Chapter 1

Introduction

1.1 Motivation of the Book

Whilst the concept of Orthogonal Frequency Division Multiplexing (OFDM) has been known since 1966 [1], it only reached sufficient maturity for employment in standard systems during the 1990s. OFDM exhibits numerous advantages over the family of more conventional serial modem schemes [2], although it is only natural that it also imposes a number of disadvantages. The discussion of the associated design tradeoffs of OFDM and Multi-Carrier Code Division Multiple Access (MC-CDMA) systems constitutes the topic of this monograph and in this context our discussions include the following fundamental issues:

1) A particularly attractive feature of OFDM systems is that they are capable of operating without a classic channel equaliser, when communicating over dispersive transmission media, such as wireless channels, while conveniently accommodating the time- and frequency-domain channel quality fluctuations of the wireless channel.

   Explicitly, the channel SNR variation versus both time and frequency of an indoor wireless channel is shown in a three-dimensional form in Figure 1.1 versus both time and frequency, which suggests that OFDM constitutes a convenient framework for accommodating the channel quality fluctuations of the wireless channel, as will be briefly augmented below. This channel transfer function was recorded for the channel impulse response of Figure 1.2, by simply transforming the impulse response to the frequency domain at regular time intervals, while its taps fluctuated according to the Rayleigh distribution.

   These channel quality fluctuations may be readily accommodated with the aid of sub-band-adaptive modulation as follows. Such an adaptive OFDM (AOFDM) modem is characterised by Figure 1.3, portraying at the top a contour plot of the above-mentioned wireless channel's signal-to-noise ratio (SNR) fluctuation versus both time and frequency for each OFDM subcarrier. We note at this early stage that these channel quality fluctuations may be mitigated with the aid of frequency-domain channel equalisation,

OFDM and MC-CDMA: A Primer L. Hanzo and T. Keller

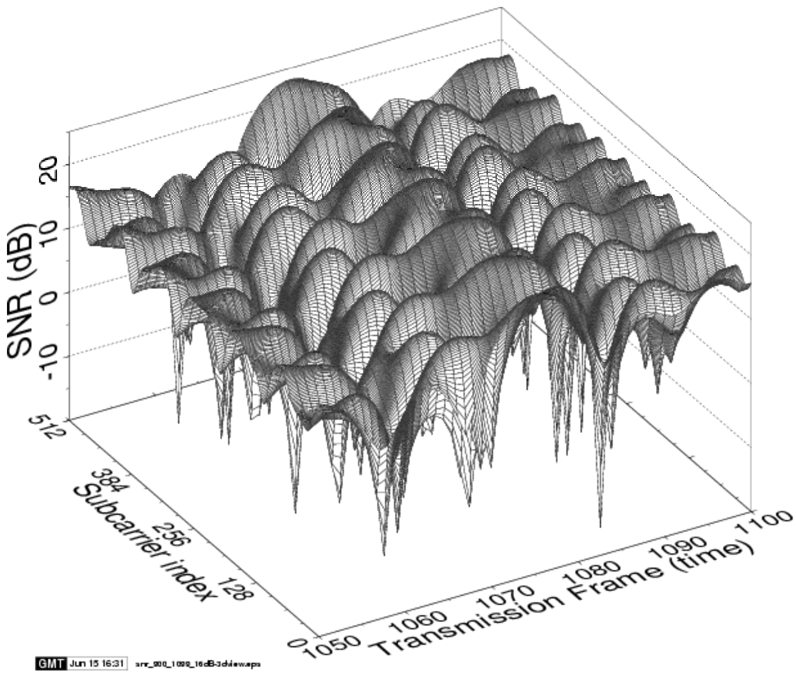

Figure 1.1: Instantaneous channel SNR for all 512 subcarriers versus time, for an average channel SNR of 16 dB over the channel characterised by the channel impulse response (CIR) of Figure 1.2.

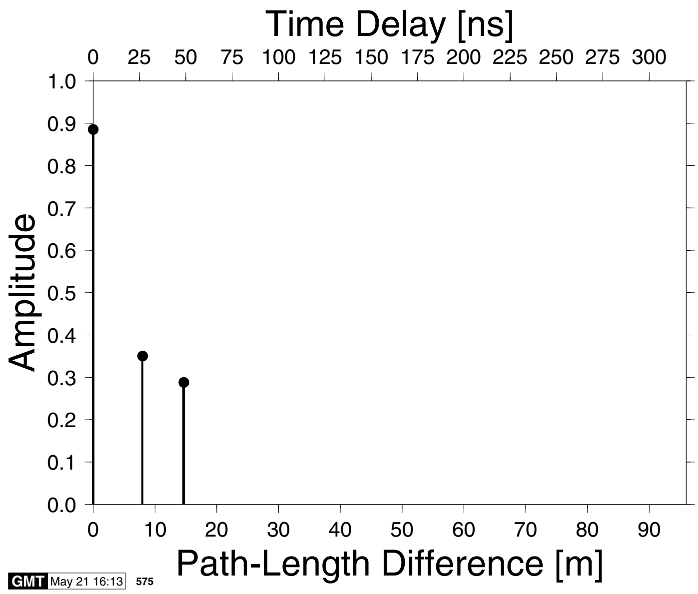

Figure 1.2: Indoor three-path WATM channel impulse response.

as will be detailed throughout the book, but nonetheless, they cannot be entirely eradicated.

