IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**UWB Channel Characterization in Indoor Office Environments**
Date Submitted	[20 August 2004]
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Re:	[Response to Call for Contributions from 15.4a Channel Modeling Subgroup]
Abstract	[This document summarizes the UWB channel parameters reported in the literature for indoor office environments. At the end of this document, a set of unique channel parameters, which are suitable for studying the performances of 15.4a PHY proposals in indoor office environments, is recommended based on the generic channel model proposed in [22].]
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1. INTRODUCTION

In this document, we briefly describe the model [22, 23] adopted by the 15.4a channel modeling subgroup and summarize the parameters extracted from various measurement campaigns in the literature for UWB indoor office environments. Details of the extraction processes for various parameters can be found in [20], [21] and [25]. One of our main aims in this channel modeling activity is to keep our model simple and at the same time, to make sure that it reflects a real environment as close as possible.

As the channel parameters are greatly dependent on the environments, distance, frequency band etc., the parameters reported in the literature vary from one measurement to another. This document summarizes the UWB channel parameters reported in the literature for indoor office environments. Different multipath channel models (S-V model [3, 18, 10, 5, 6, 24], variation of the S-V model [20, 22], simple exponential model [1, 2, 7, 4, 14, 15, 16], etc.), hence different parameters, have been used in these reports to characterize UWB indoor office propagation environments. However, some parameters such as decaying factors, excess mean delay etc., are still comparable across these different models and therefore, have been included in this report.

At the end of this document, a set of unique channel parameters, that are suitable for studying the performances of 15.4a PHY proposals in indoor office environments, is recommended based on the generic channel model proposed in [22].

2. LARGE-SCALE PARAMETERS

The distance dependent path loss (in dB), at a distance *d,* is given by

$$PL(d) = \left[PL_0 + 10\nu\log_{10}\left(\frac{d}{d_0}\right)\right] + S; \qquad d \geq d_0 \tag{1}$$

Where,

- d_0 is a reference distance, e.g., d_0 = 1 m.
- PL_0 is the intercept and ν is the path loss exponent.
- S (in dB) is the shadowing component.
- ν is the path loss exponent.

S is generally assumed to be a zero-mean Gaussian random variate with standard deviation σ_S.

The frequency dependent path loss *PL(f)* is modeled by the following equation:

$$PL(f) \propto \left[\frac{f}{1GHz}\right]^{-r} \tag{2}$$

In (2), r denotes the frequency dependent path loss exponent. Table (1) and (2) list the large-scale parameters that are reported in the literature for various indoor office environments.

3. TEMPORAL PARAMETERS

Mean excess delay, τ_m and root square mean excess delay, τ_{rms} can be calculated from the following equations:

$$\mathrm{i^{th}\ order\ moment:}\ \tau^i = \frac{\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}^2 \tau_{k,l}^i}{\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}^2}$$

$$\tau_m = \tau^1, \quad \tau_{rms} = \sqrt{\tau^2 - (\tau^1)^2} \tag{3}$$

Temporal parameters from various measurement campaigns are tabulated in table (3).

4. SALEH-VALENZUELA MULTIPATH PARAMETERS

802.15.4a channel modeling sub-committee adopted the following discrete-time model for the channel measurements campaign:

$$h(t) = \sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}\delta(t - T_l - \tau_{k,l}) \tag{4}$$

Where,

- T_l: Delay of the l^{th} cluster
- $\tau_{k,l}$: delay of the k^{th} MPC of the l^{th} cluster
- $a_{k,l}$: amplitude of the k^{th} MPC in the l^{th} cluster
- K: Total number of MPCs in a cluster
- L: Total number of clusters
- $\tau_{0,1} = T_0 = 0$

The cluster and ray arrival times are respectively described by the following Poisson processes:

$$\begin{aligned} p(T_l|T_{l-1}) &= \Lambda \exp[-\Lambda(T_l - T_{l-1})], l>0 \\ p(\tau_{k,l}|\tau_{k,l-1}) &= \lambda \exp[-\lambda(\tau_{k,l} - \tau_{k,l-1})], k>0 \end{aligned} \tag{5}$$

Where,

- Λ: Cluster arrival rate
- γ: Ray arrival rate

Average PDP (Power Delay Profile) at $T_l + \tau_{k,l}$ is described by the following exponential function:

$$E\{|a_{k,l}|^2\} = E\{|a_{0,0}|^2\}\exp\left[-\frac{T_l}{\Gamma}\right]\exp\left[-\frac{\tau_{k,l}}{\gamma}\right] \tag{6}$$

The S-V model is characterized by the following parameters:

- Γ: Cluster decay factor

- γ: Ray decay factor
- Λ: Cluster arrival rate
- λ: Ray arrival rate

Table (4) lists the S-V parameters from various channel measurement campaigns.

