Mobile Propagation and Channel in Multipath Environments

Mobile Propagation and Channel in Multipath Environments

By

Shigeru Kozono

Cambridge Scholars Publishing

Mobile Propagation and Channel in Multipath Environments

By Shigeru Kozono

This book first published 2023

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-4438-9469-9
ISBN (13): 978-1-4438-9469-2

CONTENTS

Preface viii

Chapter 1 1
Introduction

Chapter 2 6
Mobile propagation and received signals
2.1 Mobile Propagation
2.1.1 The mobile propagation and communication systems
2.1.2 Mobile propagation and features
2.2 A received signal level in a narrow band
2.2.1 A received signal level and its properties
2.2.2 Received signal amplitude and phase distribution

Chapter 3 20
Mobile wireless channels
3.1 Principles of a wireless channel
3.2 The mobile wireless channel with coherent detection
3.2.1 Original wireless channel with movement in a multipath environment
3.2.2 Mobile wireless channelization with channel compensation
3.3 The mobile wireless channel with delay detection
3.4 Mobile wireless channel degeneration
3.4.1 A transmission system with an adaptive white Gaussian noise
3.4.2 The inter-symbol interference due to an excess time delay

Chapter 4 35
The development of mobile communication technology
4.1 The channels and systems with multipath countermeasures
4.1.1 Measurers for dealing with fading
4.1.2 Measures for dealing with an excess time delay
4.2 Channels and systems with effective-frequency utilization
4.2.1 Signal and transmission systems
4.2.2 Cell composition and channel allocation

Chapter 5 48
Received signal level distribution with received bandwidth
5.1 Derivation of a received signal level with received bandwidths and their features
5.1.1 Derivation of a received signal level
5.1.2 The features of the received signal level variations and a new propagation parameter
5.2 Study of the distribution of the received signal level by simulation
5.2.1 Basic properties
5.2.2 Characterization of a variation in received signal levels
5.3 Field experiment
5.3.1 Outline of the experiment
5.3.2 Receiving signal level properties
5.3.3 Multipath properties
5.3.4 Validation of the variation of the received signal levels and fading depths

Chapter 6 78
The street cell and co-channel interference measurement method
6.1 Street cell propagation and cell design
6.1.1 Propagation loss
6.1.2 Measurement of multipath time delay
6.1.3 Street cell design with propagation loss and delay spread
6.2 Co-channel interference measurement method
6.2.1 Measurement method
6.2.2 Determination of the sampling timing
6.2.3 Measurement results

Chapter 7 116
Space and $\pm\alpha$polarization diversity antenna correlation between branches
7.1 The correlation coefficient on space diversity reception
7.1.1 Theoretical model and correlation coefficient derivation
7.1.2 The correlation characteristics of space diversity
7.1.3 Experiment and result
7.2 The correlation coefficient on $\pm\alpha$polarization diversity reception
7.2.1 The theoretical model and polarization diversity characteristic
7.2.2 The experiment and result

Chapter 8 145
Integrated and wideband correlation coefficients in mobile channels
8.1 The integrated correlation coefficient
8.1.1 The multipath and analysis model
8.1.2 Derivation of an integrated correlation coefficient
8.1.3. Simulation
8.1.4 A mobile wireless channel with the user parameter
8.2 The correlation coefficient in a wideband channel
8.2.1 The autocorrelation coefficient
8.2.2 The frequency correlation coefficient

Chapter 9 183
MIMO channel models and channel properties
9.1 SU-MIMO channel model with propagating mechanism and channel properties
9.1.1 The SU-MIMO channel model and channel matrix
9.1.2 The correlation between the SU-MIMO channel matrix elements
9.1.3 The simulation and considerations
9.1.4 The eigenvalue property of the SU-MIMO channel matrix
9.2 MU-MIMO channel model with user parameters and channel properties
9.2.1 The MU-MIMO channel model and channel matrix
9.2.2 Analysis of the correlation
9.2.3 The simulation

Chapter 10 228
Applications
10.1 The application of the integrated correlation -Pilot signal allocation on OFDM-
10.1.1 OFDM transmission system and derivation of a demodulated signal level with ICI
10.1.2 Dependence of the transmission efficiency on the pilot signal allocation
10.2 Application of the SU-MIMO channel matrix -The BER performance of MIMO-OFDM with a Turbo code-
10.2.1 The simulation model
10.2.2 BER performance of the MIMO-OFDM with Turbo code

Index.. 254

PREFACE

This book describes an analysis of the multipath propagation and diverse channels in mobile communication systems that the author(s) performed at the Nippon Telegraph and Telephone Corporation (NTT) Laboratories and the Chiba Institute of Technology (CIT). During the author's tenure at NTT laboratories, which saw the development of the first and second generations of mobile communications. He studied propagation in the urban, tunnel and street cell environments, the co-channel interference measurement method, the diversity antenna branch correlation, multipath properties and cell design, etc. The author and his colleagues had the goal of developing diversity systems and the co-channel measurement method by analyzing the properties of multipath environments and conducting field tests.

After moving to CIT, the author continued to study mobile channels and analyze multipath properties, especially the received signal level distribution for wideband channels and orthogonal frequency division multiplexing (OFDM) systems. The level distribution turned out to be a new one that was neither a Rayleigh nor a Nakagami-Rice distribution. In the OFDM system, he derived a formula for the demodulated signal level with inter-carrier interference (ICI).

