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Research Article

Research on Maritime Radio Wave Multipath Propagation Based on Stochastic Ray Method

Han Wang[1] and Wencai Du[1,2]

[1]*College of Information Science & Technology, Hainan University, 58 Renmin Avenue, Haikou, Hainan 570228, China*
[2]*FITM, City University of Macau, Choi Kai Yan Building, Taipa, Macau*

Correspondence should be addressed to Wencai Du; wencai@hainu.edu.cn

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Multipath effect in vessel communication is caused by a combination of reflections from the sea surface and vessels. This paper proposes employing stochastic ray method to analyze maritime multipath propagation properties. The paper begins by modeling maritime propagation environment of radio waves as random lattice grid, by utilizing maximum entropy principle to calculate the probability of stochastic ray undergoing k time(s) reflection(s), and by using stochastic process to produce the basic random variables. Then, the paper constructs the multipath channel characteristic parameters, including amplitude gain, time delay, and impulse response, based on the basic random variables. Finally, the paper carries out a digital simulation in two-dimensional specific fishery fleet model environment. The statistical properties of parameters, including amplitude response, probability delay distribution, and power delay profiles, are obtained. Using these parameters, the paper calculates the root-mean-squared (rms) delay spread value with the amount of 9.64 μs. It is a good reference for the research of maritime wireless transmission rate of the vessels. It contributes to a better understanding of the causes and effects of multipath effect in vessel communication.

1. Introduction

As we know that about 70% of the Earth surface is covered by the ocean waters and over 90% of the world's goods are transported by merchant fleet over sea. Maritime communication plays an important role in many marine activities, such as offshore oil exploitation, maritime transportation, and marine fishery. The current maritime communication systems mainly include signal sideband (SSB) short-wave radio system, VHF radiotelephone, coast cellular mobile communication network, and maritime satellite communication network. Maritime VHF radio telephone is mainly used for ship-to-shore and ship-to-ship voice communication scenario. The transmission distance of the maritime VHF radio is limited to 20 nautical miles. Another drawback of the maritime VHF radio is its lack of support of data services. Maritime satellite communication systems [1, 2], such as the Inmarsat-F system and Fleet-Broadband maritime data service, are suitable for ocean sea ship communications. However, the satellite communication system is relatively expensive, due to the high cost of the terminal equipment and high maintenance and upgrade costs. Although the service fee is high, the data transmission rate is far from the user requirements. Consequently, maritime communications which can deliver voice and higher data transmission rates are hot topic in current and future research.

Generally, the approaches to modeling wireless channel propagation can be divided into two categories: statistical measurement and electromagnetic field prediction. The former is a mainstream channel modeling methodology, which includes parametric statistical modeling method and physical propagation modeling method. The latter is an approach, which includes ray method, finite difference time domain method, and moment method. Maritime communication channel modeling based on statistical measurements of empirical models has been widely studied. The majority of scholars have utilized measurement and estimation data to predict a particular path loss in mobile channel modeling over sea [3–8]. In [8], authors have extended the ITU-R P.1546-5 as a radio over sea propagation model for investigating the path loss curve.

However, the analysis of large-scale fading in vessel communication environment or ship to shore communication environment cannot reflect the multipath channel characteristics, where multipath effect should be considered. The vast majority of small-scale multipath analyses are based on field measurements [9–12]. Measurements are carried out in different sea areas, but the conclusions have regional limitations. The finite difference time domain method is also adopted in maritime channel modeling [7, 13]. However, this method has high calculation costs and requires well-defined communication environment.

The paper will contribute to technique in modeling wireless channel propagation in the sea. The sea surface reflections and other ships reflections are considered in exploring the multipath rms delay spread in fishery fleet communication environment by employing the stochastic ray method to measure maritime wireless radio multipath propagation properties, by utilizing lattice grid to describe the maritime fishery fleet propagation scenario and using Brownian bridge process to construct the basic statistical properties of random variables and by numerical simulation to obtain the rms delay spread value. This study provides stochastic ray channel modeling method that can effectively evaluate the maritime multipath propagation channel.

