PULSE RESPONSE OF UWB ANTENNA: MEANING AND SIMPLE MEASUREMENT PROCEDURE

M. Bury*, Y. Yashchyshyn *

*Institute of Radioelectronics Warsaw University of Technology ,Poland, M.Bury@ire.pw.edu.pl

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Abstract

Paper concerns the applicability of the antennas' pulse response in the ultra-wideband systems. It provides information, why it is important to determine this parameter and describes simple measurement procedure. Measurement results for selected exemplary antennas are also given.

1 Introduction

Great development of Ultra Wideband (UWB) Systems was observed in the last decade. They proved their applicability in many domains, such as communication, medical imaging systems and security systems, to mention just a few. Nevertheless it is still difficult to choose an appropriate antenna for such system during the designing stage [1]. The reason for such situation is the fact that well known and widespread antenna parameters fail to provide enough information to describe transmission of UWB signals. Considering the further development of UWB systems, this situation should be carefully analyzed and resolved.

2 Pulse response versus conventional antenna parameters

2.1 Frequency characteristics of the antenna

The phase and amplitude versus frequency antenna characteristics are already known and relatively easy to measure. Combined, they consist transmission of the antenna complex, frequency dependent coefficient by which every signal transmitted through antenna is multiplied. They can be also considered a Fourier transform of the antennas pulse response. When narrowband signals are concerned, the meaning of phase characteristic and impact of its shape on a signal are negligible. Therefore, hardly any antenna producer provides such chart in antennas' datasheets. When UWB signals and antennas are concerned though, the phase versus frequency characteristics determines the changes to the signal duration caused by antenna. That means that most of the wideband antenna producers do not provide enough information to evaluate antennas' applicability in UWB system.

Although the phase and amplitude characteristics of antenna – if both available – provide enough information to model and calculate antenna behaviour in an UWB system as well as the deformation introduced to the transmitted signal they fail to provide possibility of estimation "at first glance".

Since many UWB systems utilize the ultra-short pulses (some of them shorter than 100ps), the length of the signal after transmission is critical for their performance. In fact the application of the logoperiodic antenna in the system utilizing pulses shorter than 1ns, can entirely prevent it from operating [1].

2.2 Phase center of the antenna

A curve that shows the relation between the antenna's phase center location and the frequency is probably the parameter given most often, by the antannas' producers to present the behaviour of an antenna in the ultrawide frequency band. If an ultrawideband system designer was given the datasheets of two antennas then probably he would be immediately able to judge which antenna deforms the ultrawideband signals more and which less. However, he would be able neither to estimate nor to calculate the range of deformation and the exact shape of signal after transmission.

The location of the antenna's phase center can be considered as a hyphotetical point from which the radiowave of certain frequency is radiated [2]. Thus the dislocation of the phase center means the change of both the length of the wave propagation in the free space and the length of the wave propagation within the structure of the considered antenna [3]. The velocity of radiowaves in the air or free space is well known. So is the path of the signal outside antenna. However the velocity and the path of the signal within the antenna structure are sometimes extremely difficult. Thus knowledge of the phase center location in whole frequency bandwidth of the signal is not equivalent to the knowledge of the delays between the frequency componnets. Therefore, given only the phase center location curve, one cannot calculate the shape of the known signal after it is transmitted by the antenna of concern.

As opposed to phase and amplitude versus frequency characteristics, phase center location curve gives possibility of immediate estimation the antenna UWB properties but fails to give full information. Thus, phase center location curve is not applicable in the simulations of the UWB system performance. Particularly it does not provide possibility to take into account the antenna properties while measuring and simulation the radio-channel pulse response.

2.3 Pulse response of the antenna

Pulse response gives the same amount of information as the combination of amplitude and phase versus frequency characteristics. In fact, they are the Fourier transform of pulse response. However, the length of the antennas pulse response of the antenna can be determined directly from the plot. Therefore the pulse response somehow visualizes the deformation in the UWB signal caused by transmission through antenna. Naturally it can be also calculated from the complex frequency characteristics. Such approach, though, would require calculation of the Fourier transform and scallar products which operations are rather difficult to perform mentally without a computer.

