# A Frequency-dependent Pathloss Model for UWB Indoor Non-line-of-sight Environment

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**Abstract**

*Antenna system and many propagation processes would introduce frequency dependent characteristic within frequency band of UWB signal. This would cause the frequency dependence of path loss. In this paper, a frequency dependent UWB path loss model for NLOS environment is proposed base on the analysis of the Intel experimental data. The proposed model can model the frequency dependence caused by antenna system and propagation processes separately by introducing frequency dependent path loss exponent in traditional model. The fitting of the experimental data shows that the path loss exponent can be modelled as Gaussian function when taking into account its changes with frequency.*

## 1. INTRODUCTION

Ultra-wideband (UWB) signals are defined as signals with either a large relative bandwidth (typically, larger than 20 %), or a large absolute bandwidth (> 500 MHz). This large bandwidth leads to interesting new possibilities for both commercial and scientific applications. In particular, UWB is envisaged to be one of the most promising wireless technologies for applications in the wireless personal area networks (WPAN). In the US, the UWB transmissions have been authorized in the band 3.1-10.6 GHz. In Europe the regulation bodies are also leaned towards similar power limits in the band 3.1 - 10.6 GHz, assuming, however, sharper edges. Therefore, in the last four years many experiments have been made to characterize the indoor propagation of UWB signals in this band [1]-[3].

Path loss is a fundamental characteristic of electromagnetic wave propagation and is incorporated in the system design and link budgets, to predict expected received power. The key differences of path loss between UWB propagation channels and conventional channels (narrow/wideband continuous wave) lie in the frequency dependence of the transfer function. Conventional channels show frequency dependence of the local (or instantaneous) transfer functions due to the different runtimes of multipath components; those variations typically occur within a bandwidth of a few MHz. UWB channels show not only these variations, but also variations of the averaged transfer functions; these variations are caused by the different attenuations that different frequency components of the UWB signal encounter.

It has been shown that the antenna response's frequency dependence is the primary reason for dependence on frequency of free-space propagation received power of UWB signals [4] - [6]. Spreading loss in free-space is not frequency dependent, which is demonstrated by Buehrer's measurements [7]. It is clear that, for LOS environment, the path loss's frequency dependence is determined only by transfer function of antenna system. However, most environments of interest do not involve simple LOS propagation. Rather, the path between the transmitter and receiver will have other objects in the environment, perhaps completely blocking the LOS path. The NLOS environment provides the opportunity for substantial pulse interaction, possible frequency selectivity, and the introduction of frequency dependence into the channel. Thus, it is necessary to accommodate this frequency dependence in the model. However, there is no clear consensus on the dependence of path loss on frequency (excluding antenna effects), currently. Again, there is no clear path loss model which can modelling the frequency dependent measurement data, and gives the explicit physical explanation.

## 2. MEASUREMENTS AND DATA PROCESSING

### A. UWB signal propagation experiment

In this paper, a statistical analysis of the data collected by Intel Research Labs in 2002 is present. The experimental data can be accessed freely from [8]. The townhouse layout where measurements were taken is given in Fig. 1.

The measurement adopted a frequency domain channel sounder with a vector network analyzer scans a particular frequency band by stepping through discrete frequencies. The Intel UWB propagation measurement was done on 1601sampling points of the 2-8 GHz band with frequency resolution of 3.75 MHz and time resolution of 62.5 ps. The bandwidth capabilities of the equipment, including antennas, filters and gain stages, permitted channel measurements over the frequency range of 2-8 GHz. The measurements include both LOS and NLOS channels with antenna separation 1-20 meters. The details of the measurements set-up and data format can be found in [9].

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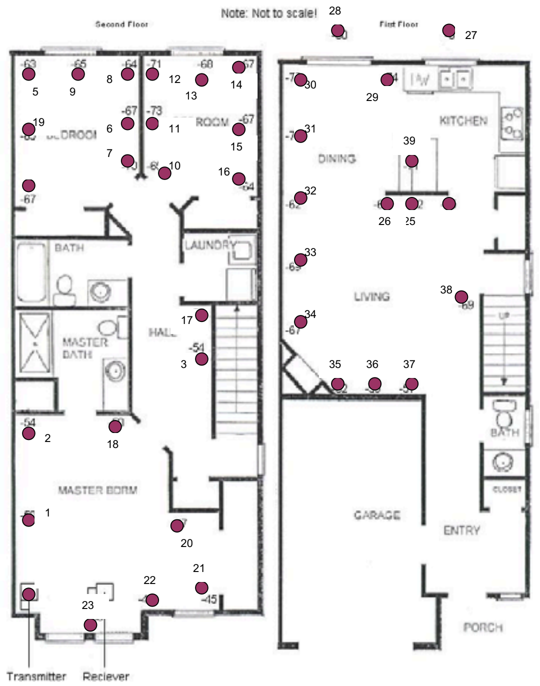


Fig. 1: Townhouse layout where channel impulses are measured. The spots in the figure denote the locations of transmitter and receiver antennas.

