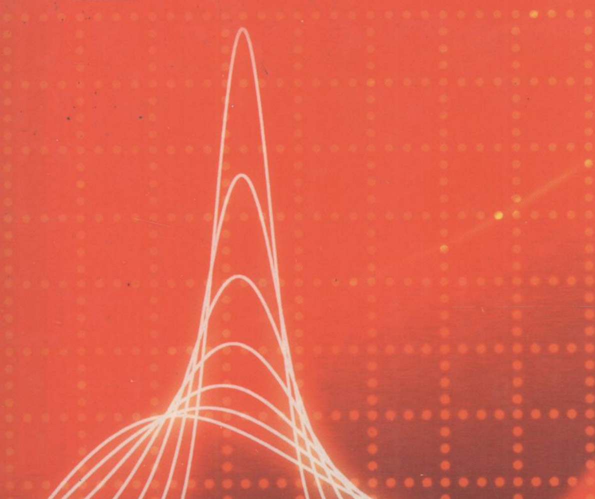
HENRIK SCHULZE
CHRISTIAN LÜDERS



THEORY AND APPLICATIONS OF OFDM AND CDMA

WIDEBAND WIRELESS COMMUNICATIONS

WILEY

Companion Website

Theory and Applications of OFDM and CDMA

Wideband Wireless Communications

Henrik Schulze
and
Christian Lüders

Both of
Fachhochschule Südwestfalen
Meschede, Germany

John Wiley & Sons, Ltd

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-13 978-0-470-85069-5 (HB)
ISBN-10 0-470-85069-8 (HB)

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India.
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire.
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Theory and Applications of OFDM and CDMA

Preface

Wireless communication has become increasingly important not only for professional applications but also for many fields in our daily routine and in consumer electronics. In 1990, a mobile telephone was still quite expensive, whereas today most teenagers have one, and they use it not only for calls but also for data transmission. More and more computers use wireless local area networks (WLANs), and audio and television broadcasting has become digital.

Many of the above-mentioned communication systems make use of one of two sophisticated techniques that are known as *orthogonal frequency division multiplexing* (OFDM) and *code division multiple access* (CDMA).

The first, OFDM, is a digital multicarrier transmission technique that distributes the digitally encoded symbols over several *subcarrier* frequencies in order to reduce the symbol clock rate to achieve robustness against long echoes in a multipath radio channel. Even though the spectra of the individual subcarriers overlap, the information can be completely recovered without any interference from other subcarriers. This may be surprising, but from a mathematical point of view, this is a consequence of the *orthogonality* of the base functions of the Fourier series.

The second, CDMA, is a multiple access scheme where several users share the same physical medium, that is, the same frequency band at the same time. In an ideal case, the signals of the individual users are *orthogonal* and the information can be recovered without interference from other users. Even though this is only approximately the case, the concept of *orthogonality* is quite important to understand why CDMA works. It is due to the fact that pseudorandom sequences are approximately orthogonal to each other or, in other words, they show good correlation properties. CDMA is based on *spread spectrum*, that is, the spectral band is *spread* by multiplying the signal with such a pseudorandom sequence. One advantage of the enhancement of the bandwidth is that the receiver can take benefit from the multipath properties of the mobile radio channel.

OFDM transmission is used in several digital audio and video broadcasting systems. The pioneer was the European DAB (Digital Audio Broadcasting) system. At the time when the project started in 1987, hardly any communication engineers had heard about OFDM. One author (Henrik Schulze) remembers well that many practical engineers were very suspicious of these rather abstract and theoretical underlying ideas of OFDM. However, only a few years later, the DAB system became the leading example for the development of the digital terrestrial video broadcasting system, DVB-T. Here, in contrast to DAB, coherent higher-level modulation schemes together with a sophisticated and powerful channel estimation technique are utilized in a multipath-fading channel. High-speed WLAN systems like IEEE 802.11a and IEEE 802.11g use OFDM together with very similar channel coding and modulation. The European standard HIPERLAN/2 (High Performance Local Area Network, Type 2) has the same OFDM parameters as these IEEE systems and differs only in a few options concerning channel coding and modulation. Recently, a broadcasting system called DRM (Digital Radio Mondiale) has been developed to replace the antiquated analog AM radio transmission in the frequency bands below 30 MHz. DRM uses OFDM together with a sophisticated multilevel coding technique.