More specifically, as can be seen in Figure 1.1, that when the channel is of high quality — as for example in the vicinity of the OFDM symbol index of 1080 — the sub-band-adaptive modem considered here for the sake of illustration has used the same modulation mode, as the identical-throughput conventional fixed-rate OFDM modem in all subcarriers, which was 1 bit per symbol (BPS) in this example, as in conventional Binary Phase Shift Keying (BPSK). By contrast, when the channel is hostile — for example, around frame 1060 — the sub-band-adaptive modem transmitted zero bits per symbol in some sub-bands, corresponding to disabling transmissions in the low-quality sub-bands. In order to compensate for the loss of throughput in this sub-band, a higher-order modulation mode was used in the higher quality sub-bands.

In the centre and bottom subfigures of Figure 1.3 the modulation mode chosen for each 32-subcarrier sub-band is shown versus time for two different high-speed wireless modems communicating at either 3.4 or 7.0 Mbps, respectively, again, corresponding to an average throughput of either 1 or 2 BPS.

However, these adaptive transceiver principles are not limited to OFDM transmissions. In recent years the concept of intelligent multi-mode, multimedia transceivers (IMMT) has emerged in the context of a variety of wireless systems [2–7]. The range of various existing solutions that have found favour in already operational standard systems has been summarised in the excellent overview by Nanda *et al.* [5]. *The aim of these adaptive transceivers is to provide mobile users with the best possible compromise amongst a number of contradicting design factors, such as the power consumption of the hand-held portable station (PS), robustness against transmission errors, spectral efficiency, teletraffic capacity, audio/video quality and so forth [4].*

2) Another design alternative applicable in the context of OFDM systems is that the channel quality fluctuations observed, for example, in Figure 1.1 are averaged out with the aid of frequency-domain spreading codes, which leads to the concept of Multi-Carrier Code Division Multiple Access (MC-CDMA). In this scenario typically only a few chips of the spreading code are obliterated by the frequency-selective fading and hence the chances are that the spreading code and its conveyed data may still be recoverable. The advantage of this approach is that in contrast to AOFDM-based communications, in MC-CDMA no channel quality estimation and signalling are required. Therefore OFDM and MC-CDMA will be comparatively studied in Part II of this monograph. Part III will also consider the employment of Walsh-Hadamard code-based spreading of each subcarrier's signal across the entire OFDM bandwidth, which was found to be an efficient frequency-domain fading counter-measure capable of operating without the employment of adaptive modulation.

3) A further technique capable of mitigating the channel quality fluctuations of wireless channels is constituted by space-time coding, which will also be considered as an attractive anti-fading design option capable of attaining a high diversity gain. Space-time coding employs several transmit and receive antennas for the sake of achieving diversity gain and hence an improved performance.

