Spatio-Spectral Normalisation for Ultra Wideband Antenna Dispersion

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Abstract: Frequency variance of antenna characteristics may result in severe signal distortion in an ultra wideband communications system. We identify the antenna parameters important in the context of propagation and channel modelling, and analyse their variation with frequency. The group delay, VSWR, impedance and radiation pattern of omni-directional UWB antennas are studied over a range of frequencies. We propose a spatio-spectral normalisation scheme to isolate the effect of the antenna from the channel, which can be useful in channel measuremnts. We anticipate that higher SNR can be obtained with the proposed angular compensation technique.

1. INTRODUCTION

The defining characteristic of ultra wideband (UWB) communication systems is the large bandwidth that the signal occupies. This signal bandwidth far exceeds the channel coherence bandwidth, due to which frequency selective behaviour is observed. Fig. 1 illustrates this frequency selective behaviour of the channel with the help of a power-normalised channel transfer function measured using a vector network analyser (VNA) in a typical indoor environment. Through the inverse Fourier transform, this frequency selectivity can be translated to time dispersion, which results in multiple paths of propagation that are resolvable due to the large bandwidth [1].

For the operation of a UWB communication system within acceptable error, efficient channel estimation is essential. This requires accurate channel modelling during system design that provides a faithful picture of the actual channel. In this regard, the frequency behaviour of antennas, front-end amplifiers and other non-linear elements of the transmitter and receiver must be taken into account.

One approach is to consider the antenna as a part of the channel itself, and not of the transceiver. However it may be argued that the opposite is more reflective of the actual situation, as the transceiver components are logically unrelated to the channel. The isolation of the antennas from the channel allows for the modelling of the channel independent of the particular antennas used in channel measurements, and for the compensation of the spatial and spectral dispersion caused by the antennas.

The use of antennas as pulse shaping filters dates back to the spark gap transmitters of Hertz and can also be seen today in impulse-based UWB systems. While this application of antennas is important, dependence on the frequency-selective behaviour of antennas can also result in undesirable effects. Considerable frequency distortion is caused to the received signal by the antenna. Interpreted in the time domain, the impulse response of the

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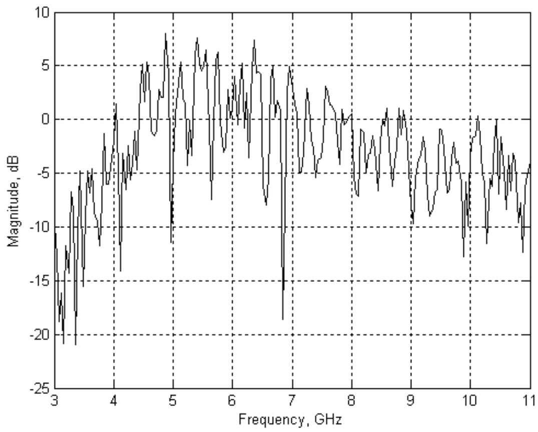


Fig. 1. The UWB indoor channel

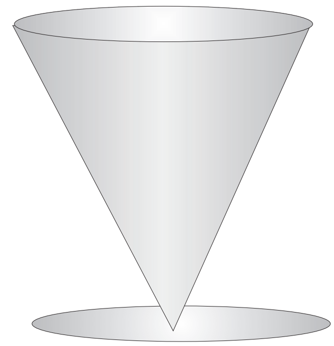


Fig. 2. A discone antenna with a circular ground plane and a feed at the bottom

antenna is not an impulse; instead it persists for a finite interval of time. This effect is more pronounced in narrowband antennas, but wideband antennas, such as the discone shown in Fig. 2, also suffer from it to an extent [2]. Fig. 3 demonstrates that the impulse response of a discone antenna consists of a strong impulse at zero delay followed by reverberations that are not insignificant. The latter cause temporal distortion of the signal due to the additional perceived multipaths on reception.

Furthermore, the directivity of a non-isotropic antenna may also contribute to angular dispersion. If a constant gain antenna with a radiation pattern similar to a dipole is used, its asymmetric H-plane pattern also distorts the channel profile. Furthermore, the gain may be a function of frequency depending on the antenna design. Such effects of the antenna are often erroneously ignored account during channel modelling.

It is desirable to operate in the frequency band where the antenna response is flat, and the behaviour of other antenna parameters is also either innocuous or predictable. This can be achieved effortlessly in a narrowband system, but it is often difficult to design antennas that provide linear behaviour over several octaves as is typically required in UWB.

