Frequency Domain Analysis of the IEEE 802.15.4a Standard Channel Models

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I. Introduction

• Fair comparison of UWB signaling schemes requires a set of statistical channel model that fairly represent channel conditions in typical environments.

• Standard channel models for residential and office environment were developed by IEEE 802.15.3a and extended to industrial and outdoor by 4a task group.

<table>
<thead>
<tr>
<th></th>
<th>Residential</th>
<th>Office</th>
<th>Outdoor</th>
<th>Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>CM1</td>
<td>CM3</td>
<td>CM5</td>
<td>CM7</td>
</tr>
<tr>
<td>NLOS</td>
<td>CM2</td>
<td>CM4</td>
<td>CM6</td>
<td>CM8</td>
</tr>
</tbody>
</table>
• The Saleh-Valenzuela time domain model adopted by the 3a and 4a task group captures the tendency of MPC arrivals in clusters

• Estimation of the statistical distribution of the SV model parameters requires considerable time and effort
II. Approach

- We use an autoregressive frequency domain (AR-FD) approach to model the UWB channel frequency responses.
- The CFR model offers three significant advantages over CIR models:
  - CFR models are simpler and characterized in a more compact form with fewer parameters.
  - Most UWB measurements are done in frequency domain; modeling CFR parameters directly avoids inverse Fourier transform and a host of other processing steps.
  - AR-FD allows us to visualize entire CFRs at a glance.
Past Work and Its Limitations

• Several frequency domain modeling approaches have been proposed over the years
  – Alvarez 03
  – Kunisch 02

• Past efforts to apply AR-FD techniques have focused on particular environments
  – Office, Laboratory [Howard and Pahlavan 92]
  – Residential [Ghassemzadeh 04]
Objectives

- Determine the order of autoregressive frequency domain AR-FD model most appropriate for each CM 1-8 case using AIC
- Use the distribution of poles of the AR-FD model to interpret both the physical significance and diversity of each CM models
- Determine the probability distribution that best describes the parameters of AR-FD model
- Assess the suitability of the AR-FD approach in each of the eight cases
II. Approach

• The AR process in this context models the UWB channel frequency response as the output of a linear time invariant system driven by white noise.

\[ \hat{H}(f_k, t; x) + \sum_{i=1}^{p} a_i \hat{H}(f_{k-i}; x) = U(f_k, t; x) \]

• Our use of the AR-FD model is based upon the assumption that the UWB channel is stationary.
AR-FD Model

• Taking z-transform on both sides of the previous equation, we can view \( \hat{H}(f_k, t; x) \) as the output of a linear filter.

\[
G(z) = \frac{1}{1 + \sum_{i=1}^{k} a_i z^{-i}}
\]

or

\[
G(z) = \frac{1}{\prod_{i=1}^{k} (1 - p_i z^{-1})}
\]
System Overview

1. Channel impulse response (CIR)
2. Channel frequency response
3. Pole distribution of AR model
   \[ G(z) = \frac{1}{a_0 + a_1 z^{-1} + a_2 z^{-2}} \]
4. Regenerated channel response
5. Estimated channel impulse response
Akaike Information Criterion

- Select the appropriate order for AR-FD model, which minimizes the theoretic function

\[ AIC = \log(V) + \frac{2k}{N} \]

- \( V \) – variance of the estimated parameters
- \( k \) – number of estimated parameters
- \( N \) – the number of data used for estimation
- \( 2k/N \) – is the penalty for use extra parameter
AIC in diverse environments

9 Mar 2007
Location of the AR-FD Poles

- 2nd order AR method models two main cluster arrival in time domain.
- Poles close to the unit circle represent spectra with sharp peaks and significant energy (as in 1).
- Poles close to the origin represent spectra with significant attenuation (as in 2).
Dispersion of the AR-FD Poles

- Dispersion of the AR-FD poles reflects arrival time of cluster.
  \[ \tau_{\text{propagation}} = -\frac{\text{ang}(p)}{\omega_s} \]

- Tightly clustered poles show channel energy is concentrated at certain delays and the RMS delay spread has low variance (as in 3).

- Dispersed poles imply cluster arrivals spread out in time (larger RMS delay spread variance); poles at the II quadrant shows channel with larger maximum excess delay (as in 4).
Residential Channel Model

CM1 – Line of Sight

CM2 – Non Line of Sight
Office Channel Model

CM3 – Line of Sight

CM4 – Non Line of Sight
Outdoor Channel Models

CM5 – Line of Sight

CM6 – Non Line of Sight
Industrial Channel Models

CM7 – Line of Sight

CM8 – Non Line of Sight
AR-FD Model Parameters

- Modeling each environment using the AR-FD formulation involves determining the probability distributions.

- In each environment and for each parameter, we tested a wide range of standard distributions in order to obtain the best fit.
Statistical distribution of AR-FD parameters

- Extreme value distribution

\[ f(a_1 | \alpha, \beta) = \beta^{-1} \exp \left\{ \alpha \cdot \frac{1}{\beta} - \exp \left( \frac{\alpha - 1}{\beta} \right) \right\} \]
• Beta distribution

\[ f(a_2 | \alpha, \beta) = \frac{(1 - a_2)^{\beta-1} a_2^{\alpha-1}}{B(\alpha, \beta)} \]

\[ B(\alpha, \beta) = \frac{(\alpha - 1)!(\beta - 1)!}{(\alpha + \beta - 1)!} \]
## AR-FD Model Parameters for CFR1 to CFR8

<table>
<thead>
<tr>
<th>Environment</th>
<th>Parameter</th>
<th>Distribution</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Environment</th>
<th>Parameter</th>
<th>Distribution</th>
<th>$\alpha$</th>
<th>$\beta$</th>
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Summary for parameter distribution

• We found the first order coefficient $a_1$ follows an extreme value distribution in most of the environments.

• The Weibull and Normal distribution provide a better fit in the office, outdoor and industrial NLOS environment.

• The second order coefficient $a_2$ can be modeled as an extreme value or beta distributed variable.
IV. Validation of Model

• We validate the AR-FD model parameters in two ways.
  – Compare the envelope distribution of the AR-FD generated CFR_{sim} with those generated by Fourier transforming the output of 4a SV model CIR_{orig}
  – Transform the AR-FD generated CFR_{sim} to CIR_{sim} and compare the second order statistics RMS delay spread with those that were originally produced
Channel Envelope Distribution

- CFR_{sim} vs CFR_{org}
Outdoor RMS Delay Spread

![Graph showing outdoor RMS delay spread comparison between LOS and NLOS scenarios.](image-url)
Industrial RMS Delay Spread

![Industrial RMS Delay Spread Graph](image)

- **industry LOS**
- **simulated industry LOS**
- **industry NLOS**
- **simulated industry NLOS**

Probability > Abscissa

- Probability distribution for different LOS and NLOS conditions in an industrial environment.
V. Conclusions

- We applied the autoregressive frequency domain modeling technique to the eight CM channel models developed by the IEEE 802.15.4a task group.
  - We conclude from AIC analysis that *office LOS* and the *outdoor* channels are the most accurately represented by the AR-FD method.
  - The office and industrial NLOS channels are the least accurately represented; this is likely due to the lack of a dominant cluster in their impulse responses.
  - The distribution of the AR poles for CM8 industrial NLOS is very much narrower than the other seven models. The channel energy is very concentrated at certain delays for that particular environment.
Work in Progress

- AR-FD for Modeling UWB Channels inside Boeing 737 Aircraft Cabin

[Diagram showing Second Order AR Pole Plot with Rx @ Armrests]

1. all seats occupied
2. 50% of the seats occupied
3. empty aircraft

Locations of the Transmitter Antenna

Location of Vector Network Analyzer

A typical receiving antenna location.
References


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