Empirical Ultra Wide Band Path Loss Model in Office Environments

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***Abstract* — This paper reports the empirical path loss model of Ultra Wide Band (UWB) communications in office environments. The channel transfer functions of 46 transmitter-receiver location pairs are acquired using channel measurement system based on frequency sweep method. From the measured data, parameters of log-distance path loss formula are extracted considering propagation environments and existence of a line of sight path. The effect of frequency to the path loss properties of ultra wideband signal is presented also. Finally, statistical properties of received signal power with respect to the receiver conditions are analyzed.**

Keywords - Ultra WideBand (UWB), Empirical Channel Model, Pathloss Model, Channel Measurement and Frequency dependency.

I. Introduction

The Ultra Wide Band (UWB) system has drawn one's attention as a new short range high data rate wireless communication system. Especially, after Federal Communication Commission (FCC) approved the regulation for UWB transmission, discussions about the commercial UWB systems have been very active [1]. In order to develop the efficient UWB system and predict its effects on other communication systems, it is crucial to understand the UWB channel properties first. The literature has reported the measurement campaigns and results for UWB channel models [2]~[7]. However, the channel characterization works in frequency domain are insufficient even though the wide frequency band is the most distinguishable feature of the UWB system [8][9].

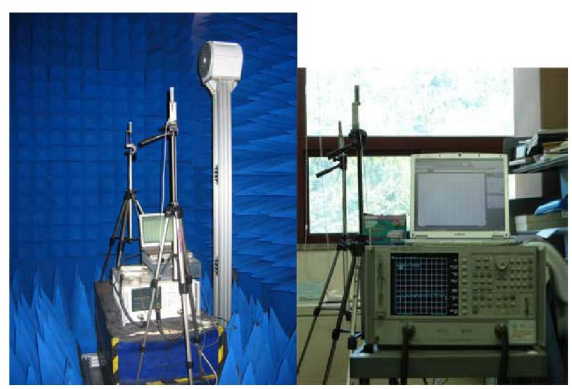
In this study, we investigated the empirical UWB path loss model in frequency domain at office environments. The path loss behavior is the most fundamental parameter among the radio propagation characteristics to develop the wireless communication systems and predict the interference to other communications. For UWB system, it is more emphasized because the UWB is expected to co-exist with many other systems and its large frequency bandwidth is the underlying suspect for interference problem. The office environment is selected for the study of channel properties because it is one of the most probable for the coexistence of multiple wireless devices with high data rate. We measured the complex channel transfer functions in 3 different office environments with the frequency sweep method. From the measured results, we suggest the practical and useful log-distance path loss model for UWB systems. The parameters are analyzed considering propagation environments near te receiver and the existence of a line of site (LOS) path. Then, path loss exponent variation with frequency is analyzed. Finally, we investigate the statistical properties of the received signal for LOS and non-LOS(NLOS) locations

This paper is organized as follows. Section 2 presents the channel measurement system and measurement scenario. Section 3 provides the measured results and analysis. Finally, the conclusion is followed in section 4.

II. Measurement Campaign

A. Measurement system

Among UWB channel measurement methods, we selected the frequency domain channel sounding method for measurements [10]. In this measurement technique, wide frequency bands are swept using a set of narrow-band signals and channel frequency responses are recorded using a vector network analyzer (VNA). The measurement system is shown in Figure1. A VNA (Agilent 8719ES) transmits 801 continuous wave tones uniformly distributed from 5GHz ~ 6.6GHz with the frequency separation of 2MHz. This frequency interval allows us to capture multipaths with the maximum excess delay of 500 nano-seconds and the bandwidth of 1.6GHz gives the time resolution of 0.625 nano-seconds.



a) b)

Figure 1 Pictures of measurement system in a) anechoic chamber and b) measurement environment.