As it is presented in the further sections of this paper, antenna's pulse response is relatively easy to measure in an antenna laboratory. Thus it can be determined by most of the UWB antenna producers as opposed to the UWB systems developers who rarely have an access to specialised antenna measurement equipment.

3 Pulse response measuring procedure

Exact determination of the antenna's pulse response requires suppresion of the multipath propagation. That means that measurment procedure should take place either in anechoic chamber or in the place that allows elimination of reflected signals by means of the time windowing. Since it is radio-link not the antenna response what can be directly measured, a reference antenna of known properties is required.

The measurements can be realized either in time or in frequency domain.

3.1 Time domain measurements

The most obvious approach to the determination of the pulse response of the antenna is application of the pulse shorter than signlas to be transmitted (with spectrum covering whole frequency band of the antenna). An exemplary measurement setup by means of which measurement results shown in the Section 5.1 were obtained, is shown in Fig. 1.

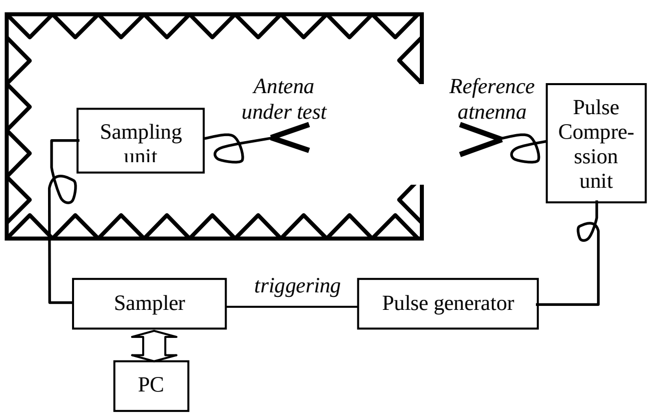

Figure 1: Time domain measurement setup

Let $\tilde{h}(t)$, $h_r(t)$, $p(t)$, denote measured pulse response of radiochannel, the pulse response of the reference antenna, and ultra-short pulse fed to the input of the transmitting antenna, respectively. Assuming that measuring system is callibrated and there is no multipath propagation within an radiolink so it is perfectly transparent to the radiowave, following equation is valid:

$$\tilde{h}(t) = p(t) * h_r(t) * h(t) \qquad (1)$$

where $h(t)$ denotes unknown pulse response of the antenna under test and operation " $*$ " means convolution.
Since convolution in time domain is equivalent to the product in frequency domain, it is easier to solve Equation (1) in frequency domain:

$$H(f) = \frac{\tilde{H}(f)}{P(f) \cdot H_r(f)} \qquad (2)$$

where $\tilde{H}(t)$, $H(t)$, $H_r(t)$, $P(t)$ are a Fourier transforms of $\tilde{h}(t)$, $h(t)$, $h_r(t)$, $p(t)$, respectively.
Practically, when digital representation of the measurement data is concerned, then functions in Equations (1) and (2) assumes form of the vectors of the samples:

$$\begin{aligned} \tilde{H}(k) &= \mathcal{DFT}\{\tilde{h}(n)\} \\ H_r(k) &= \mathcal{DFT}\{h_r(n)\} \\ P(k) &= \mathcal{DFT}\{p(n)\} \end{aligned} \qquad (3)$$

where $n \in \{0...N-1\}$ is an index of the time, $k \in \{0...N-1\}$ is the index of the frequency, N is the number of samples and $\mathcal{DFT}$ denotes Digital Fourier Transform.
Equation (2) assumes then its digital form:

$$H(k) = \left\{ \frac{\tilde{H}(k)}{P(k) \cdot H_r(k)} \quad for \quad P(k) \cdot H_r(k) \neq 0 \right. \qquad (4)$$

where $k \in \{0...N-1\}$ and N is a number of samples.

