ABSTRACT: We have suggested a novel time-dispersion multipath channel model for wideband wireless systems. This extended model incorporates the microcell site-specific information by including the frequency dependence of individual paths. A new super-resolution algorithm has been used to estimate the path delay and frequency dependence of each individual path.

Multipaths Improve System Performance

Recently, the spread spectrum-based code division multiple access (CDMA) has become very important to cellular and personal communications, due to its characteristics such as potential capacity, anti-multipath capabilities, soft capacity, and soft hand-off [1-5]. The performance of wideband wireless systems, like the CDMA systems, in cellular, mobile radio, indoor wireless communications, and personal communication services is mainly limited by multipath fading. The major complexity in the multipath environment results from tracking each multipath at the RAKE receiver [1]. Therefore, effectively modeling the multiple paths is extremely important to the performance of the overall CDMA systems [4-5]. In these systems, the multipath is not just a source of performance degradation, but instead it is used to provide the diversity benefit [1-3]. The reason is that different multipath arrivals are regarded as independent receptions of the signal and can be combined to provide a diversity gain by the RAKE receiver. In the actual CDMA system trial, we found that the RAKE receiver often was locked to three “fingers” (multipaths). The second finger usually was 10 dB weaker than the first finger, and the third one 20 dB~30 dB weaker than the first finger. Then these three fingers were combined to form an aggregate finger with stronger $E_b/N_0$.

There exists a limitation in the widely used Turin model [3-4] for wideband CDMA channel. The frequency dependency of an individual ray path is not included in Turin model. We will develop a novel model incorporating the path frequency dependence.

Physics of Path Frequency Dependence

There are three propagation mechanisms: line of sight (LOS), reflection, and diffraction. Among those, only diffraction causes the strength of diffraction field to be frequency-dependent (with a term $\omega^\alpha$ in the diffraction field expression). The frequency dependence factor $\alpha$ is determined by the geometric configurations of the objects as listed in Table 1 [4]. For instance, the field strength of a ray undertaking a diffraction by an edge like a wall edge has a frequency dependence $1/\omega^{0.5}$ or $\alpha=-0.5$. However, for a corner like a corner of a desk, the frequency dependence is $1/\omega$ or $\alpha=-1$. The frequency dependency can be used to trace, detect, and characterize a ray path. Further, it can be used for channel modeling. For example, as illustrated in Fig. 2, a ray coming from a line-of-sight (LOS) or reflection path (Path A) has no frequency dependence, while a ray from the diffraction of the wall edge (Path B) has the frequency dependence of $1/\omega^{0.5}$. A multiple diffraction ray (Path C), which is first diffracted by the wall edges ($\alpha=-0.5$) and then by another wall edge ($\alpha=-0.5$), has $1/\omega$. Therefore, after tracing the frequency dependence of individual ray paths, say Path A, B, C in Fig. 2, we can gain more insights into the propagation features of a specific channel. These insights should find important applications in channel modeling, especially site-specific channel modeling. For instance, together with the layout of a physical environment and the time delay of ray arrivals, we can then trace and detect the path taken by a specific ray, say Path B, and this then can tell us how a ray propagates in such an environment. This finding can be applied in various aspects, such as measurement campaigns, microcell or picocell designs and plans, etc.
A Novel Multipath Channel Model

Mathematically, the impulse response of the modified multipath fading channel in the frequency domain is given by [4]

\[ H(\omega) = \sum_{k=1}^{N} \beta_k e^{j\Phi_k} \alpha_k e^{-j\omega \tau_k} \]  
(1)

where N versions of the transmitted signal are assumed to be received. Frequency dependencies \( \omega^\alpha \) of common structures have been listed in Table 1. For instance, for a single wall edge diffraction, we have \( \alpha = -0.5 \) or \( 1/\omega^{0.5} \). For a double wall edge diffraction, we have \( \alpha = -1 \) or \( 1/\omega \). To make the concept more clear, we compare the block diagram of Turin’s model shown in Fig. 2 with our modified model in Fig. 3. We should mention three points. First, the signal transmitted from the base station reaches the portable radio receivers via one or more main waves. Second, these main waves may consist of a line-of-sight ray and several rays reflected and/or diffracted by main structures like outer walls, floor, ceiling, furniture, etc. Third, the main paths may arrive with too close delays to resolve, but have different frequency dependence. In this situation, we can detect the “effective frequency dependence” of the merged observable.

Fig. 1 A Wireless Microcell Channel Model Incorporating the Frequency Dependency of Individual Paths. The field strength of path A has zero frequency dependency, since its ray undergoes only reflection. Path B has a frequency dependency \( \omega^\alpha \) (\( \alpha = -0.5 \)), due to the first-order diffraction causing the field strength to be frequency-dependent. Path C has a frequency dependency \( \omega^\alpha \) (\( \alpha = -0.5 \rightarrow 0.5 \rightarrow -1 \)), due to the second-order diffraction.

<table>
<thead>
<tr>
<th>Physical Mechanism</th>
<th>Frequency Dependence Factor ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line of Sight</td>
<td>0</td>
</tr>
<tr>
<td>Reflection</td>
<td>0</td>
</tr>
<tr>
<td>Diffraction from smooth or flat surface</td>
<td>0</td>
</tr>
<tr>
<td>Diffraction by Edge</td>
<td>-0.5</td>
</tr>
<tr>
<td>Diffraction by Corner or tip</td>
<td>-1</td>
</tr>
<tr>
<td>Diffraction by Axial Cylinder Face</td>
<td>+0.5</td>
</tr>
<tr>
<td>Diffraction by Broadside of a Cylinder</td>
<td>+1</td>
</tr>
</tbody>
</table>
Channel Estimation Using a New Algorithm

We reduce the frequency dependency factors and ray arrival delays in terms of the complex poles of the linear system. In general, it is easy to estimate the rays arrivals. However, it is very difficult to estimate the frequency dependence. Here we show a novel approach, based on the Taylor Series, to obtain the frequency dependence and ray arrival times simultaneously. In fact this approach is very accurate.

Input

\[ \tau_1 \quad \tau_2 - \tau_1 \quad \ldots \quad \tau_L - \tau_{L-1} \]

\[ \beta_1 e^{i\phi} \quad \beta_2 e^{i\phi} \quad \beta_L e^{i\phi} \]

\[ \Sigma \]

Output

Fig. 2 Block diagram for the discrete delay channel model.

Input

\[ \tau_1 \quad \tau_2 - \tau_1 \quad \ldots \quad \tau_L - \tau_{L-1} \]

\[ \beta_1 e^{i\phi} \quad \beta_2 e^{i\phi} \quad \beta_L e^{i\phi} \]

\[ \omega^\alpha_1 \quad \omega^\alpha_2 \quad \omega^\alpha_L \]

\[ \Sigma \]

Output

Fig. 3 Block diagram for the modified model incorporating the frequency dependency of individual rays.
Now we sample our signals in Eq. (1) using 
\[ \omega = \omega_0 + n \cdot \omega_s; \quad n=1,2, \ldots, N, \] where \( \omega_0 \) is the lowest angular frequency, \( \omega_s \) is the sampling interval in the frequency domain, \( m \) is the sample index, and \( N \) is the total number of samples in the frequency domain. Using a Taylor series, we get

\[ H[n] = H(\omega_0 + n \cdot \omega_s) = \sum_{k=1}^{N} a_k Z_k^n \]  

\[ Z_k = \exp \left( \frac{\omega_0}{\omega} \right) \cdot \omega_s \]  

\[ a_k = \beta_k e^{j \cdot \omega_0 \cdot n_k} \]  

From (2), the impulse response of the channel is expressed as a set of complex exponentials that can be estimated by a number of algorithms in the Spectral Estimation community [5]. For the modified channel model, it is more convenient to measure or simulate the channel response in the frequency domain. In the frequency-domain measurements of radio channel, the magnitude and phase of the measured frequency response are measured directly.