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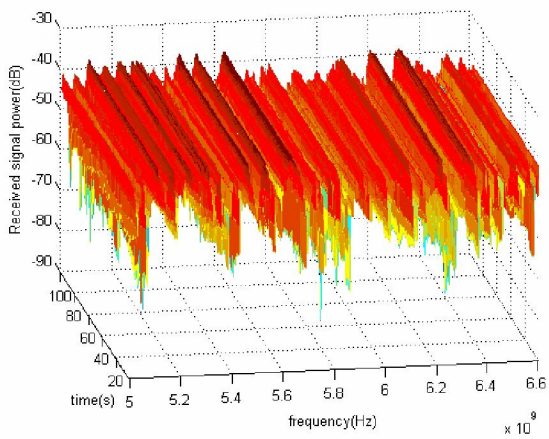
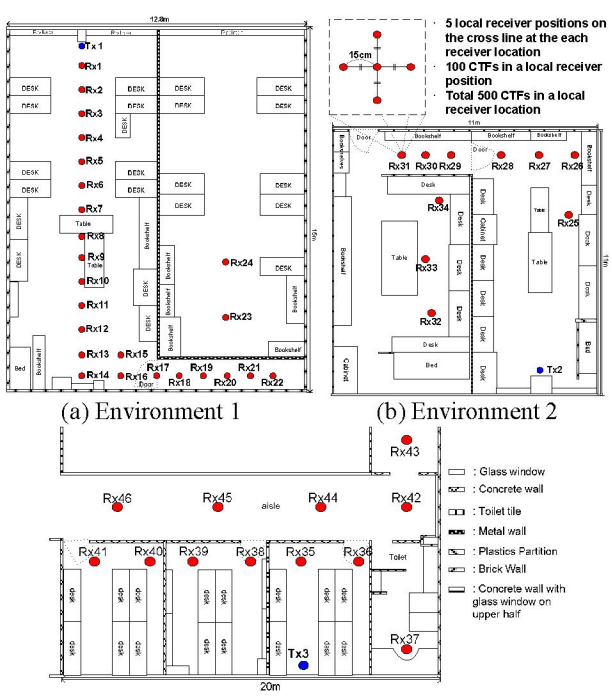


Figure 2 Typical measured channel transfer function at a LOS position

The path loss of up to 110dB can be compensated to guarantee the proper input power to VNA by using a power amplifier and a step attenuator. The transmitting and receiving antennas are omni-directional with 2.1dBi gain and mounted on the 1.6m tripods. The typical measured channel transfer function obtained by this measurement system is illustrated in Figure 2.

B. *Measurement Scenario*

The frequency sweep measurements are carried out at three different office environments in Seoul National University, Korea.



(a) Environment 1 (b) Environment 2

(c) Environment 3

Figure 3. Three office environments where measurements performed

The locations of transmitting antenna and receiving antenna are illustrated in Figure 3 with the floor plan and wall-type description. The Environment 1 is located on the 5th floor of a ferroconcrete building, Environment 2 and Environment 3 are located on the 2nd floor the 4th floor of the other ferroconcrete building. The Environment 1 and 2 have metal walls in the middle to divide a large room into two small offices while the Environment 3 consists of small offices and corridors. During measurements, all doors are kept opened and pedestrians are restricted. Out of 46 receiver locations, 21 locations have LOS path to transmitter and remaining 25 locations do not. The each receiver location had 5 local receiver positions for sector average and 100 frequency responses were collected at each position (500 responses in single receiver location). The time interval between consecutive responses is one second which is much larger than the general maximum excess delay in indoor environments [11,15,16].

III. Measured Data and Analysis

A. *Linear regression fit to path-loss formula*

For the characterization of UWB path loss behavior, we use the widely known log-distance path loss formula. The formula is given in Equation (1) where $PL(d_0)$ means path loss at the reference distance d_0(=1m), d is separation between the transmitter and receiver, n is the path loss exponent and X_σ is the standard deviation of shadowing factor [9].