### *B. Data processing*

The experimental data includes 612 tx/rx pairs (172 LOS, 420 NLOS) and provides good coverage of the possible home propagation paths for the town house studied. In this paper, we focused on the 420 NLOS measurement. The data was formatted into amplitude and phase vector, separately. Typical profiles measured over in townhouse are shown in Fig. 2.

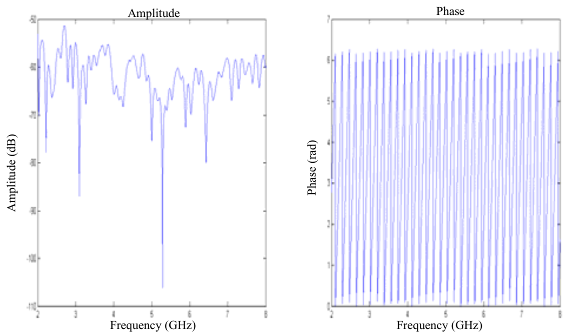


Fig. 2: A typical actual measurement data in frequency-domain.

In data processing, several compensations were applied directly to network analyzer data. First of all, for the purposes of counting the number of multiple paths, and to avoid leaking of energy of one path to the next, 1601 point Hamming frequency domain windows have been applied to the 6 GHz bandwidth spectrum in experimental data. We chose a Hamming window as its side lobe suppression of 35 dB was considered accurate enough, while time resolution was only reduced 50%.

Secondly, previous work for wideband (but not UWB) soundings has concentrated on a complex baseband (CBB) analysis. This is useful for studying carrier-modulated signals whose reception involves the generation of in-phase and quadrature signals. However, UWB signals are carrierless, it uses pulse based tx/rx techniques that does not use a CBB receiver. Hence, the real passband (RPB) approach was adopted in our data processing. The spectrum was zero padded from 0 to 2 GHz, the complex conjugate of the spectrum was flipped to give the negative frequency portion of the spectrum, guaranteeing the inverse Fourier transform would be real. It is found that timing resolution has been improved from CBB signal's 167 ps/sample to RPB's 62.5 ps/sample.

The inverse Fourier transform was then used to generate the estimation of the channel impulse response (CIR). Fig. 3 shows a typical NLOS CIR extracted from Intel measurement.

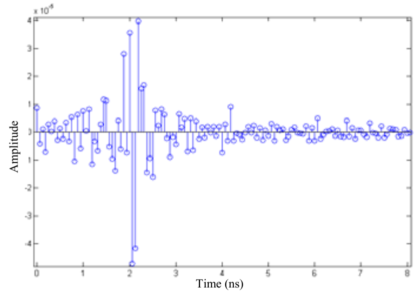


Fig. 3: A typical NLOS CIR of frequency-domain experimental data

### *C. Path loss characteristic analysis*

In this subsection, the path loss characteristic of Intel measurement data is analyzed. For NLOS environment, path loss can be represented as

$$\overline{PL}(r)[dB] = \overline{PL}(r) + X_\sigma = \overline{PL}(r_0) + 10n\log\left(\frac{r}{r_0}\right) + X_\sigma \qquad (1)$$

where $\overline{PL}(r)[dB]$ is average path loss in the distance $r$ and $\overline{PL}(r_0)$ is the path loss in a reference distance $r_0$, $n$ is the path loss exponent, $X_\sigma$ is a log-normal random variable (it is a zero mean Gaussian in dB) with standard deviation $\sigma$.

As can be seen from (1), there are two terms that must be determined by the environment: the path loss exponent and the standard deviation of the shadowing. In this paper, we simply combined all measurements from 420 similar NLOS environments and determined the best fit of the two terms mentioned above to the experimental data. By defining the reference point distance $r_0$ to be 1 meter, the directly calculate the free-space path loss $\overline{PL}(r_0)$ for reference point was adopted. Defining the reference measurement to be free-space has the advantage that it is possible to directly calculate the reference point, thus eliminating the need for a reference measurement.

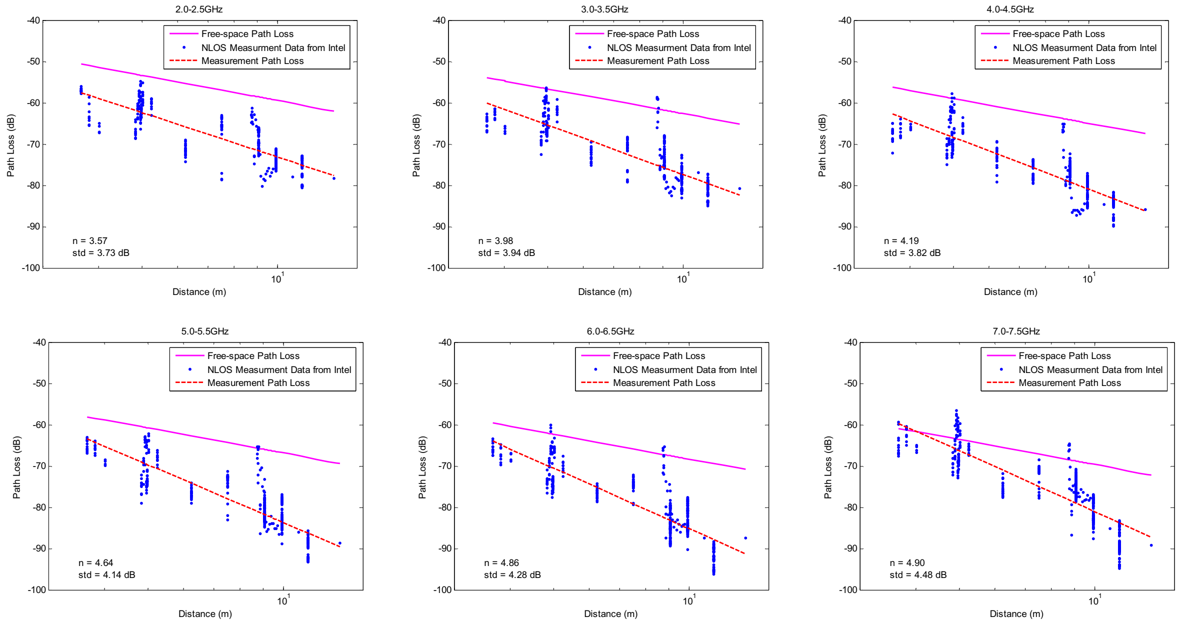

Fig. 4: 500MHz bandwidth UWB experimental data's path loss characteristics in 2-8GHz

Every 500MHz bandwidth from 2 to 8GHz UWB experimental data's path loss was obtained by evaluating (1). Some of the result has been shown in Fig.4, it is found that the path loss exponent for UWB data has significant changes over the experiment bandwidth. Details for path loss exponent together with standard deviation $\sigma$ changing with frequency are given in Table Ⅰ.

TABLE Ⅰ: FREQUENCY DEPENDENT OF PATH LOSS EXPONENT

| Frequency （GHz） | Path Loss Exponent n | Standard Deviation $\sigma$ |
|---|---|---|
| 2.0-2.5 | 3.5616 | 3.73 |
| 2.5-3.0 | 4.289 | 3.92 |
| 3.0-3.5 | 3.9824 | 3.95 |
| 3.5-4.0 | 3.8559 | 4.25 |
| 4.0-4.5 | 4.1848 | 3.83 |
| 4.5-5.0 | 4.8861 | 3.85 |
| 5.0-5.5 | 4.6418 | 4.15 |
| 5.5-6.0 | 4.9044 | 4.77 |
| 6.0-6.5 | 4.8678 | 4.29 |
| 6.5-7.0 | 4.6952 | 4.29 |
| 7.0-7.5 | 4.8875 | 4.49 |
| 7.5-8.0 | 4.3654 | 5.91 |

Fig. 4 and Table Ⅰ show that path loss has clear frequency dependence. Note that this frequency dependence is shown in an ensemble average of path loss in a particular environment at various distances, not just a single channel realization, hence we must accommodate this in the path loss model.

## 3. ANALYSING AND MODELLING

We know that antenna system can introduce frequency dependence to path loss characteristics, as shown in Friis transmission formula (2), where transmit and receive antenna are all constant aperture antenna.

$$PL(r)[dB] = 10\log\frac{P_t}{P_r} = -10\log\frac{G_t G_r \lambda^2}{(4\pi r)^2} \qquad (2)$$

where $G_t$ and $G_r$ are transmit and receive antenna gain, separately.

The existence of $\lambda$ in the path loss equation is thus interpreted as frequency dependent path loss. It can be obtain by $\lambda = C/f$, where $C$ is propagation velocity of light in free space and $f$ is the geometrical mean of the upper and lower frequency limits of experiment bandwidth [10]. However, the term $\lambda$ is explicitly introduced as an antenna effect. To make this more obvious, it is instructive to consider another type of antenna, a constant aperture antenna. The path loss characteristic for transmit and receive antenna being all constant aperture antenna is given by

$$PL(r)[dB] = -10\log\frac{A_{et} A_{er}}{(\lambda r)^2} \qquad (3)$$

where $A_{et}$ and $A_{er}$ are the effective aperture of the transmit and receive antenna, separately.

