High-Resolution Algorithms for Multipath Resolving and Indoor Channel Modelling

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Abstract Multiple ray paths are resolved using high-resolution digital signal processing algorithms. The conventional complex channel model for wireless indoor propagation is extended to include the frequency dependence of individual rays which can be used to classify the ray arrivals and provide physical insight of the channel. This approach may be crucial to broadband CDMA systems.

1. Introduction

The performance of wireless communication systems such as cellular mobile radio, indoor wireless communications, and personal communication services is limited by the multipath fading [1-4]. Fortunately, the broadband CDMA technique with RAKE receivers can be employed to improve signal to noise ratios and hence to yield larger channel capacities in environments with deep frequency-selected fades [1-3]. In systems using RAKE receivers, the multipath effect is no longer just a source of performance degradation. In fact it can be used to provide diversity because various multipath arrivals are regarded as independent receptions of the signal. In other words, each signal path can be treated as a different channel, and each received signal taking a specific path holds the full information of the transmitted signal. The signal power received at a RAKE receiver is the sum of individual powers of the resolved multipath arrivals. The more paths can be detected and resolved, the better is the performance of the CDMA system. Thus, an effective modeling technique for resolving the multiple paths is extremely relevant to the performance of the overall CDMA systems.

A great number of empirical and theoretical channel models have been used to describe the statistics of multipath fading in indoor environments [5-8]. Among these models, Turin's approach is widely employed, in which the channel is represented in terms of uncorrelated discrete impulse responses [9]:

\[
\begin{align*}
    h(t) &= \sum_{n=1}^{N} a_n \delta(t-t_n) e^{j\theta_n}, \\
    H(\omega) &= \sum_{n=1}^{N} a_n e^{-j(\omega t_n + \theta_n)}
\end{align*}
\]

where \( a_n, t_n, \) and \( \theta_n \) are the strength, modulation delay, and carrier phase shift of the \( n \)-th arrival. However, the model in (1) has two shortcomings. First, the channel response in (1) does not include the frequency dependent information of individual rays. In practice, various diffractions and reflections pertain to different frequency dependent behaviors. Secondly, not all relevant terms in (1) can always be resolved by the conventional approaches [7]. Generally speaking, a path-resolving algorithm has to be applied to the experimental data to determine the statistics of the unknown parameters in (1) for a practical indoor environment [8]. It is obvious that an algorithm with higher
resolution can provide more accurate channel models. In the conventional approaches the Fast Fourier Transform (FFT) is commonly used for path resolving. Unfortunately, there usually are more relevant arrivals than those can be handled by the FFT. This is due to the fact that the time resolution of the FFT is limited by the frequency bandwidth of the measured data, which is relatively fixed by the experimental setup.

In this paper, we use high resolution signal processing algorithms to overcome these two shortcomings and extend the model in (1) to include the frequency dependence of individual rays:

\[ H(\omega) = \sum_{n=1}^{N} a_n e^{-j(\omega t_n - \omega_0)} \]  

(2) can explain most practical diffraction phenomena occurring on the buildings, windows, and furnitures, such as line of sight \((\alpha_n = 0)\), edges \((\alpha_n = -0.5)\), corners \((\alpha_n = -1)\), cylinder faces(axial) \((\alpha_n = +1)\), cylinder(broadside) \((\alpha_n = +0.5)\), and flat plate \((\alpha_n = +1)\). For example, a ray coming from a line of sight path does not have frequency dependence. A ray from the diffraction of the wall edge has the frequency dependence of \(s_\omega(\omega) = \omega^{0.5}\). A multiple diffraction ray, which is first diffracted by the wall edges \((\alpha = -0.5)\) and then by the desk corner \((\alpha = -1)\), has \(s_\omega(\omega) = \omega^{1.5}\). Thus, the multiple ray paths can be tracked with better accuracy and higher resolution by our approach than by conventional methods.

2. Methodology

The first step is to convert (2) into a standard damped sinusoidal sum for spectral estimation. A conventional way is to express slowly varying \(\omega\) dependent terms in (2) as \(\exp(-\alpha_n \ln \omega)\). Because of numerical instability, this representation is not suitable when the transfer function in (2) is not in baseband. Therefore we take out the common fast varying components from the phases and yield

\[ H(\omega) = \sum_{n=1}^{N} A_n e^{\Delta \omega (t_n - \omega_0)}, \quad \Delta \omega = \omega - \omega_0, \quad (3) \]

\[ A_n = a_n e^{-j \omega t_n + j \beta_n - \alpha_n \ln \omega_0} \]

where \(\omega_0\) is the angular carrier frequency and the approximation \(\ln(1 + \Delta \omega / \omega_0) = \Delta \omega / \omega_0\) has been assumed. The second step is to use a high resolution algorithm to estimate the complex amplitudes and exponents in (3). There exist many conventional methods [10] but none can work satisfactorily for our applications. The Periodogram, Black-Tukey, and MUltilpe SIgnal Classification (MUSIC) methods cannot provide the real parts of the complex exponents. Prony-based algorithms can only work in conditions with very low signal to noise ratios (SNR). The AutoRegressive (AR) and AutoRegressive Moving Average (ARMA) time series usually have trouble to relate their estimated results directly to the physical unknowns \(t_n\) and \(\alpha_n\). To remedy these difficulties, we apply a new algorithm which is originally developed for identifying scattering centers for target identification [11].

