Three-Dimensional Equalization of Ultrawideband Antenna Distortion

(Invited Paper)

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***Abstract*— A typical ultrawideband (UWB) antenna acts as a space-frequency filter. As a result, the UWB signal transmitted or received by such an antenna undergoes joint angular-spectral distortion, and consequently the system suffers serious performance degradation. We discuss a technique to compensate for this distortion and recover the original signal using multiple antenna arrays. To evaluate its performance, the proposed technique is applied to UWB signal propagation in an indoor multipath environment simulated using a specialized ray-tracing approach. The results demonstrate that our antenna equalization scheme significantly reduces the effect of small-scale fading introduced by the antennas, and can therefore improve the performance of a UWB communications link as well as facilitate the extraction of antenna-independent channel measurements.**

I. Introduction

The power radiation pattern of a typical ultrawideband (UWB) antenna varies considerably with frequency [1], [2]. Propagating through a typical UWB indoor channel, the signal undergoes three-dimensional scattering with large angular spreads [3]. The antennas therefore cause direction-dependent distortion to the UWB signal waveforms. As a consequence, the effective channel bandwidth is reduced considerably, leading to system performance degradation, as we have shown in our recent work [2]. In addition, the angularly nonuniform frequency-selectivity of the antenna leads to increased signal fading and inaccurate direction-of-arrival (DoA) determination, as we demonstrated with UWB channel measurements in [4]. Furthermore, this effect is detrimental to empirical channel modeling since antenna distortion can alter the apparent channel characteristics considerably, rendering the channel models antenna specific and therefore of reduced value.

In this paper, we study some of these effects of antenna distortion on signal propagation in terms of the channel statistics using a deterministic channel modeling approach. We also describe an antenna array based technique for the three-dimensional angular and frequency equalization of the antenna radiation pattern, which helps recover the antenna-independent version of the signal. It is straight forward to extend the technique proposed in this paper to the similar problem of array pattern distortion, which is frequently encountered in multiple-antenna array systems such as beamformers.

II. Antenna Equalization Algorithm

We consider UWB signal transmission spanning the frequency band $W = [f_l, f_h]$. In the current paper, we will limit our discussion to receiver antenna compensation for the sake of simplicity. After propagating through the channel, the multipath signal components, $r_r(\theta_r, \phi_r, \tau)$, arrive at the receiver from directions θ_r and ϕ_r that represent the elevation and azimuth angles, respectively; here τ denotes the time delay with respect to the first arrival. In order to equalize the space-frequency filtering caused by the antenna, we require the following information over the frequency range of interest, i.e. $f \in W$: (1) the amplitude radiation pattern of the antenna, $A_r(\theta_r, \phi_r, f)$, which is easily measurable *a priori* as it depends on the antenna design and near-field environment, and (2) the multipath amplitudes and DoAs, $r_r(\theta_r, \phi_r, \tau)$, which can be estimated at runtime in a dynamic multipath environment with the help of a multiple-antenna receiver.

Receiver antenna equalization is achieved by scaling the received multipath signal, $R_r(\theta_r, \phi_r, f)$, by the amplitude radiation pattern, $A_r(\theta_r, \phi_r, f)$, of the receiver antenna, where $R_r(\theta_r, \phi_r, f)$ is obtained as the Fourier transform of $r_r(\theta_r, \phi_r, \tau)$. If the compensation of the transmitting antenna is also desired, its radiation pattern, $A_t(\theta_t, \phi_t, f)$, can be similarly measured and removed from the received signal; however this process will require multipath direction-of-departure (DoD) information obtained from a multiple-antenna array at the transmitter. Fig. 1 illustrates the process of transmitting and receiving antenna equalization, performed at the receiver, to extract the signal distorted only by the multipath channel and not by the antennas.

III. Performance Analysis

We now apply the technique developed above to the indoor UWB channel. To this end, we simulate the channel using a ray-tracing procedure followed by antenna compensation post-processing and analysis of the key channel statistics.