If the denominator is equal to zero it means that either applied short pulse or the the reference antenna fails to provide any information signal at certain frequency.
Samples of the antennas pulse response are obtained by means of the Inverse Digital fourier transform:

$$h(n) = \mathcal{DFT}\{H(k)\} \qquad (5)$$

It should be stressed that Fourier transform of antennas pulse response can be rewritten as:

$$H(f) = A(f) \cdot e^{j\varphi(f)} \qquad (6)$$

where $A(f)$ and $\varphi(f)$ are respectively amplitude and phase versus frequency characteristics of the antenna.

3.2 Frequency domain measurements

Alternatively all measurements can be performed in frequency domain. This approach eliminates the need to take into account the shape of the pulse. On the other hand, before processing it is difficult to verify whether the assumption about the one path propagation was valid or not. The measurement setup in which results presented in Section 5.2 were obtained is shown in Fig. 2.

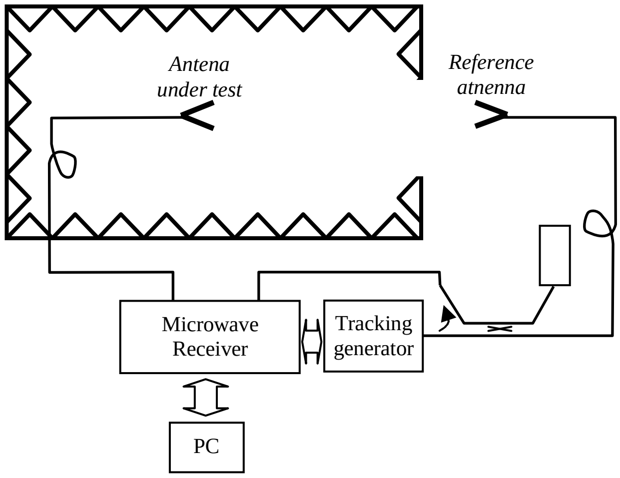

Figure 2: Frequency domain measurement setup

In this case it is transmittance $\tilde{H}(f)$ of the radiolink what is measured directly. There is no input pulse shape to be taken into account so the Fourier transform of the antenna under test can be calculated by means of the formula analogus to Equation (2):

$$H(f) = \frac{\tilde{H}(f)}{H_r(f)} \qquad (7)$$

which digital form is:

$$H(k) = \left(\frac{\tilde{H}(k)}{H_r(k)} \quad for \quad P(k) \neq 0 \right. \qquad (8)$$

Samples of the antenna's under test pulse response are calculated according to the Equation (5)

4 Discussion of the reference antenna

4.1 Requirements for the reference antenna

It is apparent that measurements of the antennas pulse response are not particularly difficult if only a reference antenna of known pulse response or complete frequency characteristics is available. Obviously measurements of antennas pulse response are valid only within the frequency band covered by the operating bandwidth of the reference antenna. Otherwise it may happen that denominators in Equations (2), (4) and (7),(8) are equal to or close to zero. It would mean that either those equations are at some frequencies indeterminate or the error is extreamly high.

The pratical condition is that the operating frequency band of the reference antenna must cover whole operating band of the antenna under test. Otherwise measurement results are not reliable.

4.1 Determination of reference antenna's pulse response

The problem with the reference antenna's pulse response is that according to the measurement procedure described above one would need another reference antenna in order to measure the pulse response of the reference antenna. That would lead to a problem with the first reference antenna. It can be resolved by performing measurements for a number of wideband antennas. Let us consider an advantageous situation when there are two identical wideband antennas available (if they were not identical then a third wideband antenna would be required in order to solve the problem).
Identical antennas can be measured either in time or in frequency domain. The pricnciple is the same in both cases: two identical antennas are measured in either measurement setup. The problem of the determination of their pulse response is then reduced to Equation (9).