The idea of spread spectrum systems goes back to military applications, which arose during World War II, and were the main field for spread spectrum techniques in the following decades. Within these applications, the main benefits of spreading are to hide a signal, to protect it against eavesdropping and to achieve a high robustness against intended interference, that is, to be able to separate the useful signal from the strong interfering one. Furthermore, correlating to a spreading sequence may be used within radar systems to obtain reliable and precise values of propagation delay for deriving the position of an object.

A system where different (nearly orthogonal) spreading sequences are used to separate the signals transmitted from different sources is the Global Positioning System (GPS) developed in about 1970. Hence, GPS is the first important system where code division multiple access (CDMA) is applied. Within the last 10 years, CDMA has emerged as the most important multiple access technique for mobile communications. The first concept for a CDMA mobile communication system was developed by Qualcomm Incorporated in approx 1988. This system proposal was subsequently refined and released as the so-called IS-95 standard in North America. In the meantime, the system has been rebranded as cdmaOne, and there are more than 100 millions of cdmaOne subscribers in more than 40 countries. Furthermore, cdmaOne has been the starting point for cdma2000, a third-generation mobile communication system offering data rates of up to some Mbit/s. Another very important third-generation system using CDMA is the Universal Mobile Telecommunications System (UMTS); UMTS is based on system proposals developed within a number of European research projects. Hence, CDMA is the dominating multiple access technique for third generation mobile communication systems.

This book has both theoretical and practical aspects. It is intended to provide the reader with a deeper understanding of the concepts of OFDM and CDMA. Thus, the theoretical basics are analyzed and presented in some detail. Both of the concepts are widely applied in practice. Therefore, a considerable part of the book is devoted to system design and implementation aspects and to the presentation of existing communication systems.

The book is organized as follows. In Chapter 1, we give a brief overview of the basic principles of digital communications and introduce our notation. We represent signals as vectors, which often leads to a straightforward geometrical visualization of many seemingly abstract mathematical facts. The concept of orthogonality between signal vectors is a key to the understanding of OFDM and CDMA, and the Euclidean distance between signal vectors is an important concept to analyze the performance of a digital transmission system. Wireless communication systems often have to cope with severe multipath fading in a mobile radio channel. Chapter 2 treats these aspects. First, the physical situation of multipath propagation is analyzed and statistical models of the mobile radio channel are presented. Then, the problems of digital transmission over these channels are discussed and the basic principles of Chapter 1 are extended for those channels. Digital wireless communication over fading channels is hardly possible without using some kind of error protection or channel coding. Chapter 3 gives a brief overview of the most important channel coding techniques that are used in the above-mentioned communication systems. Convolutional codes are typically used in these systems, and many of the systems have very closely related (or even identical) channel coding options. Thus, the major part of Chapter 3 is dedicated to convolutional codes as they are applied in these systems. A short presentation of Reed–Solomon Codes is also included because they are used as outer codes in the DVB-T system, together with inner convolutional codes. Chapter 4 is devoted to OFDM. First, the underlying ideas and the basic principles are explained by using the basic principles presented in Chapter 1. Then implementation aspects are discussed as well as channel estimation and synchronization aspects that are relevant for the above-mentioned systems. All these systems are designed for mobile radio channels and use channel coding. Therefore, we give a comprehensive discussion of system design aspects and how to fit all these things together in an optimal way for a given channel. Last but not least, the transmission schemes for DAB, DVB-T and WLAN systems are presented and discussed. Chapter 5 is devoted to CDMA, focusing on its main application area – mobile communications. This application area requires not only sophisticated digital transmission techniques and receiver structures but also some additional methods as, for example, a soft handover, a fast and exact power control mechanism as well as some special planning techniques to achieve an acceptable radio network performance. Therefore, the first section of Chapter 5 discusses these methods and some general principles of CDMA and mobile radio networks. CDMA receivers may be simple or quite sophisticated, thereby making use of knowledge about other users. These theoretically involved topics are treated in the following three subsections. As examples of CDMA applications we discuss the most important systems already mentioned, namely, GPS, cdmaOne (IS-95), cdma2000 and UMTS with its two transmission modes called Wideband CDMA and Time Division CDMA. Furthermore, Wireless LAN systems conforming to the standard IEEE 802.11 are also included in this section as some transmission modes of these systems are based on spreading.

