A Method to Include Antenna Pattern Characteristics in UWB System Design

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Abstract

In UWB system design and optimization, antennas are usually represented by a single transfer function relating the input voltage to the radiated electric field in the free space. However, the transfer function of planar ultra-wideband antennas depends on not only frequency but also direction. In this paper we present a strategy that helps the UWB system designer to select the best transfer function (and the best reference direction) for the antenna. In the process we demonstrate that good pattern stability of a UWB antenna within a particular band is advantageous to ease the complexities in the selection of the transfer function. We have thus emphasized the importance of having stable patterns for UWB antennas. Pulse optimization algorithms that meet FCC spectrum requirements are presented as examples.

1. Introduction

An antenna is one of the important elements in a UWB system. One major concern of UWB system design is to confer with regulations and standards. A primary requirement for any UWB device is to comply with the emission masks enforced by FCC (Federal Communication Commission, USA), OfCom (Office of Communication, UK) or any other regulatory body of the respective region, [1]. To minimize interference with other systems, very low power is expected to emit from UWB systems. Then correlation detectors with known templates are expected to capture most of the available energy in order to achieve high-speed data transfer. Therefore, it is important to understand pulse deformation occurring at the antenna. Especially, the dispersion effects may be minimized to achieve optimal radiation from an antenna. Furthermore, the knowledge of an antenna transfer function [2] is necessary for designing filters at the radio front end for pulse shaping [3].
Correlation patterns were introduced for base band pulse radiating antennas in [4]. Similarly, the fidelity concept has also been presented for characterizing the pulse deformation by antennas. These concepts were adopted in [5] to define the correlation energy of a UWB antenna. The correlation energy is the amount of detectable energy per pulse after correlating with a known template. However, it is obvious that when the antenna has different transfer functions in different directions, selecting a specific template to maximize the correlated energy is difficult, if not impossible. In this paper we use correlation concepts to reemphasize the importance of having stable radiation patterns for UWB antennas. It is shown that antenna(s) having stable radiation patterns can be coupled in random directions without affecting system performance severely. As the pattern stability is linked with far–field correlation, which in turn is related to pulse detection, we can show that pattern stable antennas can be easily represented by a single transfer function. A selected transfer function is well correlated to all other, possibly infinite number of, transfer functions. Therefore, any optimization done on one of the reference functions are valid for other directions as long as radiation patterns remain stable in those directions.

2. Theory

2.1. Pattern Stability

For a UWB antenna we can write correlation energy and a total energy in a particular direction in the time domain. Pulses are time limited and band limited as well. In [5], U_E (total energy) and U_C (correlated energy) are defined as follows.

$$U_E = \frac{1}{\eta}\int_{-\infty}^{\infty} \left|e(\vec{r},t)\right|^2 r^2 dt \qquad (1)$$

$$U_C = \frac{\left[\frac{1}{\eta}\int_{-\infty}^{\infty} e(\vec{r},t)\,T(t)\,r dt\right]^2}{\int_{-\infty}^{\infty}\left|T(t)\right|^2 dt} \qquad (2)$$

η- Free space wave impedance
$e(\vec{r},t)$ - E-field at the far-field point $r = |\vec{r}|$
T(t)- Template function

Consider the ratio U_C/U_E, a measure of efficiency. For this ratio to be one, a proper selection of template function is necessary. A good candidate for this can be the E-field itself in a reference direction $\vec{R}$. Then in that direction,

$$\frac{U_C}{U_E}\left(\vec{R}, T = e(\vec{R},t)\right) = 1 \qquad (3)$$

This alone does not guarantee that the correlation efficiency is unity in all the other directions. To build up a relationship between the radiation patterns and the ratio U_C/U_E, calculation in the frequency domain can be done:

$$F^2(\vec{R},\vec{r}) = \frac{U_C}{U_E} = \frac{\left|\int_{BW} E(\vec{r},f)E^*(\vec{R},f)df\right|^2}{\int_{BW} \left|E(\vec{r},f)\right|^2 df \int_{BW} \left|E(\vec{R},f)\right|^2 df} \qquad (4)$$

Note that this is equivalent to the fidelity calculation presented in [4] (the reason behind the selection of notation). Only difference is the detection template is now similar to a radiation spectrum in one of the directions. Condition for F^2 to become unity can be expressed as:

$$E(\vec{r},f) = K(\vec{r})E^*(\vec{R},f) \qquad (5)$$

where K is a constant with frequency. Note the equality given in (5) is the condition for ideal pattern stability.

