The Improvements of the Antenna Parameters in Ultra-Wideband Communications

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Abstract: **The Ultra-Wideband (UWB) technology is based on the new concepts of a very short pulse signals. This technology is a good candidate for the next generation (4G) networks, but it requires a new approach to antenna design in order to achieve UWB characteristics.This work analyzes the UWB antenna design problems and presents UWB antenna simulations in transient mode used to verify antenna parameters improvements. Simulation results show that possible improvements of the antenna parameters can be achieved by properly selecting antenna dimensions, antenna patterns and materials used to build antenna.**

I. INTRODUCTION

Ultra Wideband (UWB) radio systems usually employ short pulses, typically of the order of sub-nanoseconds. These pulses has an extremely broad bandwidth, larger than 20% or 500 MHz.

The UWB systems may possibly interfere with existing electronic systems since the short pulses occupy extremely wide spectar of frequencies. To lower potential interference, the Federal Communications Commission (FCC) issued UWB Regulations, under Part 15 of Commision's Rules.[1] According to these rules, UWB signals may be transmitted between 3.1 GHz and 10.6 GHz at the effective isotropic radiated power (EIRP) levels up to - 41dBm/MHz for the unlicenced use of commercial UWB communication systems.[1]

These emission limits are the crucial consideration in the design of the UWB antenna. The FCC limits put on UWB antenna design additional challenges compared to conventional narrow band antenna design. The impedance matching, dispersion, radiation efficiency and group delay are among the parameters that must be considered with great care during design. These parameters are usually almost constant in the narrow band antenna but in ultra wideband frequency range they vary significantly.

This paper gives a brief overview of the UWB antenna design. The commercial simulation tool is used to show how antenna size and shape influence the UWB antenna parameters. Based on simulation, a method to improve UWB parameters is proposed.

This paper is organized as follows: in the second chapter the short introduction and definition of UWB antenna parameters are given. The third chapter gives three basic principles of broadband antenna shortly described. In the fourth chapter UWB antenna design requirements are given and the fundamental limitations on antenna size and performance are described. The fifth chapter gives simulation results for three types of antenna. The three types of antenna are compared: (1) Bow-tie antenna, (2) Circular dipole and (3) Elliptical dipole UWB antenna. Antenna size is considered on the example of the circular dipole antenna. The simulation results of the circular antennas with three different radius 24 mm, 12 mm and 6 mm are compared and analyzed. The sixth chapter concludes the paper.

II. UWB ANTENNA PARAMETERS

A. BANDWIDTH

The main characteristic of UWB antenna is bandwidth.[2] There are two ways to express bandwidth: (1) The ratio of the upper frequency f_H and lower frequency, f_L. The UWB has approximately $f_H : f_L=3:1$. (2) The fractional bandwidth (bw) of a system is the ratio of the bandwidth BW to the center frequency, f_C. [2]

$$bw = \frac{BW}{f_C} = \frac{f_H - f_L}{f_C} = 2 \cdot \frac{f_H - f_L}{f_H + f_L} \tag{1}$$

The bandwidth of the system is often described relatively to the center frequency, fC which is calculated in formula (2).

$$f_C = \frac{f_H + f_L}{2} \tag{2}$$

The Federal Communications Commission (FCC) issued a report and order to define a UWB systems in terms of -10dB power bandwidth meaning that upper and lower frequencies are those where the radiated spectral power density is -10dB down from the center frequency. According to FCC definition [1] of UWB system, UWB antenna has bandwitdh greater than 500MHz or a fractional bandwidth greater than 0.2 where fractional bandwidth is defined as in formula (1).[2]

B. GROUP DELAY AND DISPERSION

An UWB antenna can be analyzed as a filter by means of the magnitude and phase responses. By representing the receiver/transmitter antenna as a filter, we can determine its phase linearity within the frequency band of interest by looking at its group delay. Group delay is the measure of a signal transition time through a device [3]. It is classically defined as the negative derivative of phase versus frequency given by (3).

$$Groupdelay = -\frac{\partial\theta(\omega)}{d\omega} \tag{3}$$

The phase response and group delay are related to the antenna gain response. The group delay variation induced by the radiation pattern of the antenna appears to be a very important parameter in the overall receiver system performance, since it can bring relatively large timing errors.

The lower frequency radiates from larger part of antenna and higher frequency radiates from smaller part of antenna [2].

