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Ye (Geoffrey) Li
Gordon L. Stüber (Eds.)

Orthogonal Frequency Division Multiplexing for Wireless Communications

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ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING FOR WIRELESS COMMUNICATIONS

Edited by

YE (GEOFFREY) LI
GORDON STÜBER
Georgia Institute of Technology

Springer

Editors:

Ye (Geoffrey) Li
Georgia Institute of Technology
School of Electrical & Computer Engineering
777 Atlanta Drive
Atlanta, GA 30332-0250

Gordon L. Stüber
Georgia Institute of Technology
School of Electrical & Computer Engineering
777 Atlanta Drive
Atlanta, GA 30332-0250

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PREFACE

Orthogonal frequency division multiplexing (OFDM) has been shown to be an effective technique to combat multipath fading in wireless channels. It has been and is going to be used in various wireless communication systems. This book gives a comprehensive introduction on the theory and practice of OFDM for wireless communications. It consists of seven chapters and each has been written by experts in the area. Chapter 1, by G. Stüber, briefly motivates OFDM and multicarrier modulation and introduces the basic concepts of OFDM, Chapter 2, by Y. (G.) Li, presents design of OFDM systems for wireless communications, various impairments caused by wireless channels, and some other types of OFDM related modulation. Chapters 3 to 6 address different techniques to mitigate the impairments and to improve the performance of OFDM systems. Chapter 3, by J. Cioffi and L. Hoo, focuses on system optimization techniques, including channel partitioning, loading of parallel channels, and optimization through coding. Chapter 4, by S. K. Wilson, addresses timing and frequency offset estimation in OFDM systems. It also briefly discusses sampling clock offset estimation and correction. Chapter 5, by Y. (G.) Li, deals with pilot aided and decision-directed channel estimation for OFDM systems. Chapter 6, by C. Tellambura and M. Friese, discusses various techniques to reduce the peak-to-average power ratio of OFDM signals. Chapter 7, by G. Stüber and A. Mody, presents recent results on synchronization for OFDM systems with multiple transmit and receive antennas for diversity and multiplexing. To facilitate the readers, about 300 subject indexes and 300 references are given at the end of the book.

This book is designed for engineers and researchers who are interested in learning and applying OFDM for wireless communications. The readers are expected to be familiar with technical concepts of communications theory, digital signal processing, linear algebra, probability and random processes.

It can be also used as a textbook for graduate courses in advanced digital communications. Nevertheless, to accommodate readers having a variety of technical backgrounds, most of the key concepts in our book are developed with detailed derivations and proofs.

Even through each chapter is written by different people, we have tried to make symbols, notations, writing styles in different chapters consistent.

The editors of the book would like to thank L. Cimini, Jr. for initiating the book project, discussing skeleton of the book, identifying potential chapter contributors, and providing insight comments on the first draft of almost every chapter. The editors are also deeply indebted to J. Cioffi, L. Hoo, S. Wilson, P. O. Börjesson, P. Ödling, J. J. van de Beek, C. Tellambura, M. Friese, and A. Mody, who not only have done important and crucial work in OFDM related research topics but also contributed chapters in this book.

In particular, Y. (G.) Li would like to thank Professor S.-X. Cheng of Southeast University, P. R. China, who first introduced the concept of parallel modem (an OFDM related modulation) to him about 20 years ago. He wishes to thank some of his pervious colleagues at AT&T Labs - Research, including, L. Cimini, Jr., N. Sollenberger, J. Winters, and J. Chuang, for their technical advising and help in his OFDM related research. He also thanks his wife, Rena, for constant support and his sons, Frank and Micheal, for understanding while carrying out the book project.

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Ye (Geoffrey) Li and Gordon Stüber
Atlanta, Georgia

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CONTENTS

Chapter 1

INTRODUCTION

Gordon Stüber

Digital bandpass modulation techniques can be broadly classified into two categories. The first is single-carrier modulation, where data is transmitted by using a single *radio frequency* (RF) carrier. The other is multi-carrier modulation, where data is transmitted by simultaneously modulating multiple RF carriers. This book is concerned with a particular type of multi-carrier modulation known as *orthogonal frequency division multiplexing* (OFDM). OFDM has gained popularity in a number of applications including digital subscriber loops, wireless local area networks. It is also a strong contender for fourth generation cellular land mobile radio systems.

OFDM transmits data in parallel by modulating a set of orthogonal sub-carriers. OFDM is attractive because it admits relatively easy solutions to some difficult challenges that are encountered when using single-carrier modulation schemes on wireless channels. Simplified frequency domain equalization is often touted as a primary advantage of OFDM over single-carrier modulation with conventional time-domain equalization. However, frequency domain equalization can be applied just as easily to single-carrier modulation techniques as it can to OFDM. Perhaps the greatest benefit of using OFDM is that the modulation of closely-spaced orthogonal sub-carriers partitions the available bandwidth into a collection of narrow sub-bands. Motivated by the water-pouring capacity of a frequency selective channel, adaptive transmission techniques can be readily used to increase the overall bandwidth efficiency. One such possibility is to use adaptive bit loading techniques, where the modulation alphabet size on each sub-carrier is adjusted according to channel conditions. A larger signal constellation is used on sub-carriers where the received signal-to-noise ratio is large, and vice versa. As will be shown later in this book, OFDM waveforms are resilient to timing errors, yet highly sensitive to frequency offsets and phase noise in the transmitter and receiver RF and sampling clock oscillators. These characteristics are op-

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posite those of single-carrier modulation, which is more sensitive to timing errors and less sensitive to frequency offsets. This is a manifestation of the long OFDM modulated symbol duration and the closely-spaced orthogonal sub-carriers. Hence, OFDM has its own set of unique implementation challenges that are not present in single-carrier systems. This book provides a comprehensive treatment of these challenges and their solutions.

1.1 High Rate Wireless Applications

The demand for high speed wireless applications and limited RF signal bandwidth has spurred the development of power and bandwidth efficient air interface schemes. Cellular telephone systems have gone through such a growth process. After the introduction of the first analog cellular systems in the early 1980s, subscriber growth for basic cellular voice services increased dramatically. This lead to the introduction of several second generation digital cellular standards in the early 1990s, such as the *Global System for Mobile communication* (GSM) and *Code Division Multiple Access* (CDMA), with the objective of providing greater system capacity so that the growing demand for voice services could be accommodated with scarce bandwidth resources.

The 1990s also seen a tremendous growth of Internet related services and applications, mostly using a wired Internet Protocol (IP) infrastructure. With the growing demand for wireless data and multimedia applications, cellular telephony and the Internet have become convergent technologies. This has lead to the development of third generation cellular standards, such as *Wideband CDMA* (WCDMA) and cdma2000, that support wireless voice, data, and multimedia applications. With the pervasiveness of the Internet, the cellular telephone network is evolving from a circuit switched to a packet switched IP-based core network. Such an infrastructure can support not only delay insensitive applications such as mobile data, but delay sensitive applications such as *voice over IP* (VoIP) as well.

The growth of the Internet also led to the development of various *wireless local area network* (WLAN) standards, such as those developed under IEEE802.11, to permit mobile connectivity to the Internet. Such services typically operate in unlicensed bands. With a surging demand for wireless Internet connectivity, new WLAN standards have been developed including IEEE802.11b, popularly known as Wi-Fi that provides up to 11 Mb/s raw data rate, and more recently IEEE802.11a/g that provides wireless connectivity with speeds up to 54 Mb/s. IEEE802.11b uses a signaling technique

Data Rate	6, 9, 12, 18, 24, 36, 48, 54 Mb/s
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding	1/2, 2/3, 3/4 CC
Number of subchannels	52
Number of pilots	4
OFDM symbol duration	4 μs
Guard interval	800 ns
Subcarrier spacing	312.5 kHz
3 dB bandwidth	16.56 MHz
Channel spacing	20 MHz

Table 1.1. Key parameters of the IEEE 802.11a OFDM standard, from [1].

based on *complementary code keying* (CCK), while IEEE802.11a uses OFDM which is the subject of this book. The main physical layer parameters of the IEEE 802.11a OFDM standard are summarized in Table 1.1. Dual mode radio access devices have been developed allowing access both public cellular networks and private WLANs, to provide a more ubiquitous and cost efficient connectivity.

More recent developments such as IEEE802.16 *wireless metropolitan area network* (WMAN) standard address *broadband fixed wireless access* (BFWA), that provides a last mile solution to compete with wireline technologies such as *Asymmetric Digital Subscriber Loop* (ADSL), coaxial cable, and satellite. Similar to IEEE802.11a, IEEE802.16 uses OFDM. The emerging *Mobile Broadband Wireless Access* (MBWA) IEEE802.20 standard extends IEEE802.16 to mobile environments. Once again, IEEE802.20 is based on OFDM. OFDM is also being considered in the IEEE802.11n standard that considers *Multiple-Input Multiple-Output* (MIMO) systems , where multiple antennas are used at the transmitter for the purpose of spatial multiplexing or to provide increased spatial diversity. Finally, OFDM has also found application in *Digital Audio Broadcast* (DAB) and *Digital Terrestrial Video Broadcast* (DVBT) standards in Europe and Japan.