Furthermore while at CIT, the author attempted to analyze the properties of multipath to create a new channel which was effective in its frequency utilization and supported high bit rate signals. That is, based on his experience gained through technology development and under conditions in which a multipath channel could be used as a medium of a mobile wireless channel and the channel could be controlled and compensated in near real-time even when the receiving site moves. The multipath and analysis models with physical parameters taking into account those conditions were developed. The multipath model was based on a delay profile wherein the multipath state remains steady when moving through a distance of a few wavelengths, and the analysis model had a domain with space, frequency and path axes. With the derived integrated correlation, a general idler of a different channel appears in the domain when the correlation is low. Moreover, a mobile channel was realized with a unique parameter, called the user parameter, which represents individual user actions.

While at CIT, the author developed the above ideas into a multi-user multiple-input multiple-output (MU-MIMO) channel model with a propagation mechanism consisting of a multipath, user parameter and mobile and base station antennae. The model included the autocorrelation between the user's own antenna elements in the channel matrix and the spatial correlation with movement factor, or correlation between users. It was found that channel interference does not happen even if both users are close to each other in LOS.

Through research and development in mobile communications, and to generalise the characteristics and systematize the technology in mind, the author has been trying to propose channel and analysis models with physical parameters. He analyzed them and derived the related formulas, and verified those channel properties through simulation and field tests.

Through those, the author recognized that the solution derived under a law of nature and engineering conditions suggested the property and main factors. Even though he was in the dark during the experiment. This is when he learned;

“***In seeing it as it is,***
the truth comes to me”.

The author hopes that this book will help the reader gain a better understanding of mobile communications and the properties of multipath environments as well as an insight into multipath analysis for designing systems with diverse and high-quality channels.

The author would like to thank Mr Masayuki Sakamoto of NTT Laboratories for his valuable advice on multipath analysis, and his colleagues in research and development at NTT. Moreover, the author is grateful to Jiang Yan (PhD), Dr Hiroaki Nakabayashi and the author’s students at CIT for their exciting discussions and cooperation.

The author would like to thank commissioning editor Helen Edwards of Cambridge Scholars Publishing for the offer to publish this book, senior commissioning editor Rebecca Gladders for help throughout the publishing, and also Eleanor Harris for her help with proofreading.

Lastly, the author is thankful to his wife Etsuko, parents Eizou and Ise and sisters Miyo, Masako and Toyoko for their support and patience throughout the years.

S. Kozono, July 2022

CHAPTER 1

INTRODUCTION

The final goal of communication is to be able to communicate anytime, any place, to anyone and in any media. Mobile communications have been developed with this goal in mind. Over the years, mobile communications have seen remarkable growth in terms of the number of customers, and many technological developments have provided remarkably improved services. These days, a mobile phone is a necessity of daily life; it is a portable super-communication tool.

Let us look back on the development of the technology used in the system design of mobile communications. The first generation of mobile communications with small cell zones were analogue systems using Frequency Division Multiple Access (FDMA). They needed propagation loss characteristics to provide service anywhere. The second-generation systems were digital and used Time Division Multiple Access (TDMA). They required multipath data to be measured, in particular, the delay profile with an excess time delay, for the service to be offered in any media such as fax and data. The third generation offered services at any time and to anyone. To avoid a busy line, the system capacity needed to increase through the use of Code Division Multiple Access (CDMA). To design the rake receiver they used the number of effective arriving waves in a multipath environment had to be analyzed. Moreover, the variety of the service content (menus) that could be offered expanded with the deployment of post-third-generation systems; these systems required support for real-time multimedia. So the fourth-generation systems support services in any media through effective frequency utilization, which is achieved through the use of the OFDM and MIMO systems. Moreover, this development required the characterization of a channel between the base station and mobile sites, including antenna configurations, multipath and the movements of an individual user. The fifth-generation systems use OFDM and MIMO to support high bit-rate signals and increase the system capacity as more advanced systems than the fourth-generation systems.

Through that research and development, there are two main issues in the development of mobile communication systems that use radio waves as a personal user channel and where communication occurs on the move in a multipath environment: One is the need for effective-frequency utilization, as the radio frequency spectrum is a limited resource. Here, the assigned frequency bandwidth needs to be effectively utilized and ways have to be found to increase the system capacity and provide an adequate service to a large number of customers. The other is overcoming the problems of multipath channels, i.e., fading (received signal level variation) and limitation of the bit rate of the signal. As a guide to handling these issues, this book mainly describes the technology developed by the author(s) through multipath analyses, simulations and field tests. The most of formulas derived in the analyses are recorded in the text or the appendix of the chapter.

This book is organized into three parts: 1) Chapters 2, 3 and 4 comprise an introduction to mobile communication systems. They provide answers to the questions of what mobile propagation is like and how information is transmitted through a wireless channel. Furthermore, they examine some of the technologies used in today's communication systems. 2) Chapters 5−9 describe the technology developed by the author(s) through multipath analyses, simulations and experiments. 3) Chapter 10 describes an application of the developed technology.

Chapter 2 describes mobile propagation and the received signal level. In mobile communications, the user communicates individually while on the move in a multipath environment by the use of radio waves. Mobile communications are thus different from other wireless communications, e.g. broadcasting and satellite communications. The chapter starts by describing the mobile propagation model and the features of propagation. The free space propagation losses and multipath properties are also described. Next, a received signal level on the move in multipath is expressed. It is shown that the level varies, or fades, as the receiving site moves, and the principle of the fading phenomenon is illustrated. Moreover, the received signal amplitude and phase distributions are described with formulas and figures.

Chapter 3 provides the reader with knowledge on how to transmit data through a wireless channel and describes how difficult it is to make a steady channel with a high bit rate when the receiver is moving in a multipath environment. First, the principle of a wireless channel under ideal conditions is explained. Next is a step-by-step description of how to turn the ideal case into a mobile wireless channel with a high bit rate and steady transmission line. After that, the mobile channel degeneration caused by white Gaussian noise and the time delay in a multipath environment is discussed. The delay spread is presented as an index of the influence of a multipath channel in digital signal transmission, and the principle of the broking phenomenon for high-bit-rate signals is illustrated.