5. SMALL-SCALE AMPLITUDE STATISTICS

The small-scale amplitude statistics are generally modeled by log-normal [3,10,18], Nakgami [14,15,20] or Weibull distributions [3,11,19]. However our results in [20] and the results in [14,15] suggest that Nakagami distributions give the best fit to the amplitude statistics. Details of amplitudes statistics reported in the literature for UWB indoor office environments are tabulated in table (5).

In [14,15], it is reported that Nakagami m-factor decreases (from 6 to 1) with increasing delay. However, this phenomenon was not observed in our measurement campaign. Instead, we observed that the m-factors for all the scenarios fit well into a log-normal cdf [20].

6. CONCLUSIONS

Based on the results reported in the literature, we recommend a unique set of channel parameters in table (7) for simulation purposes. Corresponding simulated values (from a Matlab program) are given in table (8). In the Matlab simulations we used fixed Nakagami m-factors (mean values).

7. REFERENCES

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Ref.	Source	Freq. range (GHz)	LOS			NLOS		
			ν	PL_0	S [dB]	ν	PL_0	S [dB]
[1], [7]	Kunish, Pamp Kull et.al.	(1-11)	1.6			2.0		
[8]	Kunish & Pamp	(1-11)	3			2		
						3		
[17]	Yano	(1.25-2.75)				2.1		3.6
[2]	Pagani et. al.	(4-6)	1.5			2.5		
[3], [18]	Kignart & Daniele et. al.	(2-6)	1.6			3.8		
						4.8		
[3], [11], [19]	Kignart, Valera, Alvarez et. al.	(1-9)	1.4		0.4	3.2		1.2
						4.1		1.9
[6]	Buehrer (Bicone & TEM antennas)	(0.1-12)	1.3 (Biconical)		2.8	2.3		2.8
			1.3 (TEM Horn)		3.6	2.4		5.4
[24]	Virginia Tech. (Bicone & TEM antennas)	(1-12)	1.7 (Biconical		1.7	2.5		3.2
			1.7 (Tem Horn)		1.6	2.7		6.0
[9]	Hovienen et. al.	(2-8)	1.1			3.9		
			1.8			3.3		
			1.4			3.2		
[10]	Kignart et. al.	(2-6)	1.6			3.7		
						4.8		
[12]	Muqaibel et. al.	(0.1-12)	1.6 (biconical)		1.9	2.4		3.3
			1.6(TEM Horn)		1.6	2.6		6.1
[14], [4]	Cassioli, Win and Molish	BW=1				2.4		5.9
[15]	Win, Cassioli and Molish	BW=1				2.0 (<=11m)		4.3
						7.4 (>11m)	-56	4.3
[21]	Kannan et. al	(3-6)	1.8	-36.6	1.5	1.8	-52	2.4
						2.1	-46.4	4.2

Table (1): Distance dependent large-scale parameters

Ref.	Source	Freq. Range (GHz)	LOS		NLOS	
			μ_r	σ_r	μ_r	σ_r
[1], [7]	Kunish, Pamp Kull et.al.	(1-11)	1.2		1.1	
[8]	Kunish & Pamp	(1-11)	1.1		1.01	
					1.3	
[21]	Kannan et. al		0.48	0.12	1.83	0.15
					0.88	0.13

Table (2): Frequency dependent large-scale parameters

Ref.	Source	Freq. Range (GHz)	LOS		NLOS	
			τ_m	τ_{rms}	τ_m	τ_{rms}
[3], [18]	Kignart & Daniele et. al.	(2-6)	7.4	10.9	17.7	16.5
					32.2	22.4
[5], [6]	Buehrer & McKinstry et. al.	(0.1-12)	4.2 (Biconical)	4.55	14.4	18.5
			0.44 (TEM Horn)	0.53	1.52	2.3
[24]	Virginia Tech.	(1-12)	3.93 (Biconical)	4.74	10.75	10.27
			0.8 (TEM Horn)	0.53	2.09	2.61
[10]	Kignart et. al.	(2-6)	6.42	10.07	16.01	14.78
					18.85	17.64
[16]	Kignart & Daniele	(2-6)	6.92	10.68	19.38	16.31
[20]	Kannan et. al.	(3-6)	5.8	15.6	15.7	23.6
					16.3	18.7