A. Ray-Tracing Simulation

An indoor environment is simulated to carefully replicate the propagation conditions of the physical environment used

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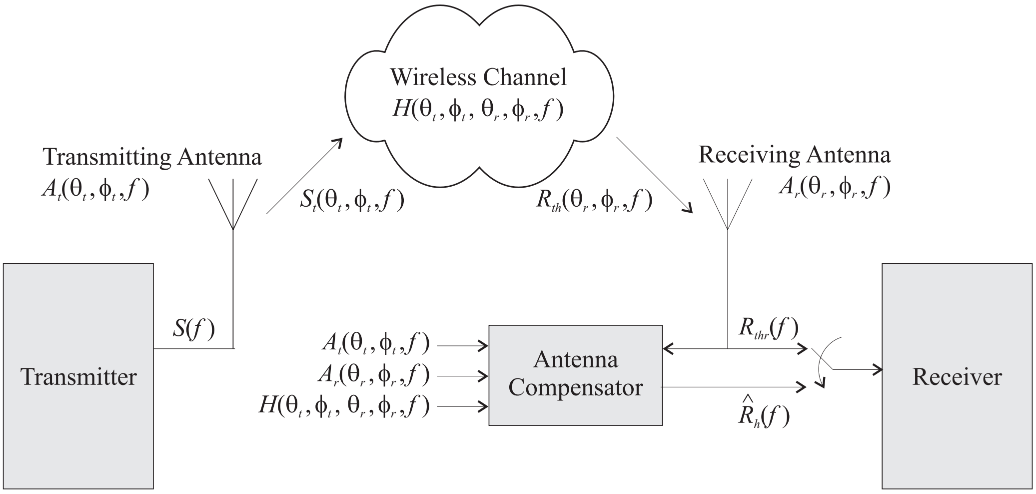


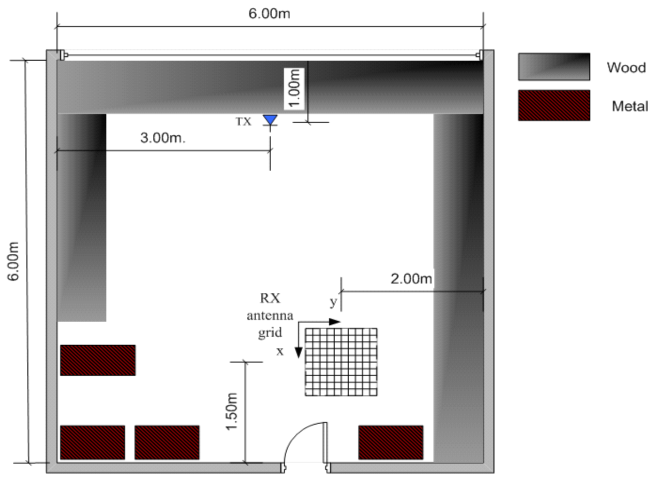
Fig. 1. Angularly asymmetric signal distortion is caused to the UWB signal, *S(f)*, due to the antennas in a multipath environment. The antenna compensator equalizes the antenna distortion – only at the receiver in the case illustrated here.

for channel measurements in [4]. It consists of a small office room with dimensions 6 m × 6 m, housing some metallic furniture and equipment. The transmitting antenna is fixed at a single location within the room. The receiver translates horizontally over an automated positioning grid of dimensions 0.5 m × 0.5 m, with inter-position separation of 2.5 cm. This process generates a set of channel realizations over a local region in space, which can be used for small-scale channel analysis. The transmitter and receiver are at a distance of approximately 4 m. The UWB channel is simulated with parameters $f_l = 3.1$ GHz, $f_h = 10.6$ GHz, and $W = f_h - f_l = 7.5$ GHz. Fig. 2(a) depicts the simulated indoor multipath environment designed to match the measurement site in [4].