The existence of a reference direction and a set of other directions $\vec{r}$ fulfilling the condition (5) is possible within pattern stable beam for a given UWB antenna element. Ideal pattern stability is practically impossible to achieve, however, (4) can be the basis for developing a figure of merit for UWB pattern stability. Considering the linear properties of the antennas, condition (5) may also be imposed on the directional transfer function, $H(\vec{r},f)$ [2]. From (5) and (4) it can be argued that for a pattern stable antenna, radiation in every direction is well correlated to all the other directions. Therefore, any directional transfer function may be selected to represent the antenna in a system. However, as the degree of stability decreases a method to identify the "Reference Transfer Function" is due.

2.1. Design for FCC Mask

Design of pulse shaping filters to meet with the radiation limits set by FCC was presented in [3].

Referring to Fig. 1, the filter incorporated with the antenna can be given as:

$$G_A(f) = \frac{E(f)}{P(f)H_A(f)} \qquad (6)$$

where $E(f)$ is the radiated pulse, which complies with the FCC mask. $P(f)$ stands for the generator pulse, usually a Gaussian derivative, And $H_A(f)$ is the transfer function representing the antenna. Hereon, our discussion is focused on selecting the best $H_A(f)$ for expected system performance.

For a given antenna we may calculate a set of directional transfer functions for any direction $\vec{r}$:

$$H(\vec{r},f) = E(\vec{r},f)/\{P(f)G_A(f)\} \qquad (7)$$

Then the pulse radiated in a particular direction through the filter-antenna combination shown in Fig. 1 is,

$$E(\vec{r},f) = P(f)G_A(f)H(\vec{r},f) = X(f)\frac{H(\vec{r},f)}{H_A(f)} \qquad (8)$$

$X(f)$ is a selected pulse spectrum that is bounded by the FCC mask, called the expected on-air pulse [3]. It may be synthesized as a linear combination of Gaussian Second derivatives, *sinc* pulses or simply a Gaussian 4th derivative. In order to guarantee that $E(\vec{r},f)$ always lie within the FCC mask we may propose two different algorithms to select $H_A(f)$.

(a) Selecting maximum values of amplitude transfer function out of all directions at each and every frequency f_o and construct $H_A(f)$.

$$H_A(f_o) = \max_{\vec{r}} H(\vec{r},f_o) \qquad (9)$$

then,

$$\left|\frac{H(\vec{r},f)}{H_A(f)}\right| \le 1, \forall \vec{r} and \forall f$$

Therefore, at all the frequencies under consideration none of the directions will have on-air radiation above the regulatory mask.

(b) For a pattern stable antenna we can select main beams in one or more directions independent of the frequency. One of such directions can be selected as $H_A(f)$.

$$H_A(f) = H(\vec{R},f) \qquad (10)$$

where, $\vec{R}$ is the direction of one of the stable main beams. In other words we may select a $K(\vec{r})$ in (5) to be always less than one $\forall \vec{r}$.

$$\left| \frac{H(\vec{r}, f)}{H_A(f)} \right| \le K(\vec{r}) \le 1$$

Note that (9) can be applied to any set of transfer functions of a given antenna, where as, (10) is successfully applicable to antennas with relatively stable pattern. It guarantees not only the compatibility with FCC mask but also the correlation between radiated pulses in different directions. This is one advantage of having pattern stable antennas in UWB systems as demonstrated in the following section with an example.

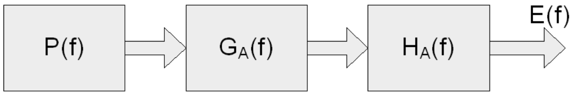


Figure 1. Antenna incorporated with a filter block for pulse shaping.