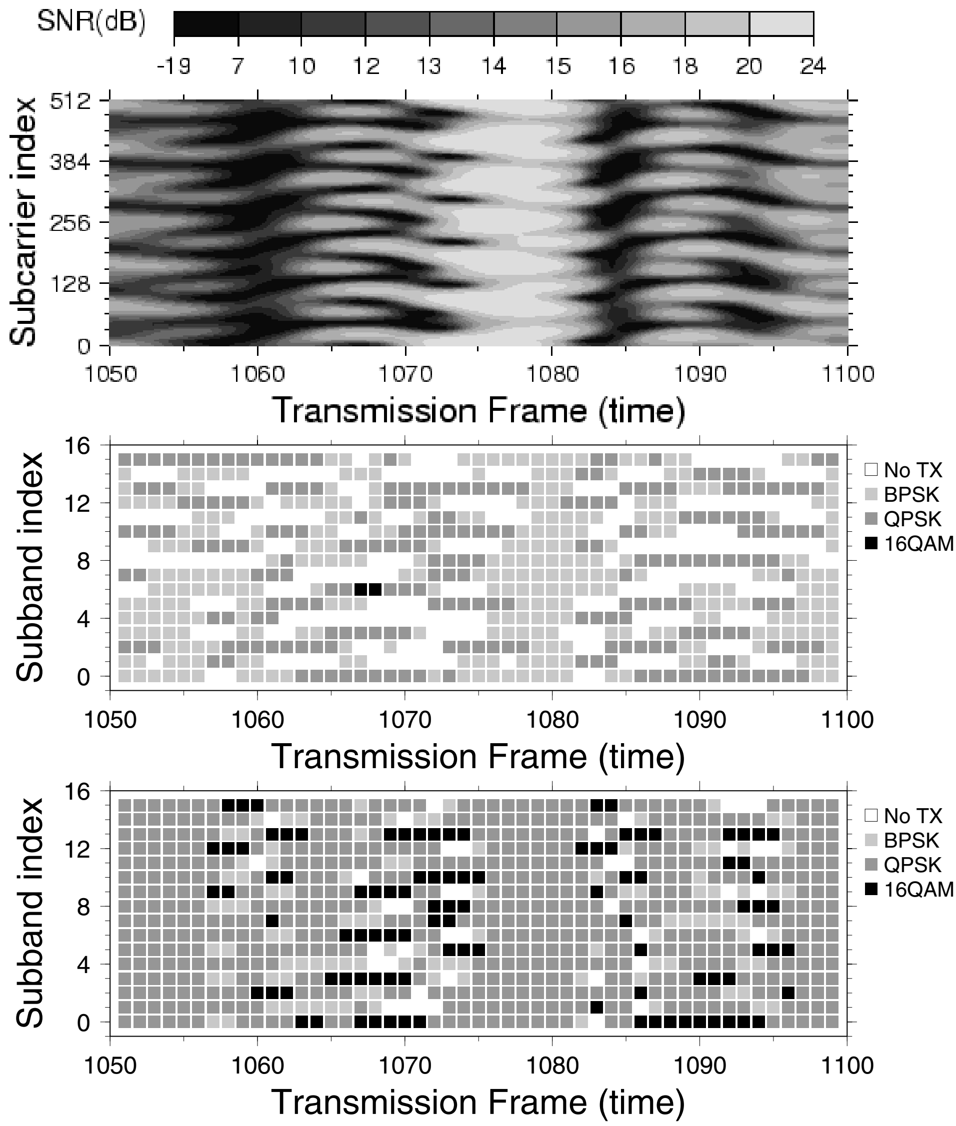

Figure 1.3: The micro-adaptive nature of the sub-band-adaptive OFDM modem. The top graph is a contour plot of the channel SNR for all 512 subcarriers versus time. The bottom two graphs show the modulation modes chosen for all 16 32-subcarrier sub-bands for the same period of time. The middle graph shows the performance of the 3.4 Mbps sub-band-adaptive modem, which operates at the same bit rate as a fixed BPSK modem. The bottom graph represents the 7.0 Mbps sub-band-adaptive modem, which operated at the same bit rate as a fixed QPSK modem. The average channel SNR was 16 dB.

4) By contrast, in Part III of the book we employ multiple antennas at the base-station for a different reason, namely for the sake of supporting multiple users, rather than to achieving transmit diversity gain. This is possible, since the users' channel impulse responses (CIR) or channel transfer functions are accurately estimated and hence these channel transfer functions may be viewed as unique user signature sequences, which allow us to recognise and demultiplex the transmissions of the individual users, in a similar fashion to the unique user-specific spreading codes employed in CDMA systems. We note, however, that this technique is only capable of reliably separating the users communicating within the same bandwidth, if their CIRs are sufficiently different. This assumption is typically valid for the uplink, although it may have a limited validity, when the base station receives from mobile stations in its immediate vicinity. By contrast, different techniques have to be invoked for downlink multi-user transmissions.

Our intention with the book is:

1) First, to pay tribute to all researchers, colleagues and valued friends, who contributed to the field. Hence this book is dedicated to them, since without their quest for better transmission solutions for wireless communications this monograph could not have been conceived. They are too numerous to name here, hence they appear in the author index of the book. Our hope is that the conception of this monograph on the topic will provide an adequate portrayal of the community's research and will further fuel this innovation process.

2) We expect to stimulate further research by exposing open research problems and by collating a range of practical problems and design issues for the practitioners. The coherent further efforts of the wireless research community is expected to lead to the solution of the range of outstanding problems, ultimately providing us with flexible wireless transceivers exhibiting a performance close to information theoretical limits.

1.2 Orthogonal Frequency Division Multiplexing History

1.2.1 Early Classic Contributions and OFDM Standards

The first OFDM scheme was proposed by Chang in 1966 [1] for dispersive fading channels. During the early years of the evolution of OFDM research the contributions due to the efforts of Weinstein, Peled, Ruiz, Hirosaki, Kolb, Cimini, Schüssler, Preuss, Rückriem, Kalet *et al.* [1, 8–20] have to be mentioned. As unquestionable proof of its maturity, OFDM was standardised as the European digital audio broadcast (DAB) as well as digital video broadcast (DVB) scheme. It constituted also a credible proposal for the recent third-generation mobile radio standard competition in Europe. Finally, OFDM was recently selected as the high performance local area network's (HIPERLAN) transmission technique as well as becoming part of the IEEE 802.11 Wireless Local Area Network (WLAN) standard.

The system's operational principle is that the original bandwidth is divided into a high number of narrow sub-bands, in which the mobile channel can be considered non-dispersive. Hence no channel equaliser is required and instead of implementing a bank of sub-channel modems they can be conveniently implemented with the aid of a single Fast Fourier Transformer (FFT), as it will be outlined in Chapter 2.

These OFDM systems - often also termed frequency division multiplexing (FDM) or multi-tone systems - have been employed in military applications since the 1960s, for example by Bello [21], Zimmermann [8], Powers and Zimmerman [22], Chang and Gibby [23] and others. Saltzberg [24] studied a multi-carrier system employing orthogonal time–staggered quadrature amplitude modulation (O-QAM) of the carriers.

The employment of the discrete Fourier transform (DFT) to replace the banks of sinusoidal generators and the demodulators was suggested by Weinstein and Ebert [9] in 1971, which significantly reduces the implementation complexity of OFDM modems. In 1980, Hirosaki [20] suggested an equalisation algorithm in order to suppress both intersymbol and intersubcarrier interference caused by the channel impulse response or timing and frequency errors. Simplified OFDM modem implementations were studied by Peled [13] in 1980, while Hirosaki [14] introduced the DFT-based implementation of Saltzberg's O-QAM OFDM system. From Erlangen University, Kolb [15], Schüssler [16], Preuss [17] and Rückriem [18] conducted further research into the application of OFDM. Cimini [10] and Kalet [19] published analytical and early seminal experimental results on the performance of OFDM modems in mobile communications channels.

More recent advances in OFDM transmission were presented in the impressive state-of-the-art collection of works edited by Fazel and Fettweis [25], including the research by Fettweis *et al.* at Dresden University, Rohling *et al.* at Braunschweig University, Vandendorp at Loeven University, Huber *et al.* at Erlangen University, Lindner *et al.* at Ulm University, Kammeyer *et al.* at Bremen University and Meyr *et al.* [26, 27] at Aachen University, but the individual contributions are too numerous to mention. Important recent references are the books by van Nee and Prasad [28] as well as by Vandenameele, van der Perre and Engels [29].

As a summary of this section, we outline the milestones and the main contributions found in the OFDM literature in Table 1.1, which culminated in the ratification of numerous OFDM-based standards in recent years.

While OFDM transmission over mobile communications channels can alleviate the problem of multipath propagation, recent research efforts have focused on solving a set of inherent difficulties regarding OFDM, namely the peak-to-mean power ratio, time and frequency synchronisation, and on mitigating the effects of the frequency selective fading channel. These issues are addressed below with reference to the literature, while a more in-depth treatment is given throughout the book.

