Fading Channel Model of Short Range Wireless Communications by Mixtures of Rice Distributions

Zhongbao Ji

Wenzhou Vocational and Technical College, Wenzhou 325035, China

14644404@qq.com

Abstract

Properties of short-range wireless channel are different from conventional fading channel models, such as Rayleigh and Rice distributions. To better analyze performance and applications in short-range wireless communications, we need a channel model that better characterizes the properties in short-range scenario. In this paper, we investigate the properties of short-range wireless channels and propose Rice mixtures as channel model. We provide an algorithm to estimate model parameters. The algorithm incorporates the moment method, parameter space search, and Kolmogorov-Smirnov test (KS-test). We conduct an experiment, by which we demonstrate the properties of short-range channel and verify our proposed model.

Keywords

Rice Mixtures; Fading Model; Sensor Networks; Fading Envelope.

1. Introduction

The performance of wireless communications is highly dependent on the channel conditions. The fading channel model is the important foundation which facilitates performance analyses, such as the bit error rate (BER), fade margin, fade duration, channel capacity, and outage probability. Besides, certain power control, channel coding, and adaptive modulation schemes are built on the basis of channel models. To enable these analyses and applications, the fading channel model plays a crucial role.

The Rayleigh, Rice, and Nakagami distributions have been investigated to model fading channel. In these conventional models, the underlying assumptions are large number of scatters. Thus these models are suitable for long-range wireless communications, where number of scatters and multi-paths is large. However, in short-range wireless communications, the scenarios are different from those assumptions. In short-range scenario, the number of scatters is small, thus the small number of strong paths may dominate the multi-path effects. To better characterize short-range fading channel, we need to build the new fading channel model based on the short-range channel properties.

In recent years, many applications are built on the IEEE 802.11 Wireless LAN, sensor networks, and ad hoc networks. These network architectures are more and more popular because, in contrast to wired network, they do not need infrastructures and thus they are easy to be deployed. However, these network architectures are energy constrained and network nodes communicate by short-range wireless links. Thus a short-range wireless fading channel model is important in these short-range scenarios. The performance metrics and power control schemes can be better analyzed based on the more accurate short-range fading models.

In this paper, we investigate the properties of short-range wireless channels and propose the Rice mixtures channel model. The goal of our model is to fit the probability density function (pdf) of narrowband signal envelopes. The procedures of estimating model parameters are described. We conduct an experiment to demonstrate the properties of short-range wireless channels, as well as verify our proposed model and the parameter estimation algorithm.

2. Short-range fading model by Rice mixtures

The random phasor approaches are conducted to analyze the envelope pdfs under various scenarios. The results show that, when the number of scatters is large without strongly dominant components, the pdf of fading envelopes is Rayleigh distribution. And pdfs of fading envelopes is derived as Rice distribution when a single strong component exists.

In short-range wireless channel, the channel gain are dominated by limited number of strong components, including direct paths and reflected paths, either in line-of-sight (LOS) or non-line-of-sight (NLOS). Because the number of dominant components is small, unlike long-range channel, the effects of large amount of scatters may not hold in the short-range channel.

One special property of the short-range channel is that, in some scenarios, the separations among channel states are obvious. For example, the strong reflector may exist for some time and then disappear for the some other time, where the channel can be clearly separated into two states. These phenomena cause the envelope pdfs to be multi-modal.

The Rice pdf is parameterized by σ and ν as

$$f_{Rice,\sigma,\nu}(r) = (\frac{r}{\sigma^2})\exp(\frac{-(r^2+\nu^2)}{2\sigma^2})I_0(\frac{r\nu}{\sigma^2}) \tag{1}$$

where $I_0(.)$ is the modified Bessel function of the first kind with order zero. In our proposed model, we use Rice mixtures to model pdfs of the signal envelopes. The envelope pdf, denoted as f_x, is the linear combinations of the Rice pdfs f_{rice,σ_i,ν_i} i.e.

$$f_x = \sum_{i=1}^{n}\alpha_i f_{Rice,\sigma_i,\nu_i}, \tag{2}$$

where α_i is all positive value, $\sum_{i=1}^{n}\alpha_i = 1$, and the n corresponds to the number of modes in the envelope pdf.

The reasons for choosing this model are the following:

--This model can model multi-modal pdfs, corresponding to the scenario when the channel states are clearly separated.

--The Rice pdf degenerates to Rayleigh pdf when choosing the parameter $\nu = 0$. And by choosing n=1, this model is single-modal. Thus this model includes conventional Rayleigh and Rice model as special cases.