Table (3): Temporal parameters

Ref.	**Source**	**Freq. Range (GHz)**	**LOS**					**NLOS**				
			Λ	λ	Γ	γ	**NP10dB**	Λ	λ	Γ	γ	**NP10dB**
[3], [18]	Kignart & Daniele et. al.	(2-6)	0.025	0.045	14.5	8	2.47	0.4	5.5	14	7.5	51.4
								0.8	4	20	15	92.8
[13]	Cramer &Win	BW= 1GHz						0.0220	0.435	27.9	84.1	
[10]	Keignart & Daniele	(2-6)	0.0065	1.26	29	10	2	0.09	1.05	19.7	1.06	46.8
								0.17	1.06	19.8	1.1	75.8
[5], [6], [24]	Buehrer, McKinstry et.al.	(0.1-12)	0.2	1.42	7.1	2	23.2 (biconical) 7 (TEM Horn)	0.1	0.71	21	8	52.9 (biconical) 19.3 (TEM)
[2]	Pagani et. al.	(4-6)			25.1					25.1		
[1], [7]	Kunish, Pamp Kull et.al.	(1-11)			14					14		
[8]	Kunish & Pamp	(1-11)			10					9.5		
										12.5		
[4], [14]	Cassioli, Win and Molish	BW=1GHz								39.8		
[15]	Win, Cassioli and Molish	BW=1 GHz								16.1		
[16]	Kignart & Daniele	(2-6)			31.7					47.1		
[20]	Kannan et. al.	(3-6)	0.0186	0.28	27.8	14.1	6.5	0.0134	0.27	30.4	25.3	30.3
								0.0024	0.36	24.6	33.8	41.43

Table (4): Multipath parameters

Ref.	Source	Freq. Range (GHz)	LOS: amplitude statistics	NLOS: amplitude statistics
[14], [15]	Cassioli, Win and Molish	BW= 1 GHz	Nakagami distribution. m factor decreases with increasing delay. m factor is modeled by truncated Gaussian pdf. m=1-6.	Nakagami distribution. m factor decreases with increasing delay. m is factor modeled by truncated Gaussian pdf. m= 1-6
[3], [11] & [19]	Kignart, Valera, Alvarez et. al.	(1-9)	Power variations is modeled by Weibull pdf with μ=-306, Σ= 311, λ=45.	Power variations is modeled by Weibull pdf with μ=-304,Σ= 320, λ=46 (NLOS1). Power variations is modeled by Weibull pdf with μ=-304, Σ= 322, λ=45 (NLOS2).
[3], [18]	Kignart & Daniele et. al.	(2-6)	Lognormal distribution with σ = 4dB.	Lognormal distribution with σ = 4dB.
[1], [7]	Kunish, Pamp Kull et. al.	(1-11)	Lower amplitudes or amplitudes at low delay intervals (within 1ns) fit a Rician pdf. Larger amplitudes at larger delay intervals fit a Gamma pdf.	Lower amplitudes or amplitudes at low delay intervals (within 1ns) fit a Rician pdf. Larger amplitudes at larger delay intervals fit a Gamma pdf.
[[8]	Kunish & Pamp	(1-11)	Rayleigh distribution	Rayleigh distribution
[2]	Pagani et. al.	(4-6)	Rayleigh distribution. With increasing bandwidth, it can be better modeled by Gaussian pdf.	Rayleigh distribution. With increasing bandwidth, it can be better modeled by Gaussian pdf.
[10]	Keignart & Daniele	(2-6)	Lognormal with σ decreasing from 5dB to 1dB with excess delay.	Lognormal with σ decreasing from 5dB to 1dB with excess delay.
[5]	McKinstry & Buehrer	(0.1-12)	Log-normal distribution with σ = 5dB	Log-normal distribution with σ = 2dB
[20]	Kannan et. al	(3-6)	Nakagami distribution. m factors fit well into a log-normal pdf with mean = 0.42 dB and variance = 0.31 dB.	Nakagami distribution. m factors fit well into a log-normal pdf with mean = 0.50 dB and variance = 0.25 dB.

Table (5): Amplitude statistics

Parameters	LOS	NLOS
Large-scale Parameters		
ν	1.63	3.07
σ_S (dB)	1.9	3.9
PL_0 (dB)	36.6	51.4
r (μ_r , σ_r)	(0.93, 0.12)	(1.22, 0.14)
Multipath Parameters		
Γ (ns)	14.6	19.8
γ (ns)	6.4	11.2
Λ (1/ns)	0.016	0.19
λ (1/ns)	0.22	0.71
NP10dB	3.4	33
Temporal Parameters		
Mean Excess Delay, τ_m (ns)	5.78	17.92
RMS Delay Spread, τ_{RMS} (ns)	9.42	17.63
Amplitude Statistics		
Amplitude Statistics	Nakagami Distribution	Nakagami Distribution
m-factor: Mean (dB)	0.42	0.50
m-factor: Variance (dB)	0.31	0.25

Table (7): Recommended values for parameters (from the measured data)

Parameters	LOS	NLOS
τ_m (ns)	9.0	25.8
τ_{rms} (ns)	10.0	22
NP10dB	4.3	28.0

Table (8): Simulated values (from Matlab)