A Path Link Model for Ultra Wide Band Pulse Transmissions

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Abstract

Pulsed UWB (Ultra-Wide Band) signals are more nearly transient phenomena than they are continuous waves. Multipath effects for the most part manifest themselves as time delayed replicants of the pulses. Short pulses propagate with the free space law, and only when the differential delay among pulses and replicants is less than about half the pulse length do the signal exhibit destructive interference. The propagation model described here is based on the free space law with the additional effect of transmission losses through typical home or office walls. The conditions for destructive interference of pulses is also derived.

1. Introduction

UWB (Ultra Wide Band) radio signals [1] often comprise pulses of sub-nanosecond duration that do not experience multipath interference in the usual "continuous wave" sense. The propagation model presented here predicts received SNR (signal-to-noise ratio) of propagated UWB pulses in indoor environments including average building losses, without resorting to a "processing gain" determination. The model includes UWB system link loss mechanisms.

2. Discussion

The received SNR of a UWB radio system can be written entirely in terms of the transmitter effective radiated power $P_T$, the system data bandwidth $BW$, the UWB transmission center frequency $f_c$, transmission distance $d$ in meters, and system loss budget $L_{sys}$.

$$\text{SNR} = 10 \log(P_T) - 10 \log(BW) + \ldots$$

$$- 10 \log(k T) + P_L + L_{sys}$$

(1)

The system loss budget includes noise figure, implementation losses and ambient noise and interference. $k = 1.38 \times 10^{-23} \text{ J/K}$ is Boltzmann's constant and $T = 290 \text{ K}$ is the nominal noise temperature and $P_L \text{ dB}$ is free space path loss between unity gain antennas, modified by building obstruction losses

$$P_L = 20 \log\left(\frac{c}{4\pi dl}\right) - L_{sys}(d > 4)$$

(2)

Here, $c$ is the velocity of light, in-building losses are modeled by a constant $L_{in} \text{ dB per meter beyond 4 meters}$. The Heaviside function $\phi$ here is 1 for $d > 4$ and zero otherwise. Average building losses are $L_{in} - 0.7 \text{ dB/m}$ based on this work and Honcharenko [2]. The system losses $L_{sys}$ include receiver noise figure and implementation losses which can range from about 3 to 14 dB in our various implementations.

Figure 1. UWB system range as a function of system bandwidth.

Figure 1 shows the predicted data rate capability as a function of UWB radio link distance for three UWB
experimental system scenarios. The left most curve shows a near-worst case in-building scenario for 120 microwatts transmitted power using wide band dipoles in a system with 6 dB implementation losses and providing 10 dB SNR. The prediction is generally supported by our measurements. The middle curve shows the same system without the in-building wall losses. The "o" is a measured point with equivalent system parameters. The severe impact of the exponential losses due to the $L_w$ term in equation (2) is dramatically evident and is a major limiting factor for in-door propagation, for both UWB and narrow band CW systems.

The in-building model realistically assesses link performance involving transmission through an average of one wall every three meters. Anomalous measurements have been noted, including apparent $d^{-1.5}$ law performance in a long hallway, similar to a case reported by Honcharenko [2]. In fact, specific in-building propagation results can be as lossy as the left most curve in Figure 1, while relatively rare anomalous cases might occur to the right of the free space curve.

The right most curve models an outdoor case operating at 2.5 milliwatts transmitted power, with 6 dB receiver antenna, 11 dB implementation losses, and providing a 20 dB SNR. The "x" represents an experimental point with these parameters. The UWB pulses were in the sub-nanosecond range and the geometries of all the cases in Figure 1 were such that the ground reflected pulse was delayed by more than the pulse duration, so ground reflection interference and multipath destructive effects were not a consideration.

3. Ground Reflected Pulses

Propagation over a smooth earth involves a reflection from the ground. The relevant geometry is shown in Figure 2. The direct path and reflected path lengths $D$ and $R$ in terms of the antenna heights and the separation distance $d$ are

$$D = \sqrt{d^2 + (H_1 - H_2)^2}$$

and

$$R = \sqrt{d^2 + (H_1 + H_2)^2}$$

With reference to the geometry of Figure 2, the differential delay between the reflected ray path and the direct path over a plane earth can be written

$$\Delta t = (R - D)/c$$

where $c$ is the velocity of light, $D$ is from (3) and $R$ is from (4).

![Figure 2. Geometry for two-path propagation. Source: [3].](image)

The ground reflection coefficient for the cases of interest where the direct and reflected propagation delays are within a fraction of a nanosecond is very nearly $-1$, so the reflected pulse undergoes a phase reversal. Reflected pulses that arrive by paths having differential delays greater than a half pulse length, like Paths 1 and 2 in Figure 3, add to the total received energy, as described elsewhere in these Proceedings [4]. Pulses with a differential delay of less the half a pulse length portrayed by like Path 2, begin to exhibit destructive interference in the receive window.

![Figure 3. The pulse replicant arriving by Path 2 is not delayed enough to be distinct form the Direct pulse. The Path 1 pulse is distinct.](image)

Figure 4 shows differential delay given by equation (5) evaluated for heights above ground of 1 and 10 meters. For pulses that are 0.3 nanoseconds long the destructive interference occurs when the differential delay in less than 0.15 nanoseconds.

4. Comparisons with Narrow Band Radio

CW (continuous wave) narrow band radio systems behave in much the same way as the UWB pulses systems for the same scenarios, with the exception that the narrow band continuous wave signals are further subject to indoor diffraction losses as described by Honcharenko [2] and as shown in Figure 5. The additional losses are related to
diffraction from clutter near the floor, and clutter near the ceiling or in the plenum of an office area.

\[ H_1 = H_2 = 10 \text{ m} \]
\[ H_1 = H_2 = 1 \text{ m} \]

![Figure 4. When the differential delay \( \Delta t < 0.15 \text{ ns} \), propagation transitions from the free space law to inverse 4th power.](image)

The lower curve of the three pairs of curves in Figure 5 are at 2 GHz, while the upper curves are at 4 GHz. The left most pair shows indoor CW narrow band system performance with wall losses and diffraction losses, the middle pair represents a UWB system with wall penetration losses, while the right most pair shows free space law performance for both CW and UWB systems.

In general, pulse systems do not undergo the multipath destructive interference that manifests itself as Rayleigh fading prevalent in continuous wave systems, but rather show up as delayed replicants of the direct pulse. As a result, the various urban area path loss models used for CW narrow band signals cannot be expected to predict pulse propagation. Furthermore, the delayed pulses can be gathered in as additional signal energy using RAKE receiver techniques.

5. Conclusion

A system path link model was presented for UWB systems involving short pulse transmissions. The model accounts for building losses as a cumulative attenuation with distance starting at the first wall. The effect dramatically reduces propagation distances in buildings and shows that in-building wall transmission losses are a significant limit to indoor radio link performance. Continuous wave narrow band systems encounter the same losses as UWB signals with the addition of diffraction losses due to CW wave interference. The model correctly predicts the performance of prototype UWB system experiments. Propagation over a plane earth involving small differential delays ultimately leads to inverse 4th power propagation law.

6. References