In this paper, we consider the frequency variance of UWB antennas. To this end, we investigate the case of a discone antenna, which is a wideband omni-directional antenna with a monopole-like radiation pattern. We measure the variation of return loss, impedance and radiation pattern of this antenna with frequency. Finally, we propose a scheme for separating the effect of antennas from channel propagation. This is achieved with the help of frequency and spatial normalisation of the received signal.

2. FREQUENCY-DEPENDENCE OF ANTENNA PARAMETERS

In this section, we analyse some of the standard properties of an antenna and investigate their variation with frequency. This is done with the help of theoretical prediction and measurements in the anechoic chamber. A discone antenna provides a large bandwidth of operation and generates a vertically polarised, omni-directional field. Such an antenna

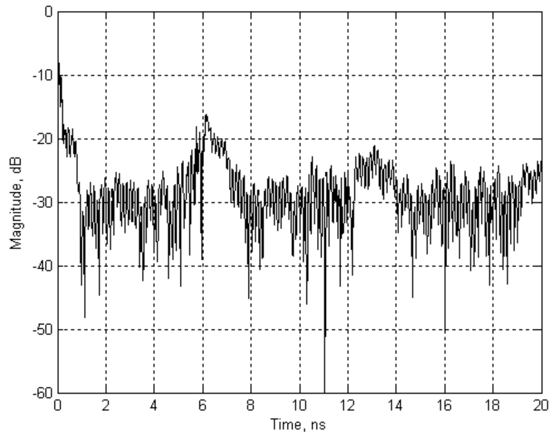


Fig. 3. Normalised impulse response of antenna

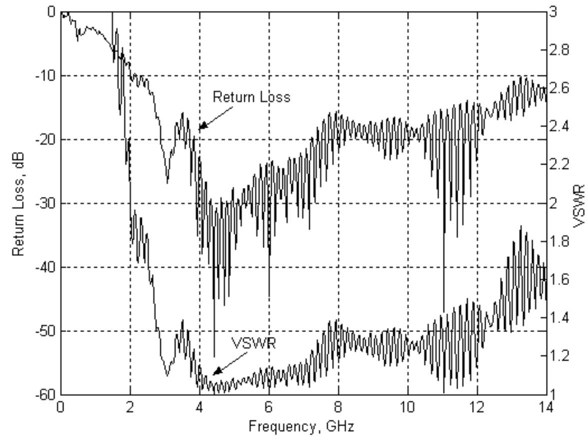


Fig. 4. Antenna return loss and VSWR

consisting of a cone with a spherical cap and a circular ground plane is designed for the purpose. The design parameters are the cone length l, cone half-angle θ_h and ground plane diameter d. This antenna operates efficiently in the indoor UWB communications band, which lies between 3.1 and 10.6 GHz under the current regulations [3].

The frequency range of efficient radiation of power for an antenna can be determined from a measurement of the S_{11} parameter with the help of a VNA in the anechoic chamber. The complex values of S_{11} give the reflection coefficient $\Gamma(f)$ as a function of frequency:

$$\Gamma(f) = \alpha(f) + j\beta(f) \tag{1}$$

The return loss $R(f)$, shown in Fig. 4, is equal to $-20\log_{10}\Gamma(f)$ and is expressed in dBs. The band of operation of an antenna is usually taken to be between the points where $R(f)$ crosses the -10 dB line. Within this band, 90% of the power is transmitted and only 10% is reflected. For our discone antenna, $R(f)$ in the UWB band is less than -15 dB, as shown in Fig. 4. However, $R(f)$ is not perfectly uniform in the band, and radiation efficiency is higher at 4-6 GHz than at 8-10 GHz.

Also shown in Fig. 4 is the voltage standing wave ratio, VSWR, which is given by

$$VSWR(f) = \frac{1+|\Gamma(f)|}{1-|\Gamma(f)|} \tag{2}$$

VSWR is a measure of mismatch; a good match for wideband antennas occurs for the range of frequencies for which the *VSWR* is below 3:1. The *VSWR* of the discone under consideration is less than 1.5:1 for the UWB band.

