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A RELIABLE LOW-COST METHOD FOR ACCURATE CHARACTERIZATION OF ANTENNAS IN TIME DOMAIN

In this paper, a time domain-based approach to practical characterization of antennas is presented. The goal is to prove that time domain-based approach, after appropriate processing, represents an accurate and more practicable alternative to the typically used (yet highly expensive) antenna characterization measurements that are performed in anechoic chamber through a Vector Network Analyzer (VNA). To this purpose, two commercial antennas, differing in operating frequency band, are considered as significant test-cases. Reflectometric measurements performed in Time Domain (TD) are subsequently transformed in Frequency Domain (FD), and compared with VNA reference measurements directly obtained in anechoic chamber. Results demonstrate that the preliminary choice of an optimal time window is the main factor leading to a substantial enhancement of the overall measurement accuracy, which is comparable to that provided by VNA measurements in anechoic chamber. This demonstrates that a good insight into the antenna characteristics can be obtained even without using highly expensive facilities.

Keywords: Time Domain Reflectometry (TDR), antenna measurements, reflection scattering parameter, time domain measurements, frequency domain measurements.

1. INTRODUCTION

Traditionally, measurements on antennas are carried out in the Frequency Domain (FD) through expensive instruments, such as a Vector Network Analyzer (VNA), in dedicated facilities (i.e., anechoic chamber). Although this procedure undoubtedly provides highly accurate results, the high costs involved make such procedure virtually impracticable on an every-day basis. On such basis, there is an abiding interest for assessing alternative methods (less expensive and yet accurate) for antenna characterization, particularly for the evaluation of the reflection scattering parameter.

Over the years, the possibility of characterizing antennas in Time Domain (TD) has been consistently considered as a promising and attractive alternative to FD-based measurements [1, 2, 3, 4, 5, 6, 7]. In fact, TD-based measurements, after suitable

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processing based on the Fast Fourier Transform (FFT), can provide similar information with definitely lower related costs [8].

Indeed, by appropriately adjusting some measurement parameters, such as the time window (T_W), the number of averages and the sampling period (T_S), it is possible to extrapolate highly accurate results in frequency domain. Additionally, instruments operating in TD are usually less expensive and many of them are also portable, thus they represent an appealing solution also for practical "in situ" and real-time measurements [9].

Advantages and drawbacks of a TD approach for characterizing electronic devices have been extensively addressed in literature [1, 2, 3, 4, 5, 6, 7]. Nevertheless, dealing with antennas makes the issue more critical (since the measurement environment can interfere with the radiating antenna), and no work describes a simple procedure to be practically implemented for antenna characterization when basic TD instrumentation (i.e., without any specific additional tool) is used.

In order to fill this gap, in the present paper, the reflection scattering parameter, $S_{11}(f)$, of two different commercial antennas is evaluated through Time Domain Reflectometry (TDR) along with an FFT-based processing on the TD data. Starting from theoretical considerations, the crucial steps for an accurate TDR-based antenna characterization are pinpointed, so as to individuate the appropriate conditions that can avoid the use of anechoic chamber in conjunction with a VNA.

In particular, it is demonstrated that the choice of an optimal time window is the crucial parameter that has the major effect on the accuracy of the corresponding FD-processed data. In fact, an optimal time window can ensure good balance among the following aspects: 1) optimization of the frequency resolution, 2) maximization of the signal to noise ratio (SNR), 3) acquisition of a TD-signal long enough to include a complete spectral response, and, finally 4) exclusion of spurious reflections coming from the surrounding objects.

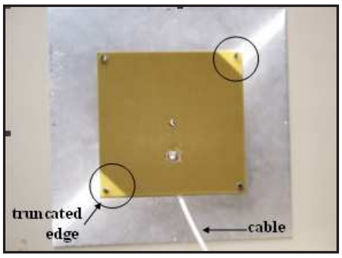
In order to assess the proposed method, the $S_{11}(f)$ is evaluated from TDR measurements performed under different experimental conditions (i.e., choosing different acquisition windows, applying digital filters on TD data, placing reflecting objects near the antenna). The obtained data are compared to VNA reference measurements performed in an anechoic chamber $S_{11,REF}(f)$, thus definitely validating the metrological performance.