C. ANTENNA DIRECTIVITY, GAIN AND RADIATION EFFICIENCY

Directivity (D) is defined as the ratio of the radiation intensity P in a given direction from the antenna to the radiation intensity averaged over all directions. [4] The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. [4] Radiation intensity is defined as the power radiated from an antenna per unit solid angle. [2, 4]

$$D = \frac{peakenergy}{averageenergy} = \frac{|P(\theta,\phi)|_{\max}}{\frac{1}{4\cdot\pi}\oint_S |P(\theta,\phi)|\cdot\sin\theta\cdot d\theta\cdot d\phi} \tag{5}$$

According to [4] absolute gain, is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically.

$$G = \eta\cdot D \tag{6}$$

Radiation efficiency (η) is determined by the ratio of the radiated power, P_{rad} to the input power at the terminals of the antenna, P_{in} . [2, 4]

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{G}{D} \tag{7}$$

The formulas (5), (6) and (7) describe connection between directivity (D) , gain (G) and efficiency (η). Gain is

D. IMPEDANCE MATCHING

Impedance is the ratio of the electric and magnetic fields. Impedance is complex value since the electric and magnetic fields are not necessarily in phase. If an impedance of a transmission line (Z_0) and the antenna impedance (Z_A) are not identical then there will be a mismatch to the antenna terminals and some of the incident signal will be reflected back to the source. This reflection is characterized with reflection coefficient (Γ) which is ratio of the reflected voltage (V_0^-) to the transmitted voltage (V_0^+).

$$\Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_A - Z_0}{Z_A + Z_0} \tag{8}$$

The other parameter frequently used to characterize impedance matching is Voltage Standing Wave Ratio (VSWR). The VSWR is defined as the ratio of the peak voltage maximum to peak voltage minimum in the standing wave pattern at an impedance discontinuity. [4, 5]

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{9}$$

For the perfect matching VSWR=1, there is no reflection and return loss. In the real UWB system it is very hard to achieve a perfect match over a wide frequency match so it is define that have VSWR < 2 is still good matching system. [2, 3]

III. BROADBAND ANTENNA THEORY

The basic principles of broadband antenna are:

(1) The principle of the frequency-independent antenna that was proposed by V.Rumsey [6]. This principle suggest that the impedance and radiation pattern properties of antenna will be frequency independent if the antenna shape is specified only in terms of angles. The antenna to satisfy this principle should be infinite in size and described by means of angles. The frequency independent antenna because its size is dispersive as it radiates different frequency components from different parts of the antenna, e.g. smaller part radiates higher frequencies and larger parts radiates lower frequencies. [2]

(2) The principle of self-complementary antenna was introduced by Mushiake[7]. The self complementary antenna structures are similar to a positive and negative in photography.[2] A self-complementary structure can be made to exactly overlay its complement through translation and/or rotation. The product of the impedances of two complementary antennas is constant. It is given by formula (10). Z_{orig} is impedance of original antenna structure, Z_{compl} is impedance of complementary antenna structure and η is impedance of the free space(376.7 Ω). According to self-

complementary principle impedance of the antenna is frequency independent if the antenna is self complementar. [7] The self-complementary principle assumes that antenna size is infinite and dispersive so it is not siutable for UWB applications

$$Z_{orig} \cdot Z_{compl} = \frac{\eta^2}{4} \tag{10}$$

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(3) The third principle of broadband antenna design is to use thick metal [2]. It is well known that thin wire dipole antenna has very sharp resonant frequencies because thin wire concentrate currents and reactive energy leading to narrower bandwidth. If the wire diameter increases the dipole becomes fat and widens its bandwidth.The quality factor, Q, describes the ratio of reactance energy stored in the system and resistance. In the narrowband antenna quality factor Q is very high. The way to widen antenna bandwidth is to decrease the quality factor Q of antenna.

IV. UWB ANTENNA DESIGN

A. UWB ANTENNA DESIGN REQUIREMENTS

The UWB antenna requirements are:

(1) The UWB antenna must operate in frequency range from 3.1 GHz to 10.6 GHz. [1] Therefore, UWB antenna impedance must achieve 7.5 GHz bandwidth in order to avoid a large return loss and matching problem.

(2) The UWB antenna should have linear phase through frequency range and constant group delay for the given frequency range. This means that UWB antenna should have as less as possible dispersion of pulses. [2]

(3) An omni-directional radiation pattern is desirable because of user mobility and freedom in the transmitter or receiver position. Omni-directional radiation pattern means that the signal waves passing through antenna shall be able to travel in all directions. This implies minimizing UWB antenna gain and directivity for use in communication systems.

