.g.4]. As a simple case, 3 loads can be used for two-by-two modulation (Figure 1.b). This allows forming various index-dependent functions insensitive to the transfer impedance. For instance, using load nb.2 as reference, the following function can be introduced as ratio of two measured data at the reader port:

$$S(n) = \frac{\Delta\rho(n)\big|_{1,2}}{\Delta\rho(n)\big|_{2,3}} = \frac{\Delta\tilde{\rho}_L(n)\big|_{1,2}}{\Delta\tilde{\rho}_L(n)\big|_{2,3}} = \frac{Z_2 - Z_1}{Z_3 - Z_2}\,\frac{Z_T(n) + Z_3}{Z_T(n) + Z_1} \tag{4}$$

By similarity with RCS-based antenna impedance measurement [9,10], the loads 1 and 3 are advantageously chosen as short-circuit and open-circuit, respectively. Then Equation (4) can be simplified:

$$S(n) = \frac{Z_2}{Z_T(n)} \tag{5}$$

In such a case, the index dependent function $S(n)$ is very simply related to the probe impedance $Z_T(n)$. This function can be normalized with respect to a reference index $n_{ref} = \sqrt{\varepsilon_{ref}}$, resulting in a Z_2 independent formula:

$$\hat{S}(n/n_{ref}) = \frac{S(n)}{S(n_{ref})} = \frac{Z_T(n_{ref})}{Z_T(n)} \tag{6}$$

Assuming that the probe is buried in a medium with index n and operated at frequency f, and using Deschamps theorem [14], Equation (6) can be more explicitly written as follows:

$$\hat{S}(n/n_{ref}) = \frac{n}{n_{ref}}\,\frac{Z_T(1, n_{ref} f)}{Z_T(1, nf)} \tag{7}$$

These simple equations allow taking into account any situation of practical relevance and, hence, constitute an efficient tool to assess the feasibility of wireless reflectometer setups in arbitrary scenarios.

4. A Test Case: the Center-Loaded Dipole

As a test case, the center-loaded electric dipole has been selected (Figure 1.b). Practically, dipole or electrically small antennas may indeed constitute relevant probe elements in many applications. Furthermore, the probe impedance can be very easily calculated from variational formulas [15] or derived from explicit formulas [16] for electrically small dipoles. The results presented below correspond to a supposed reference index $n_{ref} = 2$, while index n is varied in the range $1 \le n \le 6$. The dipole length is L and its radius $a = L/20$. Considering the index n and the length L as parameters, and introducing the index ratio $N = n/n_{ref}$, Equation (7) becomes:

$$\hat{S}(N/kL) = N\,\frac{Z_T(kL)}{Z_T(NkL)} \tag{8}$$

where $k = 2\pi/\lambda$ and λ is the wavelength in the reference medium. The load impedances are the following ones: $Z_1 = 2\ \Omega$ (# short-circuit), $Z_3 = (0.2 - j3000)\ \Omega$ (# open-circuit). As already observed, Z_2 does not impact $\hat{S}(N/kL)$, but only $S(n)$. Figure 2 shows the variations of the normalized index sensitivity $\hat{S}_{dB}(N/kL) = 20 * \log_{10}\left|\hat{S}(N, kL)\right|$ for $0.5 \le N \le 3$, for dipole length ranging from electrically short up to half-wavelength, namely $kL = \pi/3$, $\pi/2$, $2\pi/3$ and π. A good agreement is obtained between the exact value based on Equation (4) and the approximate one based on Equation (6) assuming $Z_1 = 0$ and Z_3 infinite. The slope $d\hat{S}/dN$ at $N = 1$ remains positive as long as $kL = 2\pi/3$, and is negative for $kL = \pi$. The transition between these two regimes occurs for $kL \approx 0.85\pi$, which approximately corresponds to $X_T = 0$ for $L/a = 20$. For electrically short dipoles, Z_T can be approximated by its reactive part jX_T, which is proportional to $(kL)^{-1}$ [16]. Within such an approximation, $\hat{S}(N/kL) = N^2 = \varepsilon_r/\varepsilon_{ref}$, which means, from a physical viewpoint, that, as intuitively expected, short dipoles behave like a simple capacitive probe.

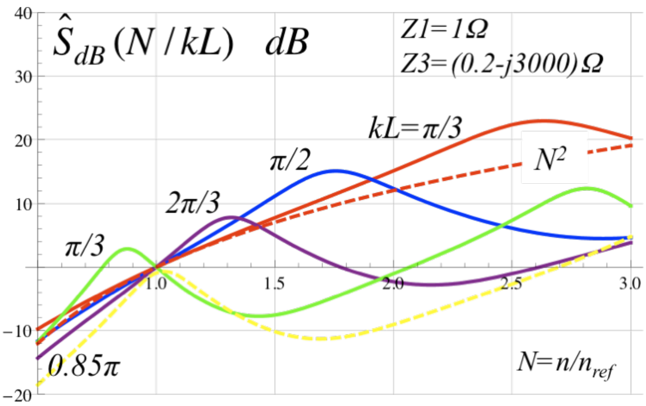

Figure 2: Normalized index sensitivity $\hat{S}(N/kL)$ for center-loaded dipoles, *L/a=20*

7. Conclusion

The reciprocity- based formulation allows obtaining the wireless reflectometer equation, without any free-space or far-field assumption. Furthermore, using simple and explicit formulas, the sensitivity of the modulated probe response can be easily assessed. This paves the way for optimizing modulated sensors dedicated to specific sensing applications. The ternary modulation scheme avoids any inconsistency resulting from the transfer impedance. Today, there is no existing chip offering a ternary modulation scheme. Only miniaturized discrete components have been used until now. However, there is no particular technological difficulty to design such a chip. In this paper, only dipole probes in lossless media have been considered. Other examples including meander line antennas as well as tuned probes in lossy media and various modulation scenarios will be provided during the oral presentation.

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