1.2.2 Peak-to-Mean Power Ratio

It is plausible that the OFDM signal - which is the superposition of a high number of modulated sub-channel signals - may exhibit a high instantaneous signal peak with respect to the average signal level. Furthermore, large signal amplitude swings are encountered, when the time domain signal traverses from a low instantaneous power waveform to a high power waveform, which may results in a high out-of-band (OOB) harmonic distortion power, unless the transmitter's power amplifier exhibits an extremely high linearity across the entire signal level range. This then potentially contaminates the adjacent channels with adjacent channel interference. Practical amplifiers exhibit a finite amplitude range, in which they can be con-

Year	Milestone
1966	First OFDM scheme proposed by Chang [1] for dispersive fading channels.
1967	Saltzberg [24] studied a multi-carrier system employing Orthogonal QAM (O-QAM) of the carriers.
1970	U.S. patent on OFDM issued [30].
1971	Weinstein and Ebert [9] applied DFT to OFDM modems.
1980	Hirosaki designed a subchannel-based equalizer for an orthogonally multiplexed QAM system [20].
	Keasler *et al.* [31] described an OFDM modem for telephone networks.
1985	Cimini [10] investigated the feasibility of OFDM in mobile communications.
1987	Alard and Lasalle [32] employed OFDM for digital broadcasting.
1991	ANSI ADSL standard [33].
1994	ANSI HDSL standard [34].
1995	ETSI DAB standard [35]: the first OFDM-based standard for digital broadcasting systems.
1996	ETSI WLAN standard [36].
1997	ETSI DVB-T standard [37].
1998	ANSI VDSL and ETSI VDSL standards [38, 39].
	ETSI BRAN standard [40].
1999	IEEE 802.11a WLAN standard [41].
2002	IEEE 802.11g WLAN standard [42].
2004	ETSI DVB-H standard [43].
	IEEE 802.16 WMAN standard [44].
	Candidate for IEEE 802.11n standard for next generation WLAN [45].
	Candidate for IEEE 802.15.3a standard for WPAN (using MB-OFDM) [46].
2005	Candidate for 4G standards in China, Japan and South Korea (CJK) [47].

Table 1.1: Milestones in the history of OFDM.

sidered almost linear. In order to prevent severe clipping of the high OFDM signal peaks - which is the main source of OOB emissions - the power amplifier must not be driven to saturation and hence they are typically operated with a certain so-called back-off, creating a certain ”head room” for the signal peaks, which reduces the risk of amplifier saturation and OOB emission. Two different families of solutions have been suggested in the literature, in order to mitigate these problems, either reducing the peak-to-mean power ratio, or improving the amplification stage of the transmitter.

More explicitly, Shepherd [48], Jones [49], and Wulich [50] have suggested different coding techniques which aim to minimise the peak power of the OFDM signal by employing different data encoding schemes before modulation, with the philosophy of choosing block codes whose legitimate code words exhibit low so-called crest factors or peak-to-mean power envelope fluctuation. Müller [51], Pauli [52], May [53] and Wulich [54] suggested different algorithms for post-processing the time domain OFDM signal prior to amplification, while Schmidt and Kammeyer [55] employed adaptive subcarrier allocation in order to reduce the crest factor. Dinis and Gusmão [56–58] researched the use of two-branch amplifiers, while the clustered OFDM technique introduced by Daneshrad, Cimini and Carloni [59] operates with a set of parallel partial FFT processors with associated transmitting chains. OFDM systems with increased robustness to non-linear distortion have been proposed by Okada, Nishijima and Komaki [60] as well as by Dinis and Gusmão [61]. These aspects of OFDM transmissions will be treated in substantial depth in Part II of the book.

1.2.3 Synchronisation

Time and frequency synchronisation between the transmitter and receiver are of crucial importance as regards the performance of an OFDM link [62, 63]. A wide variety of techniques have been proposed for estimating and correcting both timing and carrier frequency offsets at the OFDM receiver. Rough timing and frequency acquisition algorithms relying on known pilot symbols or pilot tones embedded into the OFDM symbols have been suggested by Claßen [26], Warner [64], Sari [65], Moose [66], as well as Brüninghaus and Rohling [67]. Fine frequency and timing tracking algorithms exploiting the OFDM signal's cyclic extension were published by Moose [66], Daffara [68] and Sandell [69]. OFDM synchronisation issues are the topics of Chapter 5.

1.2.4 OFDM/CDMA

Combining multi-carrier OFDM transmissions with code division multiple access (CDMA) allows us to exploit the wideband channel's inherent frequency diversity by spreading each symbol across multiple subcarriers. This technique has been pioneered by Yee, Linnartz and Fettweis [70], by Chouly, Brajal and Jourdan [71], as well as by Fettweis, Bahai and Anvari [72]. Fazel and Papke [73] investigated convolutional coding in conjunction with OFDM/CDMA. Prasad and Hara [74] compared various methods of combining the two techniques, identifying three different structures, namely multi-carrier CDMA (MC-CDMA), multi-carrier direct sequence CDMA (MC-DS-CDMA) and multi-tone CDMA (MT-CDMA). Like non-spread OFDM transmission, OFDM/CDMA methods suffer from high peak-to-mean power ratios, which are dependent on the frequency domain spreading scheme, as investigated by Choi, Kuan and Hanzo [75]. Part II of the book considers the related design trade-offs.