This book is supported by a companion website on which lecturers and instructors can find electronic versions of the figures contained within the book, a solutions manual to the problems at the end of each chapter and also chapter summaries. Please go to ftp://ftp.wiley.co.uk/pub/books/schulze

Contents

1

Basics of Digital Communications

1.1 Orthogonal Signals and Vectors

The concept of *orthogonal signals* is essential for the understanding of OFDM (orthogonal frequency division multiplexing) and CDMA (code division multiple access) systems. In the normal sense, it may look like a miracle that one can separately demodulate overlapping carriers (for OFDM) or detect a signal among other signals that share the same frequency band (for CDMA). The concept of orthogonality unveils this miracle. To understand these concepts, it is very helpful to interpret signals as vectors. Like vectors, signals can be added, multiplied by a scalar, and they can be expanded into a base. In fact, signals fit into the mathematical structure of a vector space. This concept may look a little bit abstract. However, vectors can be visualized by geometrical objects, and many conclusions can be drawn by simple geometrical arguments without lengthy formal derivations. So it is worthwhile to become familiar with this point of view.

1.1.1 The Fourier base signals

To visualize signals as vectors, we start with the familiar example of a Fourier series. For reasons that will become obvious later, we do not deal with a periodic signal, but cut off outside the time interval of one period of length T. This means that we consider a well-behaved (e.g. integrable) real signal $x(t)$ inside the time interval $0 \leq t \leq T$ and set $x(t) = 0$ outside. Inside the interval, the signal can be written as a Fourier series

$$x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos\left(2\pi \frac{k}{T} t\right) - \sum_{k=1}^{\infty} b_k \sin\left(2\pi \frac{k}{T} t\right). \tag{1.1}$$

The Fourier coefficients a_k and b_k are given by

$$a_k = \frac{2}{T} \int_0^T \cos\left(2\pi \frac{k}{T} t\right) x(t)\, \mathrm{d}t \tag{1.2}$$

Theory and Applications of OFDM and CDMA Henrik Schulze and Christian Lüders

and

$$b_k = -\frac{2}{T}\int_0^T \sin\left(2\pi \frac{k}{T} t\right) x(t)\,\mathrm{d}t. \tag{1.3}$$

These coefficients are the amplitudes of the cosine and (negative) sine waves at the respective frequencies $f_k = k/T$. The cosine and (negative) sine waves are interpreted as a *base* for the (well-behaved) signals inside the time interval of length T. Every such signal can be expanded into that base according to Equation (1.1) inside that interval. The underlying mathematical structure of the Fourier series is similar to the expansion of an N-dimensional vector $\mathbf{x} \in \mathcal{R}^N$ into a base $\{\mathbf{v}_i\}_{i=1}^N$ according to

$$\mathbf{x} = \sum_{i=1}^{N} \alpha_i \mathbf{v}_i. \tag{1.4}$$

The base $\{\mathbf{v}_i\}_{i=1}^N$ is called *orthonormal* if two different vectors are orthogonal (perpendicular) to each other and if they are normalized to length one, that is,

