UWB Small Scale Channel Modeling and System Performance

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Abstract—**Recently, ultra-wideband (UWB) technology based on the transmission of short duration pulses has gained much interest for its application to wireless communications. UWB small scale channel modeling work, including statistical characterization and potential models, are discussed. The significance, in terms of performance, of the channel impulse response model chosen for the simulation of UWB communications systems is also evaluated. Three traditional models are found to be useful for modeling NLOS UWB channels, but not LOS channels. A new model for LOS UWB channels is presented and shown to represent LOS channels much more accurately than the traditional models.**

Keywords- ultra-wideband; UWB; channel model; small scale; Saleh-Valenzuela; -K; Rake receiver

I. INTRODUCTION

Accurate channel models are extremely important for the design of communications systems. Knowledge of the features of the channel provides communications system designers with the ability to predict the performance. However, useful models must accurately predict communications system performance, not just match some of the statistics of the channel. Useful channel models must also balance detailed description of channel features with a simplicity that is still sufficient to accurately predict system performance. Since impulsive ultra-wideband (UWB) for communications is still a relatively new technology, to date only a limited amount of work has been done to develop accurate UWB specific channel models.

II. MEASUREMENT BASED MODELING

A. Measurement Campaign

Numerous indoor UWB measurements were taken by researchers of the Time Domain Laboratory of Virginia Tech as a part of a collaborative research effort. Both LOS and a limited number of NLOS measurements were taken. Measurements were taken using a pulse generator capable of generating approximately Gaussian shaped pulses each with a duration of less than 200 ps, a 20 GHz digital sampling oscilloscope (effective sampling rate of 100 GHz), and either a set of TEM horn antennas or a set of biconical antennas. Details of the specific measurement scenarios and measurement system used are given in [1].

B. Data Processing and Analysis Methodology

The received signal from a measurement set is a function of the pulse shape at the transmitter and the transfer functions of the channel and both antennas. The transfer functions of the channel and antennas are all functions of frequency and the three dimensional antenna structure or environment. However, in this work the angular dependencies of the responses are subsumed into the channel impulse response. Therefore, the resulting channel impulse response from analysis will be somewhat antenna dependent, but will still offer general characterization of the channel as would be seen by similar antennas (similar in this case being most significantly the spatial pattern of the antenna). The received signal can then approximated by

$$r(t) = p_{rx,LOS}(t) * h_{chan}(t) \tag{1}$$

where $p_{rx,LOS}(t)$ is the undistorted pulse from the LOS path only (thus accounting for the antenna effects) and $h_{chan}(t)$ is the impulse response of the channel.

The impulse response of a channel can be extracted from a measurement set by deconvolving the undistorted LOS pulse from the received signal (the measurement). The CLEAN algorithm was used to perform the deconvolution. The CLEAN algorithm was chosen over other deconvolution techniques because the CLEAN algorithm treats the channel as an FIR filter (combination of discrete multipath components) which is easier to statistically characterize in the time domain than a continuous impulse response. The CLEAN algorithm has been used by other UWB researchers and its implementation is given in [2]. A 15 dB threshold was used as the stopping criteria for the algorithm.

III. CHANNEL SMALL SCALE STATISTICS

It is useful to have some parameters that generally describe the multipath channel structure as a function of delay. The most commonly used time dispersion parameters are mean excess delay, RMS delay spread, and maximum excess delay [3]. The average values for these parameters are recorded in Table I. While some researchers [2][4] report a correlation between distance and delay spread, no such correlation is evident from the available data sets here. Since these data sets represent a fairly diverse set of environments (different

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rooms/scatterers/materials), it is concluded that for these particular sets the physical environment has a much more significant impact on the time dispersive nature of the channel than the distance.

It is also of interest to know how many distinct multipath components are present in the channel. The average number of detected multipath components is shown in Table II. As expected, the LOS channels are less dispersive and have less multipath components than NLOS channels, and channels calculated for TEM horns (highly directional) are less dispersive and have less multipath components than channels calculated for biconical antennas (omnidirectional).