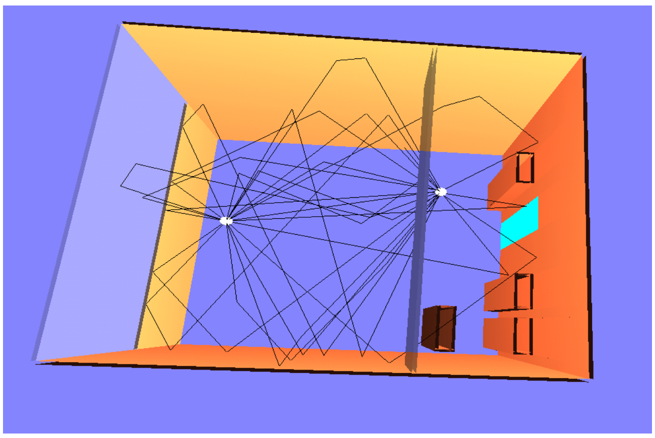
A true three-dimensional ray-tracing model has been developed for UWB propagation in indoor environments, as described in [5]. Through the use of geometric optics (GO) and the uniform geometrical theory of diffraction (UTD), the model performs ray launching techniques in order to evaluate reflected, transmitted, and diffracted rays from a simplified description of the given environment. All dominant paths traversed by the waves from the transmitter to the receiver are determined. The model inherently contains the DOD and DOA information for each physical ray path. In contrast with most conventional ray-tracing tools, our model operates in the time domain and therefore facilitates efficient simulation and convenient analysis of UWB multipath channels. This tool is used to predict the UWB channel response for each receiver location. The reflection order (i.e. the maximum number of reflections) considered in the ray-tracing model is set to 3. Fig. 2(b) illustrates the dense 3-D multipath propagation within the environment considered as obtained from ray-tracing.

B. Results

In order to evaluate the mitigation of antenna distortion by compensation, we compare the pre- and post-compensation



(a)



(b)

Fig. 2. The ray-tracing simulation: (a) a plan view of the simulated indoor propagation environment, and (b) three-dimensional visualization of the ray paths at the center of the receiving grid.