$$\mathbf{v}_i \cdot \mathbf{v}_k = \delta_{ik},$$

where δ_{ik} is the Kronecker Delta ($\delta_{ik} = 1$ for $i = k$ and $\delta_{ik} = 0$ otherwise) and the dot denotes the usual scalar product

$$\mathbf{x} \cdot \mathbf{y} = \sum_{i=1}^{N} x_i y_i = \mathbf{x}^T \mathbf{y}$$

for real N-dimensional vectors. In that case, the coefficients α_i are given by

$$\alpha_i = \mathbf{v}_i \cdot \mathbf{x}.$$

For an orthonormal base, the coefficients α_i can thus be interpreted as the projections of the vector $\mathbf{x}$ onto the base vectors, as depicted in Figure 1.1 for $N = 2$. Thus, α_i can be interpreted as the *amplitude* of $\mathbf{x}$ in the direction of $\mathbf{v}_i$.

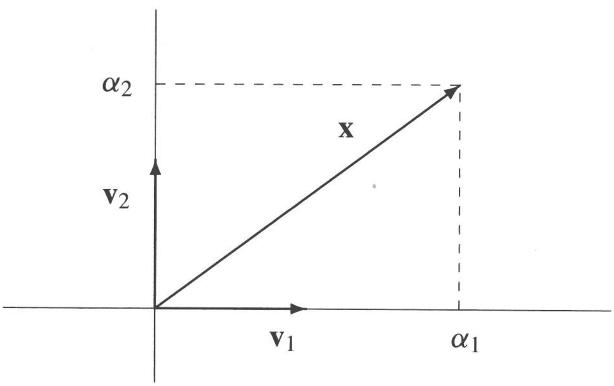


Figure 1.1 A signal vector in two dimensions.

The Fourier expansion (1.1) is of the same type as the expansion (1.4), except that the sum is infinite. For a better comparison, we may write

$$x(t) = \sum_{i=0}^{\infty} \alpha_i v_i(t)$$

with the normalized base signal vectors $v_i(t)$ defined by

$$v_0(t) = \sqrt{\frac{1}{T}}\,\Pi\left(\frac{t}{T} - \frac{1}{2}\right)$$

and

$$v_{2k}(t) = \sqrt{\frac{2}{T}}\cos\left(2\pi\frac{k}{T}t\right)\Pi\left(\frac{t}{T} - \frac{1}{2}\right)$$

for even $i > 0$ and

$$v_{2k+1}(t) = -\sqrt{\frac{2}{T}}\sin\left(2\pi\frac{k}{T}t\right)\Pi\left(\frac{t}{T} - \frac{1}{2}\right)$$

for odd i with coefficients given by

$$\alpha_i = \int_{-\infty}^{\infty} v_i(t)x(t)\,\mathrm{d}t,$$

that is,

$$\alpha_{2k} = \sqrt{T/2}a_k$$

and

$$\alpha_{2k+1} = \sqrt{T/2}b_k.$$

Here we have introduced the notation $\Pi(x)$ for the rectangular function, which takes the value one between $x = -1/2$ and $x = 1/2$ and zero outside. Thus, $\Pi(x - 1/2)$ is the rectangle between $x = 0$ and $x = 1$. The base of signals $v_i(t)$ fulfills the orthonormality condition

$$\int_{-\infty}^{\infty} v_i(t)v_k(t)\,\mathrm{d}t = \delta_{ik}. \tag{1.5}$$

We will see in the following text that this just means that the Fourier base forms a set of orthogonal signals. With this interpretation, Equation (1.5) says that the base signals for different frequencies are orthogonal and, for the same frequency $f_k = k/T$, the sine and cosine waves are orthogonal.

