

Postprint: Research on Improved Multipath Uncorrelated Wireless Channel Model Based on MCM

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Abstract

To improve the single-path autocorrelation statistical characteristics of Rayleigh fading channels, an improved multipath uncorrelated wireless channel simulation model is proposed. This model introduces, for the first time, a multipath factor k into the Angle of Arrival (AOA) of the Monte Carlo Method (MCM), thereby improving the AOA value assignment methodology. Through simulation analysis of the channel model parameters AOA, k , the number of low-frequency oscillators N , and the Mean Square Error (MSE), the results demonstrate that this model achieves excellent agreement with the reference model in terms of correlation statistical characteristics. Moreover, compared with MCM, under equivalent implementation overhead, the MSE of the single-path autocorrelation function for the fading channel of the improved model is approximately one-quarter that of MCM within the maximum allowable time interval, indicating a substantial improvement in accuracy and enabling more precise characterization of wireless channels. The proposed model provides a novel methodology for the design of wireless channel simulators and the modeling of frequency-selective channels.

Full Text

Preamble

Improved Model Based on MCM for Simulation of Multiple Uncorrelated Wireless Channel Model

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Abstract: To improve the statistical properties of multipath fading and enable more accurate description of wireless channels, this paper proposes an improved simulation model for uncorrelated multiple Rayleigh fading channels based on the Monte Carlo method (MCM). For the first time, a multipath factor k is introduced into the angle of arrival (AOA) of the MCM, improving the method for evaluating AOA. Through simulation analysis of channel model parameters including AOA, k , the number of low-frequency oscillators N , and mean square error (MSE), results demonstrate that the proposed model exhibits excellent agreement with the reference model in terms of correlation statistical properties. Moreover, compared with MCM under identical implementation overhead, the MSE of the single-path autocorrelation function for the improved model is approximately one-quarter that of MCM within the maximum allowable time interval, representing a significant improvement in accuracy and enabling more precise characterization of wireless channels. The new model provides a novel approach for the design of wireless channel simulators and the modeling of frequency-selective channels.

Key Words: channel simulation; Rayleigh fading channels; multipath; autocorrelation; angle of arrival

0 Introduction

With the development and application of multiple-input multiple-output (MIMO) technology, diversity techniques, and broadband wireless network communication systems, wireless channel modeling has become increasingly important in modern wireless communication equipment research and testing. When simulating multipath fading channels for digital communications, the complexity and variability of real wireless channels make accurate channel characterization critical to communication quality. Consequently, generating multiple fading channels with good single-path autocorrelation statistics and mutual uncorrelation remains a key focus in wireless communication channel modeling.

For typical Rayleigh fading channel modeling, two primary approaches exist: filtering methods and the sum-of-sinusoids (SOS) method. Filtering methods involve high computational complexity and require generation of independent complex Gaussian random processes. In contrast, SOS-based channel simulation can model various wireless fading channels including Rayleigh and Ricean, generate waveforms of specific lengths as needed, and offers advantages of easy implementation and high efficiency, making it more widely applicable in practical simulations.

Based on SOS, Jakes proposed a simplified fading model following Clarke's classic channel reference model. However, Jakes' model exhibits limitations in channel stationarity and statistical independence, and the generated signals are not ergodic, with correlated components between channel paths. To improve single-path autocorrelation and reduce inter-channel correlation, various

improved models have been proposed in literature [5-12], yet each has significant shortcomings. Pop et al. [5] introduced randomly distributed phases to address non-stationarity but could not generate multipath uncorrelated channels. Zheng et al. [6,7] proposed a stochastic model that greatly improved cross-correlation between orthogonal components of Rayleigh fading channels, with excellent statistical properties suitable for multipath Rayleigh fading. However, Zheng's model only considered random distribution characteristics of the same path without incorporating multipath factors. Li et al. [8] reasonably designed Doppler frequencies to simulate multipath independent Rayleigh fading, but the AOA was not randomly distributed. While the MCM model in [9] features random AOA distribution, its in-phase component autocorrelation performance is poor. Models improved in [10-12] introduce multipath factors based on methods such as equal-distance (MED), equal-area (MEA), or precise Doppler spread (MEDS), yet their correlation statistical properties still differ significantly from the reference model.

In summary, analyzing existing fading channel models and their limitations for multipath uncorrelated wireless channels, this paper proposes, for the first time, introducing a multipath factor into the AOA of the traditional MCM model, developing a novel AOA model that improves MCM implementation. The proposed method significantly enhances autocorrelation properties for each path while maintaining inter-path uncorrelation, enabling more accurate description of wireless fading channels.