1.2.5 Decision-Directed Channel Estimation

In recent years numerous research contributions have appeared on the topic of channel transfer function estimation techniques designed for employment in single-user, single transmit antenna-assisted OFDM scenarios, since the availability of an accurate channel transfer function estimate is one of the prerequisites for coherent symbol detection with an OFDM receiver. The techniques proposed in the literature can be classified as *pilot-assisted*, *decision-directed* (DD) and *blind* channel estimation (CE) methods, as detailed in the extended version of this monograph [90].

In the context of pilot-assisted channel transfer function estimation a subset of the available subcarriers is dedicated to the transmission of specific pilot symbols known to the receiver, which are used for "sampling" the desired channel transfer function. Based on these samples of the frequency domain transfer function, the well-known process of interpolation is used for generating a transfer function estimate for each subcarrier residing between the pilots. This is achieved at the cost of a reduction in the number of useful subcarriers available for data transmission. The family of *pilot-assisted* channel estimation techniques was

Year	Author	Contribution
'91	Höher [76]	Cascaded 1D-FIR channel transfer factor interpolation was carried out in the frequency- and time-direction for frequency-domain PSAM.
'93	Chow, Cioffi and Bingham [77]	Subcarrier-by-subcarrier-based LMS-related channel transfer factor equalisation techniques were employed.
'94	Wilson, Khayata and Cioffi [78]	Linear channel transfer factor filtering was invoked in the time-direction for DDCE.
'95	van de Beek, Edfors, Sandell, Wilson and Börjesson [79]	DFT-aided CIR-related domain Wiener filter-based noise reduction was advocated for DDCE. The effects of leakage in the context of non-sample-spaced CIRs were analysed.
'96	Edfors, Sandell, van de Beek, Wilson and Börjesson [80]	SVD-aided CIR-related domain Wiener filter-based noise reduction was introduced for DDCE.
	Frenger and Svensson [81]	MMSE-based frequency-domain channel transfer factor prediction was proposed for DDCE.
	Mignone and Morello [82]	FEC was invoked for improving the DDCE's remodulated reference.
'97	Tufvesson and Maseng [83]	An analysis of various pilot patterns employed in frequency-domain PSAM was provided in terms of the system's BER for different Doppler frequencies. Kalman filter-aided channel transfer factor estimation was used.
	Höher, Kaiser and Robertson [84, 85]	Cascaded 1D-FIR Wiener filter channel interpolation was utilised in the context of 2D-pilot pattern-aided PSAM
'98	Li, Cimini and Sollenberger [86]	An SVD-aided CIR-related domain Wiener filter-based noise reduction was achieved by employing CIR-related tap estimation filtering in the time-direction.
	Edfors, Sandell, van de Beek, Wilson and Börjesson [87]	A detailed analysis of SVD-aided CIR-related domain Wiener filter-based noise reduction was provided for DDCE, which expanded the results of [80].
	Tufvesson, Faulkner and Maseng [88]	Wiener filter-aided frequency domain channel transfer factor prediction-assisted pre-equalisation was studied.
	Itami, Kuwabara, Yamashita, Ohta and Itoh [89]	Parametric finite-tap CIR model-based channel estimation was employed for frequency domain PSAM.

Table 1.2: Contributions to channel transfer factor estimation for single-transmit antenna-assisted OFDM [90].

Year	Author	Contribution
’99	Al-Susa and Ormondroyd [91]	DFT-aided Burg algorithm-assisted adaptive CIR-related tap prediction filtering was employed for DDCE.
	Yang, Letaief, Cheng and Cao [92]	Parametric, ESPRIT-assisted channel estimation was employed for frequency domain PSAM.
’00	Li [93]	Robust 2D frequency domain Wiener filtering was suggested for employment in frequency domain PSAM using 2D pilot patterns.
’01	Yang, Letaief, Cheng and Cao [94]	Detailed discussions of parametric, ESPRIT-assisted channel estimation were provided in the context of frequency domain PSAM [92].
	Zhou and Giannakis [95]	Finite alphabet-based channel transfer factor estimation was proposed.
	Wang and Liu [96]	Polynomial frequency domain channel transfer factor interpolation was contrived.
	Yang, Cao and Letaief [97]	DFT-aided CIR-related domain one-tap Wiener filter-based noise reduction was investigated, which is supported by variable frequency domain Hanning windowing.
	Lu and Wang [98]	A Bayesian blind turbo receiver was contrived for coded OFDM systems.
	Li and Sollenberger [99]	Various transforms were suggested for CIR-related tap estimation filtering-assisted DDCE.
	Morelli and Mengali [100]	LS- and MMSE-based channel transfer factor estimators were compared in the context of frequency domain PSAM.
’02	Chang and Su [101]	Parametric quadrature surface-based frequency domain channel transfer factor interpolation was studied for PSAM.
	Necker and Stüber [102]	Totally blind channel transfer factor estimation based on the finite alphabet property of PSK signals was investigated.

Table 1.3: Contributions to channel transfer factor estimation for single-transmit antenna-assisted OFDM [90].

investigated for example by Chang and Su [101], Höher [76, 84, 85], Itami *et al.* [89], Li [93], Tufvesson and Maseng [83], Wang and Liu [96], as well as Yang *et al.* [92, 97, 103].

By contrast, in the context of Decision-Directed Channel Estimation (DDCE) all the sliced and remodulated subcarrier data symbols are considered as pilots. In the absence of symbol errors and also depending on the rate of channel fluctuation, it was found that accurate channel transfer function estimates can be obtained, which often are of better quality, in terms of the channel transfer function estimator's mean-square error (MSE), than the estimates offered by pilot-assisted schemes. This is because the latter arrangements usually invoke relatively sparse pilot patterns.