TABLE I. AVERAGES OF DELAY STATISTICS

		mean excess delay (ns)	***RMS delay spread (ns)***	***max excess delay (ns)***
TEM horns	LOS	0.44	0.53	4.15
	NLOS	1.52	2.30	23.90
bicones	LOS	4.20	4.55	36.41
	NLOS	11.47	9.87	65.77

TABLE II. AVERAGE NUMBER OF MULTIPATH COMPONENTS

		average number of paths
TEM horns	LOS	7.0
	NLOS	19.3
bicones	LOS	23.2
	NLOS	52.9

IV. FIT TO TRADITIONAL IMPULSE RESPONSE MODELS

The three traditional indoor channel impulse response models considered are the Saleh-Valenzuela model [5], the Δ-K model [6][7] and a single Poisson process arrival time model. A search was performed to find model parameters such that the average mean excess delay, average RMS delay spread, and average number of multipath components of sample impulse responses from the model match those statistics of the measurement data. Appropriate parameters were found for each of the three models and for each of the measurement scenario types (LOS vs. NLOS; TEM horns vs. bicones).

A. Traditional Models

First, the data was fit to a modified version of the Saleh-Valenzuela model which is similar to the model proposed in [8]. This model is modified from the original such that it is a baseband model (all real) rather than complex baseband. Therefore, there is no phase term, but multipath components have a random polarity (inversions are possible due to reflections). Very fine time spacing (sub-pulse width) is used such that distortion due to multipath interference is possible. Paths amplitudes are modeled by lognormal random variables rather than Rayleigh random variables as in the original model. Parameters for the bicones cases are shown in Table III.

The second model considered, a discrete version of the Δ-K model presented by [7], was modified here, and this implementation is a mix between the continuous and discrete versions of the model. In the discrete version given by [7], the time axis is divided into bins, and the probability of a path arriving in a given bin is based on whether a path arrived in the previous bin (probability being higher by a factor of K if a path was present). However, for this modeling, the time spacing between samples (or bins) is much finer than that assumed by [7] resulting in the possibility of overlapping pulses which is not possible in the original discrete model. Therefore, in this modified version, the probability that a path arrives at a given sample time is based on whether a path a path has arrived in the past d sample times rather than just the previous sample time, where d samples corresponds to Δ seconds. As with the modified Saleh-Valenzuela model, this model is a baseband model and the amplitudes are modeled by lognormal random variables. Parameters for the LOS bicone case are shown in Table IV.

Both the Saleh-Valenzuela and Δ-K models assume the paths tend to arrive in clusters. The third traditional model considered is a simplified version of both of these models that assumes that only one cluster is present in the impulse response (or equivalently, no clustering of paths). For this model the path arrival times follow a single Poisson process. Parameters for the bicones cases are shown in Table V.

B. Comparison of Traditional Models Performance

One of the primary goals in developing channel models is to allow simple, efficient, and accurate simulation of communications systems. Therefore, it is not necessarily sufficient that the models share certain key statistics with the true channels (known through the measurements). A communications system designer is concerned with the system performance (measured by such things as receiver energy capture, signal to noise ratio, and bit error rate (BER)) and thus the model must be able to faithfully recreate the performance.

Using the model parameters found that correspond to the LOS bicone cases, 100,000 impulse responses for each of the single Poisson arrival time model, the modified Saleh-Valenzuela model, and the modified Δ-K model are generated. The received baseband pulse from the measurements using the bicone antennas is used in these simulations.

The (unit energy) pulse is convolved with the impulse response to create a simulated received signal. Each impulse response is normalized to have unit energy (such that the sum of the square the taps is equal to 1). The energy capture of a coherent Rake receiver using maximal ratio combining is calculated using the matched filter output of the received signal. The peaks in the matched filter output are chosen such that the first finger is the strongest correlation, the second finger is the next strongest correlation, and so on. The finger delays are chosen such that they are separated by at least the duration of the template.

The energy capture for different numbers of Rake fingers is calculated for each individual simulated signal. The average energy capture as a function of the number of fingers for each model considered is then calculated. The BER of a UWB system using antipodal signaling and binary PPM were also calculated at different SNR values for each simulated received signal.

The average energy capture for a Rake receiver in channels from each of the three traditional models is shown in Figure 2.

The average BER for the baseband bicone pulse signal with antipodal signal is shown in Figure 1.