We note that the orthonormality condition and the formula for α_i are very similar to the case of finite-dimensional vectors. One just has to replace sums by integrals. A similar geometrical interpretation is also possible; one has to regard signals as vectors, that is, identify $v_i(t)$ with $\mathbf{v}_i$ and $x(t)$ with $\mathbf{x}$. The interpretation of α_i as a projection on $\mathbf{v}_i$ is obvious. For only two dimensions, we have $x(t) = \alpha_1 v_1(t) + \alpha_2 v_2(t)$, and the signals can be adequately described by Figure 1.1. In this special case, where $v_1(t)$ is a cosine signal and $v_2(t)$ is a (negative) sine signal, the figure depicts nothing else but the familiar phasor diagram. However, this is just a special case of a very general concept that applies to many other scenarios in communications.

Before we further discuss this concept for signals by introducing a scalar product for signals, we continue with the complex Fourier transform. This is because complex signals are a common tool in communications engineering.

Consider a well-behaved complex signal $s(t)$ inside the time interval $[0, T]$ that vanishes outside that interval. The complex Fourier series for that signal can be written as

$$s(t) = \sum_{k=-\infty}^{\infty} \alpha_k v_k(t) \tag{1.6}$$

with the (normalized) complex Fourier base functions

$$v_k(t) = \sqrt{\frac{1}{T}} \exp\left(j2\pi \frac{k}{T}t\right) \Pi\left(\frac{t}{T} - \frac{1}{2}\right). \tag{1.7}$$

The base functions are orthonormal in the sense that

$$\int_{-\infty}^{\infty} v_i^*(t) v_k(t)\, \mathrm{d}t = \delta_{ik}. \tag{1.8}$$

holds. The Fourier coefficient α_k will be obtained from the signal by the Fourier analyzer. This is a detection device that performs the operation

$$\alpha_k = \int_{-\infty}^{\infty} v_i^*(t) s(t)\, \mathrm{d}t. \tag{1.9}$$

This coefficient is the complex amplitude (i.e. amplitude and phase) of the wave at frequency f_k. It can be interpreted as the component of the signal vector $s(t)$ in the direction of the base signal vector $v_k(t)$, that is, we interpret frequency components as vector components or vector *coordinates*.

Example 1 (OFDM Transmission) *Given a finite set of complex numbers s_k that carry digitally encoded information to be transmitted, we may use the complex Fourier series for this purpose and transmit the signal*

$$s(t) = \sum_{k=0}^{K} s_k v_k(t). \tag{1.10}$$

The transmitter performs a Fourier synthesis. *In an ideal transmission channel with perfect synchronization and no disturbances, the transmit symbols s_k can be completely recovered at the receiver by the Fourier analyzer that plays the role of the detector. One may send K new complex symbols during every time slot of length T by performing the Fourier synthesis for that time slot. At the receiver, the Fourier analysis is done for every time slot. This method is called* orthogonal frequency division multiplexing (OFDM). *This name is due to the fact that the transmit signals form an orthogonal base belonging to different frequencies f_k. We will see in the following text that other – even more familiar – transmission setups use orthogonal bases.*

1.1.2 The signal space

A few mathematical concepts are needed to extend the concept of orthogonal signals to other applications and to represent the underlying structure more clearly. We consider (real or complex) signals of finite energy, that is, signals $s(t)$ with the property

$$\int_{-\infty}^{\infty} |s(t)|^2 \, \mathrm{d}t < \infty. \tag{1.11}$$

The assumption that our signals should have finite energy is physically reasonable and leads to desired mathematical properties. We note that this set of signals has the property of a vector space, because finite-energy signals can be added or multiplied by a scalar, resulting in a finite-energy signal. For this vector space, a scalar product is given by the following:

Definition 1.1.1 (Scalar product of signals) *In the vector space of signals with finite energy, the scalar product of two signals $s(t)$ and $r(t)$ is defined as*

$$\langle s, r \rangle = \int_{-\infty}^{\infty} s^*(t) r(t) \, \mathrm{d}t. \tag{1.12}$$

Two signals are called orthogonal if their scalar product equals zero. The Euclidean norm of the signal is defined by $\|s\| = \sqrt{\langle s, s \rangle}$, and $\|s\|^2 = \langle s, s \rangle$ is the signal energy. $\|s - r\|^2$ is called the squared Euclidean distance *between $s(t)$ and $r(t)$.*

We add the following remarks:

- This scalar product has a structure similar to the scalar product of vectors $\mathbf{s} = (s_1, \ldots, s_K)^T$ and $\mathbf{r} = (r_1, \ldots, r_K)^T$ in a K-dimensional complex vector space given by

$$\mathbf{s}^\dagger \mathbf{r} = \sum_{k=1}^{K} s_k^* r_k,$$

  where the dagger (†) means conjugate transpose. Comparing this expression with the definition of the scalar product for continuous signals, we see that the sum has to be replaced by the integral.