The family of *decision-directed* channel estimation techniques was investigated for example by van de Beek *et al.* [79], Edfors *et al.* [80, 87], Li *et al.* [86], Li [99], Mignone and Morello [82], Al-Susa and Ormondroyd [91], Frenger and Svensson [81], as well as Wilson *et al.* [78]. Furthermore, the family of *blind* channel estimation techniques was studied by Lu and Wang [98], Necker and Stüber [102], as well as by Zhou and Giannakis [95]. The various contributions have been summarised in Tables 1.2 and 1.3.

In order to render the various DDCE techniques more amenable to use in scenarios associated with a relatively high rate of channel variation expressed in terms of the OFDM symbol normalized Doppler frequency, linear prediction techniques well known from the speech coding literature [104, 105] can be invoked. To elaborate a little further, we will substitute the CIR-related tap estimation filter - which is part of the two-dimensional channel transfer function estimator proposed in [86] - by a CIR-related tap prediction filter. The employment of this CIR-related tap prediction filter enables a more accurate estimation of the channel transfer function encountered during the forthcoming transmission time slot and thus potentially enhances the performance of the channel estimator. We will be following the general concepts described by Duel-Hallen *et al.* [106] and the ideas presented by Frenger and Svensson [81], where frequency domain prediction filter-assisted DDCE was proposed. Furthermore, we should mention the contributions of Tufvesson *et al.* [88, 107], where a prediction filter-assisted frequency domain pre-equalisation scheme was discussed in the context of OFDM. In a further contribution by Al-Susa and Ormondroyd [91], adaptive prediction filter-assisted DDCE designed for OFDM has been proposed upon invoking techniques known from speech coding, such as the Levinson-Durbin algorithm or the Burg algorithm [104, 108, 109] in order to determine the predictor coefficients.

In contrast to the above-mentioned single-user OFDM scenarios, in a multi-user OFDM scenario the signal received by each antenna is constituted by the superposition of the signal contributions associated with the different users or transmit antennas. Note that in terms of the multiple-input multiple-output (MIMO) structure of the channel the multi-user single-transmit antenna scenario is equivalent, for example, to a single-user space-time coded (STC) scenario using multiple transmit antennas. For the latter a Least-Squares (LS) error channel estimator was proposed by Li *et al.* [110], which aims at recovering the different transmit antennas' channel transfer functions on the basis of the output signal of a specific reception antenna element and by also capitalising on the remodulated received symbols associated with the different users. The performance of this estimator was found to be limited in terms of the mean-square estimation error in scenarios, where the product of the number of transmit antennas and the number of CIR taps to be estimated per transmit antenna approaches the total number of subcarriers hosted by an OFDM symbol. As a design alternative, in [111] a DDCE was proposed by Jeon *et al.* for a space-time coded OFDM scenario of two transmit antennas

Year	Author	Contribution
’99	Li, Seshadri and Ariyavisitakul [110]	The LS-assisted DDCE proposed exploits the cross-correlation properties of the transmitted subcarrier symbol sequences.
’00	Jeon, Paik and Cho [111]	Frequency-domain PIC-assisted DDCE is studied, which exploits the channel’s slow variation versus time.
	Li [112]	Time-domain PIC-assisted DDCE is investigated as a simplification of the LS-assisted DDCE of [110]. Optimum training sequences are proposed for the LS-assisted DDCE of [110].
’01	Mody and Stüber [113]	Channel transfer factor estimation designed for frequency-domain PSAM based on CIR-related domain filtering is studied.
	Gong and Letaief [114]	MMSE-assisted DDCE is advocated which represents an extension of the LS-assisted DDCE of [114]. The MMSE-assisted DDCE is shown to be practical in the context of transmitting consecutive training blocks. Additionally, a low-rank approximation of the MMSE-assisted DDCE is considered.
	Jeon, Paik and Cho [115]	2D MMSE-based channel estimation is proposed for frequency-domain PSAM.
	Vook and Thomas [116]	2D MMSE based channel estimation is invoked for frequency domain PSAM. A complexity reduction is achieved by CIR-related domain-based processing.
	Xie and Georghiades [117]	Expectation maximization (EM) based channel transfer factor estimation approach for DDCE.
’02	Li [118]	A more detailed discussion on time-domain PIC-assisted DDCE is provided and optimum training sequences are proposed [112].
	Bölcskei, Heath and Paulraj [119]	Blind channel identification and equalisation using second-order cyclostationary statistics as well as antenna precoding were studied.
	Minn, Kim and Bhargava [120]	A reduced complexity version of the LS-assisted DDCE of [110] is introduced, based on exploiting the channel’s correlation in the frequency-direction, as opposed to invoking the simplified scheme of [118], which exploits the channel’s correlation in the time-direction. A similar approach was suggested by Slimane [121] for the specific case of two transmit antennas.
	Komninakis, Fragouli, Sayed and Wesel [122]	Fading channel tracking and equalisation were proposed for employment in MIMO systems assisted by Kalman estimation and channel prediction.

Table 1.4: Contributions on channel transfer factor estimation for multiple-transmit antenna assisted OFDM [90].

and two receive antennas.

Specifically, the channel transfer function[1] associated with each transmit-receive antenna pair was estimated on the basis of the output signal of the specific receive antenna upon *subtracting* the interfering signal contributions associated with the remaining transmit antennas. These interference contributions were estimated by capitalising on the knowledge of the channel transfer functions of all interfering transmit antennas predicted during the $(n-1)$-th OFDM symbol period for the n-th OFDM symbol, also invoking the corresponding remodulated symbols associated with the n-th OFDM symbol. To elaborate further, the difference between the subtraction-based channel transfer function estimator of [111] and the LS estimator proposed by Li *et al.* in [110] is that in the former the channel transfer functions predicted during the previous, i.e. the $(n-1)$-th OFDM symbol period for the current, i.e. the n-th OFDM symbol are employed for both symbol detection *as well as* for obtaining an updated channel estimate for employment during the $(n+1)$-th OFDM symbol period. In the approach advocated in [111] the subtraction of the different transmit antennas' interfering signals is performed in the frequency domain.