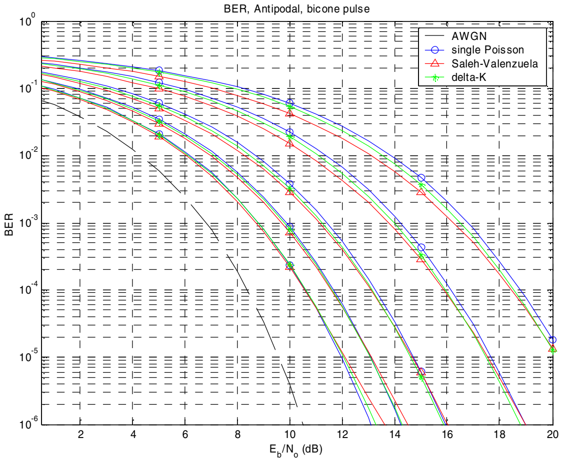

Figure 1. Comparison of average BER for antipodal signaling and a Rake receiver when using different channel models (1, 2, 5, 10, and 20 finger cases, from right to left)

The overall difference in the simulated system performance between these models is relatively small and is even further decreased for higher order Rake receivers. Therefore, from a communications system simulation perspective, the choice between these three channel models appears to make little difference.

C. *Comparison of Models to LOS Measurement Data*

The same procedure to determine energy capture and BER performance was performed on the 132 measurement sets corresponding to the LOS bicone scenarios. The mean value performance curves for the measurement sets are plotted with the mean value performance curves of the model generated impulse responses and are shown in Figure 2 and Figure 3. For the BER plot, the Saleh-Valenzuela and Δ-K models are not shown to make the plot more viewable.

There is a significant difference between the performances determined when using the LOS measurement channels versus the channels generated from the models, despite the similar statistics (mean excess delay, RMS delay spread, and number of multipath components). This difference is likely due to the fact that the measurement sets correspond to LOS conditions and the LOS component is much stronger than any later arriving paths. The models considered assume an exponential power decay, but the LOS component (and perhaps other strong reflections such as are seen in hallway scenarios) likely do not fit the exponential decay that the later paths are expected to follow. It must be remembered that the models considered have previously been primarily suggested for NLOS channels.

Figure 4 shows a bar graph of the energy captured by different fingers of the Rake receiver for the model and measured impulse responses. The finger numbers shown correspond to the ordering of greatest to least energy capture within each profile regardless of the temporal ordering. As expected, because of the LOS component and other strong reflections, the averages of the strongest three paths in the measurement data are larger than the corresponding paths for the models.

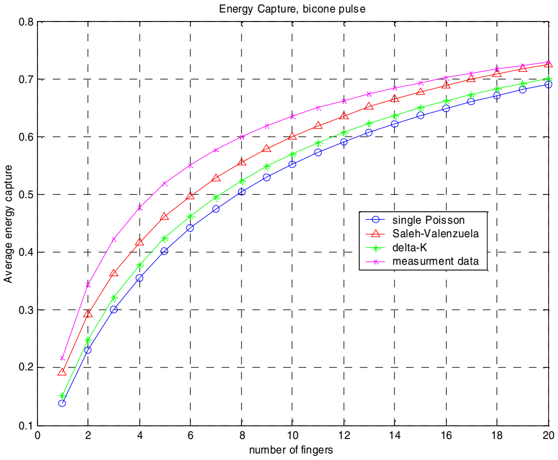

Figure 2. Average energy capture for a Rake receiver when using different channel models compared with the measured LOS channels

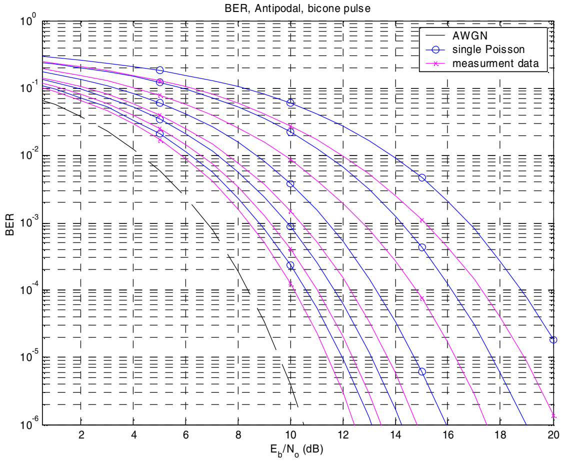

Figure 3. Average BER for antipodal signaling and a Rake receiver when using single Poisson model compared with the measured LOS channels (1, 2, 5, 10, and 20 finger cases, from right to left)

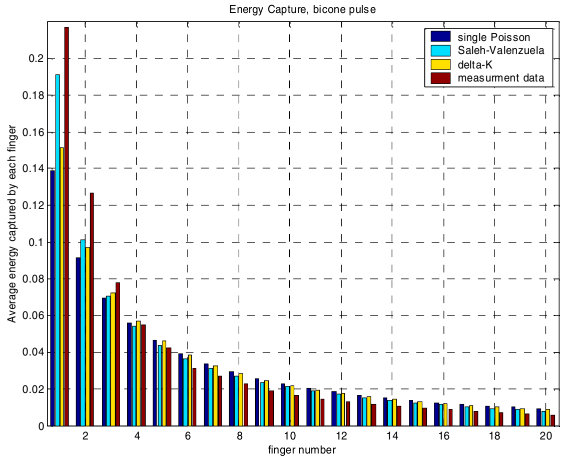

Figure 4. Average energy capture for each Rake finger when using different channel models compared with the measured LOS channels

D. New Model for LOS UWB Channels

Due to the discrepancy in the BER performance between the measurement channels and the model channels for LOS scenarios, a modified version of the single Poisson arrival time model with dominant early multipath components was developed to more accurately represent LOS channels. The model is based on the characteristics observed in the measurement data.

The first multipath components have significantly more energy than the later arriving components. The number of dominant components, *M*, is randomly chosen to be two, three, or four (each has equal likelihood). This agrees with the trends seen in the measurement data. The interarrival times of the dominant components are exponentially distributed with mean arrival rate, $_1$. The amplitude of each dominant component is given by a lognormal random variable with unit mean energy and fading parameter $_1$. The interarrival times of the weaker components also follow an exponential interarrival, but with a different mean arrival rate $_2$ and start arriving after all of the dominant components. The mean energies of the weaker components follow a traditional exponential decay. The first component from this group has mean energy *W* dB less than the mean of the dominant components and the means of the later components are taken relative to this first weak path. The weaker path amplitudes are also lognormal variables with a different fading parameter, $_2$. A more detailed description of this model is given in [9].

Appropriate parameters for this new model to match the average mean excess delay, average RMS delay spread, and average number of multipath components of the bicone LOS data were determined and are shown Table VI. These parameters were used to generate 1000 sample impulse responses, where only the paths within 15 dB of the strongest path were kept. The average energy captures for each finger of a Rake receiver are shown in Figure 5 compared with the impulse responses from the measurement data. Figure 6 shows the average energy capture of a Rake receiver and Figure 7 shows the corresponding BER curves for antipodal signaling.

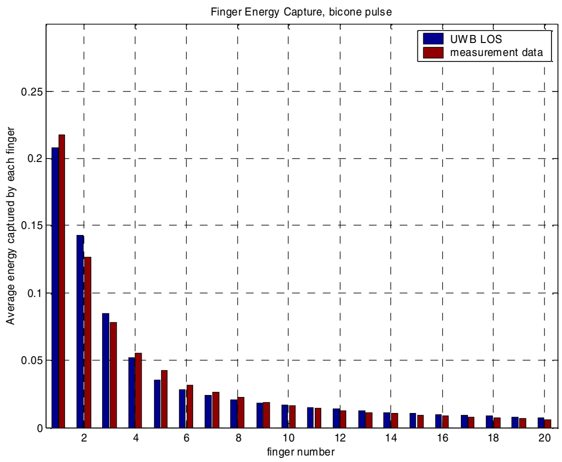

Figure 5. Average energy capture for each Rake finger for new LOS channel model compared with the measured LOS channels

As seen from these figures, the mean BER curves achieved using the new models do not agree exactly with the measurement data, but the agreement is far better than for any of the previously considered models (single Poisson, Saleh-Valenzuela, or Δ-K), especially at lower SNR levels. For LOS channels, it is not sufficient for a model only to match the delay statistics and number of multipath components. To accurately predict communications systems performance, the distribution of the energy among the paths is also very significant.