On the basis of the aforementioned discussion, the ultimate goal of this work is to demonstrate that TDR-based measurements, in conjunction with a specific data processing, can be regarded as a robust and cost-effective method for accurate characterization of antennas.

2. EXPERIMENTAL SET-UP

The proposed approach has been tested on two antennas, namely an Alien ALR-8610-AC antenna and a Clampco Sistemi AP3000 biconical antenna. These antennas have very different characteristics in terms of operating frequency band; in fact, the former is narrowband antenna and operates in the 865 MHz – 940 MHz frequency range, whereas the latter is a wideband antenna designed to work in a large frequency range (80 MHz – 3 GHz). The different performance of these two considered antennas can assess the proposed approach for a wide range of possible practical conditions.

The Alien ALR-8610-AC antenna is a commercial antenna, used for Radio Frequency Identification (RFID) applications. The configuration of the antenna is shown in Fig. 1a. It is worth mentioning that the truncated edges (highlighted with circles in Fig. 1a) are realized to guarantee circular polarization with only one feed point and to generate two closely-spaced resonant frequencies, between which the antenna should operate [10].

a)


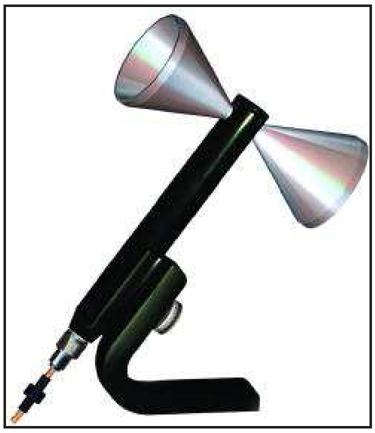
b)


Fig. 1. RFID-reader antenna a), and biconical antenna b).

The second considered antenna is a biconical antenna (Fig. 1b), generally used for Electromagnetic Compatibility (EMC) measurements.

The instrument used to perform the TDR-based measurements is a Tektronix®Digital Serial Analyzer (DSA8200), equipped with a TDR module (Tektronix®TDR80E04). This instrument generates an electromagnetic step-like signal, whose rise time is approximately 23 ps (corresponding to a frequency bandwidth of about 15 GHz) [11]. The maximum number of points that can be acquired in the TD is 4,000 (over the considered time window).

3. PROPOSED APPROACH

As mentioned in Section I, the proposed experimental procedure for characterizing antennas includes two major steps: the acquisition of the TDR antenna waveform and, successively, the FFT-based processing on TD data for retrieving the corresponding FD information. Indeed, these aspects are intrinsically intertwined; in fact, the FD-results strongly depend on how the TD acquisitions are performed. In this section, both these steps will be thoroughly discussed, so as to provide the necessary theoretical basis leading to the validation of the subsequent experimental considerations.

As well known, once the number of acquisition points in TD is fixed at the maximum (according to the specifications of the used instrument), the time window is the only major parameter that can be modified. This parameter considerably influences the results of the successive FD-transformation, hence it must be chosen wisely so as to attain the expected advantages of the TD-based approach.

Before discussing how the optimal time window should be chosen, it is useful to briefly summarize how a TDR-based system performs measurements. The electromagnetic step-like signal generated by the TDR unit is launched into the antenna. Any impedance mismatch causes a portion of signal to be reflected towards the TDR unit. The characteristics of the reflected signal are intrinsically related to the $S_{11}(f)$ of the antenna [12].

The reflected waveform includes the so-called multiple reflections (happening at longer times after the "first reflection" has occurred), due to the signal traveling back and forth between the measurement instrument and the device under test [9]. Multiple reflections contain additional spectral information. Therefore, an optimal time window should include as many multiple reflections occurring before the steady-state condition is achieved. This way, the subsequent FD-transformation would provide a complete spectral representation of the antenna behaviour.

Additionally, the frequency resolution (Δf) of the FD-transformed data is inversely proportional to the time window (T_W), according to the well-known equation

$$\Delta f = \frac{1}{T_W}, \tag{1}$$

hence, longer time windows would provide a better frequency resolution.

As a matter of fact, there are other limitations concerning the maximum selectable time window. First of all, when characterizing antennas, part of the signal transmitted into the antenna is radiated by the antenna itself. When this signal impinges on any "obstacle" (e.g., walls, objects, etc.), it is reflected towards the antenna. As a consequence, the measured TDR waveform might include unwanted contributions due to spurious reflections that do not belong to the antenna: an optimal time windowing can exclude such effects. Indeed, this is a relevant advantage of TD-based measurements over the direct FD-measurements, and can be considered as the practical way for avoiding the use of the anechoic chamber [5].

This aspect is clarified in Figs. 2a and 2b. In particular, Fig. 2a shows a simplified schematization of a measurement set-up in which an antenna is connected to the TDR unit through an L_C-long cable and the nearest reflecting object is placed at a distance d from the antenna.

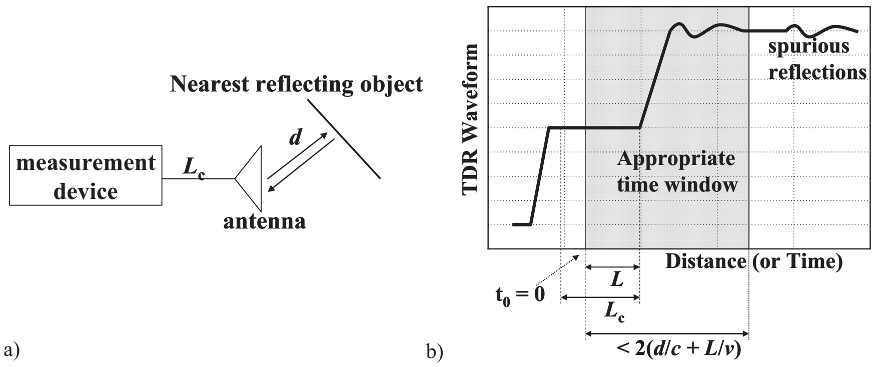


Fig. 2. Schematization of possible interferences from the environment a), and of the corresponding TDR waveform b).

In this condition, the time window that excludes unwanted reflections can be calculated through the following equation:

$$T_W = 2\left(\frac{d}{c} + \frac{L}{v}\right), \tag{2}$$

where $c = 3 \cdot 10^8$ m/s is the speed of light in vacuum, L is the fraction of L_C that corresponds to the portion of the cable included in the time window, and v is velocity of the signal propagated in the cable. In practice, the L-long cable portion inclusion is necessary for effectively performing the subsequent FD-transformation, as reported in [9, 11] (if no cable is used, then it should be included a portion of the waveform before the first reflection caused by the antenna occurs). Fig. 2b shows a typical schematization of the corresponding TDR waveform: in particular, the grey-colored area (which starts at the appropriately-chosen instant, t_0) corresponds to the portion of the signal that should be included in the acquisition window. The effect of reflecting obstacles on the TDR waveform is experimentally verified in the following section.

Other limitations for the maximum time window include noise limitations due to the intrinsic performance of the experimental set-up and sampling-rate limitation of the used instrument. Both these aspects will be detailed in the next section.

From the aforementioned discussion, it is clear that the optimal time window should provide a trade-off among different contrasting effects.

The second step of the proposed procedure deals with the evaluation of the $S_{11}(f)$ of the antenna through a dedicated FD transformation algorithm described in [9].

This algorithm takes into account several issues involved in the signal transformation from TD to FD: the time-domain windowing and truncation, the pre-processing operations (such as Nicolson algorithm and zero-padding), and the compensation for parasitic effects through calibration techniques (in fact, for each antenna waveform, also Short-Open-Load calibration measurements are performed in TD).

4. EXPERIMENTAL RESULTS

TDR measurements were performed outdoor, making sure that no object was in the nearby of the antenna while the TDR waveforms were being acquired. TDR measurements were repeated, for each antenna, setting several different time windows. For each time window, the corresponding $S_{11}(f)$ was evaluated, according to the FD-transformation procedure described in [9].