The amount of power delivered to the antenna, and thus the antenna efficiency, is determined by the *VSWR*, which is a measure of the mismatch of antenna impedance Z_i with the line characteristic impedance Z_0. Maximum power is delivered when Z_0 equals $Z_i(f)$, when

$$Z_i(f) = R_i(f) + jX_i(f) = \frac{\eta_0}{2\pi}\ln\left(\cot\frac{\theta_h}{2}\right) = 60\ln\left(\cot\frac{\theta_h}{2}\right) \tag{3}$$

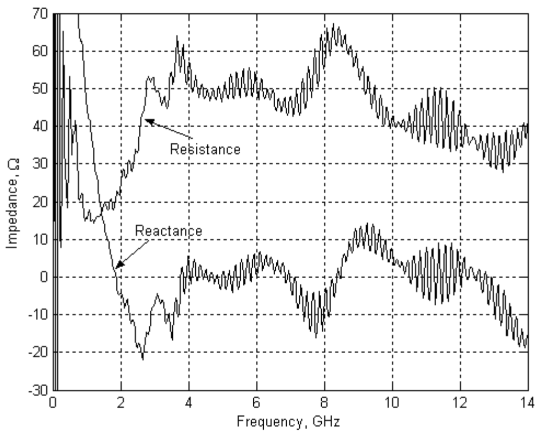


Fig. 5. Antenna input impedance

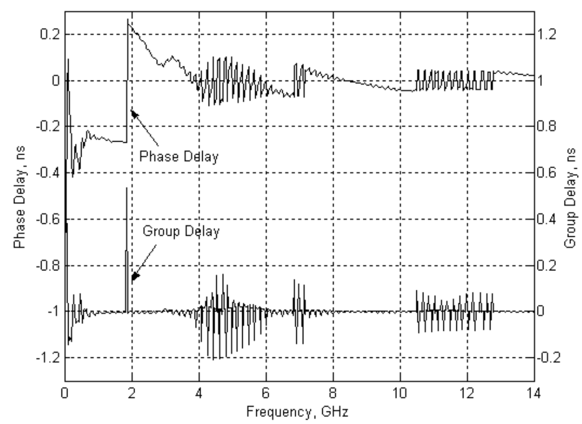


Fig. 6. Antenna phase delay and group delay

where θ_h is the half-angle of the discone in radians and η_0 is the impedance of free-space [4]. For θ_h = 45°, Z_i = 52.8 Ω, which yields an almost perfect match. Fig. 5 shows the measured input impedance of the discone antenna, for which $R_i(f)$ = 50 Ω and $X_i(f)$ = 0 with a variation of about ±10 with frequency. The impedance of an infinite discone is purely resistive since there are no reflections from discontinuities, but higher modes propagate through a finite discone, introducing $X_i(f)$ and $VSWR(f)$. However, X_i diminishes for large θ_h.

Phase delay is defined as

$$\tau_p(f) = -\frac{\beta(f)}{2\pi f} \tag{4}$$

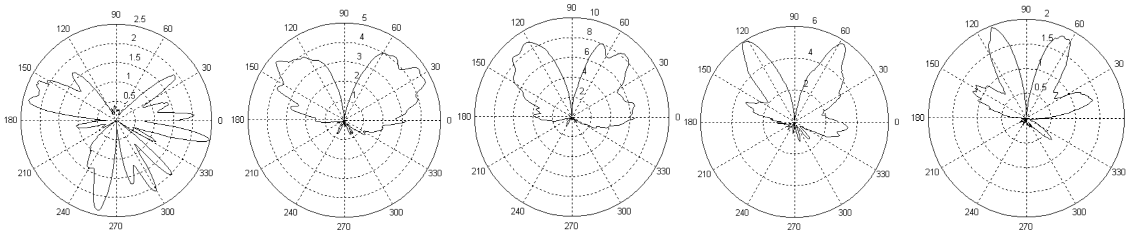
and group delay is defined as

$$\tau_g = -\frac{1}{2\pi}\frac{\partial \beta(f)}{\partial f} \tag{5}$$

A linear phase delay and a constant group delay ensure pulse shape fidelity, while any deviation causes temporal dispersion. The measured values of τ_p and τ_g are shown in Fig. 6. Within the UWB band, τ_p is approximately linear. Similarly, τ_g is mostly zero, with some oscillations of up to 0.2 ns at frequencies of perfect resonance indicated by the zero crossings of $X_i(f)$.While these delays are low for a well-designed antenna, the frequency variance may cause some signal distortion.