By contrast, in [112] a similar technique was proposed by Li with the aim of simplifying the DDCE approach of [110], which operates in the time domain. A prerequisite for the operation of this parallel interference cancellation (PIC)-assisted DDCE is the availability of a reliable estimate of the various channel transfer functions for the current OFDM symbol, which are employed in the cancellation process in order to obtain updated channel transfer function estimates for the demodulation of the next OFDM symbol. In order to compensate for the channel's variation as a function of the OFDM symbol index, linear prediction techniques can be employed, as it was also proposed for example in [112]. However, due to the estimator's recursive structure, determining the optimum predictor coefficients is not as straightforward as for the transversal FIR filter-assisted predictor as described in Section 15.2.4 of the extended version of this book [90] for single-user DDCE.

A comprehensive overview of further publications on channel transfer factor estimation for OFDM systems supported by multiple transmit antennas is provided in Table 1.4.

1.2.6 Uplink Detection Techniques for Multi-User SDMA-OFDM

Combining adaptive antenna-aided techniques with OFDM transmissions was shown to be advantageous for example in the context of suppressing co-channel interference in cellular communications systems. Amongst others, Li, Cimini and Sollenberger [148–150], Kim, Choi and Cho [151], Lin, Cimini and Chuang [152] as well as Münster *et al.* [153] have investigated algorithms designed for multi-user channel estimation and interference suppression.

The related family of Space-Division-Multiple-Access (SDMA) communication systems has recently drawn wide research interests. In these systems the L different users' transmitted signals are separated at the base-station (BS) with the aid of their unique, user-specific spatial signature, which is constituted by the P-element vector of channel transfer factors between the users' single transmit antenna and the P different receiver antenna elements at the BS, upon assuming flat-fading channel conditions such as those often experienced in the context of each of the OFDM subcarriers.

[1] In the context of the OFDM system the set of K different subcarriers' channel transfer factors is referred to as the channel transfer function, or simply as the channel.

Year	Author	Contribution
'96	Foschini [123]	The concept of the BLAST architecture was introduced.
'98	Vook and Baum [124]	SMI-assisted MMSE combining was invoked on an OFDM subcarrier basis.
	Wang and Poor [125]	Robust sub-space-based weight vector calculation and tracking were employed for co-channel interference suppression, as an improvement of the SMI-algorithm.
	Wong, Cheng, Letaief and Murch [126]	Optimization of an OFDM system was reported in the context of multiple transmit and receive antennas upon invoking the maximum SINR criterion. The computational was reduced by exploiting the channel's correlation in the frequency direction.
	Li and Sollenberger [127]	Tracking of the channel correlation matrix' entries was suggested in the context of SMI-assisted MMSE combining for multiple receiver antenna assisted OFDM, by capitalizing on the principles of [86].
'99	Golden, Foschini, Valenzuela and Wolniansky [128]	The SIC detection-assisted V-BLAST algorithm was introduced.
	Li and Sollenberger [129]	The system introduced in [127] was further detailed.
	Vandenameele, Van der Perre, Engels and de Man [130]	A comparative study of different SDMA detection techniques, namely that of MMSE, SIC and ML detection was provided. Further improvements of SIC detection were suggested by adaptively tracking multiple symbol decisions at each detection node.
	Speth and Senst [131]	Soft-bit generation techniques were proposed for MLSE in the context of a coded SDMA-OFDM system.
'00	Sweatman, Thompson, Mulgrew and Grant [132]	Comparisons of various detection algorithms including LS, MMSE, D-BLAST and V-BLAST (SIC detection) were carried out.
	van Nee, van Zelst and Awater [133–135]	The evaluation of ML detection in the context of a Space-Division Multiplexing (SDM) system was provided, considering various simplified ML detection techniques.
	Vandenameele, Van der Perre, Engels, Gyselinckx and de Man [136]	More detailed discussions were provided on the topics of [130].

Table 1.5: Contributions on multi-user detection techniques designed for multiple transmit antenna assisted OFDM systems [90].

Year	Author	Contribution
'00	Li, Huang, Lozano and Foschini [137]	Reduced complexity ML detection was proposed for multiple transmit antenna systems employing adaptive antenna grouping and multi-step reduced-complexity detection.
'01	Degen, Walke, Lecomte and Rembold [138]	An overview of various adaptive MIMO techniques was provided. Specifically, pre-distortion was employed at the transmitter, as well as LS- or BLAST detection were used at the receiver or balanced equalisation was invoked at both the transmitter and receiver.
	Zhu and Murch [139]	A tight upper bound on the SER performance of ML detection was derived.
	Li, Letaief, Cheng and Cao [140]	Joint adaptive power control and detection were investigated in the context of an OFDM/SDMA system, based on the approach of Farrokhi *et al.* [141].
	van Zelst, van Nee and Awater [142]	Iterative decoding was proposed for the BLAST system following the turbo principle.
	Benjebbour, Murata and Yoshida [143]	The performance of V-BLAST or SIC detection was studied in the context of backward iterative cancellation scheme employed after the conventional forward cancellation stage.
	Sellathurai and Haykin [144]	A simplified D-BLAST was proposed, which used iterative PIC capitalizing on the extrinsic soft-bit information provided by the FEC scheme used.
	Bhargave, Figueiredo and Eltoft [145]	A detection algorithm was suggested, which followed the concepts of V-BLAST or SIC. However, multiple symbols states are tracked from each detection stage, where - in contrast to [136] - an intermediate decision is made at intermediate detection stages.
	Thoen, Deneire, Van der Perre and Engels [146]	A constrained LS detector was proposed for OFDM/SDMA, which was based on exploiting the constant modulus property of PSK signals.
'02	Li and Luo [147]	The block error probability of optimally ordered V-BLAST was studied. Furthermore, the block error probability is also investigated for the case of tracking multiple parallel symbol decisions from the first detection stage, following an approach similar to that of [136].