As aforementioned, the reflection scattering parameter of each of the considered antennas was also measured with a VNA in an anechoic chamber: these reference $S_{11,REF}(f)$-data were compared with the $S_{11}(f)$ measurements obtained from the proposed procedure.

For both the antennas, the *rmse* (root mean square error) between the $S_{11,REF}(f)$ and each of the $S_{11}(f)$ values evaluated for each considered time window was evaluated, thus ultimately validating the approach.

4.1. RFID antenna

The RFID antenna can be regarded as a narrowband antenna, hence its analysis can be limited to the specific operating range (810 MHz – 960 MHz), in which the antenna has the two closely spaced resonant frequencies.

Fig. 3a shows the waveform for a T_W = 100 ns. The first portion of the waveform at approximately 0.25 V corresponds to the 50 Ω-cable that feeds the antenna (Fig. 3b). The measured time between the beginning of the acquisition window and the end of the cable is 2.8 ns, corresponding to the length L in (2). After this portion of cable, there is an abrupt change in the amplitude of the waveform due to the considerable impedance mismatch introduced by the physical connection to the antenna. The following portion of the waveform carries the antenna "imprint" and, subsequently, the reflected signal approaches the steady-state condition (around the value of 0.5 V that corresponds to the open circuit) through several multiple reflections, whose shape is related to the resonant behaviour of the antenna. The attenuating response of the multiple reflections can be clearly distinguished until their peak-to-peak signal excursion is comparable with the noise level.

Taking into account the theoretical considerations made in the previous section, an explanation on the choice of an optimal time window is addressed. The RFID

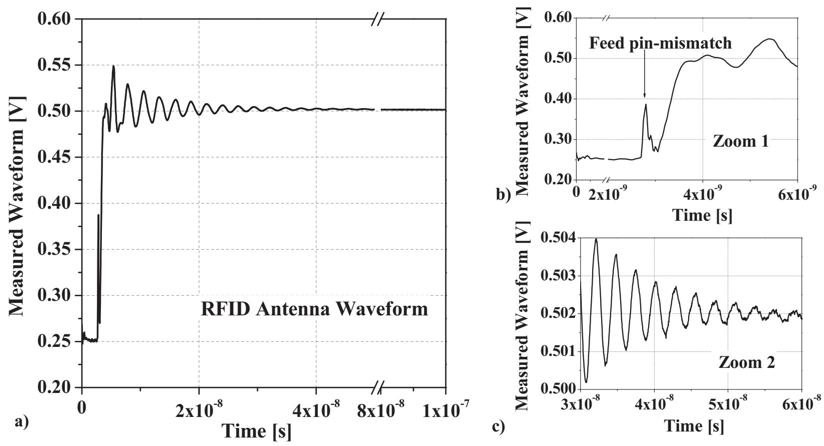


Fig. 3. TDR waveform of the RFID antenna for a 100 ns-long time window a), zoom of the initial portion of the waveform b), zoom of the noise-corrupted multiple reflection at longer times c).

antenna was characterized choosing, from time to time, a different acquisition window, ranging from 10 ns to 100 ns. The "starting point" (t_o) of the T_W was kept the same throughout the measurements. For each time window, the corresponding $S_{11}(f)$ and its *rmse* (compared to $S_{11,REF}(f)$) were evaluated: results are reported in Fig. 4 and Table 1, respectively.

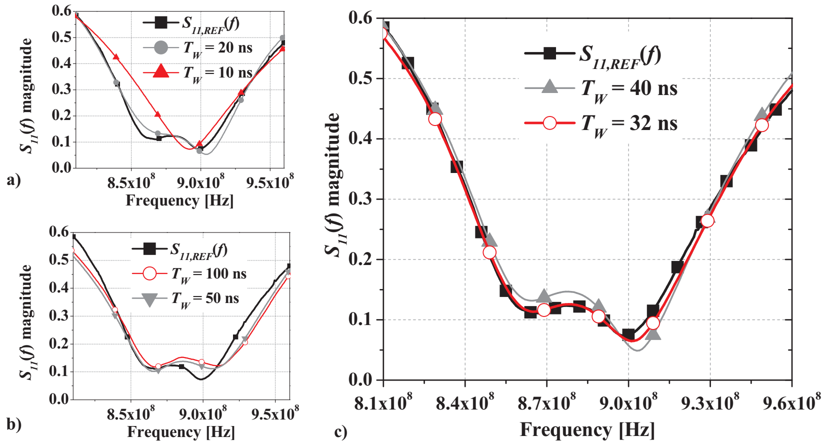


Fig. 4. Comparison between $S_{11,REF}(f)$ and the $S_{11}(f)$ curves obtained from FD-transformed data for different time windows (T_W), for the RFID antenna.

First, the lower limit for T_W is mainly related to obtaining a suitable frequency resolution. The analysis of the FD-transformed data in the 810-960 MHz range, confirmed that for T_W = 10 ns, T_W = 20 ns and T_W = 30 ns, the correspondent frequency resolution

(Δf) ensures the presence of one, three, and four spectral components, respectively. Fig. 4a shows the magnitude of the $S_{11}(f)$ evaluated from a 10 ns-long time window and from a 20 ns-long time window. Evidently, the Δf provided by the 10 ns-long time window cannot even resolve the two closely-spaced resonant frequencies of the antenna; similarly, the 20 ns-long time window is hardly sufficient to discriminate the two resonances. From antenna specifications, it is known that the two resonant frequencies occurs in a 30 MHz frequency range; therefore, the lowest limit for the windowing is $T_{W-low} > 30$ ns.

Table 1. *Rmse* between the FD-processed $S_{11}(f)$ obtained for different acquisition windows and $S_{11,REF}(f)$ for the RFID reader antenna.

T_W (ns)	*rmse*
100	0.040
50	0.037
40	0.019
35	0.019
32	0.010
20	0.021
10	0.068

On the other hand, the major limit for the upper time window (T_{W-up}) is related to the intrinsic limitation of the used instrument in terms of noise. As expected, when time window is increased, noise contribution becomes more relevant, as shown in Fig. 3c. At approximately 40 ns, noise contributions clearly distort the peak-to-peak oscillations of multiple reflections. Fig. 4b sows the $S_{11}(f)$ curves evaluated for T_W = 50 ns, and for T_W = 100 ns.

SNR represents a useful figure of merit for establishing where the acquisition should be stopped in order to reduce the noise corruption. From the instrumentation specifications, it is known that the rms noise value is $\hat{N}_{rms} \geq 0.6$ mV. Considering that the TDR measured signal magnitude, S^{MEAS}, includes noise (i.e., $S^{MEAS} = S \pm N$), the threshold value for S is S_{rms}^{MIN} =0.6 mV.

This implies that when the measured amplitude signal is comparable to noise level, the rms measured magnitude is S_{rms}^{MEAS} = 0.6 mV + 0.6 mV = 1.2 mV, corresponding to a minimum peak-to-peak signal excursion of about S_{pp}^{MIN} = 3.4 mV. Therefore, referring to the zoom of the TDR waveform reported in Fig. 3c, it appears that the upper limit for the time windowing in order to ensure a SNR > 1 is approximately $T_{W-up} < 35$ ns. SNR measurements, directly available on the used instrument, confirmed these theoretical considerations.

Indeed, longer time windows can be used, provided that the influence of noise is reduced through an appropriate post-processing of the acquired TDR waveform. This was verified by applying a moving average time-domain filter (available in MATLAB) to the antenna waveform corresponding to a 100 ns-long time window: Fig. 5 shows the comparison between the $S_{11}(f)$ curves evaluated for a 100 ns-time window, with and without filtering, and the $S_{11,REF}(f)$ curve. It can be seen that the $S_{11}(f)$ corresponding to the filtered 100ns-long T_W gives a more accurate representation of the antenna performance. A long-time windowing, together with the above-described filtering procedure, is definitely the most appropriate choice when the frequency response of the device must be retrieved also at the lowest frequencies.