- It is a common use of notation in communications engineering to write a function with an argument for the function, that is, to write $s(t)$ for a signal (which is a function of the time) instead of s, which would be the mathematically correct notation. In most cases, we will use the engineer's notation, but we write, for example, $\langle s, r \rangle$ and not $\langle s(t), r(t) \rangle$, because this quantity does not depend on t. However, sometimes we write s instead of $s(t)$ when it makes the notation simpler.

- In mathematics, the vector space of square integrable functions (i.e. finite-energy signals) with the scalar product as defined above is called the *Hilbert space* $L^2(\mathcal{R})$. It is interesting to note that the Hilbert space of finite-energy signals is the same as the Hilbert space of wave functions in quantum mechanics. For the reader who is interested in details, we refer to standard text books in mathematical physics (see e.g. (Reed and Simon 1980)).

Without proof, we refer to some mathematical facts about that space of signals with finite energy (see e.g. (Reed and Simon 1980)).

- Each signal $s(t)$ of finite energy can be expanded into an orthonormal base, that is, it can be written as

$$s(t) = \sum_{k=1}^{\infty} \alpha_k v_k(t) \tag{1.13}$$

with properly chosen orthonormal base signals $v_k(t)$. The coefficients can be obtained from the signal as

$$\alpha_k = \langle v_k, s \rangle . \tag{1.14}$$

The coefficient α_k can be interpreted as the component of the signal vector s in the direction of the base vector v_k.

- For any two finite energy signals $s(t)$ and $r(t)$, the Schwarz inequality

$$|\langle s, r \rangle| \leq \|s\| \, \|r\|$$

holds. Equality holds if and only if $s(t)$ is proportional to $r(t)$.

- The Fourier transform is well defined for finite-energy signals. Now, let $s(t)$ and $r(t)$ be two signals of finite energy, and $S(f)$ and $R(f)$ denote their Fourier transforms. Then,

$$\langle s, r \rangle = \langle S, R \rangle$$

holds. This fact is called *Plancherel theorem* or *Rayleigh theorem* in the mathematical literature (Bracewell 2000). The above equality is often called *Parseval's equation*. As an important special case, we note that the signal energy can be expressed either in the time or in the frequency domain as

$$E = \int_{-\infty}^{\infty} |s(t)|^2 \, \mathrm{d}t = \int_{-\infty}^{\infty} |S(f)|^2 \, \mathrm{d}f.$$

Thus, $|S(f)|^2 \, \mathrm{d}f$ is the energy in an infinitesimal frequency interval of width $\mathrm{d}f$, and $|S(f)|^2$ can be interpreted as the spectral density of the signal energy.

In communications, we often deal with subspaces of the vector space of finite-energy signals. The signals of finite duration form such a subspace. An appropriate base of that subspace is the Fourier base. The Fourier series is then just a special case of Equation (1.13) and the Fourier coefficients are given by Equation (1.14). Another subspace is the space of strictly band-limited signals of finite energy. From the sampling theorem we know that each such signal $s(t)$ that is concentrated inside the frequency interval between $-B/2$ and $B/2$ can be written as a series

$$s(t) = \sum_{k=-\infty}^{\infty} s(k/B) \operatorname{sinc}(Bt - k) \tag{1.15}$$

with $\operatorname{sinc}(x) = \sin(\pi x)/(\pi x)$.

We define a base as follows: