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To my wife, Jennifer, my lovely kids Heather and Edmund,
and my parents Zhengfa and Chaorong.
—William Shieh

To my parents Blagoje and Verica, brother Slavisa,
and to Milena.
—Ivan Djordjevic

Preface

We have recently witnessed a dramatic surge of interest in orthogonal frequency-division multiplexing (OFDM) from the optical communications community. This is evidenced by an increase in the number of publications, and many eye-catching "hero" experimental demonstrations of OFDM technology in a wide spectrum of applications. One of the main drivers behind the emergence of OFDM technology in optical communications is the rapid advance of silicon signal processing capability underpinned by Moore's Law. The introduction of sophisticated electronic digital signal processing (DSP) and coding could fundamentally alter optical networks as we see them today. On the other hand, although OFDM has emerged as the leading physical interface in wireless communications over the past two decades, it is still regarded as alien by many optical engineers. The most frequently asked question is whether OFDM can provide a solution to the major problems of today's "fragile" and "rigid" optical networks.

This book intends to give a coherent and comprehensive introduction to the fundamentals of OFDM signal processing and coding, with a distinctive focus on its broad range of applications. It is designed for two diverse groups of researchers: (1) optical communication engineers who are proficient in optical science and interested in applying OFDM technology, but who are intimidated by sophisticated OFDM terminologies, and (2) wireless communication engineers who are content with their DSP skill set, but are disoriented by a perceived huge gap between the optical and radio-frequency (RF) communications worlds. We have attempted to make the individual chapters self-contained while maintaining the flow and connectivity between them.

The book is organized into twelve chapters, and describes various topics related to optical OFDM, starting from basic mathematical formulation through OFDM signal processing and coding for OFDM, to various applications, such as single-mode fiber transmission, multimode fiber transmission, free space-optical systems, and optical access networks. The book also provides fundamental concepts of optical communication, basic channel impairments and noise sources, and optical system engineering process. The book presents interesting research problems in the emerging field of optical OFDM and touches the intriguing issue of standardization of optical OFDM technology.

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Author Biography

William Shieh is an associate professor and reader in the Electrical and Electronic Engineering Department at the University of Melbourne, Melbourne, Australia. He received his M.S. in electrical engineering and Ph.D. in physics from the University of Southern California, Los Angeles, in 1994 and 1996, respectively. From 1996 to 1998 he worked as a member of Technical Staff in the Jet Propulsion Laboratory, Pasadena, CA. From 1998 to 2000 he worked as a member of Technical Staff in Bell Labs, Lucent Technologies, Holmdel, NJ. From 2000 to 2003 he worked as a technical manager in Dorsal Networks, Columbia, MD. Since 2004 he has been with the Electrical and Electronic Engineering Department at the University of Melbourne, Melbourne, Australia.

Ivan Djordjevic is an assistant professor of Electrical and Computer Engineering (ECE) at the University of Arizona, Tucson. Prior to this appointment in August 2006 he was with University of Arizona, Tucson, as a research assistant professor; University of the West of England, Bristol, UK; University of Bristol, Bristol, UK; Tyco Telecommunications, Eatontown, USA; and National Technical University of Athens, Athens, Greece. His current research interests include optical networks, error control coding, constrained coding, coded modulation, turbo equalization, OFDM applications, and quantum error correction. He currently directs the Optical Communications Systems Laboratory (OCSL) within the Electrical and Computer Engineering Department at the University of Arizona. Dr. Djordjevic serves as an associate editor for *Research Letters in Optics* and as an associate editor for *International Journal of Optics*. Dr. Djordjevic is an author of about 100 journal publications and over 80 conference papers.

Contents

CHAPTER 1

Introduction

In the virtually infinite broad electromagnetic spectrum, there are only two windows that have been largely used for modern-day broadband communications. The first window spans from the long-wave radio to millimeter wave, or from 100 kHz to 300 GHz in frequency, whereas the second window lies in the infrared lightwave region, or from 30 THz to 300 THz in frequency. The first window provides the applications that we use in our daily lives, including broadcast radio and TV, wireless local area networks (LANs), and mobile phones. These applications offer the first meter or first mile access of the information networks to the end user with broadband connectivity or the mobility in the case of the wireless systems. Nevertheless, most of the data rates are capped below gigabit per second (Gb/s) primarily due to the lack of the available spectrum in the RF microwave range. In contrast, due to the enormous bandwidth over several terahertz (THz) in the second window, the lightwave systems can provide a staggering capacity of 100 Tb/s and beyond. In fact, the optical communication systems, or fiber-optic systems in particular, have become indispensable as the backbone of the modern-day information infrastructure. There has been a worldwide campaign in the past decade to push the fiber ever closer to the home. Despite the fact that the Internet "bubble" fizzled out in the early 2000s, Internet traffic has been increasing at an astounding rate of 75% per year.[1,2] The new emerging video-centric applications such as IPTV will continue to put pressure on the underlying information infrastructure.

Digital modulation techniques can be generally classified into two categories. The first is single-carrier modulation, in which the data are carried on a single main carrier. This is the "conventional" modulation format that has been the workhorse in optical communications for more than three decades. Single-carrier modulation has in fact experienced rapid advancement in recent years, and many variants to the conventional non-return-to-zero (NRZ) format have been actively explored, including return-to-zero (RZ),[3,4] duobinary,[5,6] differential phase-shift keying (DPSK),[7,8,9] and coherent quaternary phase-shift keying (QPSK).[10–12] The second category of modulation technique is multicarrier transmission, in which the data are carried through many closely spaced subcarriers. Orthogonal frequency-division multiplexing (OFDM) is a special class of MCM system that has only recently gained attention in the optical communication community, especially after being proposed as the attractive long-haul transmission format in coherent detection[13] and direct detection.[14,15]

Experiments on coherent optical OFDM (CO-OFDM) transmission at 100 Gb/s by various groups[16–18] have put the optical OFDM in the race for the next generation of 100 Gb/s Ethernet transport.

OFDM has emerged as the leading modulation technique in the RF domain, and it has evolved into a fast-progressing and vibrant field. It has been triumphant in almost every major communication standard, including wireless LAN (IEEE 802.11 a/g, also known as Wi-Fi), digital video and audio standards (DAV/DAB), and digital subscriber loop (DSL). It is not surprising that the two competing fourth-generation (4G) mobile network standards, Worldwide Interoperability for Microwave Access (WiMAX, or IEEE 802.16) from the computing community and Long-Term Evolution (LTE) from the telecommunication community, both have adopted OFDM as the core of their physical interface. Although the arrival of optical OFDM has been quite recent, it does inherit the major controversy that has lingered more than a decade in the wireless community—the debate about the supremacy of single-carrier or multicarrier transmission.[19,20] It has been claimed that OFDM is advantageous with regard to computation efficiency due to the use of fast Fourier transform (FFT), but the single carrier that incorporates cyclic prefix based on blocked transmission can achieve the same purpose.[19,20] Perhaps the advantage of the OFDM has to do with the two unique features that are intrinsic to multicarrier modulation. The first is scalable spectrum partitioning from individual subcarriers to a sub-band and the entire OFDM spectrum, which provides tremendous flexibility in either device-, or subsystem-, or system-level design compared to single-carrier transmission. The second is the adaptation of pilot subcarriers simultaneously with the data carriers enabling rapid and convenient ways for channel and phase estimation. In this book, we do not intend to resolve the debate on the superiority between single-carrier and multicarrier transmission. Instead, we focus on multicarrier modulation related to its principle, design, transmission, and application. Readers who are interested in advanced modulation formats for single-carrier transmission are referred to other excellent reading material that summarizes progress in single-carrier transmission.[21,22]

Optical OFDM bears both similarities to and differences from the RF counterpart. On the one hand, optical OFDM suffers from two well-known problems, namely high peak-to-average power ratio (PAPR) and sensitivity to phase/frequency noise. On the other hand, the optical channel has its own unique set of problems. One of the prominent differences is the existence of fiber channel nonlinearity and its intricate interaction with fiber dispersion, which is nonexistent in the RF systems. Furthermore, in the RF systems, the main nonlinearity occurs in the RF power amplifier, where a bandpass filter cannot be used to cut off the out-of-band leakage due to unacceptable filter loss. However, in optical OFDM systems, the erbium-doped fiber amplifier (EDFA; by far the most prevalent optical amplifier) is perfectly linear regardless of the level of saturation, and it is usually accompanied by a wavelength multiplexor that can remove the out-of-band spectral leakage.

In summary, after reading this book, we expect that readers—whether from an RF or an optical background—will grasp the unique promises and challenges of the optical OFDM systems.

1.1 Historical Perspective of Optical Communications

The use of light as a means of communication is natural and can be traced back to early ages of many civilizations. For instance, along the Great Wall of China is a relatively sophisticated ancient communication system composed of countless beacon towers that in many ways resembles modern-day optical communication systems. Using the color of smoke or the number of lanterns to inform the size of an invading enemy is a crude method of "multilevel" signaling. Analogous to today's repeated communication systems, the beacon towers are positioned at regular intervals along the Great Wall, and guards in each tower, upon seeing a signal from the previous one, would send the same pattern of signal to the next tower. A message could be relayed from one end of the Great Wall to the other, more than 7300 km, in slightly more than 1 hour.

Optical communication systems took a back seat for quite awhile after the advent of telegraphy, telephone, and radio networks in the first half of the 20th century. However, in the late 20th century, such electrical-based systems had reached a point of saturation in terms of capacity and reach. A typical coaxial transport system operated at a rate of 200 Mb/s needs to regenerate every 1 km, which is costly to operate. The natural trend was to study the lightwave communication systems, in which the data rate can be increased dramatically. This was boosted after the invention and the realization of a laser that gives a coherent source for the transmitter.[23] The remaining obstacle is to find an appropriate lightwave transmission medium. In 1966, Kao and Hockman proposed the idea of using the optical fiber as the lightwave transmission medium despite the fact that optical fiber at the time suffered unacceptable loss.[24] They argued that the attenuation in fibers available at the time was caused by impurities, which could be removed, rather than by any fundamental physical effects such as Rayleigh scattering. Their prophetic prediction of 20 dB/km for telecom-grade optical fiber was realized 5 years later by researchers from Corning, and currently a loss of 0.2 dB/km is the routine specification for single-mode fiber.

Despite their extremely low loss compared to that of the RF counterpart, optical systems still need regeneration for spans commonly less than 100 km. In the late 1980s and early 1990s, coherent detection communication systems were introduced to enhance the transmission distance.[25–27] However, this effort faded after the invention of the optical amplifier in the 1990s. The advent of the optical amplifier heralded a new era of optical communications in which a massive number of wavelength-division multiplexing (WDM) signals can be conveyed over thousands of kilometers.[28]