1.2 Wireless Channel

To comprehend the benefits and drawbacks of OFDM, we must first understand the basic characteristics of the radio propagation environment. Radio signals generally propagate according to three mechanisms; reflection, diffraction, and scattering. The appropriate model for radio propagation depends largely on the intended application, and different models are used for the different applications such as cellular land mobile radio, WMANs, and indoor WLANs. In general, however, radio propagation can be roughly characterized by three nearly independent phenomenon; path loss attenuation with distance, shadowing, and multipath-fading. Each of these phenomenon is caused by a different underlying physical principle and each must be accounted for when designing, evaluating, and deploying any wireless system to ensure adequate coverage and quality of service.

1.2.1 Path Loss and Shadowing

It is well known that the intensity of an electromagnetic wave in free space decays with the square of the radio path length, d, such that the received power at distance d is

$$\Omega_p(d) = \Omega_t k \left(\frac{\lambda_c}{4\pi d}\right)^2 \tag{1.2.1}$$

where Ω_t is the transmitted power, λ_c is the wavelength, and k is a constant of proportionality. Although it may seem counter-intuitive, path loss is essential in high capacity frequency reuse systems, the reason being that a rapid attenuation of signal strength with distance permits the bandwidth to be reused within a close physical proximity without excessive interference. Such principles form the basis for cellular mobile radio systems.

Free space propagation does not apply in a typical wireless operating environment, and the propagation path loss depends not only on the distance and wavelength, but also on the antenna types and heights and the local topography. The site specific nature of radio propagation makes theoretical prediction of path loss difficult, except for simple cases such as propagation over a flat, smooth, reflecting surface. A simple path loss model assumes that the received power is

$$\Omega_{p\ (\mathrm{dBm})}(d) = \mu_{\Omega_{p\ (\mathrm{dBm})}}(d_o) - 10\beta \log_{10}(d/d_o) + \epsilon_{(\mathrm{dB})} \quad (\mathrm{dBm}) \tag{1.2.2}$$

where $\mu_{\Omega_{p\ (\mathrm{dBm})}}(d_o) = \mathrm{E}[\Omega_{p\ (\mathrm{dBm})}(d_o)]$ is the average received signal power (in dBm) at a known reference distance. The value of $\mu_{\Omega_{p\ (\mathrm{dBm})}}(d_o)$ depends on the transmit power, frequency, antenna heights and gains, and other factors. The parameter β is called the path loss exponent and is a key parameter that affects the coverage of a wireless system. The path loss exponent lies in the range $3 \leq \beta \leq 4$ for a typical cellular land mobile radio environment. Usually, the path loss exponents are determined from empirical measurement campaigns.

The parameter $\epsilon_{(\text{dB})}$ in (1.2.2) represents the error between the actual and estimated path loss. It is usually modelled as a zero-mean Gaussian random variable (in decibel units). This error is caused by large terrain features such as buildings and hills, and is sometimes known as shadowing or shadow fading. Shadows are generally modelled as being log-normally distributed, meaning that the probability density function of received power in decibel units, $\Omega_{(\text{dBm})}(d)$, is

$$p_{\Omega_{p\ (\text{dBm})}(d)}(x) = \frac{1}{\sqrt{2\pi}\sigma_\Omega} \exp\left\{ -\frac{(x - \mu_{\Omega_{p\ (\text{dBm})}}(d))^2}{2\sigma_\Omega^2} \right\} \tag{1.2.3}$$

where

$$\mu_{\Omega_{p\ (\text{dBm})}}(d) = \mu_{\Omega_{p\ (\text{dBm})}}(d_o) - 10\beta \log_{10}(d/d_o) \quad (\text{dBm}) \ . \tag{1.2.4}$$

The parameter σ_Ω is the shadow standard deviation, and usually ranges from 5 to 12 dB, with $\sigma_\Omega = 8$ dB being a typical value for cellular land mobile radio applications. Shadows are spatially correlated, and sometimes modelled as having an exponential decorrelation with distance.

1.2.2 Multipath-Fading

A typical radio propagation environment exhibits multipath, where the plane waves incident on the receiver antenna arrive from many different directions with random amplitudes, frequencies and phases. Since the wavelength is relatively short (approximately 30 cm at 1 GHz), small changes in the location of the transmitter, receiver and/or scattering objects in the environment will cause large changes in the phases of the incident plane wave components. The constructive and destructive addition of plane waves combined with motion results in envelope fading, where the received envelope can vary by as much as 30 to 40 dB over a spatial distance equal to a fraction of a wavelength. Multipath-fading results in a doubly dispersive channel that exhibits dispersion in both the time and frequency domains. Time dispersion arises because the multipath components propagate over transmission paths having different lengths and, hence, they reach the receiver antenna with different time delays. Time dispersion causes intersymbol interference (ISI) that can be mitigated by using a time- or frequency domain equalizer in single-carrier systems, a RAKE receiver in CDMA systems, or frequency domain equalization in OFDM systems. Channel time variations due to mobility are characterized by Doppler spreading in the frequency domain. Such time-variant channels require an adaptive receiver to estimate and track channel the channel impulse response or parameters such as the signal-to-noise ratio that are related to the channel impulse response.