3. ANGULAR DISPERSION

The radiation pattern of the discone antenna is similar to that of a dipole. The discone is circularly symmetric and thus omni-directional in the E-plane, like a dipole. The azimuthal field distribution is thus quite uniform. The H-plane pattern nominally resembles that of a dipole, but is determined by *d, l* and θ_h. For very small θ_h, the H-plane pattern is also similar to a dipole, but in our case θ_h has a large value. The effect of the ground plane is to push the pattern away from the azimuthal plane, to a degree that depends on the frequency, which determines $k_d = 2\pi/d$.



(a) (b) (c) (d) (e)

Fig. 7. H-plane radiation pattern of the discone antenna at ultra wideband frequencies (a) 3.1 GHz; (b) 4.975 GHz; (c) 6.85 GHz; (d) 8.725 GHz; (e) 10.6 GHz

Fig. 7 shows the H-plane radiation pattern of the discone antenna at discrete, equidistant frequencies in the UWB band (3.1 to 10.6 GHz), where the top hemisphere represents the hemisphere of the cone and the 0°–180° axis corresponds to the plane of the disc. A clear evolutionary pattern can be noticed with the increase in frequency and thus k_d. In Fig. 7(a), power is radiated in the upper hemisphere close to the centre line, as desired, but there is also significant propagation in the lower hemisphere. At this comparatively lower frequency, the diameter of the disc is not large enough. This gives rise to a current along the circumference of the ground plane, which results in a field propagation on the other side of the disk. As the frequency increases, Fig. 7(b), this effect vanishes and the pattern is completely restricted to two lobes in the top half, though the slant of the pattern is greater than in Fig. 7(a) and is roughly equal to θ_h. As the frequency further increases, the lobes begin to split into two and the slant increases further, so that in Fig. 7(e), two narrower mainlobes at a higher slant and two sidelobes at a lower slant are obtained. The changing slant of the H-field pattern with frequency indicates that the different frequency components within the UWB signal are radiated at different elevations, resulting in dispersion of the signal in the elevation plane. A higher frequency signal will be transmitted by this antenna at a higher elevation θ. Similarly, a signal reaching the receiver from a steep θ will experience greater attenuation in its lower frequency components. Thus the antenna gain is a function of frequency in addition to angle, i.e. $G(\theta, \varphi, f)$.

In addition, the aperture of an omni-directional antenna and the gain of a directional antenna vary with frequency, resulting in a frequency-variant power reception factor, $w(f)$. If, for instance, aperture antennas are used at both transmitter and receiver, each frequency component in the signal undergoes an apparent gain by $w(f) = f^2$ during transmission through the antennas and channel, while for two omni-directional antenna, $w(f) = 1/f^2$ [5].

4. SPATIO-SPECTRAL COMPENSATION

A popular technique of experimental evaluation of the UWB channel is through channel sounding using a VNA. Antennas and cables used in such measurements should be carefully calibrated and their effect removed from the S_{21} parameter measured by the VNA.

The frequency-variant return loss, impedance and other factors can be normalised in this manner, in order to extract the vector descriptors of the channel. The situation is similar in an actual communications system. The frequency properties of the antenna must be taken into account in the design phase.

Thus some of these frequency-dependent problems, such as return loss variation, can be avoided by using the right frequency bands, or by the respective spectral compensation. However, the evaluation of frequency variation of antenna gain requires an understanding of the field distribution of the antenna for each frequency component. This information can then be used in conjunction with direction-of-arrival estimation at the receiver [6]. The spatial compensation factor associated with the direction of arrival of each multipath thus depends on the antenna radiation pattern. A large number of multipath signals are received in a UWB channel, arriving from a variety of angles. Accurate spatio-spectral compensation can thus remove the effect of antenna dispersion and provide a considerable increase in the signal-to-noise ratio (SNR) at the receiver.

4. CONCLUSION

We have analysed the frequency-variant behaviour of UWB antennas in order to characterise the distortion that they cause to a UWB signal. The variation of antenna parameters such as impedance, phase and group delay, and VSWR with frequency has been elucidated using measurements made with a discone antenna. The radiation pattern is shown to vary with frequency, which causes look-angle dispersion. A scheme is proposed for the compensation of the spectral and look-angle antenna dispersion. It employs the frequency characterisation of the antennas for spectral normalisation. Alongside, a gain compensation factor is calculated through direction of arrival estimation and applied on the received signal for angular power normalisation.

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