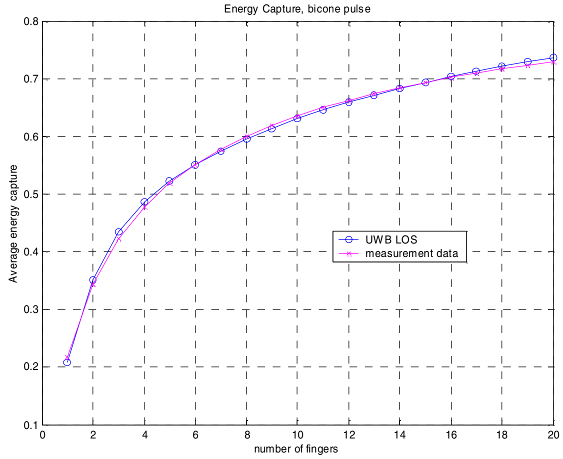

Figure 6. Average energy capture for a Rake receiver when using new LOS model compared with the measured LOS channels

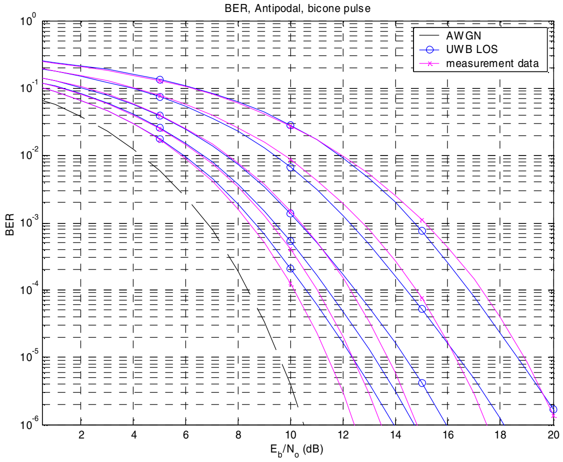

Figure 7. Average BER for antipodal signaling and a Rake receiver when using new LOS model compared with the measured LOS channels (1, 2, 5, 10, and 20 finger cases, from right to left)

E. Comparison of Models to NLOS Measurement Data

The number of available NLOS measurement profiles is limited and the profiles used for analysis above are a mixture of different types of NLOS data. Since the traditional models considered here are based on NLOS channels with no dominant paths, for analysis in this section, only the measurements corresponding to separation by a wall or corner are considered leaving 39 profiles. New parameters to match these NLOS subset statistics were found for the single Poisson model and Saleh-Valenzuela model.

The energy capture and BER performance using the measured channels were compared with the performance using 1000 impulse responses from each of the single Poisson and Saleh-Valenzuela models generated using these new NLOS parameters. Figure 8 and Figure 9 show the energy capture and BER performance of the models compared with the measurement data. These models are found to match the BER performance of the measured channels reasonably well.

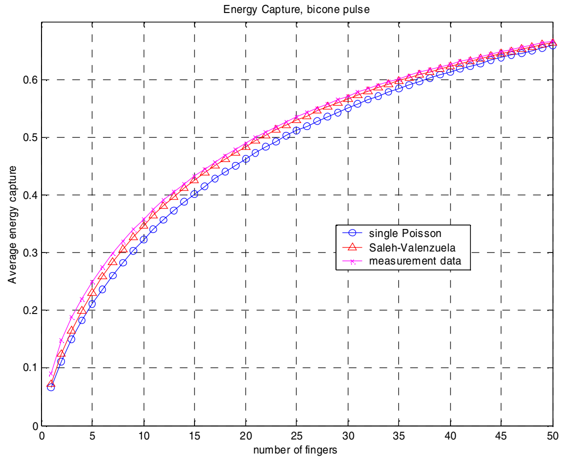

Figure 8. Average energy capture for a Rake receiver for single Poisson and Saleh-Valenzuela models compared with the measured NLOS channels