Mobile communications must provide a steady and diverse range of services, and technology has evolved along with those requirements.

Chapter 4 introduces those technologies developed for designing communication systems. These technologies are classified into multipath countermeasures against fading and time delay and frequency utilization schemes for transmission systems and cell composition etc.

Chapter 5 describes the technology developed for dealing with the variation in the received signal levels of wideband transmissions. A formula for the received signal level depending on the received bandwidth is derived, and the results of a simulation and field test are presented, showing that the signal variation becomes shallower with increasing bandwidths.

The equivalent received bandwidth $2\Delta f \Delta L_{max}$ is presented as a parameter of the level variation (fading depth), and the dependence of the fading depth on $2\Delta f \Delta L_{max}$ is examined. When $2\Delta f \Delta L_{max}$ is larger than 10 MHz·m, the received signal follows neither the Rayleigh nor Rice distributions.

Chapter 6 describes two effective-frequency utilization technologies for street cell propagation and cell design and a co-channel interference measurement method.

The chapter begins by describing a propagation experiment with a low base station antenna installed on a straight street with tall buildings on both sides: an unusual phenomenon appears wherein the received signal level is higher than the free space level at certain places. Then, it describes the Fresnel zone propagation model that was developed based on this phenomenon. A formula for the propagation loss between the base and mobile stations is also derived. Then, a street cell is designed in accordance with the propagation loss and the delay spread is measured on a straight street. It is shown that a cell with effective frequency utilization can be made by trapping a radio wave in a narrow space.

The co-channel interference measurement method is developed through a multipath analysis that involves sampling the received signal level in the presence of co-channel interference at pairs of different times, and the sampled data are treated by digital signal processing. This technology helps a small cell zone system to interchange with other channels in a cell when co-channel interference occurs during communications.

Chapter 7 describes space and the $\pm 45°$ polarization diversity reception antenna technologies used by the base station to overcome fading. The low correlation diversity antenna branch design improves transmission quality. Those formulas for the correlation between the diversity antenna branches are derived through a multipath analysis including the antenna configuration. In particular, a spatial correlation is analytically derived with a Neumann expansion. Consequently, the main factors related to space and $\pm 45°$ polarization diversity are identified, and these factors are verified by simulations and field tests.

Chapter 8 describes the technology for advanced mobile communication systems aimed at providing a diverse range of high-quality services. An analysis model with a domain consisting of space, frequency, and multipath axes is presented for a mobile channel developed through multipath propagation, and an integrated correlation between the coordinate points in the domain is derived; this correlation is connected with space and frequency through a parameter of multi-paths. This leads to the idea of a different channel when the correlation is low. Furthermore, as a unique parameter in a mobile channel, a user parameter that represents the user's position and movement based on individual user actions is presented.

Furthermore, since the received signal level variation in the wideband transmission is different from that of the narrowband transmission, the autocorrelation and frequency correlations in a wideband channel are studied in non-line of sight conditions (NLOS).

Chapter 9 describes the developments of the SU-MIMO and multi-user MIMO channel models and their channel properties. The SU-MIMO channel model with a propagation mechanism consists of a delay profile with the incident and arriving angles and an antenna configuration. The spatial correlation coefficient between the channel matrix elements is analytically derived. The properties of the correlation are then clarified. Furthermore, the eigenvalues of the channel matrix are discussed with the correlation between the matrix elements in NLOS and LOS.

The MU-MIMO channel model adds the user parameter described in Chapter 8 to the SU-MIMO model. The correlation between channel matrix elements is derived. A unique feature of the MU-MIMO channel is introduced, called a movement factor, which means a decrease in the coefficient of the spatial correlation for just u and u' user points owing to the movement difference between the two users. It is shown that even in the case of a LOS path, the correlation becomes low enough owing to the movement factor, despite that the correlation in the SU-MIMO channels is high.

Chapter 10 covers two applications related to an integrated correlation and the SU-MIMO channel matrix.

Section 10.1 describes an application of an integrated correlation. The pilot signal in an OFDM transmission is allocated in a domain with space and frequency axes, and those signals must be allocated with a high correlation to keep the accuracy of the channel compensation. Signal allocation influences transmission efficiency and BER performance, so it is an important factor. The dependence on the efficiency of the pilot signal allocation is clarified by computer simulation and is discussed by using the integrated correlation. Moreover, the demodulated signal level in OFDM with ICI is derived.

Section 10.2 describes an application of the MIMO channel matrix. The BER performance of the MIMO-OFDM with a Turbo code is simulated by using the SU-MIMO channel matrix elements with multipath and antenna parameters. The dependence of the BER on correlation, movement, speed, and being indoors and outdoors, are discussed.

CHAPTER 2

MOBILE PROPAGATION AND RECEIVED SIGNALS

2.1 Mobile Propagation

2.1.1 The mobile propagation and communication systems

The characteristics of mobile propagation are classified into two areas as shown in Table.2.1 since they are applied to cell constitution, an estimation of the service area, the transmission system design or the channel design to provide high-quality and efficient transmissions.

The cell constitution, which estimates the service area from a base station, needs an average propagation loss. The characteristics that are required are the dependence of distance between the base and mobile stations, an average propagation loss, and also the loss distribution in a small area in the cell because of the mobile communication service area within the two-or three-dimensional space. The propagation characteristics generally depend on environmental structures (buildings, trees etc.), geographical features (plains, hills etc.) and whether there are indoor or outdoor environments.