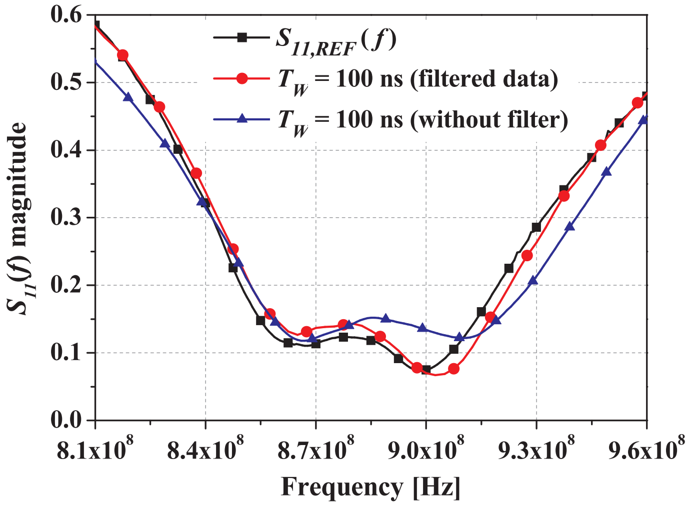


Fig. 5. Comparison between the $S_{11}(f)$ derived from the FD-transformation on a 100 ns-long acquisition window with and without the application of a moving average digital filter.

On such basis, in the considered test-case, the optimal time windowing appears to be 30 ns $< T_W <$ 35 ns. As a matter of fact, Fig. 5 shows that, among the considered time windows, the one that provides the most accurate results is the 32ns-long time window, as it provides the best trade-off among frequency resolution, inclusion of multiple reflections and noise reduction. This is confirmed by the corresponding lowest *rmse* value (Table 1).

On a side note, it is worth mentioning another aspect that usually limits the maximum time window: the need to window out possible reflections coming from surrounding objects. Since the measurements reported herein were performed outdoor, this aspect did not represent an issue. Nevertheless, the influence of reflections from the environment and the validity of (2) were verified by performing additional TDR measurements, for a fixed T_W, with an aluminium plate placed at an increasing distance from the antenna. Once the distance of the aluminium plate had reached the value given by (2), the effect of the presence of the plate on the $S_{11}(f)$ resulted negligible. Once these spurious reflections are windowed out, the TDR-based set-up actually mimics the effect of an anechoic chamber [13, 14].

4.2. Biconical antenna

As a further experimental validation of the method, a biconical antenna was considered: the wideband characteristics of this antenna anticipate different criteria for the choice of the optimal time window [14].

Similarly to the previous case, the TDR measurements on the antenna were performed by choosing several time windows, ranging from 15 ns to 150 ns; once again, the corresponding $S_{11}(f)$ was extrapolated and compared to the $S_{11,REF}(f)$ in terms of *rmse* (Table 2).

Table 2. *Rmse* between the FD-processed $S_{11}(f)$ obtained for different acquisition windows and $S_{11,REF}(f)$ for the biconical antenna.

T_W (ns)	*rmse*
150	0.010
100	0.006
80	0.007
40	0.010
30	0.013
15	0.019

The analysis of the TDR waveform of the biconical antenna (reported in Fig. 6) clearly shows that, differently from the previous case, the multiple reflections quickly die out and the signal reaches a steady-state condition in about 20 ns. Nevertheless, such a short T_W would not accurately represent the antenna response at lower frequencies. In fact, Fig. 7 shows that even a 30 ns-long time window, although providing overall accurate results, fails in accurately representing the antenna response at low frequencies.

On the other hand, if the time window is too long, this will translate in inaccurate results at high frequencies. In fact, since the maximum number of acquisition points is fixed, then the sampling period (T_S) may become too high, and hence the sampling frequency ($f_S = 1/T_S$) too low: this represents the upper limit for the maximum frequency f_M. In order to retrieve the frequency response up to $f_M = 3$ GHz, then f_S should be at least 6 GHz, so as to satisfy the sampling theorem. As a result, the corresponding T_S should be lower than 0.166 ns. Considering that, for a fixed time window, the used instrument provides 4,000 measurement points in TD, the maximum time window must be shorter than 666 ns.

Indeed, the maximum time window should be definitely shorter. In fact, the used TDR instrument performs a real-time sampling only for time windows shorter than

120 ns: beyond this limit, the instrument samples in equivalent-time. As a matter of fact, equivalent-time sampling is inappropriate when such one-shot signals are considered. Therefore, it is advisable to use windows shorter than 100 ns.