(4) The radiation efficiency must be very high as the transmit power spectar density is very low. The upper limit define by FCC is - 41dBm/MHz. [1] Conductor and dielectric losses should be minimized in order to maximize radiation efficiency. [2]

(5) The antenna is required to be physically compact and low profile, preferably planar. The antenna size should be small (comparing with wavelength) and, if possible not too heavy, but in the other hand very compact and robust. This requirement is due to small size of UWB devices and required user mobility.

B. UWB ANTENNA SIZE LIMITATION

There are certain limitations regarding the size of antenna and efficiency of radiation for broadband antenna. The fundamental limitation of antenna size is called Chu-Harington limit [7] and was later reviewed by Mclean [8]. Chu set the theory of fundamental limitation for electrically small and omni-directional antenna. He assumed that every electrically small antenna with whatever geometry and current distribution can lie within boundary sphere. The fields outside boundary sphere must be exactly the same as with an ideal point dipole. Electrically small antenna is antenna that operates on frequencies which wavelength are much greater than antenna size.

Chu calculated the lowest quality factor Q for a fixed size boundary sphere with radius R which gives the broadest bandwidth. Latter Chu results for quality factor Q was reviewed by McLean. The quality factor Q set limits to antenna where performance may be extended to the ultra wideband context with two observations: first center frequency (f_C) is the geometric average of the upper (f_H) and the lower (f_L) frequencies and bandwidth is defined by the half power or -3dB points. [2, 8]

$$Q = \frac{f_C}{BW} = \frac{\sqrt{f_H \cdot f_L}}{f_H - f_L} \tag{11}$$

The McLean limit is given in formula (12).

$$Q = \frac{1}{k^3 \cdot R^3} + \frac{1}{k \cdot R} \tag{12}$$

Where k is the wave number (k=$2\pi / \lambda_C$) and R is radius of boundary sphere. The McLean limit given in formula (12) gives connections between frequency bandwidth, antenna size and antenna radiation efficiency . The formula (11) gives connection between frequency bandwidth and antenna performance Q.

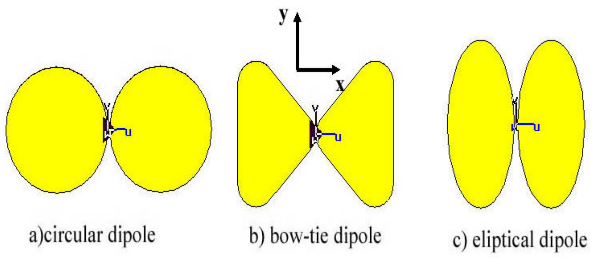
C. UWB ANTENNA DESIGN

Maxwell equations [3] are used in analysis of the UWB antenna as well as narrowband antenna but in the case of the UWB antenna it could not be simplified due to wide frequency range. Therefore the simulations are used during design and modeling of the UWB antenna. In this paper CST Microwave Studio [9] is used. The CST Microwave Studio is used in transient mode. Gausian signal is used as excitation signal. During the UWB antenna modeling process the fundamental limitations [7, 8] and the frequency–independent principles [6] should be considered.

V. THE IMPROVEMENTS OF UWB ANTENNA PARAMETERS

A. UWB ANTENNA SHAPE

We investigate how different antenna shape effect UWB antenna parameters. The UWB antenna parameters of special interest are: (1) VSWR, (2) radiation pattern, (3) radiation efficiency and (4) dispersion.



a)circular dipole b) bow-tie dipole c) eliptical dipole

Figure 1. Three UWB antenna types used for comparation

The three types of UWB planar antenna are compared: (1) Bow-tie antenna, (2) Circular dipole antenna and (3) Elliptical dipole antenna. This antennas are shown in figure (1). The dimensions of antenna are given in table 1. The dimensions are given for only one element of the dipoles. The thickness d is 1mm for all antenna.

Table 1. Three types antenna dimensions

Dimension	Bow-tie element	Circular element	Eliptical element
x	55 mm	48 mm	24 mm
y	110mm	48 mm	48 mm
d	1mm	1 mm	1 mm

The antenna models and simulations are done by CST Microwave Studio. The results obtained from simulations are used to compare the three types of antenna. The results for VSWR are shown in figure (2).