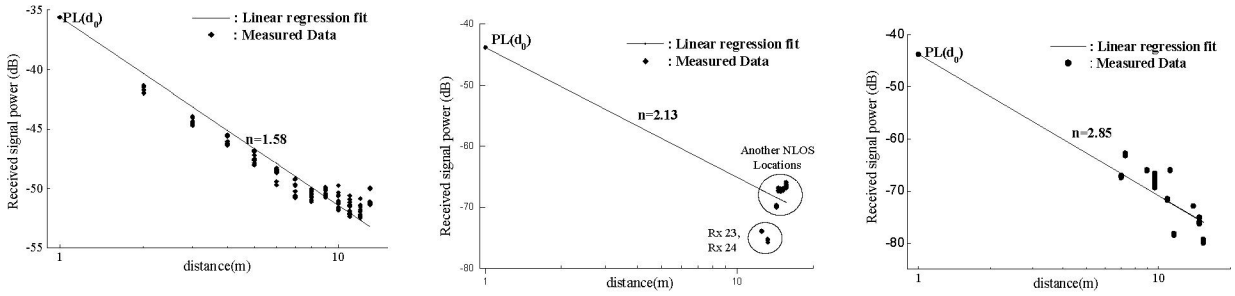
$$PL(d) = PL(d_0) + 10n\log(d/d_0) + X_\sigma(dB) \qquad (1)$$

To figure out the path-loss behavior of receiver locations with LOS path, the receiver set to 5 different local positions as shown in Figure 3(a). The typical measured results are drawn with in Figure 4(a) and the non-LOS (NLOS) result of Environment 3 is illustrated in Figure 4(b) and 4(c). The solid lines in Figure 4 are linear regression fit to the measured data using Equation (1) with fitted path loss exponents as given in Table 1. The path loss exponents and the standard deviation of shadowing factor values given in Table 1 are obtained using the minimum mean square error (MMSE) algorithm.

Table 1. The empirical path loss parameters to receiver conditions

	$PL(d_0)$ [dB]	n	X_σ [dB]
LOS (Environment1)	-35.596	1.58	1.063
NLOS (Environment 1)	-35.596	2.13	2.656
LOS (Environment 2)	-37.913	1.32	1.101
NLOS (Environment 2)	-37.913	2.10	4.546
NLOS (Environment 3)	-43.786	2.85	4.441

n: pathloss exponent X_σ :the standard deviation of shadowing factor



(a) LOS locations of Environment 1 (b) NLOS locations of Environment 1 (c)NLOS locations of Environment 3

Figure 4. Examples of linear regression fit of measured data to log distance path loss formula in three receiver conditions

For LOS locations of this measurement campaign, the path loss exponents are found to be smaller than 2, which is can be explained by the waveguide effect due to the concrete wall, the metal blind at the glass window and the metal wall in the middle of rooms in the Environment 1 and 2 [12]. For NLOS locations of Environment 1 and 2, the path loss exponent is slightly above 2, which is lower than that of Environment 3. This is due to the fact that diffracted signals around the corner of the open doors and multiple reflected signals can propagate to the NLOS locations in the aisle. The path loss comparison to the condition of NLOS receiver location explains this phenomenon statistically. As reported in Table 2, the path loss varies to the existence of diffraction path and blocking metal wall. In locations with diffraction path, the path loss is smaller than that of receiver locations behind the metal wall although distance between transmitter and receiver is bigger. For these path loss behavior of LOS and NLOS locations, the metal wall in the middle of environment reinforce the waveguide effect to the front locations and block the signal penetration to the behind locations.

B. *Effect of Frequency on path loss properties of UWB signal*

The Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) scheme proposes that the assigned frequency range for UWB system operation would be divided into sub-bands with 500MHz bandwidth [14]. For the design of MB-OFDM, the path loss properties of UWB signal with frequency has to be studied.

Table 2. Path loss comparison between NLOS receiver locations

Receiver locations [*Link description*]		Tx-Rx distance [m]	Average of Path loss [dB]
NLOS of Environment 1	Rx18 ~ Rx22 [*In aisle with diffraction path to transmitter*]	14.93	-23.688
	Rx23 ~ Rx24 [*Obstructed by metal wall and wooden shelves*]	12.40	-31.098
NLOS of Environment 2	Rx29 ~ Rx31 [*In aisle with diffraction path to transmitter*]	10.26	-15.453
	Rx32 ~ Rx34 [*Obstructed by metal wall*]	6.60	-22.291

Hence, 1.6GHz bandwidth at 5.8GHz band swept by sliding the frequency window of 500MHz bandwidth with the discrete interval of 100MHz.The path loss exponents averaged over 500MHz bandwidth are shown graphically in Figure 5 and Statistical results for the entire measurement environments are summarized in Table 3. As shown in Figure 5, frequency averaged path loss exponents increase with the center frequency and the variation in NLOS of environment 3 has the steepest slope.