$$[H_r(k)]^2 = M(k) \qquad (9)$$

where:

$$M(k) = \begin{cases} \begin{cases} \dfrac{\tilde{H}(k)}{P(k)} & P(k) \neq 0 \\ 0 & P(k) = 0 \end{cases} & \text{time domain} \\ \tilde{H}(k) & \text{frequency domain} \end{cases} \qquad (10)$$

It should be noticed that solution to the Equation (9) should be a vector not a scalar numbar. Since every sample has two square roots, there are 2^N possible vectors $H_r(k)$ satisfies Equation (9). It means that there is an additional condition required in order to select ther real one. Since the solution describes the properties of the real device, if only the Nyquist condition on sampling frequency is satisfied, then the phase of the solution must not include discontinuities. Naturally, the 0-360 degrees representation of the phase imposes the phase discontinuities of the *M(k)* . They, however, can be eliminated by so called phase unwrapping. This operation consist in correction of the radian phase angles in a vector by adding multiples of $\pm 2\pi$ when absolute jumps between its consecutive elements are greater than the π radians.
Accordingly, following solution is proposed:

$$\forall_{k \le \left\lfloor \frac{N}{2} \right\rfloor + 1} \; H_r(k) = \sqrt{|M(k)|} \cdot e^{\frac{j \cdot \phi(k)}{2}} \qquad (11)$$

where $\phi(k)$ is unwrapped phase of *M(k)*.

Please note that division by 2 of the continuous function must also give the continuous function. Thus the phase calculated in the exponent inside Equation (11) is continuous.

The remaining part of $H_r(k)$ is conjugate symetric to the one calculated by means of the Equation (11).

It should be noticed that vector $[-H_r(k)]$ also satisfies Equation (9). Nevertheless the sign of the entire pulse response is not very significatn, when the antenna aplicability for UWB system is concerned.

5 Measurement results

Measurements were performed for four antennas: two identical lens antennas one of which served as reference afterwards, a horn (aperture size 260mm*340mm) antenna and logoperiodic antenna. All antennas nominal operating bandwidth was 1-26.5GHz. Measurements in the both assemblies (Fig. 1 and Fig. 2) were performed according to the procedures described above. Resulting responses were shifted so as to beginning moment were approximately the same for the same antennas measured in different domains.

5.1 Time domain

A normalized representation of the pulse fed to the transmitting antenna is presented in Fig. 3.

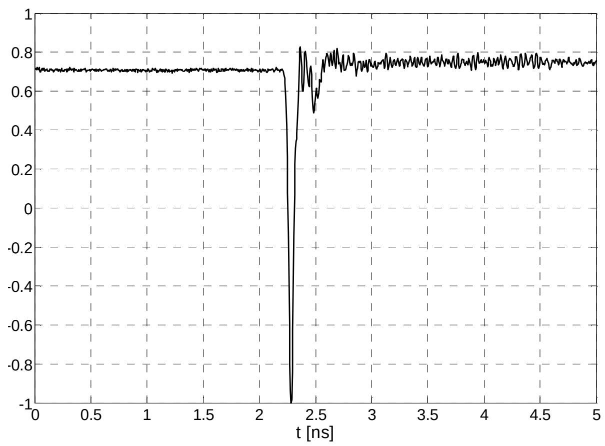

Figure 3: Normalized test pulse

Amplitude spectrum of this pulse is presented in Fig 4.

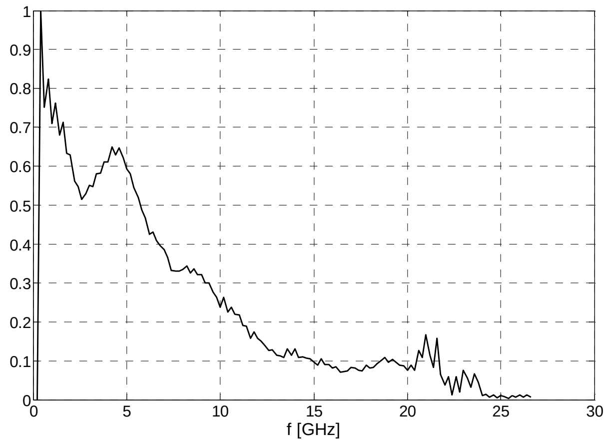

Figure 4: Amplitude spektrum of the normalized pulse

It is apparent that spectrum of the pulse hardly covers the nominal operational bandwidth of the tested antennas. In fact the magnitude at frequencies greater than 25GHz is almost equal to zero. For those frequencies Equations (2) and (4) are undetermined. Generally signal to noise ratio decreases significantly at frequencies greater than 20 GHz. Therefore an error introduced by limitation of the measuring equipment may be expected.