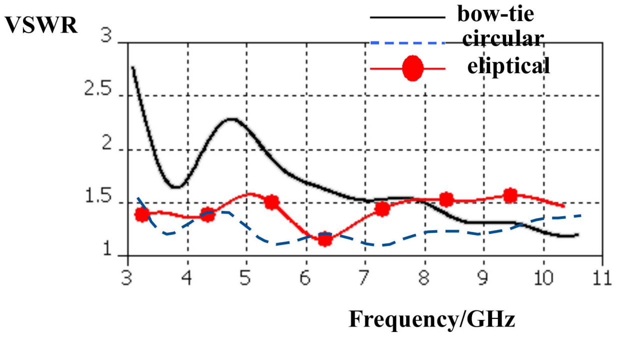


Figure 2. VSWR for bow-tie,circular and elliptical antenna

The Bow-tie antenna has VSWR > 2 in the frequency range 3.1GHz-3.45 GHz and from 4.29GHz – 5.31 GHz but VSWR < 2.5 is still acceptable for some applications. In the case of Elliptical dipole and Circular dipole the impedance matching and return loss are very good, less than or equal to VSWR < 1.5 through the UWB frequency range.

The figure (3), gives phase-frequency characteristics for antennas under consideration. The phase characteristics are obtained from S11-parameter that is ratio between return wave and incident wave and it is often used in microwave communications to calculate reflection coefficient of devices like in formula (8). [5]

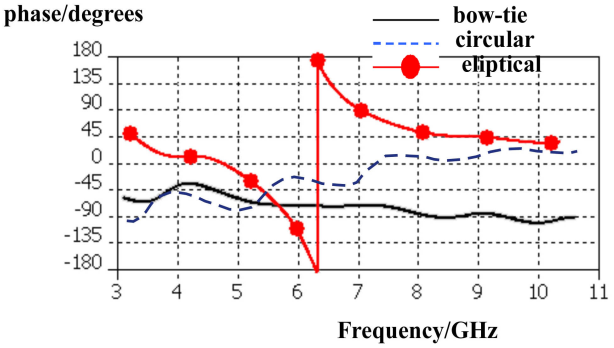


Figure 3. Phase frequency characteristics

Figure (3) shows that elliptical dipole has nonlinear phase characteristics at around 6.36 GHz and pulse dispersion for this antenna are significant. Bow-tie antenna has almost linear phase characteristics and Circular antenna has a little nonlinearity. Dispersion for those two antennas are not high but the „ringing“ effect could be seen.

The radiation pattern. it is often described by two planes, one plane (x-y) in horizontal and the other (y-z) as vertical plane. In the figure (4) shows radiation pattern at frequency 4GHz and figure (5) shows radiation pattern at 8GHz.

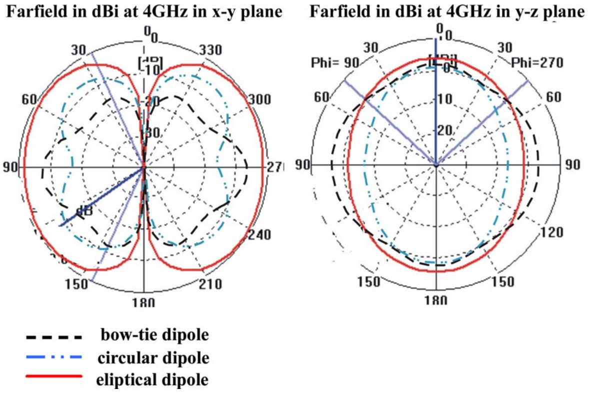


Figure 4. The radiation patterns at 4 GHz frequency

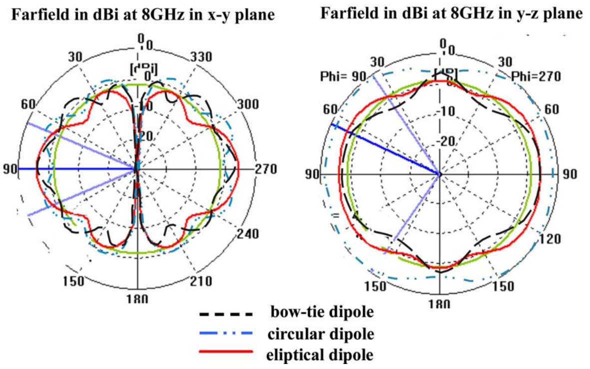


Figure 5. The radiation patterns at 8 GHz frequency

The antennas used in simulations are showing almost omnidirectional pattern in y-z plane. Comparing results for each antenna at frequencies 4 GHz and 8 GHz we noticed that neither of antenna fully satisfy the UWB requirements. Elliptical dipole antenna has radiation difference with angle comparing radiation pattern in 4GHz and 8 GHz of about -4 dBi in y-z plane and almost -9 dBi in x-y plane. Comparing the results for Bow-tie antenna at 4GHz and 8GHz gives -6dBi difference in y-z plane and -7dBi in x-y plane. Circular dipole antenna has -10dBi in y-z plane and -5dBi in x-y plane.