--The degree of freedom in parameters σ_i and ν_i allows each f_{Rice,σ_i,ν_i} to be adapted to different locations and widths. Thus this model provides sufficient degree of freedoms to model multi-modal pdfs.

3. Computation of model parameters

In this model, the model parameters are $\alpha_i, \sigma_i, \nu_i$ where i=1 to n. We denote the parameter matrix as mx3 $S = [\alpha, \sigma, \nu]$, where $\alpha = [\alpha_1, \alpha_2, ..., \alpha_n]^T$, $\sigma = [\sigma_1, \sigma_2, ..., \sigma_n]^T$, and $\nu = [\nu_1, \nu_2, ..., \nu_n]^T$. The idea is to first compute the estimated parameters. Then we refine the parameters by random search with KS-test. The procedures are stated in the following:

Step 1: The n is chosen as the number of modes in the observed envelope pdf. Then envelope sequence is separated into segments which belong to those individual modes. We can separate the sequence by computing local statistics, usually by local mean and variance, in time domain. In other words, we use a sliding window to compute the local mean and variance, and set the thresholds of the mean and variance as the criteria to distinguish segments.

Step 2: All segments which belong to the same mode are aggregated together to form a subsequence. We compute the moments of each subsequence and use the moment method to obtain initial estimate of the parameters S of each mode.

In this step we refine the parameters from step 2. We randomly deviate the parameters by a small amount, i.e. randomly deviate all elements in $[\alpha_1, \alpha_2, ..., \alpha_{n-1}]^T$, $[\sigma_1, \sigma_2, ..., \sigma_n]^T$, and $[\nu_1, \nu_2, ..., \nu_n]^T$ by i.i.d. random numbers with small variances and set $\alpha_n = 1 - \sum_{i=1}^{n-1} \alpha_i$.

We denote the deviated parameters of step 3 as $\tilde{S}$. If any one of the parameters in $\tilde{S}$ is out of the constraints, i.e. all parameters must be larger or equal to zero, this $\tilde{S}$ should be rejected and repeat step 3 until the acceptable $\tilde{S}$ is obtained.

From S and $\tilde{S}$ we obtain the corresponding envelopes pdfs f_x and $\tilde{f}_x$ by (1) (2). We compute the D-statistic of KS-test for the f_x and $\tilde{f}_x$ with respect to empirical envelope

sequence separately. The set of parameters, either S and $\tilde{S}$ with smaller D-statistic are retained and used to repeat step 3. The step 3 is iterated until the stopping criteria are reached. The stopping criteria can be the pre-defined maximum number of iterations or the passage of KS-test.

The overall idea is to first estimate parameters by the moment method, and refine the parameters by KS-test. The algorithm diagram is shown in Fig. 1.

4. Experiment results and verification and models

We conduct an experiment in an indoor environment. The scenario is intended to investigate short-range wireless links, with the distance between the transmitter (TX) and the receiver (RX) approximately 6 meters. The RX and TX are located in NLOS positions. It's conducted at the busy hallway of a campus building during the rush hours of 10 a.m. in the morning. The physical channel disturbances are non-orchestrated, such as non-cooperated pedestrians walking, waiting for elevators, and moving of elevators.

We measure the envelope of carrier frequency of 2.4 GHz. The measurement instruments and analyses of gains are shown in Fig. 2. The functionality of the crystal detector is to eliminate the high-frequency carries and bypass the envelopes of the carrier. We obtain data from the output $P(t)$ of Fig. 2. The gains of the instruments and analyses are described in Fig. 2, from which we know the measured sequence $P(t) \propto (G_2 G_1 A)^2 G^2{}_h(t)$. Since those gains G_1, G_2 and A, obtained from the datasheet of the instruments, are nominal values, they may not be exact. Besides, the accurate losses in the wires and connectors are not available. It's worth noting that the received signal envelope is proportional to channel gain, with the proportion constant involving the above mentioned gain factors. Because of these nominal and unaccountable gain factors, we need to perform normalization procedures on the measured $P(t)$ to eliminate the effects of those unknown gains and proportion constants. Denoting the lump-sum gains (or losses) of the wires, connectors, and other unaccounted factors, as k, we have

$$P(t) = k(G_2 G_1 A)^2 G^2{}_h(t) \tag{3}$$

We compute the normalized power $P_{NL}(t)$ by

$$P_{NL}(t) = \frac{P(t)}{\sqrt{E(P^2(t))}} \tag{4}$$

where time-average is used as the estimated value of $E(P^2(t))$ in computing our empirical data. By plugging (3) into (4), we obtain

$$\begin{aligned} P_{NL}(t) &= \frac{k(G_2G_1A)^2G_h^2(t)}{\sqrt{E[(k(G_2G_1A)^2G_h^2(t))^2]}} \\ &= \frac{k(G_2G_1A)^2G_h^2(t)}{k(G_2G_1A)^2\sqrt{E[(G_h^2(t))^2]}} = \frac{G_h^2(t)}{\sqrt{E[(G_h^2(t))^2]}} \end{aligned} \tag{5}$$