A normalized reference antanna's pulse response determined by means of measurements in time domain is presented in Fig. 5.

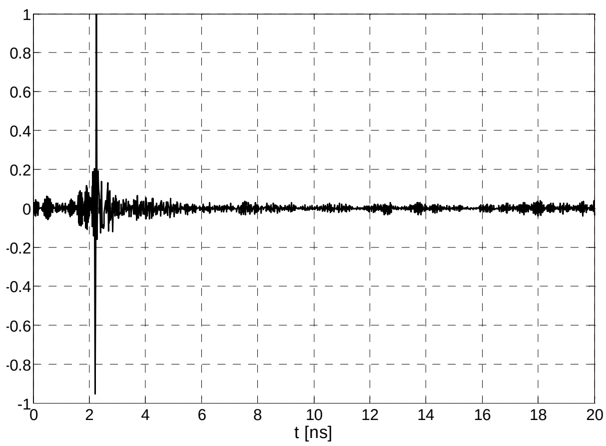

Figure 5: Reference antennas normalized pulse response

Normalized pulse responses of the horn antenna and the logoperiodic antenna, measured in time domain are presented inf Fig. 6 and Fig. 7 respectively.

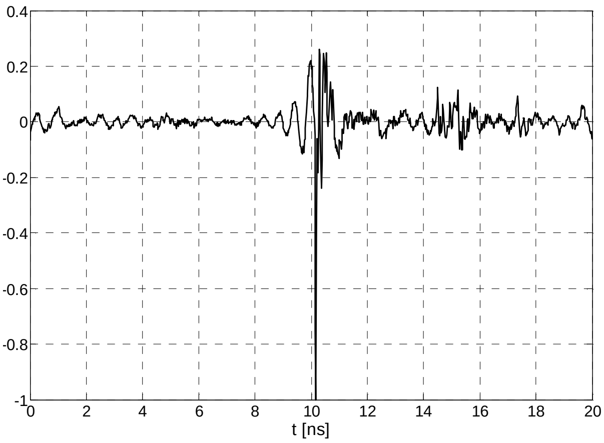

Figure 6: Normalized pulse response of the horn antenna

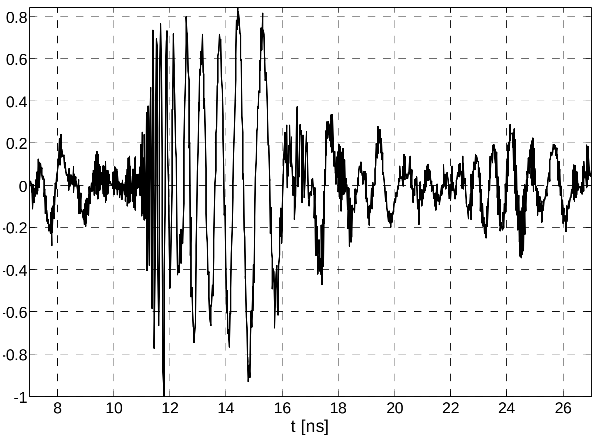

Figure 7: Normalized pulse response of the logoperiodic antenna

5.2 Frequency domain

The same measurement set was performed in frequency domain measurement assembly.