On the other hand, the transmission system requires a channel property which is characterized by an instantaneously received signal property, since the signal information is instantaneously transmitted by the channel at light speed. Moreover, the received signal varies with user movement and also depends on radio frequency. The wireless channel transmits information data by using both the amplitude and the phase of the received signal through the channel. Therefore the transmission system design requires a detailed and different channel property. When the transmission system shifts, there is quite a new requirement for the channel property. For example, the quality of an analogue transmission system, e.g. the FDMA, strongly depends on the received signal level, so the system design needs just the level property. However, when the system is shifted to a digital system, e.g. TDMA, the system design requires a new propagation property of an excess time delay in multi-path for arriving waves because of the digital signal interference. For progressing mobile communications, a new transmission system has been developed, which improves transmission quality by diversity or high bit rate and large communication capacity by MIMO. At that time, the system designs required new and more detailed channel properties. This book describes mostly the channel properties of the transmission system.

Table 2.1 Application of mobile propagation

	Mobile propagation	
Area	Cell constitution	Channel and transmission system
Property	Dependence of distance on loss Loss distribution	Level/Phase distribution Excess time delay The angle of arriving wave
Application	Large/Small/Micro cell Indoor/Outdoor cell Street cell	Analog/Digital system FDM/TDMA/CDMA/SDM Diversity/MIMO system

2.1.2 Mobile propagation and features

1) Propagation model

Mobile communications are required to communicate in a wide and diverse area of our activity with a wireless channel, so the propagation model becomes varied and complicated due to the environment. In general, in the propagation model, numerous waves which have been reflected and diffracted by surrounding structures to arrive at a receiving point via multiple paths as shown in Fig.2.1. The different propagation paths are collectively called multipath, and then mobile propagation is also called multipath propagation. The features of multipath propagation are remarkably different with or without a direct wave from the transmitting point, and then the propagation is classified into two categories, line of sight (LOS) with a direct wave path between the transmitting and receiving points, and non-line of sight (NLOS) without a direct wave path. Most of the service area in mobile communications is in NLOS because the mobile antenna height is low.

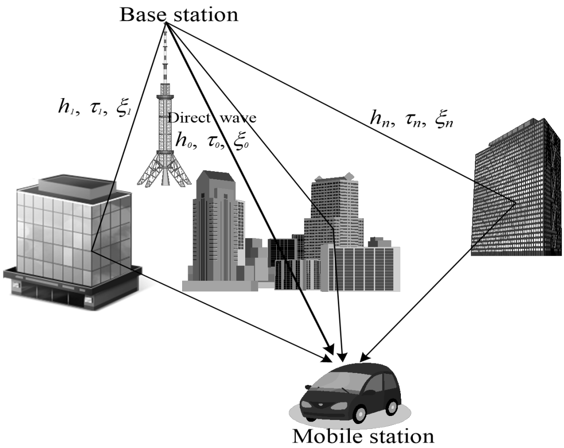


Fig. 2.1 Mobile propagation model.

2) Propagation features

a) Propagation loss

A propagation loss characteristic is required for the design of the service area and radiation power, so the loss is characterized by the dependence on the distance from the transmitting point on propagation loss. The general characteristic illustration is shown in Fig.2.2 with the received signal level. The loss becomes larger with increasing distance or becomes lower as in Fig.2.2; with closer observation, the slope of loss for distance is changing and becomes larger with increasing distance owing to a severer propagation environment.

The propagation loss between the transmitting and receiving points is defined as a ratio of radiation power P_{radi} to received power P_{reci} with both antenna gains 0 dB (isotropic antenna). In free space without obstacles, the loss is called a free space propagation loss L_{loss}, which is derived based on the Poynting vector (***E***×***H***) in electromagnetic theory, and expressed by (2.1).

$$L_{loss} = 20\, log \frac{4\pi d}{\lambda} \qquad [dB] \qquad (2.1)$$

Where *d:* is the distance from transmitting point [m], $\lambda = c/f_c$, λ: wavelength [m], *c*: light speed [m/s], and f_c: radio frequency [Hz].

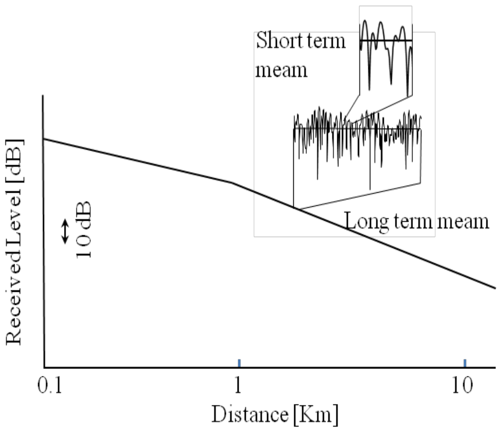


Fig. 2.2 Propagation loss and statistical treatment.

In theory, the loss L_{loss} increases 6 dB every two times of distance d or frequency f_c. However, in actual propagation environments, the loss becomes larger than the free space loss because it is not absolute free space due to the obstructions on the ground surface and the NLOS area containing buildings and trees etc., and other geographical features.