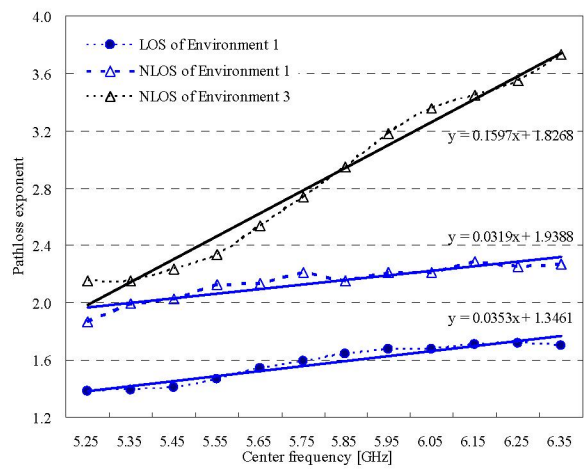


Figure 5. Variation of Path loss exponent averaged over 500MHz bandwidths with center frequency and their linear regression fit results

Table 3. Statistical values about path loss exponent variation of 500MHz frequency bands

	n $(1.6GHz)$	Min. value	Max. value	Slope of n curve
LOS (Environment 1)	1.58	1.38	1.72	0.0353
NLOS (Environment 1)	2.13	1.87	2.29	0.0319
LOS (Environment 2)	1.32	1.23	1.84	0.0587
NLOS (Environment 2)	2.10	1.96	2.35	0.0372
NLOS (Environment 3)	2.85	2.15	3.73	0.1597

In Environment 1 and 2, received powers at receiver locations having LOS path have dominant contributions along the direct paths from the transmitter to receivers, while those for NLOS receiver locations have contributions via diffracted paths or multiply reflected paths. However, Environment 3 requires that the radio signal from the transmitter should experience not only the scattered transmissions through multiple interior walls but also diffractions around the corners. As a result, path loss exponents of NLOS receiver locations in Environment 3 are larger than those of NLOS receiver locations in Environment 1 and 2 by about 0.7 on the average, and frequency selective properties of wall transmission properties of radio wave may cause the considerable extent of variation in path loss exponents with frequency.

C. *Statistical characterization of UWB received signal*

To understand the path loss properties of UWB signal properly, not only the average path loss characteristics but also the distribution of the received signal power has to be analyzed. Figure 6 illustrates the typical cumulative distribution functions (CDFs) of received signal of LOS and NLOS locations. The CDFs are based on the 500 frequency responses in each receiver location. In Figure 6, x-axis indicates the normalized received signal and y-axis means the cumulated probability. The CDF of LOS locations is similar to the Rician distribution with K=1.

And, in Figure 7, the comparison between the received signal CDF of overall frequency band and CDFs of single frequency tones in selected LOS and NLOS locations is illustrated. What we see from Figure 7 is that the CDFs of received signal power of 5 different single frequency tones at NLOS location has more variation than at LOS location. This is fact that the as the transmitted signal undergoes the frequency selective change as penetrate through the multiple interior walls.

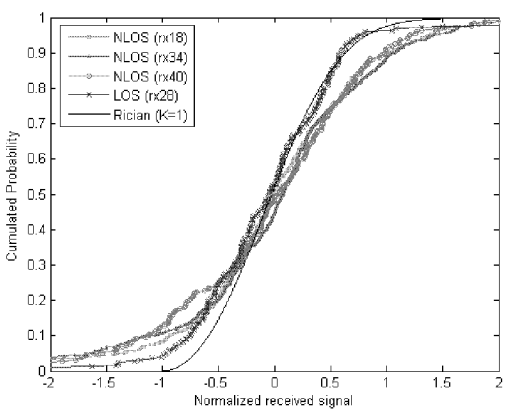


Figure 6. Comparison between received signal CDFs of LOS and NLOS locations

In case of the probabilities of the received signal powers within the relative range from the mean value do not depend on the existence of LOS path. Table 4 reports the probability of received signal power in the specific range which is related to how many standard deviations are apart from the mean value. For all range based on normalized standard deviation, no consistent tendency is observed.