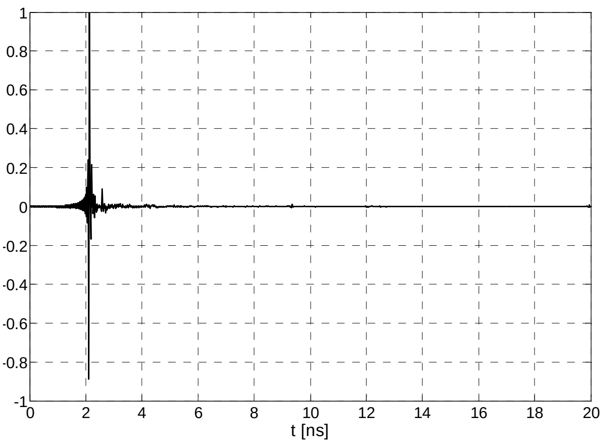

Figure 8: Reference antennas normalized pulse response

It should be noticed that the directional coupler operates acceptably at frequencies above 2GHz which means that not all operational bandwidth of the antennas under test is covered. Therefore an errors induced by the measurement assembly may occur. The pulse response of a reference antenna is presented in Fig. 8.

Normalized pulse responses of the horn antenna and the logoperiodic antenna, measured in frequancy domain are presented inf Fig. 9 and Fig. 10 respectively.

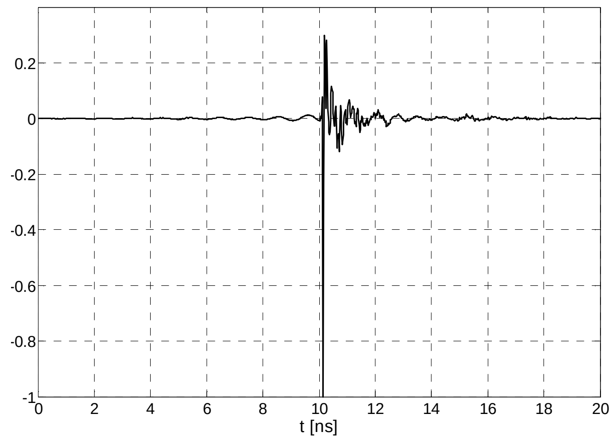

Figure 9: Normalized pulse response of the horn antenna

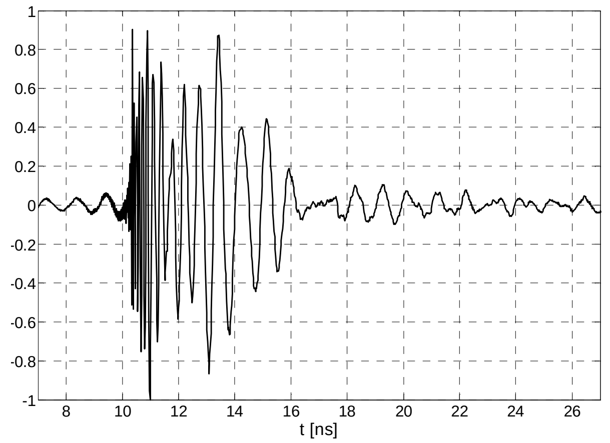

Figure 10: Normalized pulse response of the logoperiodic antenna

5.3 Domains comparison

Despite the fact that time domain measurement assembly operates less acurate at high frequencies while frequency domain assembly operates less acurate at low frequencies both method have given very similar results. This fact can be considered as a proof that they are aplicable and not very susceptible to the equipment limitation.
The same results as presented in subsections 5.1 and 5.2 of measurements are in grater scale and in comparable manner in Figs 11-13.