1 Rayleigh Fading Channel Reference Model

The SOS-based Rayleigh fading channel simulation model is implemented through superposition of a finite number of sinusoids [13,14], as expressed in equations (1) and (2):

$$s(t) = \sum_{j=1}^N a_j \cos(2\pi f_j t + \theta_j) \quad (1)$$

$$s(t) = \sum_{i=1}^N a_i \cos(2\pi f_i t + \theta_i) \quad (2)$$

where $s_1(t)$ and $s_2(t)$ represent the in-phase and quadrature components, respectively; N is the number of low-frequency oscillators required to simulate the Rayleigh channel; parameters f_i and θ_i are the discrete Doppler frequency and Doppler phase of each branch; and parameter σ is the channel Doppler coefficient, as shown in equations (3) and (4):

$$f_i = \sigma \sin(\alpha_i) f_c \quad (3)$$

$$\sigma = 2\pi v \sin(\alpha) / c \quad (4)$$

where df is the maximum Doppler frequency shift and θ is the AOA of each branch signal.

The corresponding second-order statistical parameters of this model are expressed as:

$$\left\{ \begin{aligned} & \sigma^2 J_0^2(2\sigma J_0(\theta)) \\ & \sigma^2 J_0^2(2\sigma J_0(\theta)) \\ & \sigma^2 J_0^2(2\sigma J_0(\theta)) \\ & \sigma^2 J_0^2(2\sigma J_0(\theta)) \end{aligned} \right.$$

where J_0 denotes the zero-order first-kind Bessel function; 2σ represents the Rayleigh fading parameter; $J_0^2(\theta)$ is the in-phase component autocorrelation function of the single-path channel; $J_0^2(\theta)$ is the quadrature component cross-correlation function; and $J_0^2(\theta)$ is the single-path channel autocorrelation function.

2 Improved MCM Model

2.1 AOA Representation in the Improved MCM Model

Based on the reference model representation for Rayleigh fading channels, after introducing the multipath factor into AOA, the uncorrelated multipath Rayleigh fading channel model is expressed as equations (6) and (7):

$$h(t) = \sum_{k=1}^K A_k e^{j(\omega_c t + \theta_k)} \quad \text{def 6}$$

$$A_k = \cos(2\pi N k \sin \theta) \quad \text{def 7}$$

where k is the number of generated uncorrelated waveforms. The fundamental difference between models lies in the AOA evaluation method. The new model's AOA is given by equation (10):

$$\theta = \frac{2\pi(1)}{2} \left(\frac{2(1)}{5} - \frac{3}{4} \right) + \frac{2\pi}{6} - \frac{2}{2} + \frac{1}{M}$$

where M is the number of generated uncorrelated waveforms.

Analysis of the AOA value ranges and characteristics in equations (8) and (9) leads to introducing multipath factor k into the MCM model's AOA to re-evaluate AOA values such that: (a) regardless of k value, AOA is randomly distributed within the range, thereby improving statistical properties; (b) when $k > 0$, AOA is positive, and when $k \leq 0$, AOA is non-positive; (c) changing k values enables rapid generation of required uncorrelated Rayleigh waveforms.

2.2 Analysis of the Improved MCM Model

According to the reference model, the autocorrelation function (ACF) of the k -th path Rayleigh fading waveform, $C_{ik}(t)$ is given by equation (11) [7]:

$$r_{ik} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T C_{ik}(t)C_{ik}(t + \tau)dt = E[C_{ik}(t)C_{ik}(t + \tau)]$$

where τ is the delay time and M is the number of generated uncorrelated waveforms.

Similarly, the cross-correlation function (CCF) between the k -th and l -th paths of Rayleigh fading waveforms is given by equation (12) [9]:

$$r_{kl} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T C_{ik}(t)C_{jl}(t + \tau)dt = E[C_{ik}(t)C_{jl}(t + \tau)]$$

To satisfy equation (12), the expected CCF value between model path channels should be zero, requiring AOA to meet the condition:

$$\cos(\theta_k) \sin(\theta_l) \cos(\theta_k) \cos(\theta_l), \sin(\theta_k) \sin(\theta_l), nknmnlmnlmnaaaalnkmaalnkm \neq \pm \neq \pm \neq \neq \pm \neq$$

The improved model's AOA satisfies these constraints. Substituting equation (10) into equation (11) yields the improved model's ACF as shown in equation (14):

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Note: Figure translations are in progress. See original paper for figures.

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