This result again shows frequency dependence, but here the path loss decreases with frequency. For systems with a constant gain antenna on one end of the link and a constant aperture antenna on the other end of the link, the path loss is independent of frequency, as shown in (4) and (5).

Constant gain transmit/constant aperture receive:

$$PL(r)[dB] = -10\log\frac{G_t A_{er}}{4\pi d^2} \qquad (4)$$

Constant aperture transmit/constant gain receive:

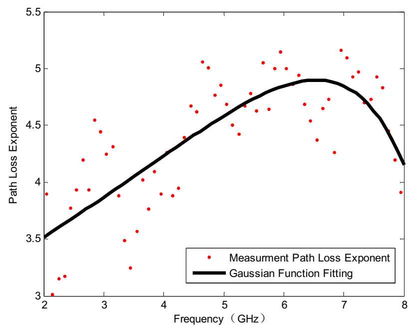


Fig. 5: Data fitting for path loss exponent

$$PL(r)\left[dB\right] = -10\log\frac{A_{et}G_r}{4\pi d^2} \qquad (5)$$

The point of this development is that while the path loss may be dependent on frequency, this is due to the antennas, not the path itself. The frequency dependence caused by antenna system can be captured in a reference measurement, completely. Therefore, for traditional narrowband signals, (1) will have none parameter that exhibits frequency dependent in NLOS environment.

For our UWB case, by defining path loss relative to a reference power measurement, the antenna effects are also subsumed into the reference measurement, as shown in (1). However, the path loss still exhibits obvious frequency dependence, as demonstrated in Section Ⅱ. The second place where frequency dependence can enter the equation in (1) is in the path loss exponent $n$ . Therefore, a frequency dependent path loss model for NLOS environment is proposed based on Intel UWB experimental data, which is shown in (6).

$$\overline{PL}(r,f)\left[dB\right] = \overline{PL}(r) + X_\sigma = \overline{PL}(r_0) + 10\cdot N(f)\cdot\log\left(\frac{r}{r_0}\right) + X_\sigma \qquad (6)$$

where the $N(f)$ is frequency dependent path loss exponent, it can only be obtained by fitting the model (6) to the experimental data.

By fitting the model (6) to Intel UWB NLOS environment experimental data mentioned in Section Ⅱ, it is find that Gaussian function fitted the data well (as shown in Fig. 5), and at the same time have a relative simple style which would be convenience in practical application. The experimental path loss exponent and dada fitting result of Gaussian function is shown in fig.5. (7) gives the path loss model for UWB NLOS environment with Gaussian frequency dependent path loss exponent. It is obvious that there are 4 parameters, i.e. $a$ , $b$ , $c$ and $X_\sigma$ , that defining the model. $X_\sigma$ has the same definition as it is in (1). Therefore, for Intel set of experimental data, the other three parameters has the values: a=4.78, b=6.29, c=7.205.

$$\overline{PL}(r,f)\left[dB\right] = \overline{PL}(r) + X_\sigma = \overline{PL}(r_0) + 10\cdot[a\cdot e^{-\frac{(f-b)^2}{c^2}}]\cdot\log\left(\frac{r}{r_0}\right) + X_\sigma \qquad (7)$$

In NLOS environment, if we consider a single channel realization, the main propagation processes, such as reflection from, and transmission through, dielectric or conductive objects, diffraction at the edge of a screen or wedge, scattering on rough surfaces, etc. will show frequency dependence within the ultra-wide band. Therefore, if an ensemble of channel realization in a particular environment at various distances is studied, it would definitely show some average frequency dependence in propagation characteristics we concern about, here in this study is path loss. It is appropriate to mention at this point that the frequency dependent path loss exponent introduced in (6) is determined by propagation processes which exhibit frequency dependence in UWB frequency band. However, the frequency dependence introduced by antenna system has no contribution to that term.

## 4. Conclusions

In NLOS environment, many propagation processes, such as reflection, transmission, diffraction and scattering, etc. would exhibit frequency dependence within UWB frequency band. In this paper, a frequency dependent UWB path loss model for NLOS environment is proposed base on the analysis of the Intel experimental data. The model has a frequency dependent path loss exponent, which models the frequency relevant characteristic introduced by the above propagation processes. By fitting the proposed model to the measurement data, it is found that path loss exponent can be modeled as Gaussian function when taking into account its changes with frequency.

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