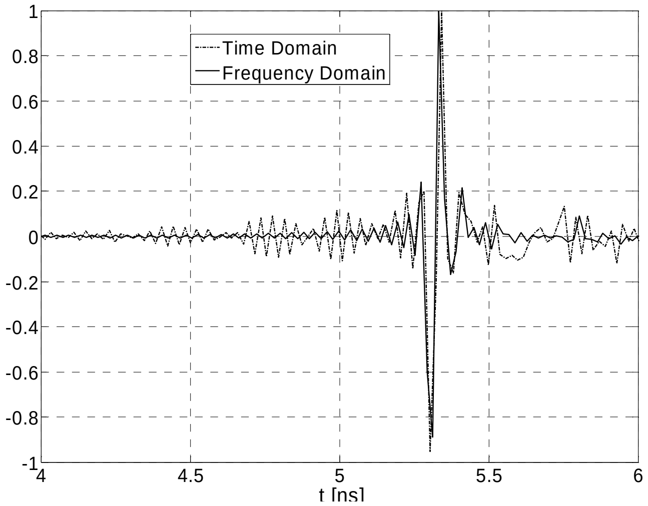

Figure 11: Normalized pulse responses of the lens antenna measured in Time and in Frequency Domains

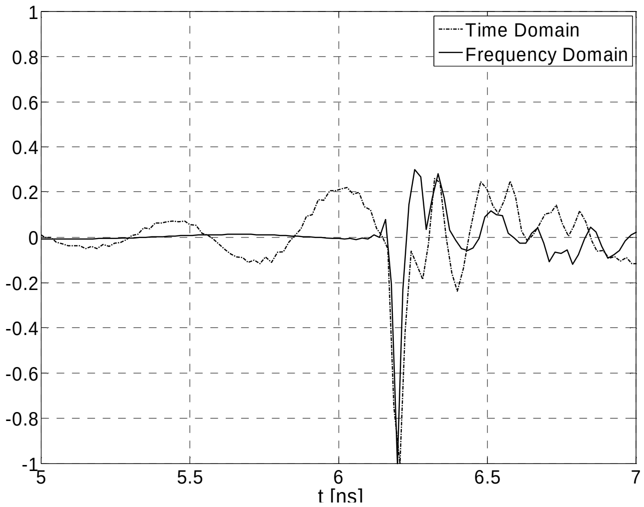

Figure 12: Normalized pulse responses of the horn measured in Time and in Frequency Domains

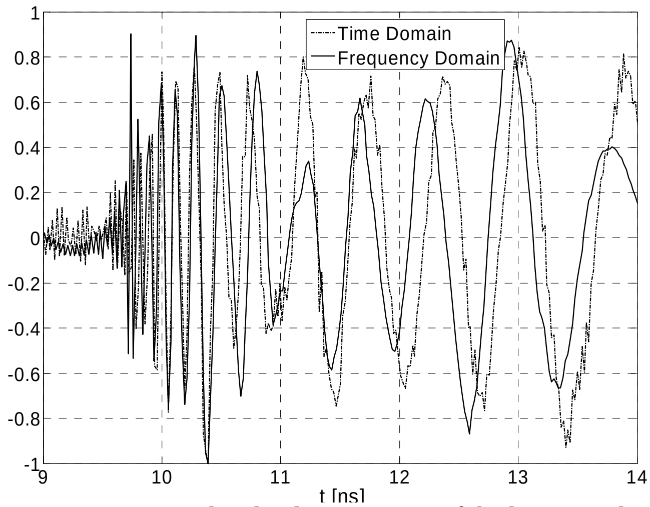

Figure 13: Normalized pulse responses of the logoperiodic antenna measured in Time and in Frequency Domains

Discrepancies visible in the Figures are indisputable. They may be caused by many factors including different connectors applied in time and frequency domain setups and calibration errors. However the general shape and the duration of measured pulse response remains the same.

6 Summary

Paper indicates the need for the including a pulse response of the antenna within it datasheet. Reasoning for this demand was that pulse response, as opposed to other parameters, gives opportunity to a human to estimate at first glance the range of UWB signal deformation caused by the antenna as well as full information needed for exact shape calculation.

Moreover, since radio-channel pulse response is widely utilized in UWB systems simulation possibility of antennas' influence determination is very desirable [4]. Antenna pulse response is a parameter relatively easy to introduce into radio-link simulators.

Although the combination of the amplitude and phase versus frequency characteristics gives theoretically the same information as pulse response, the equivalency is limited since phase versus frequency characteristics hardly ever appears in the antennas' datasheets.

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