A multipath-fading channel can be modelled as a linear time-variant filter having the complex low-pass impulse response

$$h(t, \tau) = \sum_{n=1}^{N} C_n e^{j\phi_n(t)} \delta(\tau - \tau_n) \tag{1.2.5}$$

where $g(\tau, t)$ is the channel response at time t due to an impulse applied at time $t - \tau$, and $\delta(\cdot)$ is the dirac delta function. In (1.2.5), C_n, ϕ_n, and τ_n are the random amplitude, phase, and time delay, respectively, associated with the nth propagation path, and N is the total number of arriving multipath components. The time-variant phases $\phi_n(t)$ are given by [2]

$$\phi_n(t) = 2\pi(f_{D,n}t + \phi_n) \tag{1.2.6}$$

where ϕ_n is an arbitrary random phase uniformly distributed on the interval $[-\pi, \pi]$ and

$$f_{D,n} = f_m \cos\theta_n \tag{1.2.7}$$

is the Doppler frequency associated with the nth propagation path, where $f_d = v/\lambda_c$, λ_c is the carrier wavelength, and f_d is the maximum Doppler frequency occurring when the angle of arrival $\theta_n = 0$.

1.3 Interference and Noise

All communication systems are affected by thermal noise or *additive white Gaussian noise* (AWGN). However, wireless systems that employ frequency reuse are also affected by the more dominant *co-channel interference* (CCI). Co-channel interference arises when the carrier frequencies are spatially reused. In this case, the power density spectra of the co-channel signals overlap causing mutual interference. CCI places a limit on the minimum spatial separation that is required such that the carrier frequencies can be reused. CCI is the primary additive impairment in high capacity frequency reuse systems, such as cellular land mobile radio systems. Fig. 1.1 depicts the worst case forward channel co-channel interference situation in a cellular radio environment, which occurs when the mobile station is located at the corner of a cell at the maximum possible distance from its serving base station. With omni-directional antennas, there are six primary co-channel interferers; two at distance $D - R$, two at distance D, and two at distance of $D + R$, where R is the cell radius. Using the simple path loss model in (1.2.4) and neglecting shadowing, the worst case *carrier-to-interference ratio* is

$$\begin{aligned}\frac{C}{I} &= \frac{1}{2}\,\frac{R^{-\beta}}{(D-R)^{-\beta}+D^{-\beta}+(D+R)^{-\beta}}\\ &= \frac{1}{2}\,\frac{1}{\left(\frac{D}{R}-1\right)^{-\beta}+\left(\frac{D}{R}\right)^{-\beta}+\left(\frac{D}{R}+1\right)^{-\beta}}\end{aligned} \tag{1.3.1}$$

where β is the propagation path loss exponent. The parameter D/R is called the co-channel reuse factor. In a hexagonal cell deployment D/R is related to the reuse cluster size, N, by $D/R = \sqrt{3N}$. Clearly, the C/I increases with the cluster size, thereby providing better link quality. However, at the same time the available bandwidth (and number of channels) per cell decreases, thereby increasing the new call and handoff call blocking probabilities.

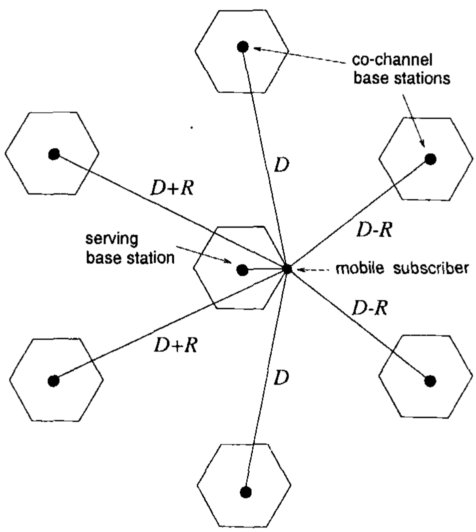

Figure 1.1. Worst case co-channel interference on the forward channel.

Frequency reuse also introduces adjacent channel interference (ACI). This type of interference arises when adjacent cells use channels that are spectrally adjacent to each other. In this case, the power density spectrum of the desired and interfering signals partially overlap. Although ACI de-

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