The next step is to use a high resolution algorithm to estimate the complex amplitudes and exponentials in (2). This step is the most critical in the whole process. For practical applications, there are three important criteria: (1) no spurious poles; (2) accurate; (3) robust. The first criterion says the algorithm gives only true poles. This is very important for practical applications. To our best knowledge, it seems that only the Eigen-Matrix Pencil Method has this feature. In addition, this method is also accurate and robust in case of white Gaussian noise. For detail, see also [4].

We outline four basic steps to get a feeling for it: (1) Form a Hankel matrix using the noisy data sequence; (2) Find the complex eigenvalues and associated eigenvectors of the formed Hankel matrix; (3) Form an Eigen-matrix pencil using principal eigenvectors and find the complex generalized eigenvalues; (4) Obtain the complex system poles using complex generalized eigenvalues.

Results

In addition to providing the super-resolution of the power profile of a channel, our approach can also supply the path delay and frequency dependence of an individual path, which are given in Table 2. The frequency dependence has been accurately estimated. From the estimated values in Table 2, the frequency dependence provides information about the "path history" of these rays. For example, from \( \alpha = -0.5 \), we know the ray with the arrival time delay of 80(ns) in the first row experiencing an edge diffraction by a wall, the ray with \( \alpha = -1 \) in the seventh row encountering a corner diffraction or two edge diffractions, and the ray with \( \alpha = -1.5 \) in the fourth row undergoing one corner and one edge diffraction or three edge diffractions. Other rays are more likely just experiencing some reflections, since there is no frequency dependence. The combination of the time delay, amplitude and the frequency dependence as well as the geometric layout of the physical channel can provide us more physical insights into the indoor or outdoor propagation channel. Based on such a combination, a tool can be devised to detect the ray propagation path. This might be relevant to the receiver design, power coverage, microcell design, system prediction and installment, etc.

In this paper we have suggested a novel discrete delay channel model for wideband systems, like a CDMA digital cellular system. This extended model incorporates the microcell site-specific information by including the frequency dependence of individual paths into the conventional model. The frequency dependence of the individual rays makes use of the similarity of environments. Then an approach that reduces the path delay and frequency dependence to the complex poles of the measured or simulated signal consisting of only complex exponentials has been adopted. Further, a new super-resolution algorithm called the SVD Eigen-Matrix Pencil Method has been used to estimate the complex poles, and then the path delay and frequency dependence. To characterize the performance of our approach to estimate the channel parameters from the measured or simulated data, a number of numerical results through the simulation of the two-path channel and the 8-path channel are given. To simulate a channel, we choose typical values of the bandwidth and the frequency band for measurement use. The frequency dependency can be used to trace, detect, and characterize a ray path; After tracing the frequency dependence of
TABLE 2 Estimation of Time Delays and Frequency Dependencies of a Simulated Wireless Microcell Propagation Channel Using a Novel High-Resolution Algorithm
(Channel Parameters: Lowest Frequency $f_l=900$ MHz, Frequency Sample Spacing $f_s=1.875$ MHz; Total Samples $N=100$)

<table>
<thead>
<tr>
<th>True Path Delays (ns)</th>
<th>Estimated Path Delays(nns)</th>
<th>True Frequency Dependence</th>
<th>Estimated Frequency Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>80.0000</td>
<td>-0.5</td>
<td>-0.50</td>
</tr>
<tr>
<td>100</td>
<td>101.3333</td>
<td>0</td>
<td>0.0001</td>
</tr>
<tr>
<td>120</td>
<td>117.3333</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>140</td>
<td><strong>141.3336</strong></td>
<td>-1.5</td>
<td>-1.58</td>
</tr>
<tr>
<td>160</td>
<td>166.3333</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>184.000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td><strong>200.000</strong></td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>220</td>
<td>226.686</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

individual ray paths, we can gain more insights into the propagation features of a specific indoor and outdoor channel; These insights should find important applications in channel modeling, especially site-specific channel modeling; The frequency dependence is important to system performance, and the extended channel model might facilitate measurement campaigns as well. Finally we believe that the work reported here should be able to find applications in wireless communications such as channel modeling, RAKE receiver, cochannel interference, power control, multiple access and diversity techniques.

Reference