B. ANTENNA SIZE

We compared circular dipole antennas with different radius 24mm, 12 mm and 6 mm. The thickness of circular dipole antennas are 1 mm.

The figure (6) shows VSWR for three Circular dipoles with radius 24mm, 12mm and 6mm.

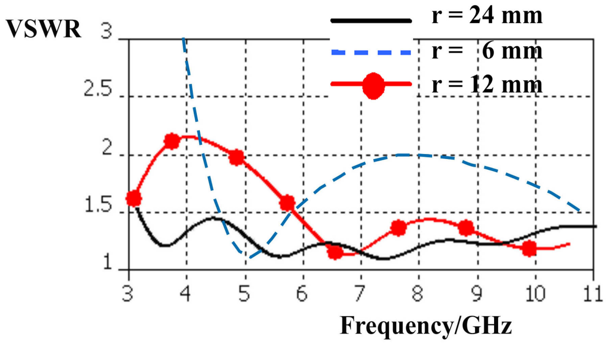


Figure 6. The VSWR of three different size of the antenna

The Circular antenna with radius 24 mm has impedance matching equal or below VSWR < 1.5. The Circular antenna with the 6mm radius has VSWR > 2 at the low UWB frequency range up to 4.1GHz. The Circular antenna with radius 12 mm has VSWR > 2 in frequency range from 3.5GHz - 4.7GHz but it is still acceptable. The Circular antenna with radius of 24mm has a very good impedance matching and VSWR < 1.5.

In the figure (7) , presented phase-frequency characteristics results for the three Circular dipole antenna with radius of 24mm, 12mm and 6mm.

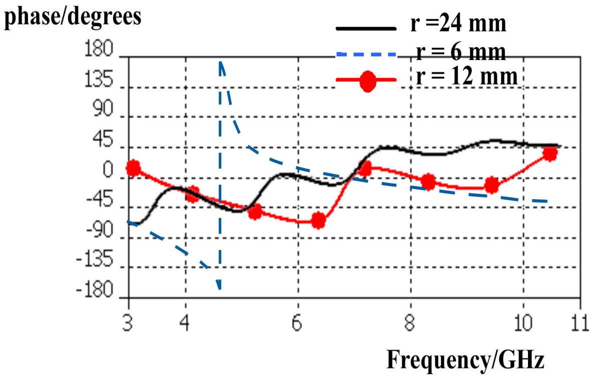


Figure 7. The phase characteristics of circular antenna with radius 24, 12 and 6mm

The Circular antenna with 6mm radius show a significant nonlinearity about 4.74 GHz. The Circular antennas with 12mm and 24 mm radius have nonlinearity and small „ringing“ effect that are still acceptable.

The radiation pattern for three Circular dipoles with radius 24mm, 12mm and 6mm are given in figure (8) at 4GHz and figure (9) at 8GHz.

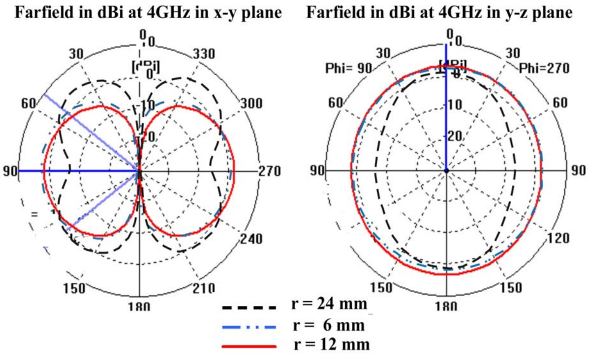


Figure 8. The radiation pattern for circular antenna with radius of 24mm, 12mm and 6mm at 4GHz

The radiation pattern at 4GHz in y-z plane shows almost ideal omnidirectional pattern for Circular dipoles with radius 12mm and 6 mm. Circular dipoles with radius 12mm and 6mm have almost identical characteristics at 4GHz because the dimensions of antennas are small comparing wavelength at 4 GHz.

