AUTOREGRESSIVE MODELING OF AN INDOOR UWB CHANNEL

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ABSTRACT

Based on frequency domain measurements in the 4.375-5.625 GHz band, a channel model for the frequency response of the indoor radio channel is introduced. In particular, a second-order Autoregressive (AR) model is proposed for frequency response generation of the ultra wide band indoor channel. A complete characterization of the model parameters is described along with probability distributions and dependencies between parameters.

1. INTRODUCTION

In this paper we present an autoregressive (AR) frequency domain, statistical model for Ultra Wideband (UWB) indoor radio propagation. UWB radio has been receiving a great deal of attention.

UWB systems have instantaneous bandwidths of at least 25% of the center frequency of the device. These systems have very wide information bandwidths, are capable of accurately locating nearby objects, and can use processing technology with UWB pulses to "see through objects" and communicate using multiple propagation paths. However, the bandwidths of UWB devices are so wide that, although their output powers, in many cases, are low enough to be authorized under the unlicensed device regulations of the NTIA and the FCC, some of the systems emit signals in bands in which such transmissions are not permitted because of potential harmful effects on critical radio communication services [1].

Using AR modeling techniques, the parameters of the channel model are determined from the measured frequency responses. A frequency domain channel sounding experiment was performed over 23 residential homes. A comprehensive 300,000 frequency response profiles were used for modeling. Details on the experimental procedures and data that we used for modeling can be found in [7]. A two-pole model, identified with two significant clusters is sufficient to regenerate the statistical behavior of all measurements.

The organization of the paper is as follows: In Section 2 an AR channel model is proposed in detail for the frequency domain. Section 3 provides characterization of model parameters and Section 4 concludes the paper.

2. FREQUENCY DOMAIN AR MODEL

The goal of frequency domain channel model is to develop a statistical representation of the channel with a minimum number of parameters to regenerate the measured channel behavior accurately in computer simulations. Note that the higher the complexity of the model, the closer the statistical resemblance to that of measured data. A lot of effort has been devoted to modeling wireless channels for in-home environments for 1 GHz band for time domain measurements [3]-[6].

We found that high order Autoregressive Moving-Average (ARMA) models allow us to approximate the measured channel frequency response data with a high degree of accuracy at each location. Similar to modeling approach in [3] we discovered that a second-order AR model of the channel frequency response captures main features of the measured data. Our model is based on UWB frequency response measurements in 23 homes of various size and building properties. The advantage of our frequency domain model over time domain models is that it uses fewer parameters and a complete characterization of their probability distributions are presented.

Our model is generative and allows simple simulation of an UWB channel. However, the parameters of this model change from location to location and, therefore, we need to characterize them statistically. In our measurements, the channel frequency response $H(f,t;d)$ does not exhibit significant variability in time and can be assumed to be stationary. Thus, we use the following model:

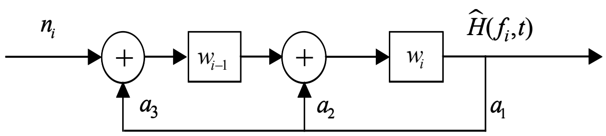

Fig. 1. Frequency Response Model.

$$\hat{H}(f_i,t;d) = a_2\hat{H}(f_{i-1},t;d) + a_3\hat{H}(f_{i-2},t;d) + n_i \quad (1)$$

where n_i is a sequence of independent zero mean and identically distributed random variables. We found that n_i can be modeled by the sequence of independent Gaussian variables with zero mean and standard deviation $\sigma(d)$ which is usually called discrete additive white Gaussian noise (AWGN).

The AR model can be implemented using IIR filter as shown in Fig. 1. Thus, the frequency response model has four complex parameters (a_2, a_3, $w_0(d)$, $w_1(d)$) and one real parameter noise standard deviation $\sigma(d)$. Thus, the model is characterized by 9 real parameters. For a model at a particular location with the T-R separation of 2 ft (0.61 m) the estimated parameters are:

$$\sigma = 1.36 \times 10^{-4}$$
$$a_2 = 1.5025 - j0.8017$$
$$a_3 = -0.4427 + j0.7538$$
$$w_0 = 0.00368 - j0.00003$$
$$w_1 = -0.00218 + j0.00286$$

The agreement between the probability distribution of the model residuals n_i obtained using equation (1) from the experimental data and normal distribution is shown in Fig. 2 for a particular location. Also the residuals satisfy the test of independence. Using this model, we simulated

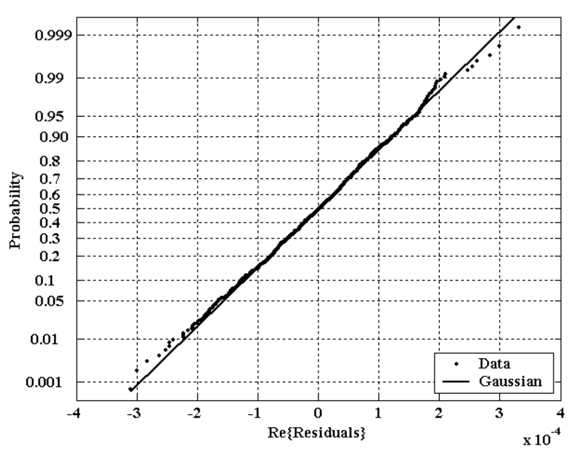

Fig. 2. Distribution of the model residuals.

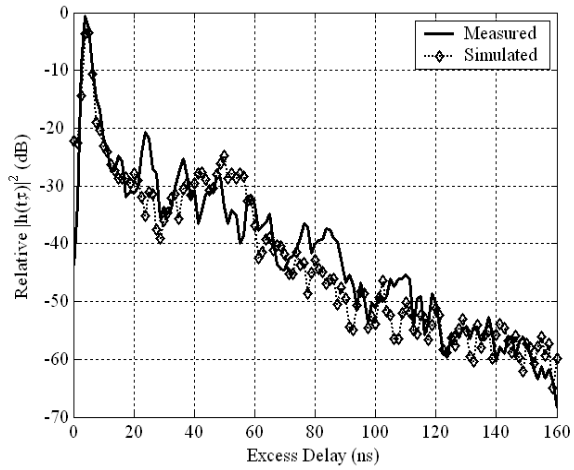

Fig. 3. Power delay-profile: simulated versus measured.

the channel frequency response.

To verify the model accuracy, we compared the modeled PDP with that of the measured data. The results are depicted in Fig. 3. Clearly, the model reproduces the frequency selectivity and the multipath propagation characteristics observed in the actual measurements.

3. CHARACTERIZATION OF THE MODEL PARAMETERS

To complete the model description, we need to describe the variation of its parameters between different locations. As we stated earlier, the model is characterized by 9 real parameters that can be characterized by a 9-dimensional probability distribution. To simplify the probability distribution, we studied the parameters dependency structure. We discovered that the mean frequency response, model coefficients, initial conditions and the noise standard deviation are independent. However, the a_2 and a_3 as well as the w_1 and w_2 are dependent. This is readily seen from Fig. 4.

3.1. Characterization of the model coefficients

The coefficient and initial condition magnitudes and phases are independent. These findings suggest that we need to describe two-dimensional probability distributions of the coefficient magnitudes and one-dimensional probability distributions for the rest of the parameters because of their strong correlation. By the measured data affine transformations, we discovered that the coefficient magnitudes for LOS could be expressed as:

$$|a_2|_{\text{LOS}} = -0.9235W + 0.3836N + 1.7869$$
$$|a_3|_{\text{LOS}} = -0.3836W + 0.9235N + 0.9837$$

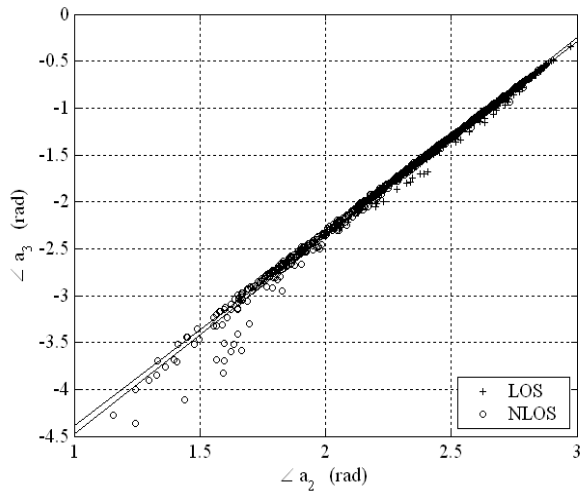

Fig. 5. Scatter plot of phases of the model coefficients.

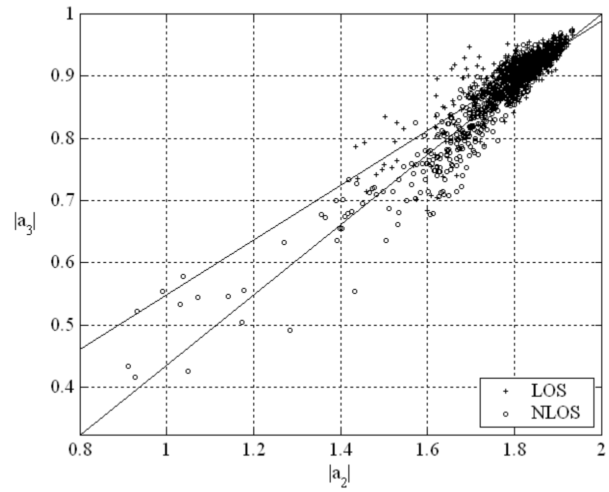

Fig. 4. Scatter plot of the model coefficient magnitudes.

Similarly, for NLS, we have:

$$|a_2|_{\text{NLS}} = -0.863W + 0.501N + 1.5369$$
$$|a_3|_{\text{NLS}} = -0.506W + 0.863N + 0.7367$$

where W is the Weibull probability distribution and is defined by

$$f(W) = \frac{\beta}{\eta}\left(\frac{W}{\eta}\right)^{\beta-1} e^{-\left(\frac{W}{\eta}\right)^{\beta}}$$
$$\eta_{\text{LOS}} = 15.191 \qquad \beta_{\text{LOS}} = 1.312$$
$$\eta_{\text{NLS}} = 8.104 \qquad \beta_{\text{NLS}} = 1.442$$

N is a zero-mean Normal random variable and standard deviation σ (σ_{LOS}=0.0202 and σ_{NLS}= 0.0234). The linear regression equations for the coefficient magnitudes have the following form:

$$|a_3|_{\text{LOS}} = 0.1993 + 0.3908|a_2|_{\text{LOS}}$$
$$|a_3|_{\text{NLS}} = -0.1345 + 0.5678|a_2|_{\text{NLS}}$$

The model coefficient phases have Weibull distribution. Because of the strong correlation between the phases (see Fig.5. Note that if we generate one of the phases, the other can be found from the following regression equations:

$$\angle a_{3\text{LOS}} = -6.4422 + 2.0505\angle a_{2\text{LOS}}$$
$$\angle a_{3\text{NLS}} = -6.5595 + 2.1022\angle a_{2\text{NLS}}$$

$\angle a_{2\text{LOS}}$ is Weibull distributed in the range of (1.95,2.97) radians with parameters η = 0.3773 and β = 16.5023; $\angle a_{2\text{NLS}}$ is also Weibull distributed in the range of (1.24,2.85) radians with parameters η = 0.001 and β = 7.8896.

3.2. Poles of the AR model

The AR model can be represented by the poles of its transfer function:

$$1 - \sum_{i=2}^{3} a_i z^{-i} = \prod_{i=1}^{2}\left(1 - p_i z^{-1}\right)$$

The scatter plot of the poles for LOS is shown in Fig. 6. (The scatter plot for NLS is similar.) It is readily seen, one of the poles (the largest) is very close to the unit circle. A pole close to the unit circle represents significant power at the delay related to the angle of the pole. The arrivals of the significant paths in all measurements are from 3 to 74 ns. The delay is calculated as:

$$\tau = -\arg(p_i)/2\pi f_s$$

where f_s is the sampling frequency. Experimenting with higher order models (e.g., 5th order models), it was observed that two significant poles exist in the range and is adequate to represent the in-home UWB channel. The two significant poles can be interpreted as two significant clusters of multipath arrivals. The interpretation of a pole as defining a cluster of paths and the distance from the unit circle as defining the power in the cluster provides a useful physical interpretation of the AR model [[3]]. In contrast to other wideband systems, the UWB channel represents itself as two pole clusters with a distinctive angular spread.

3.3. Characterization of the Initial Conditions

The initial conditions are strongly correlated. The magnitude and phase of regression lines in LOS and NLS are:

$$|w_1|_{\text{LOS}} = 0.89|w_0|_{\text{LOS}}; \quad \phi_{1\text{LOS}} = 0.9888\phi_{0\text{LOS}} + 2.26 + \nu_{\text{LOS}}$$
$$|w_1|_{\text{NLS}} = 0.93|w_0|_{\text{NLS}}; \quad \phi_{1\text{NLS}} = 0.9827\phi_{0\text{NLS}} + 2.01 + \nu_{\text{NLS}} \quad (2)$$

The magnitudes have lognormal distribution with means and standard deviation of their logarithm value equal to:

$$E\{\log_{10}|w_0(d)|\}_{\text{LOS}} = -16.3\cdot\log_{10}(d) - 47.9$$
$$STD\{\log_{10}|w_0(d)|\}_{\text{LOS}} = 5.6$$
$$E\{\log_{10}|w_0(d)|\}_{\text{NLS}} = -36.5\cdot\log_{10}(d) - 45.9$$
$$STD\{\log_{10}|w_0(d)|\}_{\text{NLS}} = 7.8$$

The phase $\phi_{0\text{LOS}}$ is uniformly distributed within the interval $(-\pi,\pi)$. $\phi_{1\text{LOS}}$ can be generated by using equation (2). The noise components in (2) have normal distribution with mean 0.0142 and standard deviation of 0.294 for LOS. Similarly, for NLS, the mean and standard deviation are 0.0594 and 0.4277, respectively. See Fig. 7.

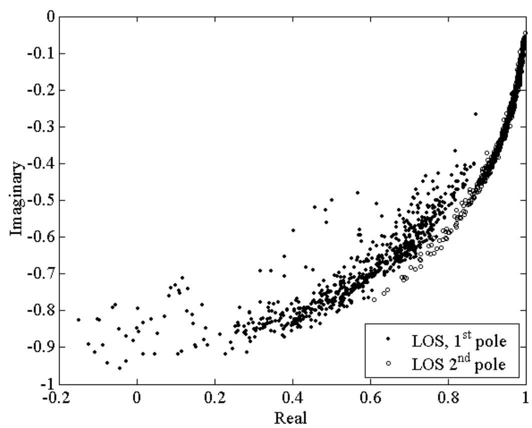

Fig. 6. Scatter plot of the model poles.

3.4. Characterization of the noise of AR model

The standard deviations, $\sigma(d)$ of the model residual noise, n_i, have lognormal distribution with mean and standard deviations (STD) given by

$$E\{\log_{10}\sigma(d)\}_{\text{LOS}} = -10.8\cdot\log_{10}(d) - 77.2$$
$$STD\{\log_{10}\sigma(d)\}_{\text{LOS}} = 3.7$$
$$E\{\log_{10}\sigma(d)\}_{\text{NLS}} = -20.1\cdot\log_{10}(d) - 78.5$$
$$STD\{\log_{10}\sigma(d)\}_{\text{NLS}} = 4.5$$

4. CONCLUSION

A frequency domain channel sounding experiment was performed over 23 residential homes. A comprehensive 300,000 frequency response profiles were used for modeling. Based on these a new statistical AR model for computer simulation of the UWB indoor radio channel was described. A two-pole model, identified with two significant clusters was shown to be sufficient to regenerate the statistical behavior of all measurements. A complete characterization of the model parameters was described, along with probability distributions and dependencies between parameters.

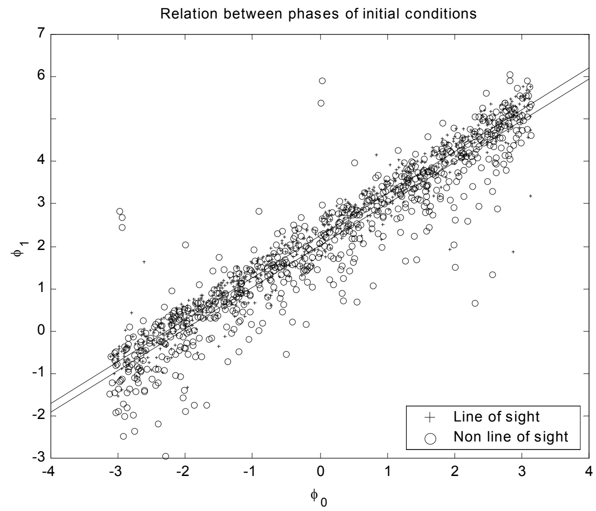

Fig. 7. Scatter plot of phases of initial conditions.

5. REFERENCES

[1] FCC document 00-163, "Revision of part 15 commission rules ET Docket No. 98-153 regarding UWB transmission systems", adopted 5-10-2000.

[2] K. Pahlavan, A.H. Levesque, *Wireless Information Networks*, John Wiley and Sons, New York, 1995

[3] S. Howard, K. Pahlavan, "Autoregressive Modeling of Wide-Band Indoor Radio Propagation", *IEEE Transaction on Commun.*, 40:1540-1552, September 1992.

[4] H. Hashemi, "The indoor Propagation Channel", *Proceedings of the IEEE*, 81:943-968, July, 1993

[5] M.Z. Win, R.A. Scholtz, M.A. Barnes, "Ultra-Wide Bandwidth Signal Propagation For Indoor Wireless Communications", *Proc. of IEEE Int. Conf. Commun.*, 1:56-60, June 1997.

[6] D. Cassioli. A. Molisch, M.Z. Win, "A Statistical Model for UWB Indoor Channel", *Proceedings of the IEEE VTC Spring 2001*, 2001 Rhodes.

[7] S. S. Ghassemzadeh, R. Jana, C. W. Rice, W. Turin, "Statistical path loss model for an in-home UWB channel", submitted to UWBST 2002.