3. Antenna Application

Pattern stability improvement of UWB planar monopoles was given in [6]. The pattern stability in the azimuth plane was improved by introducing additional cross-planar element to the planar monopole antenna. Circular planar monopole antenna and the cross-planar monopole antenna are shown in Fig. 2. Major radiation, the E_θ on the XY plane, is plotted in space frequency plots, shown in Fig. 3. (Note that the radiation in only $0 \le \phi \le 90$ is shown due to symmetry) Values on constant frequency planes represent radiation patterns where as constant angle cuts represent the transfer functions, $H(\vec{r}, f)$. A nice and smooth surface plot, as a result of omni directional radiation and coherent transfer functions-a clear difference to those of the planar monopole-is obtained for the cross planar monopole.

First, with (8) and (9) the e-field for each direction were calculated for both antennas, and shown in Fig. 4.It was shown in [8] that parameters of Gaussian 4th derivative pulse can be selected for the pulse spectrum to be enclosed within the FCC mask. In this example on-air spectrum of the radiated pulse, $E(f)$, is selected as the Gaussian 4th derivative (In [3] a curve fitting method is used to derive a similar pulse shape) . As expected, for both antennas the e-fields are well inside the FCC mask.

We can calculate the correlation, i. e. f^2, of each directional transfer function, $H(\vec{r}, f)$, to the $H_A(f)$, calculated using (9). As shown in Fig. 5, in case of cross-planar monopole the candidate transfer function for filter design is well correlated to all the other transfer functions in other directions, especially in the directions around 40-50 degrees. Therefore, we may select, $H(\vec{R}, f) = H(50, f)$ to fulfill the condition of (10). The resulting E-field spectra are plotted in Fig. 6. Note that $X(f)$, Gaussian fourth derivative, is radiated in the 50 Degrees direction in this case. It is clear that the use of antenna transfer function in one of the directions is possible with a pattern stable antenna in optimization filter calculation. Furthermore, we could decide the detection template at the receiver, as we already know a good approximation for the incident E-field on the receiving antenna, Gaussian 4th derivative.

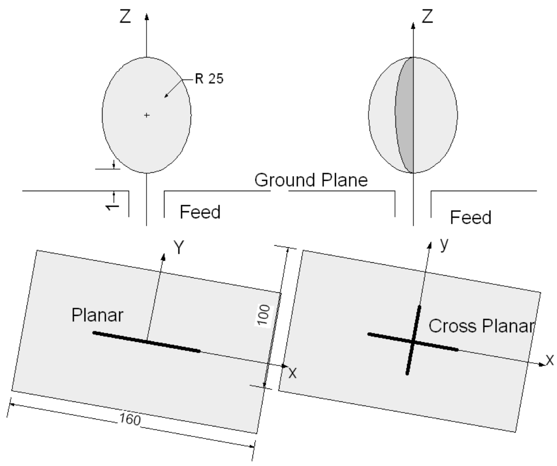
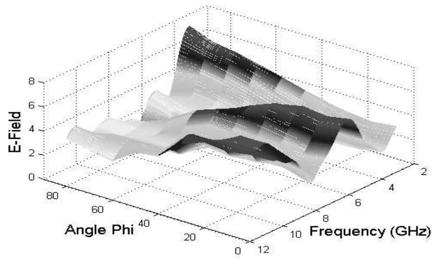
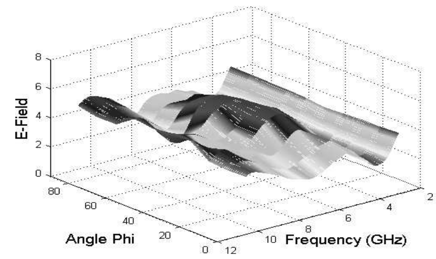


Figure 2. Cross and Planar monopoles with finite ground planes.