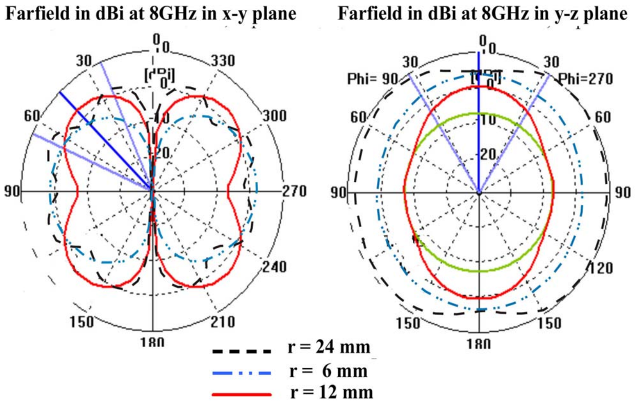


Figure 9. The radiation pattern for circular antenna with radius of 24mm, 12mm and 6mm at 8GHz

The Circular antenna with 24mm radius has better radiation pattern at 8GHz and Circular antenna with 12mm radius has better radiation pattern at 4GHz. If we compare figure (8) and (9) it could be seen that a radiation pattern of Circular dipole with radius 6mm has constant characteristics at frequencies 4GHz and 8GHz.

VI. CONCLUSION

We modeled and simulated three different UWB antenna types and three Circular dipoles with three different radius.

First, three different antenna types are simulated and analyzed. The simulated types of UWB antenna are: (1) Bow-tie antenna, (2) Circular dipole and (3) Elliptical dipole. The antennas are modeled and simulated using CST Microwave Studio. In order to compare three different antenna types we tried to have the antennas dimensions as similar as it is possible. The simulation results show very good impedance matching for circular and elliptical plannar dipole antennas with VSWR < 1.5 through UWB frequency range. Bow-tie UWB antenna results show good phase-frequency characteristics but not good impedance matching , VSWR > 2 in frequency range 3.1GHz-3.45 GHz and from 4.29GHz – 5.31 GHz. The radiation patterns for all three types of UWB antenna show almost omnidirectional pattern but neither of these three types have constant or -3dBi characteristics as it is required.

Second, we are simulated and analyzed three Circular dipole antennas with three different radius 24 mm, 12 mm and 6mm to show how antenna size influenced the UWB antenna parameters. The VSWR and phase-frequency characteristics for circular dipoles with radius 24mm and 12mm show good impedance matching and almost no dispersion. The Circular dipole with radius 6mm show very good radiation pattern at frequencies 4GHz and 8GHz but not good impedance match up to 4.7 GHz.

The UWB antenna parameters could be improve by changing antenna size and antenna shape. The improvement of one UWB parameter might influence to the other UWB parameters. Changing the size of UWB antenna could improve radiation pattern but could also effect impedance matching. The UWB design is always trade off between desired UWB parameters characteristics and the characteristics that could be achieved in reality. During the UWB design we should be aware of the limitations on antenna size.

The results obtained by simulations of different antenna shapes and antenna size show that combining the both method, changing antenna shape and antenna size, UWB antenna parameters could be improved.

REFERENCES

[1] U.S.47 C.F.R. Part15 Subpart F 15.503d Ultra-Wideband Operation (October 1, 2003 edition)

[2] Schantz, Hans:"The Art and Science of Ultra-Wideband Antennas", Artech House, 2005

[3] Stutzman,W. L., Thiele, G. A.: "Antenna Theory and Design" second edition, John Wiley &Sons,Inc.

[4] IEEE Transactions on Antennas and Propagation, Vols. AP-17, No. 3, May 1969; Vol. AP-22, No. 1, January 1974; and Vol. AP-31, No. 6, Part II, November 1983.

[5] Pozar, David M.: The Microwave Engineering, third edition, John Wiley & Sons Inc. , 2005

[6] Rumsey, Victor H., "Frequency Independent Antennas", IRE National Convention Record, August 1958,pp 251-259

[7] Chu, L. J. "Physical Limitations of Omni-Directional Antennas". Journal of Applied Physics, v. 19, Dec. 1948, pp. 1163-1175.

[8] McLean, J. "A Re-Examination of the Fundamental Limits othe Radiation Q of Electrically Small Antennas". IEEE Transactions on Antennas and Propagation, v. 44, n. 5, May 1996, pp 672-675.

[9] CST Microwave Studio Tutorials, 3D EM for High Frequencies, Computer Simulation Technology