The propagation loss is statistically treated and is generally classified into two terms as shown in Fig.2.2; the loss within a few wavelengths over distance is treated with a mean value and called a short-term mean value. The other is the mean value of the short-term value within a few 100 wavelengths and is called a long-term mean value. The property of the short term is handled as a mean value of the instantaneously received signal level, and so is applied to evaluate a signal transmission quality. The long-term mean value means an average value of level in a small area which is then applied to the cell design etc. The vertical axis in Fig.2.2 is the mean value.

b) Multipath property

i) Excess time delay

One multipath property is an excess time delay which means the time delay with reference to the first arrived wave in multipath waves from the transmitting to the receiving points. Such time delay is observed by a delay profile which is measured as multipath data with amplitude h_n and excess time delay τ_n in each of the arriving waves. An example of the measured delay profile is shown in Fig.2.3, in which horizontal and vertical axes are excess time delay τ_n, and moving distance respectively, and is measured every 1 cm to 200 cm moving distance [2.1]. In the area, there are five significant arriving waves within about a 2 μs time delay and each arriving wave varies with moving distance independently of the other. The value of the time delay depends on multipath environments, for example, the delay is small indoors but is a few μ seconds in an urban area, especially over large distances, for example, from a seaside road to an opposite shore.

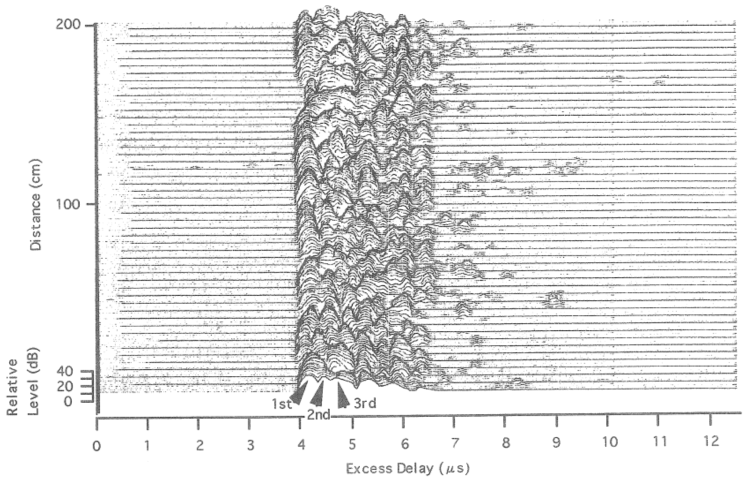
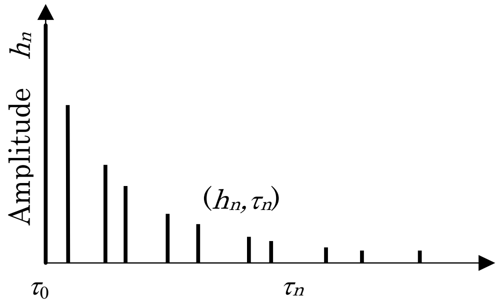


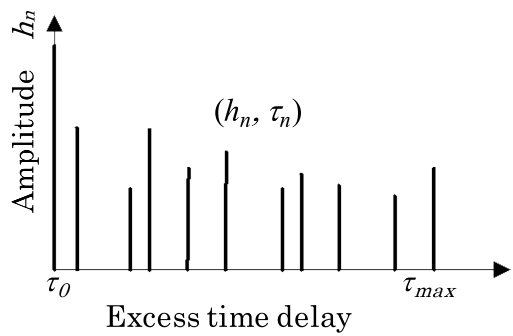
Fig. 2.3 Example of a delay profile (measurement).

Based on rich measured data, the delay profile model is created by focusing on amplitude h_n, excess time delay τ_n, and the number of arriving waves N, and an example of the model is shown in Fig.2.4 [2.2]. The delay profile is generally classified by the relationship between h_n and τ_n. For example, Fig.2.4 (a) and (b) are called exponential and random types respectively, and are usually measured in an urban area and indoors.

The excess time delay is a problem for digital signal transmission. Even if a received signal level is high, it is impossible to transmit a high-bit-rate digital signal owing to signal interference in each of the other arriving waves when the time delay τ_n is large. It is a serious problem for high-speed digital transmission.



(a) Exponential type



(b) Random type

Fig. 2.4 Example of a delay profile model.

ii) Angle of arriving wave

The angle of the arriving multipath wave, which means the direction of an arriving angle with reference to a fixed direction such as the mobile moving direction, is also an important multipath property. The angle property is measured by a rotating antenna with a sharp directive pattern and depends on the surrounding multipath environments at the receiving point. The property is characterized by each arriving wave angle ξ_n and the spread angle of multipath waves $\Delta\xi$. The example of models are shown in Fig.2.5 (a) and (b), and are called uniform and Gaussian distributions respectively, and the former is usually measured indoors or in an area surrounded by obstacles and the latter is done on a high antenna tower in an urban area.

Moreover, the angle ξ_n and time delay τ_n are generally independent of each other.

The angle characteristic is required for an evaluation of space diversity antenna with an improvement of transmission quality and of the transmission system by MIMO capable of a high-bit-rate signal speed and large system capacity.

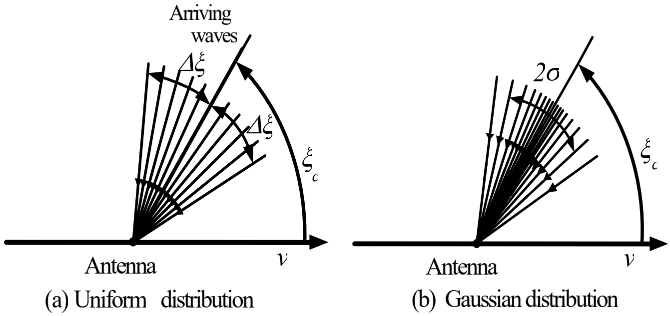


Fig. 2.5 Example of the arriving wave angle model.