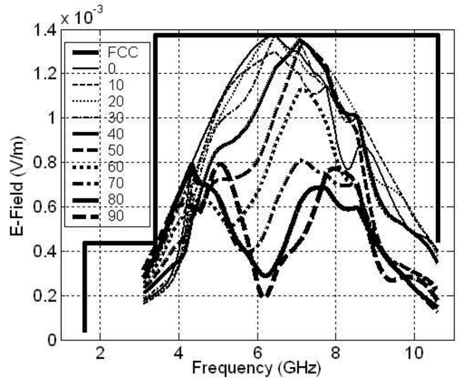


(a)

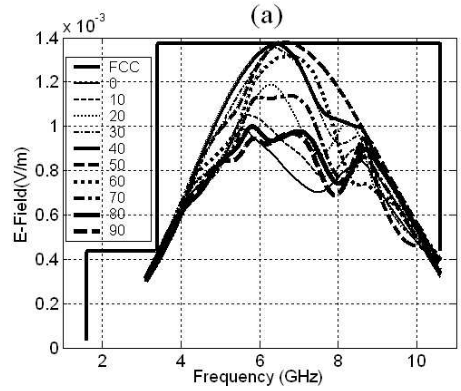


(b)

Fig. 3. Space frequency plots for a) Planar monopole b) Cross-planar monopole.



(a)



(b)

Fig. 4. Pulse radiated by each antenna (at 1m) with transfer function from (9), a) Planar monopole b) Cross-planar Monopole.

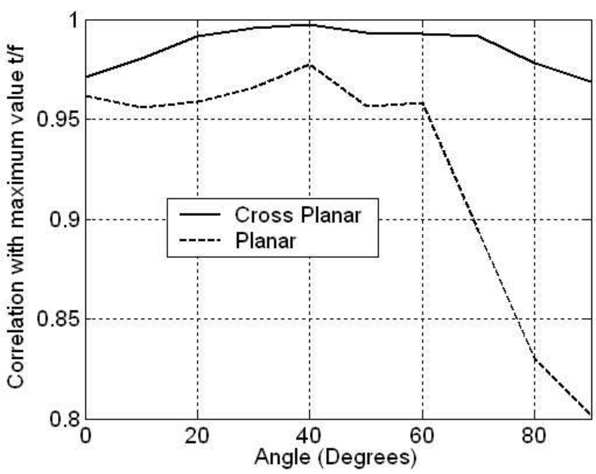


Fig 5. Correlation of transfer function by (9) to those of the antenna.

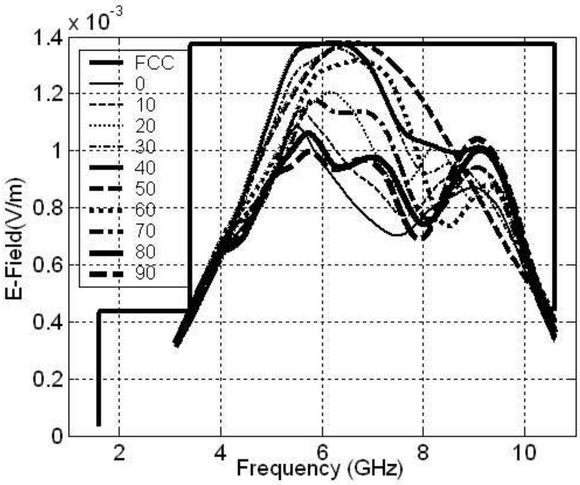


Fig 6. Pulse radiated within the mask (at 1m) as one of the transfer functions of cross-planar monopole for filter design.

4. Conclusion

The correlation and pattern stability of a UWB antenna are closely related. Although the radiated power is constrained within the regulation mask, it is possible to improve correlation energy in all directions simultaneously, for an antenna with stable patterns. There is a good chance of maximum radiation falling in the same direction at all frequencies for a pattern stable antenna (stable main beam). The system designer can easily select this direction and transfer function for pulse shaping filter design. Moreover, this "preferred" transfer function of the antenna can be verified by measurements prior to applying in the optimization. In other words, a UWB antenna can be characterized with its stable radiation patterns within the operating band and a single transfer function in a selected direction. Therefore, it is important to investigate the pattern stability of UWB antennas quantitatively as well as qualitatively.

5. Acknowledgement

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6. References

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