The rest of this paper is organized as follows: Section 2 describes the stochastic ray theory and its probability distribution. Maritime random radio wave propagation multipath statistical characteristics are given in Section 3. The simulation and analysis are presented in Section 4. Finally, the conclusion is presented in Section 5.

2. Stochastic Ray Theory and Its Probability Distribution

In the analysis of wireless channel propagation, the multipath effect under the unknown environment should be taken into consideration. Due to the complexity and sensitivity of the wireless propagation environment and the requirements of a stochastic channel model, no-wave approach is utilized in the practical electromagnetic engineering [14]. In [15, 16], the propagation environment is modeled as a random distribution of point scatters. Stochastic ray method is used to analyze the propagation process. Researches [14–17] show that stochastic ray method is an effective method to study the characteristics of urban wireless multipath propagation channel.

2.1. Stochastic Bridge Process. The process where a number of rays emitted from the source after a multihop random walk reach the destination is called beam multipath diffusion process. The formal mathematical definition of this process is given with Definition 1.

Definition 1. For all $0 \leq t \leq T$, if the trajectory of stochastic process $\{Y(t,\omega)\}$ passing through two fixed points r_0, r_1, where $\{Y(t,\omega) \mid Y(0,\omega) = r_0,\ Y(T,\omega) = r_1,\ r_0, r_1 \in R,\ 0 \leq t \leq T\}$, the process is called stochastic bridge process, denoted by $Y_{0,r_0}^{T,r_1}(t,\omega)$. It can be formulated as

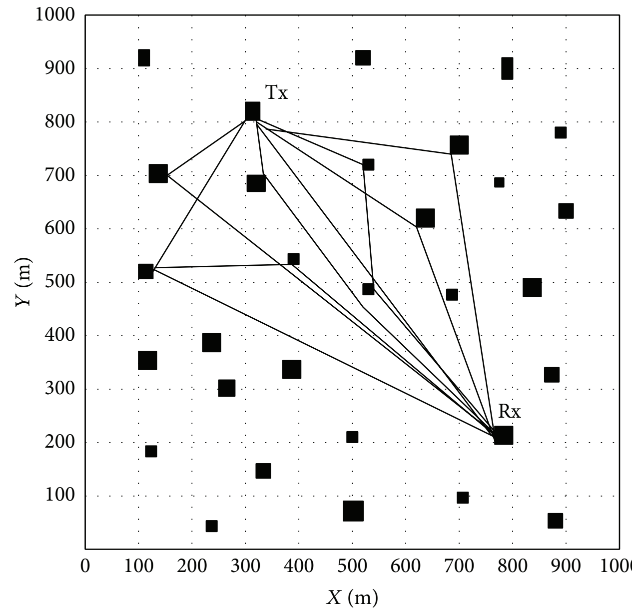

Figure 1: The maritime stochastic rays propagation in lattice, where Tx is a transmitter and Rx is a receiver.

$$Y_{0,r_0}^{T,r_1}(t,\omega) = r_0 + X(t,\omega) - \frac{t}{T}\left[X(T,\omega) - r_1 + r_0\right], \quad (1)$$

where $\{X(t,\omega)\}$ is a stochastic process with the starting point at the source point.

2.2. Random Lattice Channel. The authors in [14] proposed an idea for modeling of the urban propagation environment as a random lattice. The percolation theory was exploited in the domain of channel modeling for the first time. Consider a finite array (see Figure 1) made of square sites with side of unit length. The status (occupied or empty) of a cell is independent of the status of all other cells in the lattice and assume that empty probability is p and the occupancy probability is $q = 1 - p$. Given a very large lattice randomly occupied with probability q, percolation theory deals with the quantitative analysis of groups of neighboring empty sites (clusters): form, average size, number, and so forth. For modest values of p (say, p near zero) the average dimension of clusters is small, while for p near unity the lattice looks like a single cluster with sporadic holes. As p grows, the dimension of the empty clusters grows as well. Clearly, for $p = 1$, the whole lattice is empty. There exists a threshold level $p_c \approx 0.59275$ at which the lattice appearance suddenly changes: for $p > p_c$ a single empty cluster that spans the whole lattice forms, while for $p < p_c$ all empty clusters are of finite size. Near the percolating threshold the characteristics of the p-lattice change qualitatively; the system exhibits a phase transition. There exists an average distance among the closed clusters in the site percolation with given p, denoted by $d = a/\sqrt{1-p}$, where a is the cell side length of lattice.

In [14–16], percolation lattices are used for description of the propagation in urban areas. The conclusion is supported by field measurements in literatures. In this paper, we cannot directly use the original lattice channel theory. Therefore, we adapt it to comply with maritime propagation channel model.

Let us consider the following example. In May 2013, a fleet of 30 fishery vessels departs from Hainan province, Danzhou city, carrying out fishing activities in China Spratly Islands. The weight of each fishery vessel is above 100 tons. Taking this example into consideration, we create a two-dimensional maritime propagation model. Maritime stochastic ray propagation in lattice is presented in Figure 1. Maritime fishing fleet environment is assumed in two-dimensional equally spaced square grid. The black irregular grids represent fishery vessels. There are 30 irregular grids, which gives the occupancy probability of the lattice. The entire fishing fleet is in the scale of 1000 m × 1000 m.

2.3. The Probability Distribution of Stochastic Rays at Two-Dimensional Propagation Space after Undergoing k Time(s) Reflection(s). Since the propagation environment is modeled as a random grid channel, let us assume that the transmitter is placed at $(0,0)$, and after k time(s) reflection(s), the receiver is placed at (x,y); the arriving ray undergoing k time(s) reflection(s) among all the rays has a probability; we denote it by $f(x,y)$. Under certain constraints, using the maximum entropy principle, we can get the probability expression.

A probability density function $P(x,y)$ Shannon entropy is defined as below:

$$H(P) = -\iint_{x,y} P(x,y)\log_{10}|P(x,y)|\,dx\,dy, \quad (2)$$

where $P(x,y)$ satisfies (denoted by C1): (i) $P(x,y) \geq 0$, $x, y \in R$; (ii) $\iint_{x,y} P(x,y)dx\,dy = 1$; and (iii) $\iint_{x,y}\rho(x,y)P(x,y)dx\,dy = D_k$. In (iii), $\rho(x,y)$ is the Euclidean distance metric; D_k is the average distance associated with the reflections.

Proposition 2. *The Shannon maximum entropy $f(x,y)$, which is described by formula (2) and satisfies condition C1, can be expressed as*

$$f(x,y) = ce^{\eta\rho(x,y)}, \quad (3)$$

where c and η are constants. Proposition 2 has been proved in [18].

Proposition 3. *In the two-dimensional Euclidean distance metric, under the constraint $\iint_{x,y}\sqrt{x^2+y^2}P(x,y)dx\,dy = D_k$, the probability of arrival of the stochastic rays at a special spatial location after k time(s) reflection(s), $f(r,\theta)$, satisfies*

$$f(r,\theta) = \frac{2}{\pi D_k^2}\exp\left(-\frac{2r}{D_k}\right), \quad (4)$$

where $r = \sqrt{x^2+y^2}$, θ is the azimuth angle. The average distance of reflections is

$$D_k = dk^{\beta}, \quad (5)$$

where d is the average distance between obstacles. We consider wave propagation process as diffusion process. When $\beta = 0.5$, it indicates normal diffusion process; when $\beta < 0.5$, it indicates anomalous diffusion process.

Proof of Proposition 3. Let $\lambda = e^{\eta}$; we have $ce^{\eta\rho(x,y)} = c\lambda^{\rho(x,y)}$, and let $f(x,y) = f_0\lambda^{\sqrt{x^2+y^2}}$. Since $\iint_{x,y} f(x,y)dx\,dy = 1$, we have

$$\begin{aligned}\iint_{x,y} f_0\lambda^{\sqrt{x^2+y^2}}dx\,dy &= \iint_{r,\theta} f_0\lambda^r r\,dr\,d\theta \\ &= f_0\int_0^{2\pi}d\theta\int_0^{\infty}r\lambda^r dr \\ &= 2\pi f_0\int_0^{\infty}r\lambda^r dr.\end{aligned} \quad (6)$$

Let $\chi = \int_0^{\infty} r\lambda^r dr$; we have $\chi = 1/(\ln\lambda)^2$, $2\pi f_0/(\ln\lambda)^2 = 1$, and $\lambda = \exp(-\sqrt{2\pi f_0})$. Since $\lambda < 1$,

$$\begin{aligned}&f(r) = f_0\exp\left(-\sqrt{2\pi f_0}r\right), \\ &\int_0^{2\pi}\int_0^{\infty} rf_0\exp\left(-\sqrt{2\pi f_0}r\right)r\,dr\,d\theta = \int_0^{2\pi}f_0 d\theta \\ &\quad\cdot\int_0^{\infty}r^2\exp\left(-\sqrt{2\pi f_0}r\right)dr \\ &\quad= 2\pi f_0\int_0^{\infty}r^2\exp\left(-\sqrt{2\pi f_0}r\right)dr = -\frac{1}{\sqrt{2\pi f_0}} \\ &\quad\cdot\int_0^{\infty}\left(\sqrt{2\pi f_0}r\right)^2\exp\left(-\sqrt{2\pi f_0}r\right)d\left(\sqrt{2\pi f_0}r\right) \\ &\quad= \frac{1}{\sqrt{2\pi f_0}}\int_0^{\infty}z^2e^{-z}dz = -\frac{1}{\sqrt{2\pi f_0}}\Gamma(3) = \frac{2}{\sqrt{2\pi f_0}} \\ &\quad= D_k, \\ &f_0 = \frac{2}{\pi D_k^2}, \\ &f(r,\theta) = \frac{2}{\pi D_k^2}\exp\left(-\frac{2r}{D_k}\right).\end{aligned} \quad (7)$$

□

In three-dimensional environment, we set the Euclidean distance $r = \sqrt{x^2+y^2+z^2}$. In this case the average distance traveled by a ray in k time(s) reflection(s), D_k, is

$$D_k = \iiint_{x,y,z}\sqrt{x^2+y^2+z^2}f(x,y,z)\,dx\,dy\,dz. \quad (8)$$

Then we have a corollary.

In the three-dimensional Euclidean distance metric, under the constraint of (8), the probability of arrival of the stochastic rays at a special spatial location after k time(s) reflection(s), $f(r,\theta,\varphi)$, satisfies

$$f(r,\theta,\varphi) = \frac{27}{4\pi^2 D_k^3}\exp\left(-\frac{3r}{D_k}\right). \quad (9)$$

The proof of this corollary is similar to Proposition 3.

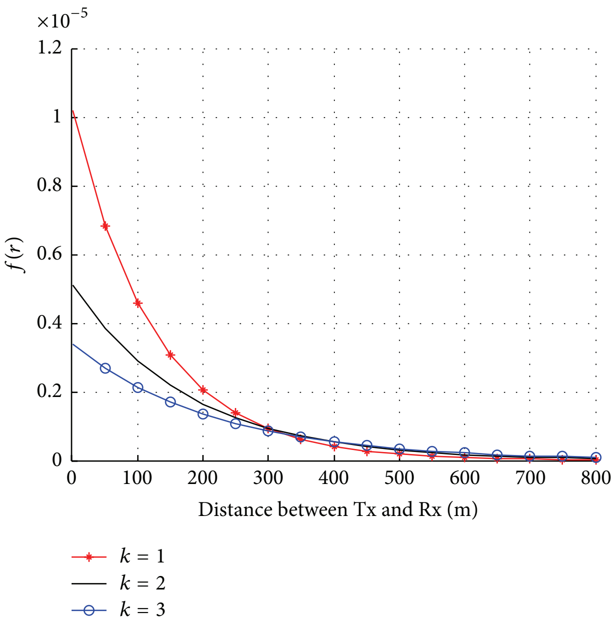

FIGURE 2: The arrival probability density curve after k time(s) reflection(s).

By (4) and (5), we can draw the two-dimensional stochastic ray probability distribution. Figure 2 shows the arrival probability density curve after k time(s) reflection(s), where $r = 800$ m, $d \approx 200$ m, and $\beta = 0.5$. It can be seen that $f(r)$ decreases with the increase of the distance. More reflections can cause lower arrival probability. When the distance changes to a certain value, the ray arrival probability becomes very small. In fact, when k is more than three, the reflected ray arrival rate is negligible. In the following analysis, we consider the case where the maximum number of reflections is two.

3. Maritime Random Radio Wave Propagation Multipath Statistical Characteristics

3.1. Brownian Bridge Process Constructs the Basic Random Variables

Definition 4. $W(t,\omega)$ is standard Brownian motion; if the stochastic process, $\{Y(t,\omega)\}$, satisfies

$$Y_{0,x_0}^{T,x_1} = x_0 + W(t,\omega) - \frac{t}{T}\left[W(T,\omega) - x_1 + x_0\right], \quad \forall 0 \le t \le T, \tag{10}$$

then we call it as Brownian bridge process, which travels through two fixed points, x_0, x_1.

Thus, the Euclidean distance of i hops Brownian bridge samples in L-dimensional space can be expressed as

$$Z_i = \sum_{k=0}^{i}\left\{\sum_{l=1}^{L}\left[Y_l(t_{k+1},\omega) - Y_l(t_k,\omega)\right]^2\right\}^{1/2}. \tag{11}$$

To simplify the analysis, we omit ω; the Euclidean distance of each hop in L-dimensional space can be expressed as

$$\begin{aligned}\Delta Z_k &= \left\{\sum_{l=1}^{L}\left[Y_l(t_{k+1}) - Y_l(t_k)\right]^2\right\}^{1/2} \\ &= \left\{\sum_{l=1}^{L}\left[W_l(t_{k+1}) - W_l(t_k) - \frac{W_l(i)}{i} + x_1 - x_0\right]^2\right\}^{1/2} \\ &= \left\{\sum_{l=1}^{L}\left[Z_0 + x_1 - x_0\right]^2\right\}^{1/2},\end{aligned} \tag{12}$$

where $Z_0 = Z_1 - Z_2, Z_1, Z_2 \sim N(0,\sigma^2)$; (12) can be rewritten as

$$\Delta Z_k = \left\{\sum_{l=1}^{L} Z^2\right\}^{1/2}, \tag{13}$$

where $Z \sim N(x_1 - x_0, 2\sigma^2)$; distribution function N means the normal distribution. We define Z_i as the Euclidean distance of i hops in L-dimensional space:

$$Z_i = \sum_{k=1}^{i}\Delta Z_k. \tag{14}$$

3.2. Amplitude Gain of Multipath. We define the amplitude gain of the ij multipath component as below [14]:

$$a_{ij} = \exp\left(\frac{-j2\pi Z_{ij}}{\lambda}\right)10^{-(1/20)[\sum_{k=0}^{i} L_{ijk} + (1-\delta(i))L_a]} Z_{ij}^{-n/2}, \quad Z_{ij} > 1, \tag{15}$$

where i is the reflection number of the multipath components during its propagation process, $i = 0, 1, \ldots$. j is the jth multipath component undergoing i time(s) reflection(s). k is the k time(s) reflection(s), $k = 0, 1, \ldots, i$. λ is the carried frequency. n is path loss parameter. L_{ijk} is the loss caused by k time(s) reflection(s) from the ij multipath component and scatterer, random variable (dB), $L_{ijk} \sim N(L_{111}, (L_{111}/10)^2)$. L_a is the loss due to the direction of antennas. $\delta(i)$ is Dirac delta function. Z_{ij} is the path length of the ij multipath component.

3.3. Multipath Time Delay. The multipath time delay of j path reflected i time(s) is

$$\tau_{ij} = \frac{Z_{ij}}{c}, \tag{16}$$

where Z_{ij} is the path length of the ij multipath component and c is the propagation speed of electromagnetic wave.

3.4. The Impulse Response of Stochastic Multipath Channel. The small-scale variations of a radio signal can be directly related to the impulse response of the radio channel. The impulse response is a channel characterization and contains all information necessary to simulate or analyze any type of radio transmission through the channel.

In (15) and (16), we give the amplitude gain of the multipath, a_{ij}, and the time delay, τ_{ij}. A channel impulse response is given as follows, which can be used to calculate power delay profile of the channel:

$$h(t,\tau) = \sum_{i=0}^{N} \sum_{j=1}^{M_i} a_{ij}\delta\left(t - \tau_{ij}\right), \quad (17)$$

where N is the reflection time and M_i is the number of i time(s) reflection(s) multipaths.

Using the stochastic ray method to establish maritime multipath channel model is described through a flow chart. Figure 3 shows the flow chart of establishing maritime multipath channel model. The process includes 6 main steps.

4. Simulation Results and Analysis

A thorough literature search has been performed on the distributions of multipath delay and amplitude gain of multipath. The main conclusions are that the multipath delay distribution meets Poisson distribution and that the amplitude gain of multipath satisfies classical distributions, such as Rayleigh and Rice distribution. In this paper, we utilize stochastic ray method to study the maritime multipath delay distribution and other maritime multipath statistical characteristics.

In order to develop some general design guidelines for wireless systems, main quantifying parameters of the multipath channel are used, such as the mean excess delay and rms delay spread. They are regarded as important factors for the design of the radio communication links. Moreover they are used for measurement of system performance degradation due to intersymbol interference. In this paper, we firstly analyze the impulse response of the maritime multipath channel $h(t,\tau)$; the power delay profile of the channel is found by taking the spatial average of $|h(t,\tau)|^2$; then the two channel parameters (mean excess delay and rms delay spread) can be determined from a power delay profile.

The simulation parameters are given as below: the transmitter is located at $(300, 800)$, the receiver is located at $(800, 200)$, and the distance $x_1 - x_0 \approx 800$ m, as shown in Figure 1. Assuming that there are maximum two times reflections and a total number of 50 multipaths, where $k = 2$, $M_i = 50$. In $Z \sim N(x_1 - x_0, 2\sigma^2)$, we set $\sigma = 30$; the purpose of this σ value is to make sure that the random ray reflection trace length is slightly greater than 800 m. This parameter choice would comply to the physical propagation environment depicted in Figure 1.

Figure 4 shows the probability density curve of multipath delay time. It can be found that the distribution is similar to noncentral Laplace bilateral distribution. The magnitude of the multipath delay is in microsecond range. The maximum probability has occurred in $\tau = 7.5\,\mu$s. Obtained results comply with measurements results given in [11, 12]; the multipath delay magnitude is consistent with the experience value.

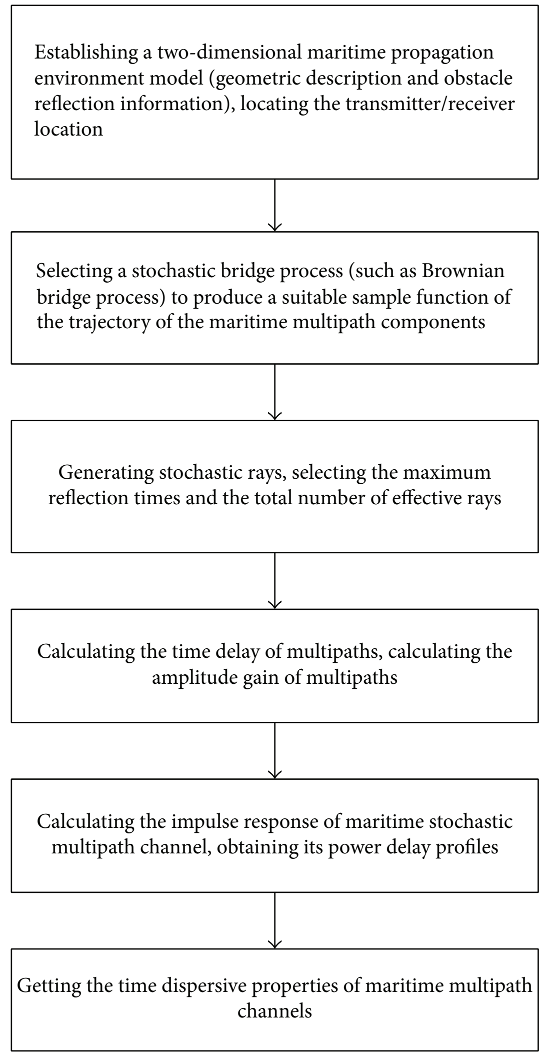

Figure 3: The flow chart of establishing maritime multipath channel model.

In the simulation of the amplitude gain, we assume that signal propagates in sea-free space; $\lambda = 950$ MHz, $L_{ijk} \sim N(3, (0.3)^2)$, $L_a = 0$ dB, and $n = 2$. The probability density function of the amplitude gain of the multipath fading is shown in Figure 5.

Figure 6 shows the impulse response of the stochastic multipath channel. We can find that the trend of multipath intensity is decreasing. With the delay time increase, the multipath intensity becomes weaker. In the range of 0 to 20 μs, the multipath signals have stronger intensity.

For small-scale channel modeling, power delay profile is defined as the power at the given time delay. The power delay profile of the channel, $P(\tau)$, is found by taking the spatial average of $|h(t,\tau)|^2$ over a local area. By this method, we can build an ensemble of power delay profiles. Figure 7 gives the power delay profiles of the stochastic multipath channel.

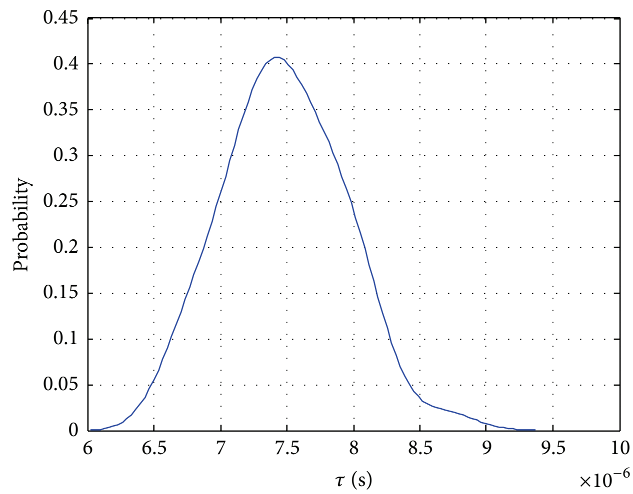

FIGURE 4: The probability density curve of multipath delay time.

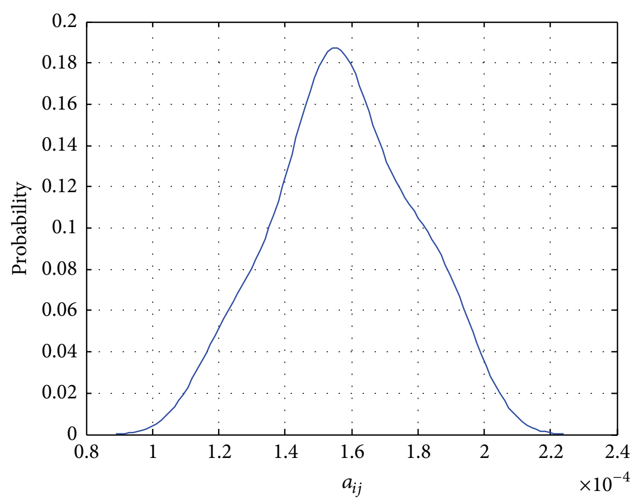

FIGURE 5: The probability density curve of amplitude gain of multipath.

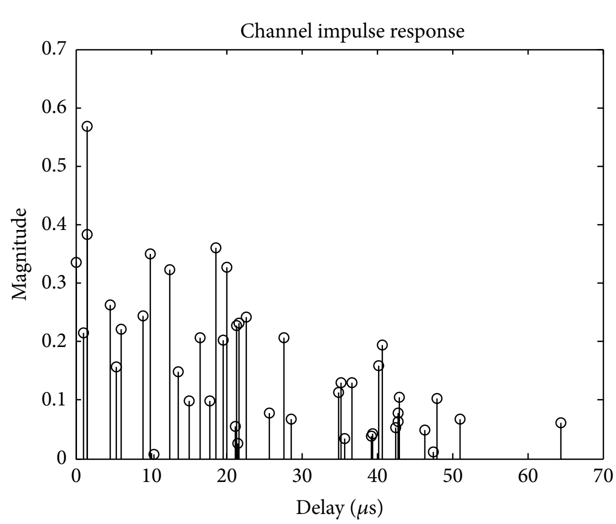

FIGURE 6: The impulse response of stochastic multipath channel.

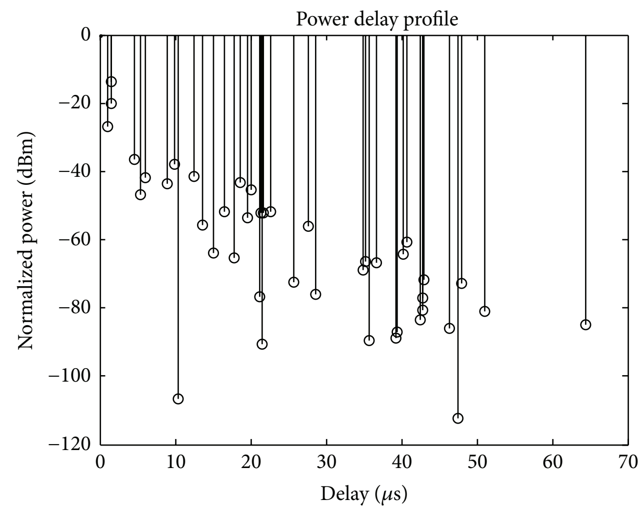

FIGURE 7: The power delay profiles of stochastic multipath channel.

The time dispersive properties of multipath channels are most commonly quantified by their mean excess delay ($\overline{\tau}$) and rms delay spread (σ_τ). The mean excess delay is the first moment of the power delay profiles and describes the degree of dispersion of the multipath signal. It is defined with $\overline{\tau} = \sum_M P(\tau_M)\tau_M / \sum_M P(\tau_M)$. The rms delay spread is the square root of the second central moment of the power delay profiles. It describes the additional delay of the standard deviation and is defined to be $\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2}$, where $\overline{\tau^2} = \sum_M P(\tau_M)\tau_M^2 / \sum_M P(\tau_M)$. These two parameters are of great significant for designing the communication system data rate and receiver. By calculation, we get the two parameters values, where $\overline{\tau} = 8.95\,\mu s$ and $\sigma_\tau = 9.64\,\mu s$. A common rule of thumb in a communication system design is to employ a proper symbol duration much larger than the average rms delay spread to avoid performance degradation due to the intersymbol interference.

5. Conclusion

The present study provides the application of stochastic ray method to measure maritime radio wave propagation multipath statistical characteristics, taking Hainan fishery fleet as a reference. We establish a two-dimensional maritime propagation environment model; the fishery vessels are modeled as irregular obstacles. We draw the flow chart of establishing maritime multipath channel model. Through analyzing of the probability of the amplitude gain of multipath and time delay, we obtain the impulse response of stochastic multipath channel. Then the time dispersive properties of multipath channels, mean excess delay ($\overline{\tau}$), and rms delay spread (σ_τ) are calculated. Mean excess delay and rms delay spread are the two significant maritime multipath channel parameters. Finally, we get the conclusion that the values of rms delay spread are on the order of microseconds in maritime fishery fleet radio wave channels.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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