By (5), we know the $P_{NL}(t)$ is the normalized channel gain without units. Since the received signal envelope is proportional to channel gain, estimating pdfs of $P_{NL}(t)$ is equivalent to estimating normalized received signal envelopes. In fitting pdfs of envelopes, the choices of units and the nominal gains greatly influence the width of the empirical pdfs, and subsequently influence the goodness-of-fit for any models. The normalization procedures eliminate the effects of those subjective choices of units and gains, and enable us to obtain objective evaluations of the goodness-of fit for our proposed model. We use the 2-modal Rice mixture and compute the fitting parameters by the algorithms. Besides, to compare the goodness-of-fit, we use the same algorithms separately to estimate parameters of the single-modal Rayleigh pdf denoted as $f_{Rayleigh}$. the single-modal Rice pdf denoted as f_{Rice}, and the 2-modal pdf of the mixture of one Rayleigh and one Rice denoted as $f_{Rayleigh,Rice}$. All their stopping criteria are set to maximum number of iterations of 3000. Our data are 2500 samples measured over 500 seconds.

5. Conclusion

In short-range wireless channel, the channel characteristics are different from conventional paradigms. We address this issue and conduct the experiment to demonstrate the properties of short-range wireless channel. We also propose using Rice mixtures as channel model. The advantages of Rice mixtures are the simplicities for parameter estimations, while maintaining enough degrees of freedom to model multi-modal pdfs. This model also includes Rayleigh and Rice as special cases.

Besides proposing this model, we provide a simple algorithm to estimate the model parameters. In this algorithm, we use moment method as initial estimate, after which we use random search to improve the model parameters by pursing smaller D-statistic of KS-test. We demonstrate using the algorithm on our field data. The goodness-of-fit is verified by KS-test and compared with other models. The experimental data verify the special properties of short-range wireless channels, as well as demonstrate the flexibilities and simplicities of Rice mixture model.

References

[1] K. Yao, M. K. Simon, and E. Biglieri, "Unified theory on wireless communication fading statistics based on SIRP," IEEE 5th Workshop on Signal Processing Advances in Wireless Communications, pp. 135-139, July 2014.

[2] H. S. Wang and P. C. Chang, "On verifying the first-order Markovian assumption for a Rayleigh fading channel model," IEEE Transactions on Vehicular Technology, vol. 45, issue 2, pp. 353-357, May 2016.

[3] P. Beckman, Probability In Communication Engineering. New York: Harcourt Brace and World, 1967.

[4] E. K. Hall and S. G. Wilson, "Design and analysis of turbo codes on Rayleigh fading channels," IEEE Journal on Selected Areas in Communications, vol. 16, issue 2, pp. 160-174, Feb. 2018.

[5] A. J. Goldsmith, S. G. Chua, "Adaptive coded modulation for fading channels," IEEE Transactions on Communications, vol.46, issue 5, pp. 595-602, May 2018.

[6] G. Caire, G. Taricco, and E. Biglieri, "Optimum power control over fading channels" IEEE Transactions on Information Theory, vol. 45, issue 5, pp. 1468-1489, July 2009.

[7] M. D. Yacoub, G. Fraidenraich, H. B. Tercius, F. C. Martins, "The symmetrical h −k distribution: a general fading distribution," IEEE Transactions on Broadcasting, vol. 51, issue: 4, pp. 504-511, Dec. 2015.

[8] S. M. Kay, Fundamentals of Statistical Signal Processing, Volume I: Estimation Theory. Prentice-Hall, Inc. New Jersey, 2013.

[9] B. W. Silverman, Density Estimation for Statistics and Data Analysis. Chapman and Hall, London U.K., 2006.

[10] E. Biglieri, J. Proakis, and S. Shamai, “Fading channels: information-theoretic and communications aspects," IEEE Transactions on Information Theory, vol. 44, issue 6, pp. 2619-2692, Oct. 2008.

[11] Z. Wang and G. B. Giannakis, "A simple and general parameterization quantifying performance in fading channels," IEEE Transactions on Communications, vol. 51, issue 8, pp. 1389-1398, Aug. 2013.