Table 4. The average of standard deviation of RSP and Probability of RSP within relative range

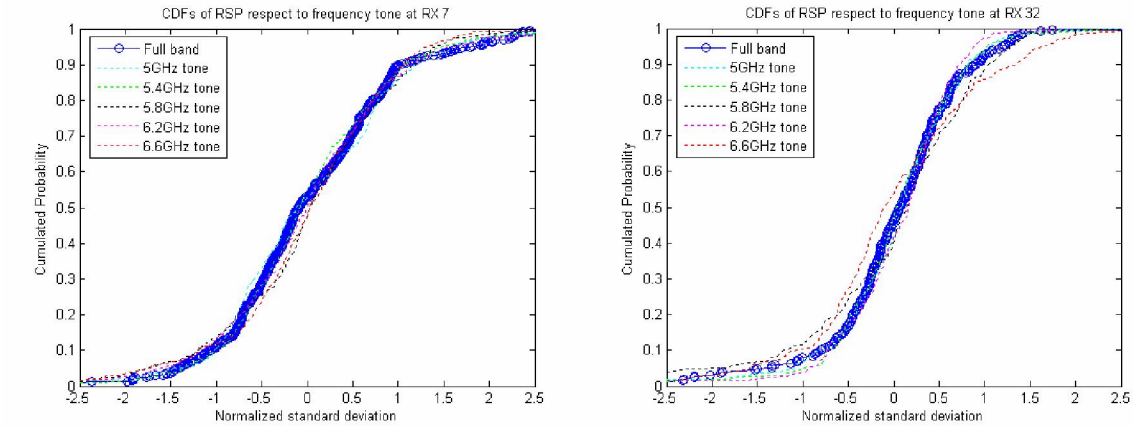
	Average (σ) [dB]	Pr (P<ε±0.5σ)	Pr (P<ε±1σ)	Pr (P<ε±1.5σ)	Pr (P<ε±2σ)
LOS (Environment 1)	0.3745	0.4410	0.7464	0.9006	0.9550
NLOS (Environment 1)	0.4930	0.4087	0.7537	0.8920	0.9690
LOS (Environment 2)	0.1113	0.4573	0.7913	0.9080	0.9560
NLOS (Environment 2)	0.1900	0.4942	0.7351	0.8978	0.9618
NLOS (Environment 3)	0.2154	0.4415	0.7356	0.8789	0.9516

Pr : Probability RSP : Received Signal Power

Pr (P<ε±0.5σ): Probability of the received signal power is in the range from (ε-0.5σ) to (ε+0.5σ)

IV. Conclusion

For UWB system performance, the experimental UWB path loss characterization, which is crucial to estimate, is carried out in office environments. The measurement system used for channel characterization adopts on the frequency sweep method. From the measured results at 3 different office environments, the path loss exponent of log distance path loss formula is about 1.5 when the LOS path is guaranteed and varies from 2.1 to 2.85 due to the propagation condition for NLOS locations. In study of the frequency dependency to the UWB signals, we found that the signal attenuation increases with center frequency of 500MHz sub-band. And variation of path loss exponents is the biggest when the transmitted signals passed through the multiple walls have the majority of received signal. Finally, statistical characteristics of UW signals are analyzed. The received signal CDF of LOS locations follows the Rician distribution while those of NLOS locations do not. And the difference between CDFs of single frequency tones at NLOS locations is bigger than that of LOS locations.



(a) CDF at Rx 7 (LOS location) (b) CDF at Rx32 (NLOS location)

Figure 7. Typical CDF comparison between received power of full band signal and single tone signals

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