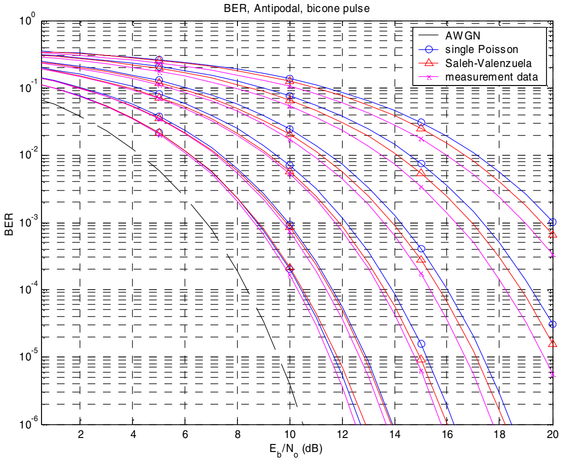

Figure 9. Average BER for antipodal signaling and a Rake receiver for single Poisson and Saleh-Valenzuela models compared with the measured NLOS channels (1, 2, 5, 10, 25, and 50 finger cases, from right to left)

V. CONCLUSIONS

For LOS and NLOS indoor scenarios, the multipath characteristics have been statistically analyzed for UWB pulses and two types of antennas. It was shown that there is little difference in the simulated performance of UWB systems when any of the traditional indoor channel models considered are used. These models are useful and appropriate to model NLOS channels, but not LOS channels. The traditional models can be made to fit the statistics of LOS channels, but they predict very pessimistic energy capture and BER performance. These models were originally developed for NLOS channels and therefore do not have the dominant early arriving paths that are present in LOS channels. A new model for LOS channels was presented and shown to more accurately represent LOS channels than the traditional models.

TABLE III. FIT TO MODIFIED SALEH-VALENZUELA MODEL

	Model parameters				
	1/Λ	**1/**	**Γ**		
LOS	5.0e-9	0.7e-9	7.1e-9	2.0e-9	5
NLOS	10.0e-9	1.4e-9	21.0e-9	8.0e-9	2

TABLE IV. FIT TO Δ-K MODEL

	Model parameters				
	1/	**Δ**	**K**		
LOS	1.2e-9	0.5e-9	2	6.0e-9	2

TABLE V. FIT TO SINGLE POISSON MODEL

	Model parameters		
	1/		
LOS	0.84e-9	6.3e-9	2
NLOS	0.7e-9	20.0e-9	2

TABLE VI. FIT TO NEW LOS UWB MODEL

	Model parameters					
	1/$_1$	$_1$	**1/**$_2$	***W***		$_2$
LOS	2e-9	0.7	0.7e-9	12	23e-9	0.5

ACKNOWLEDGMENT

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REFERENCES

[1] A. H. Muqaibel, “Characterization of Ultra Wideband Communication Channels,” Ph.D. Dissertation, Dept. of Electrical and Computer Engineering, Virginia Tech, 2003.

[2] S. M. Yano, “Investigating the Ultra-wideband Indoor Wireless Channel,” IEEE VTS 55th Vehicular Technology Conference, 2002, vol. 3, pp. 1200-1204.

[3] T. S. Rappaport, Wireless Communications: Principles and Practice, Upper Saddle River, NJ: Prentice Hall, 1996.

[4] S. S. Ghassemzadeh, R. Jana, C. W. Rice, W. Turin, and V. Tarokh, “A Statistical Path Loss Model for In-Home UWB Channels,” IEEE Conference on Ultra Wideband Systems and Technology. 2002.

[5] A. A. Saleh and R. A. Valenzuela, “A Statistical Model for Indoor Multipath Propagation,” IEEE Journal on Selected Areas in Communications, vol. SAC-5, no. 2, pp. 128-137, Feb. 1987.

[6] G. L. Turin, F. D. Clapp, T. L. Johnston, S. B. Fine, and D. Lavry, “A Statistical Model of Urban Multipath Propagation,” IEEE Transactions on Vehicular Technology, vol. VT-21, pp. 1-9, Feb. 1972.

[7] H. Suzuki, “A Statistical Model for Urban Radio Propagation,” IEEE Transactions on Communications, vol. COM-25, no. 7, pp. 673-680, July 1977.

[8] J. Foerster, “Channel Modeling Sub-committee Report Final (doc.: IEEE 802-15-02/490r1-SG3a),” submitted to IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), Feb. 2002. Available: http://grouper.ieee.org/groups/802/15/pub/2002/Nov02/

[9] D. R. McKinstry, “Ultra-wideband Small Scale Channel Modeling and its Application to Receiver Design,” Master’s Thesis, Dept. of Electrical and Computer Engineering, Virginia Tech, 2003.