2.2 A received signal level in a narrow band

2.2.1 A received signal level and its properties

To clarify the property of an instantaneously received signal level, it is assumed that the receiving point, e.g. the user, is in a small area of a multipath environment and the multipath waves arrive there. Moreover, the point is moving at speed v m/s with a fixed direction. Under these conditions, the origin of the received signal level is shown in Fig.2.6. The signals $e_n(f_c,t)$ and $E(f_c,t)$ are expressed by complex numbers with real and imaginary components. Fig.2.6 (a) shows a phase shift of the received signal $e_n(f_c,t)$, in which the nth arriving wave e_n with h_n, τ_n and ξ_n is arriving at the receiving point with movement. The signal $e_n(f_c,t)$ at the moment t is expressed by (2.2).

$$e_n(f_c,t) = h_n \, e^{j\theta_n} \,, \qquad (2.2\,\text{a})$$

$$\theta_n = 2\pi(f_c\tau_n - f_m t\cos\xi_n) + \phi_n. \qquad (2.2\,\text{b})$$

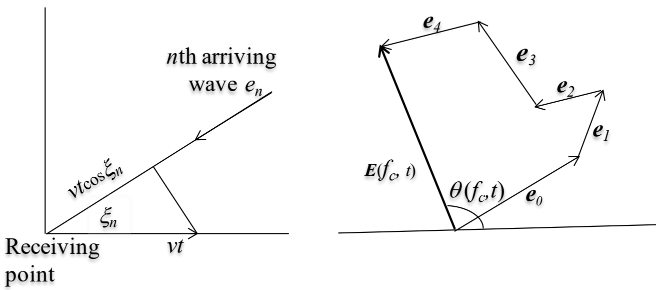
Here, θ_n is the received phase of the nth arriving wave rad, f_m is the maximum Doppler frequency calculated as v/λ_c Hz, and ϕ_n is a random phase rad. Based on (2.2), the absolute of the received level $|e_n(f_c,t)|$ does not vary and is a constant h_n, but the phase θ_n shifts by a factor of $f_m t\cos\xi_n$ with speed v and arriving angle ξ_n. Therefore the vector $\boldsymbol{e_n}$ shows that the amplitude is a constant and the phase rotates with time t. Moreover since including f_c and f_m in (2.2b), $e_n(f_c,t)$ depends on a radio frequency f_c. When all multipath waves are arriving at the receiving point, the resultant received signal level $E(f_c,t)$ is summing up all of the $e_n(f_c,t)$, and is expressed by (2.3):

$$E(f_c,t) = \sum_{n=0}^{N} h_n e^{j\theta_n} , \tag{2.3a}$$

$$= |E(f_c,t)|[\cos\theta(f_c,t) + j\sin\theta(f_c,t)]. \tag{2.3b}$$

Here n=0 means a directive wave, N is the number of arriving waves in NLOS, and $\theta(f_c,t)$ is the angle calculated by real and imaginary components in (2.3a). The state of summing up $\boldsymbol{e_n}(f_c,t)$ is shown by using the vector in Fig.2.6 (b) for N=4; the resultant of vector $\boldsymbol{E}(f_c,t)$ is calculated as the sum of all of the vector $\boldsymbol{e_n}(f_c,t)$ with independent amplitude h_n and phase θ_n.

Consequently the amplitude of vector $|\boldsymbol{E}(f_c,t)|$ varies and the phase $\theta(f_c,t)$ rotates with the receiving point moving.



(a) The nth arriving wave e_n (b) Resultant received level $\boldsymbol{E}(f_c,t)$ received with movement $\boldsymbol{v}$

Fig. 2.6 Illustration of the fading phenomenon.

The variations of amplitude $|E(f_c,t)|$ and $\theta(f_c,t)$ are shown in Fig.2.7. The amplitude varies with movement and sometimes has a deep depth within a few λ_c in movement distance; the variation is called fast fading. The propagation experiment generally measures the value of $|E(f_c,t)|$ and the data are treated as short and long-term values (as described in 2.1.2, 2). The phase $\theta(f_c,t)$ varies randomly from $-\pi$ to π rad, and the phenomenon is called random FM or troublesome irreducible noise.

Moreover, even if a receiving point is not moving, the resultant level $E(f_c,t)$ also varies with a radio frequency f_c since a phase of $e_n(f_c,t)$ shifts with the frequency f_c by (2.2b), and the variation is called selective fading.

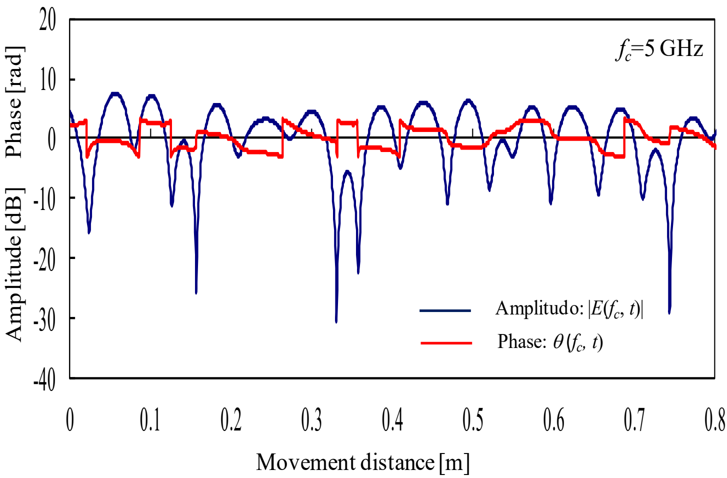


Fig. 2.7 Example of signal level variation with movement.

Therefore the amplitude of $|E(f_c,t)|$ varies with movement and radio frequency. The variation is shown in Fig.2.8, which is a domain with the distance vt and the frequency $f_c + \Delta f$ as a received bandwidth Δf [2.3]. The received level $|E(f_c,t)|$ has faded along both the distance and frequency axes, and the variation shown in Fig.2.7 corresponds to a distance axis as $f_c \approx f_c + \Delta f$, or $f_c >> \Delta f$, when the transmission system is called a narrow band system.