3. Numerical Results

To characterize the performance of our approach statistically, our approach approach is first employed to estimate the power profile of a channel containing 8 rays, among which three rays have frequency dependencies \(1/\omega^{0.5}\), \(1/\omega\) and \(1/\omega^{1.5}\), respectively, and others have no frequency dependencies. The top figure in Fig.1 shows the frequency response. The center and bottom figures in Fig. 1 show the
estimated power profiles derived by using the FFT with a Hamming window and our method, respectively. It is interesting to note the FFT is not able to resolve the rays correctly. In addition to provide accurate results of the power profile of the channel, our approach can also supply the frequency dependence of a ray, which is given in Table 1. From the estimated values in Table 1, the frequency dependencies provide information about the "path history" of these rays. For example, from $\alpha = -0.5$, we know the ray with the arrival time of 80(ns) experiencing an edge diffraction, the ray with $\alpha = -1$ encountering a corner diffraction or two edge diffractions, and the ray with $\alpha = -1.5$ undergoing one corner and one edge diffraction or three edge diffractions. Other rays are more likely just experiencing some reflections. The combination of the time delay, amplitude and the frequency dependence can provide us more physical insights into the indoor propagation channel.

Secondly, we consider the simulated data in a typical indoor environment provided by Prof. K. Pahlavan. In the top figure of Fig. 2, the channel profile is obtained using a ray tracing code that takes into account various reflection, transmission, and diffraction mechanisms. Applying our approach to the channel profile, the complex poles of the system in (3) are shown in the bottom figure of Fig. 2. Each pole denotes a received ray

| Time(ns) | Frequency Dependence $\alpha$ | Pole $|\zeta|$ | Amplitude $|\phi|$ |
|---------|-------------------------------|--------------|----------------|
| 80.0000 | 0.50                          | 1            | 0.999          |
| 101.3333| 0.001                         | 0.3          | 0.28           |
| 117.3333| 0                             | 0.63         | 0.3            |
| 141.3336| -1.58                         | 0.998        | 0.0039         |
| 165.3333| 0                             | 0            | 0.25           |
| 184.000 | 0                             | 0            | 0.75           |
| 200.000 | -1                            | 0            | 0.45           |
| 225.086 | 0                             | 0            | 0              |

Table 1. Estimation of Time Delays and Frequency Dependencies of a Simulated Wireless Indoor Propagation Channel using a Novel High-Resolution Algorithm
arrival, and we can classify these ray arrivals using the proposed model in (2). Several interesting features can only be observed by including the frequency dependence of individual rays. Note that the absolute value of the frequency dependent factor $\alpha$ of every non-negligible ray is less than 10. The early ray arrivals (time delay less than 70 ns) have smaller $\alpha$ ($<4$) and the late-time ray arrivals have larger $\alpha$ ($>4$). This means that the early ray arrivals (with shorter paths) tend to have less diffraction encounters in typical indoor environments. This may be another factor (in addition to the geometric spreading and transmission/reflection loss) contributing to the fact that the early-time rays are stronger than the late-time rays. It is also interesting to note that there exists a breakpoint for the frequency dependence at time delay of 70 ns. The breakpoint of the frequency dependent factor may be related to the break points of the receiving power in practical measurements [1]. In free space, the slope of path loss is 2 due to geometric spreading. At short distances with obstruction, the slope of path loss varies from 3 to 4. At long distance with obstruction or at any distance without a line-of-sight path, the slope can exceed 7. In our case, the early-time rays are similar to the rays at short distances in [1] which have small frequency dependence and mild obstruction; while the late-time rays are similar to the rays at long distances in [1] which have large frequency dependence and severe obstruction (without a line-of-sight path). Therefore, we conclude that the frequency dependence of a ray path can be used to classify the received ray arrivals and provide more physical insights into the channel.

4. Conclusions
Comparing to FFT-based approaches, our novel high resolution algorithm yields better resolution for multipath arrivals in wireless communication environments. In addition, it also provides the frequency dependence information of individual rays and hence enable us to extend the conventional Turin model to account for the frequency dependence features. These features can be used to classify the ray arrivals and hence provide physical insight of the channel. It is remarkable to note that the early arrivals have small frequency dependence, while the late arrivals have large frequency dependence. This means that the late-time rays tends to experience more diffraction and scattering than the early-time rays. Similar to the break points in path loss, the break points in the frequency dependent factor may be relevant to practical engineering design because larger frequency dependence are usually related to greater loss. Although just tested in indoor propagation channel so far, our approach should also work for the outdoor propagation channels. Since the frequency dependence of individual rays is critical to ray characterization and detection, it should also be crucial to the performance of wideband CDMA systems. Thus, our approach should be able to find applications in the wireless communications such as channel modeling, RAKE receiver design, cochannel interference detection, multiple access and diversity techniques.

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References