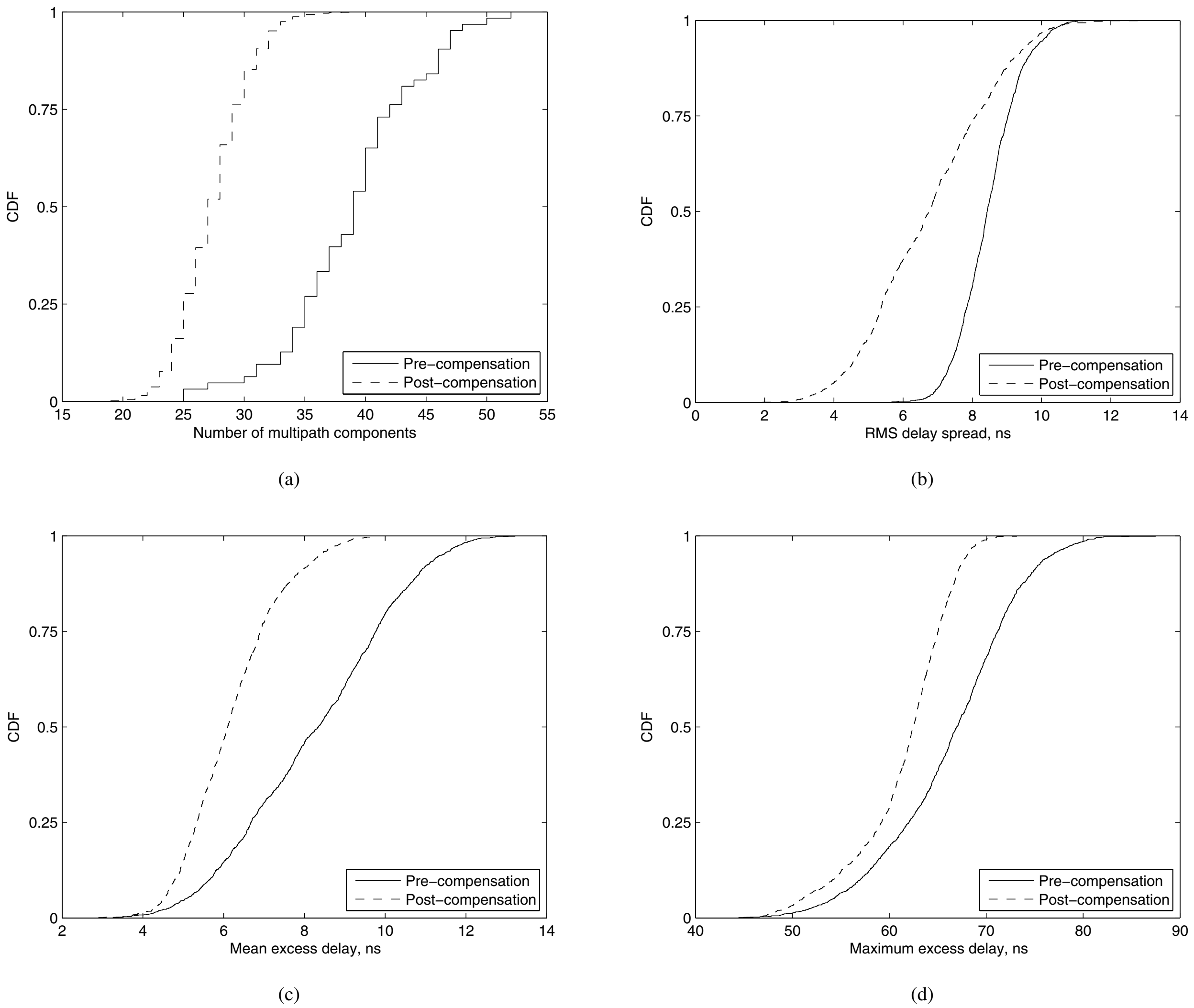


Fig. 3. The pre- and post-compensation cumulative distribution functions (CDFs) of the (a) number of multipath components, (b) rms delay spread, (c) mean excess delay, and (d) maximum excess delay.

UWB channel responses. An accurate quantitative comparison can be obtained by analyzing various channel statistics such as the number of resolved multipath components, N, the rms delay spread, τ_{rms}, the mean excess delay, τ_{mean}, and the maximum excess delay, τ_{max} [1]. These parameters, obtained from the channel impulse response, characterize the extent of small-scale fading experienced by the channel, and can therefore offer insight into the space-frequency equalization performance of our algorithm. Each channel impulse response is thresholded to 20 dB below the peak multipath power before these parameters are evaluated.

The cumulative distribution functions (CDFs) of each of these channel parameters, estimated from the ensemble of channel realizations obtained over the synthetic aperture grid, are shown in Fig. 3. We find from Fig. 3(a) that the average number of multipath components, when the antenna effect is included, is about 40. When the receiver antenna is equalized, however, this number falls to 28, which is a 30% reduction. As the channel energy is now concentrated in fewer taps, a relatively less complex rake receiver would now suffice to achieve the required level of system performance.

From Fig. 3(b)-(d), there is a substantial reduction in the multipath delay spread as a result of antenna compensation. The median rms delay spread is reduced by over 1.5 ns (i.e. by 20%), while the mean delay is reduced by over 2.3 ns (i.e. by 27%). In other words, from our results the receiver antenna increases the dispersive behavior of the UWB indoor channel by over 20%. It is well known that the delay spread is inversely related to the achievable data rate. Therefore, the mitigation of dispersion offered by antenna compensation can boost the communications link performance substantially.

The results in Fig. 3, derived from channel simulation

[1]For the definitions of these channel statistics, see, for example, [6].

using ray-tracing, closely match those obtained from physical channel measurements as reported in [4]. It is thus established that three-dimensional antenna equalization is an effective and reliable technique for isolating the radio propagation channel from the received UWB signal by removing the undesirable dispersive effects of the antenna.

IV. Conclusion

A technique for the three-dimensional equalization of UWB antennas has been presented. Performance analysis on ray-tracing simulated UWB channels has established small-scale fade mitigation and link improvement due to this technique. In particular, our results have shown that the compensation of the receiver antenna alone can reduce the number of channel taps and the delay spread by over 20%. The proposed technique can be used to obtain antenna-independent UWB channel data from measurements performed using nonisotropic antennas, and is therefore valuable for wideband and UWB channel modeling and system performance prediction.

Acknowledgment

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