Both fast and selective fading are signal transmission problems. With a signal level with fast fading, the level becomes poor around the deep depth, and then the transmission quality decreases. On the contrary, the Space

Division Multiplex (SDM) transmission system utilizes the fading property as the technology for increasing channels. In a signal transmission with a wide band, when the select fading appears within the received bandwidth, the signal is distorted and needs distortion countermeasures.

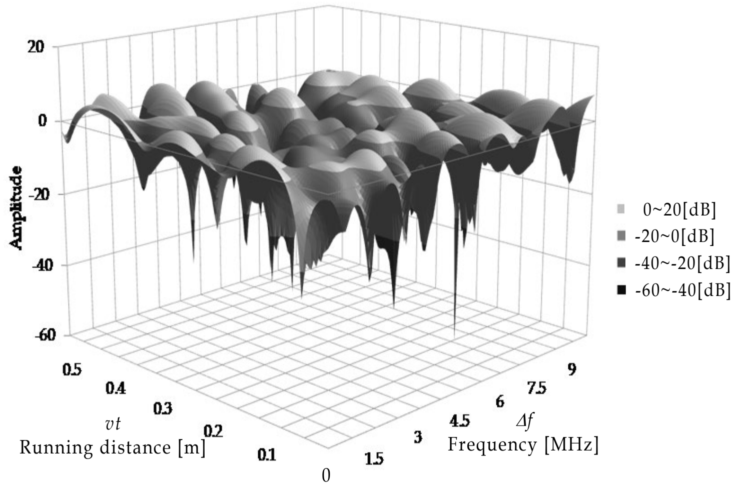


Fig. 2.8 Example of fading in the domain with space and frequency axes.

2.2.2 Received signal amplitude and phase distribution

For information transmission by radio waves, the information transmitted from the transmitting point is received instantaneously, therefore the path passed through by the information seems to see no change, or is handled as a quasi-static path even if the receiving and transmitting points are moving. An information transmission theory is established based on that assumption. Therefore the property of an instantaneously received signal level through the transmission path is needed, such as the amplitude $|E(f_c,t)|$ and phase $\theta(f_c,t)$ distributions since the information is carried in that state.

i) Amplitude distribution

When an arrived wave amplitude h_n and arriving angle ξ_n are independent of each other, moreover, ξ_n is random with $\Delta\xi = \pi$rad and the number of wave N is enough large in NLOS, S.O.Rice has shown that the probability density function (pdf) $p(r)$ of amplitude $|E(f_c,t)|$ is expressed by (2.4) [2.4],

$$p(r) = \frac{r}{b} e^{-r^2/2b} , \qquad (2.4)$$

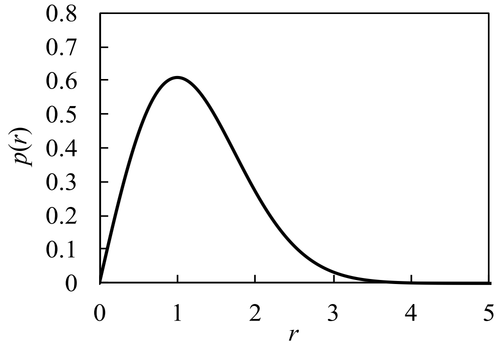
which is the Rayleigh density function. Then the fading in NLOS is called Rayleigh fading. Where r is amplitude $|E(f_c,t)|$, and b is the average power.

Furthermore, Rice showed that the probability density function $p(r)$ in LOS is expressed by (2.5) [2.5],

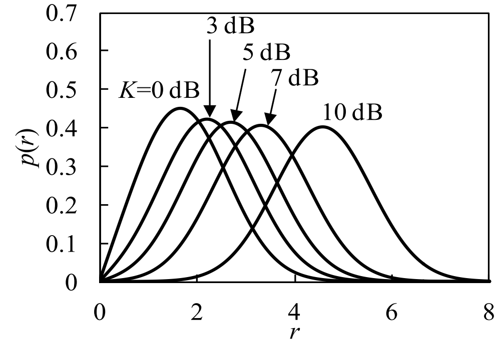
$$p(r) = \frac{r}{b} e^{-(r^2+h_0^2)/2b} \cdot I_0(rh_0/b), \qquad (2.5)$$

where $r=|E(f_c,t)|$, $|h_0|$ is a directive wave amplitude, and I_0 is a modified Bessel function of the first kind. The power ratio of the directive to non-directive waves $k=|h_0|^2/2b$ is called the Rice factor K (in dB), and the fading distribution is called an I_0 distribution.

Figs. 2.9 (a) and (b) show the probability density distributions in NLOS by (2.4) and LOS by (2.5) under b=1, changing k=1, 2, 3.15, 5 and 10. The distribution with Rayleigh fading in NLOS is non-symmetric and unique, but the fading in LOS becomes a symmetry with increasing K dB and the depth with fading is expected to be shallower.