Additionally, it is worth pointing out that, in this case, the intrinsic noise limitation is not critical, since the steady-state condition is not reached through an oscillating and attenuating transient.

The aforementioned considerations may be summarized as follows: if the T_W is too short, then results will be less accurate at low frequencies, conversely, if the T_W is too long, this will result in inaccurate results at high frequency.

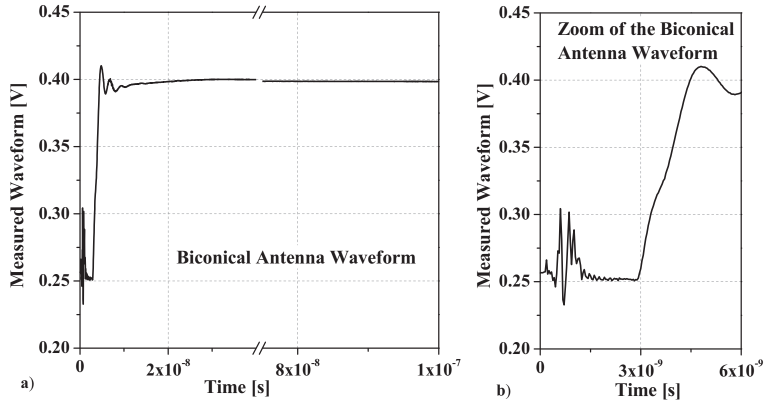


Fig. 6. TDR waveform of the biconical antenna for a 100 ns-long time window a), zoom of the initial portion of the waveform b).

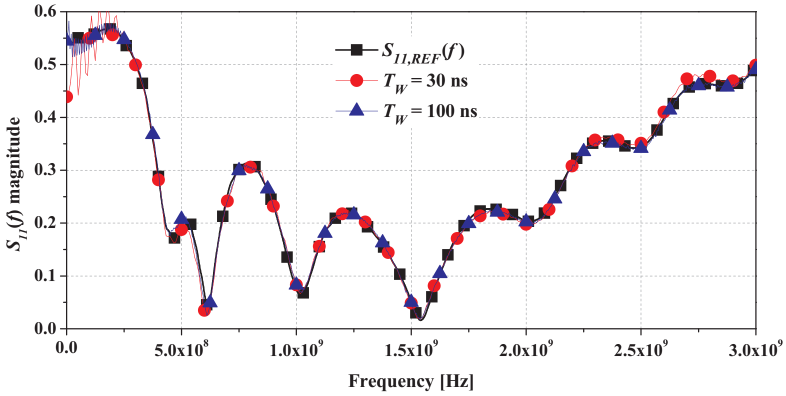


Fig. 7. Comparison between $S_{11,REF}(f)$ and the $S_{11}(f)$ curves obtained from FD-transformed data for different time windows (T_W), for the biconical antenna.

On such basis, Fig. 7 shows that a 100 ns-long time window provides overall accurate results over the entire considered frequency range. The evaluation of the *rmse* values (reported in Table 2) confirmed that a 100 ns-long time window (for which real-time sampling is assured), provides the best results in terms of accuracy. The *rmse* value corresponding to a 150 ns-long time window confirms the performance degradation for higher time windows.

5. CONCLUSIONS

In this paper an alternative TD based approach to antenna characterization has been validated. Comparative measurements of the reflection scattering parameter $S_{11}(f)$ of two different antennas have been carried out through the traditional FD approach in an anechoic chamber and through the TDR-based proposed approach. Results have shown that TDR-based measurements, together with an appropriate data processing, provide good insight into the characteristics of the considered antennas. In particular, it has been demonstrated that the choice of an optimal time window can suitably balance several contrasting effects that limit measurement accuracy: this way, measurement accuracy of the TD-based approach is greatly enhanced, and becomes comparable with that obtained through the FD approach. As a result, the presented method can ultimately be regarded as a practical and reliable procedure that successfully optimizes the trade-off between instrumentation costs and measurement accuracy.

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