(a) NLOS



(b) LOS

Fig. 2.9 Received signal amplitude distribution.

ii) Phase distribution

When the amplitude $|E(f_c,t)|$ by (2.3a) has a Rayleigh distribution, the phase $\theta(f_c,t)$ in (2.3b) has a uniform distribution from -π to π rad. With denoting $\dot{\theta}$ as a differential concerning time t for the phase $\theta(f_c,t)$, the probability density function is expressed by (2.6) [2.4].

$$p(\dot{\theta}) = \frac{1}{\omega_m\sqrt{2}}\left[1+2\left(\frac{\dot{\theta}}{\omega_m}\right)^2\right]^{-3/2}, \tag{2.6}$$

where $\omega_m = 2\pi f_m$. On the other hand, it is possible to express the phase difference $\Delta\theta$ between time t and $t+T_s$ by (2.7), assuming that T_s is statistically smaller than $1/f_m$.

$$\Delta\theta = \theta(t+T_S) - \theta(t) = \dot{\theta} T_s \tag{2.7}$$

Fig.2.10 shows the density distribution in the phase difference $\Delta\theta$ by simulation as a parameter of $f_m T_s$, which means the Doppler frequency wave number is between t and $t+T_s$ [2.6]. The distribution is symmetrical for the minus and plus sides and is concentrated around 0 rad when $f_m T_s$ is small but is widely distributed when it is large. It serves as a reference for transmission quality with incoherent detection.

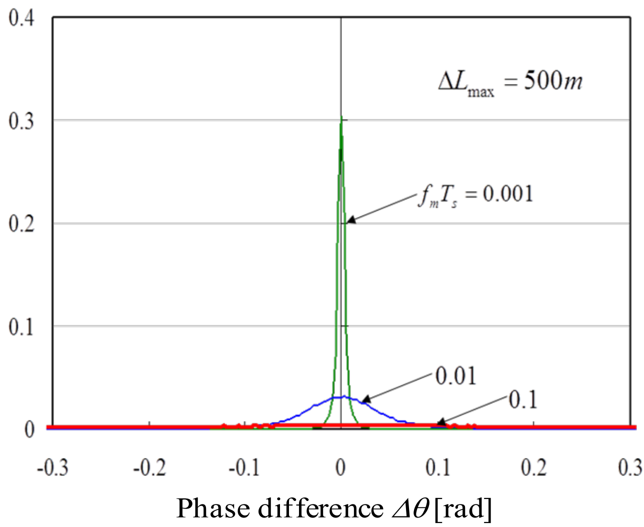


Fig. 2.10 Phase difference density distribution in Rayleigh fading.

References

[2.1] Tetsu Tanaka, Akira Akeyama, and Shigeru Kozono, "Urban Multipath Propagation Characteristics in Mobile Communications." *IEICE Trans.*, Vol. J73-B-II No. 11, 772-778, Nov. 1990.

[2.2] Shigeru Kozono, Mobile Wireless Channel in Multipath Environments -Multipath Analysis and Channel Properties. Ch. 2, Lambert Academic Publishing, 2015.

[2.3] Shigeru Kozono, Kenji Ookubo, Takeshi Kojima, and Tomohiro Hamashima, "Correlation Coefficient of Received Signal I and Q Components in a Domain with Time and Frequency Axes under Multipath Mobile Channel with LOS and NLOS" *Vehicular Technologies*. Ch. 16, Intech, Mar. 2011.

[2.4] William C. Jakes, Jr. *Microwave Mobile Communications.* Ch. 1, John Wiley & Sons, Inc., 1974.

[2.5] S.O. Rice, "Statistical Properties of a Sine Wave plus Random Noise." *B.S.T.J.*, 27, No.1, Jan. 1948.

[2.6] Shigeru Kozono and Rui Wang, "Phase Distribution Characteristics in Mobile Radio Channels-Phase Difference between Symbol Intervals and Adjacent Channels." *IEEE 59th Veh. Technol. Conf.* Milan, Spring, 2004.

CHAPTER 3

MOBILE WIRELESS CHANNELS

3.1 Principles of a wireless channel

How is information sent over radio waves? For a simple analysis, assume that a radio wave is handled as a single wave $e=h\cos(\omega_c t+\phi)$ or that the propagation path is an ideal path without multipath waves, moreover, the transmitting and receiving points are fixed [3.1]. There are three ways to carry information data by radio wave: by using the amplitude (h) of the wave, the radio frequency (ω_c), and the phase (ϕ). The corresponding ways are called amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). Here, we will discuss the quadrature phase shift keying (QPSK) on the narrowband, which is a widely used digital phase modulation. The radio wave at the transmitting site is modulated by using information data $s(t)$ and radiates from the transmitting antenna. The wave passes through a propagation path before it is received. The received radio wave $e(f_c,t,s(t))$ is expressed by (3.1a) assuming that the propagation path gain is 1, or the amplitude is 1, $\omega_c=2\pi f_c$, and $\theta(t)$ is the phase deviation due to the modulation by $s(t)$ that changes every symbol length T_s.

$$e(f_c,t,s(t)) = \cos\theta(t). \tag{3.1a}$$

$$\text{where } \theta(t) = \omega_c t + \theta_s(t), \qquad \theta_s(t) = k_{dev} s(t). \tag{3.1b}$$

The received radio wave is demodulated by the receiver. As shown in Fig. 3.1, the radio wave $e(f_c,t,s(t))$ is multiplied with $\cos\omega_c t$ and $-\sin\omega_c t$ regenerated waves, and the result is (3.2 a) and (3.2 b), which include high-frequency terms in $2\omega_c t$ and low-frequency terms in $\theta_s(t)$. The demodulation with a regenerated wave is called coherent detection.

$$e(f_c,t,s(t))\cdot\cos\omega_c t = \cos\theta(t)\cdot\cos\omega_c t = \tfrac{1}{2}[\cos(2\omega_c t+\theta_s(t))+\cos\theta_s(t)]. \tag{3.2a}$$

$$e(f_c,t,s(t))\cdot(-\sin\omega_c t) = -\cos\theta(t)\cdot\sin\omega_c t = \tfrac{1}{2}[-\sin(2\omega_c t+\theta_s(t))+\sin\theta_s(t)]. \tag{3.2b}$$