Table 1.6: Contributions on detection techniques for MIMO systems and for multiple transmit antenna assisted OFDM systems [90].

A whole host of multi-user detection (MUD) techniques known from Code-Division-Multiple-Access (CDMA) communications lend themselves also to an application in the context of SDMA-OFDM on a per-subcarrier basis. Some of these techniques are the Least-Squares (LS) [132, 138, 146, 154], Minimum Mean-Square Error (MMSE) [124–127, 129, 132, 136, 140, 154–156], Successive Interference Cancellation (SIC) [123, 128, 132, 136, 138, 143, 145, 147, 154, 156], Parallel Interference Cancellation (PIC) [144, 154] and Maximum Likelihood (ML) detection [131, 133–137, 139, 142, 154, 156]. A comprehensive overview of recent publications on MUD techniques for MIMO systems is given in Tables 1.5 and 1.6.

1.2.7 OFDM Applications

Due to their implementational complexity, OFDM applications have been scarce until quite recently. Recently, however, OFDM has been adopted as the new European digital audio broadcasting (DAB) standard [11, 12, 157–159] as well as for the terrestrial digital video broadcasting (DVB) system [65, 160].

For fixed-wire applications, OFDM is employed in the asynchronous digital subscriber line (ADSL) and high-bit-rate digital subscriber line (HDSL) systems [161–164] and it has also been suggested for power line communications systems [165, 166] due to its resilience to time dispersive channels and narrow band interferers.

More recently, OFDM applications were studied within the European 4th Framework Advanced Communications Technologies and Services (ACTS) programme [167]. The MEDIAN project investigated a 155 Mbps wireless asynchronous transfer mode (WATM) network [168–171], while the Magic WAND group [172, 173] developed a wireless local area network (LAN). Hallmann and Rohling [174] presented a range of different OFDM systems that were applicable to the European Telecommunications Standardisation Institute's (ETSI) recent personal communications oriented air interface concept [175].

1.3 Outline of the Book

- **Chapter 2**: In this chapter we commence our detailed discourse by demonstrating that OFDM modems can be efficiently implemented by invoking the Fourier transform or the fast Fourier Transform (FFT). A number of basic OFDM design issues are discussed in an accessible style.

- **Chapter 3**: The BER performance of OFDM modems achievable in AWGN channels is studied for a set of different modulation schemes in the subcarriers. The effects of amplitude limiting of the transmitter's output signal, caused by a simple clipping amplifier model, and of finite resolution D/A and A/D conversion on the system performance are investigated. Oscillator phase noise is considered as a source of intersubcarrier interference and its effects on the system performance are demonstrated.

- **Chapter 4**: The effects of time-dispersive frequency-selective Rayleigh fading channels on OFDM transmissions are demonstrated. Channel estimation techniques are presented which support the employment of coherent detection in frequency selective channels. Additionally, differential detection is investigated, and the resultant system performance is compared, when communicating over various channels.

- **Chapter 5**: We focus our attention on the time and frequency synchronisation requirements of OFDM transmissions and the effects of synchronisation errors are demonstrated. Two novel synchronisation algorithms for frame and OFDM symbol synchronisation are suggested and compared. The resulting system performance over fading wideband channels is examined.

- **Chapter 6**: Based on the results of Chapter 4, the employment of adaptive modulation schemes is suggested for duplex point-to-point links over frequency-selective time-varying channels. Different bit allocation schemes are investigated and a simplified sub-band adaptivity OFDM scheme is suggested to alleviate the associated signalling constraints. A range of blind modulation scheme detection algorithms are also investigated and compared. The employment of long-block-length convolutional turbo codes is suggested for improving the system's throughput and the turbo coded adaptive OFDM modem's performance is compared using different sets of parameters. Then the effects of using pre-equalisation at the transmitter are examined, and a set of different pre-equalisation algorithms is introduced. A joint pre-equalisation and adaptive modulation algorithm is proposed and its BER and throughput performance are studied.

- **Chapter 7**: The discussions of **Part II** of the book commence by a rudimentary comparison of OFDM, CDMA and MC-CDMA in Chapter 7.

- **Chapter 8**: Since the properties of spreading sequences are equally important in both multicarrier CDMA and in DS-CDMA, the basic properties of various spreading sequences are reviewed in Chapter 8.

- **Chapter 9**: The basic characterisation of spreading codes provided in Chapter 8 is followed by Chapter 9, analysing the achievable performance of both single- and multi-user detected MC-CDMA. The chapter is concluded by the comparative study of a sophisticated space-time block coded near-instantaneously adaptive OFDM and MC-CDMA system. These conclusions suggest that whilst both near-instantaneously adaptive OFDM and MC-CDMA exhibit a high performance, they require the transmission of channel-quality related side-information, which exhibits a high sensitivity to transmission errors, since in the presence of modem mode signalling errors catastrophic data error propagation may be experienced. A more robust 'all-weather' tool is constituted by space-time coding, which is capable of mitigating the channel-quality fluctuations imposed by co-channel interference and fading, although this is achieved at the cost of a higher complexity owing to the employment of multiple transmitters and receivers.

- **Chapter 10**: Achieving near-ML multi-user MIMO-OFDM performance at a modest complexity is the ambitious aim of this chapter, which proposes an advanced extension of the Complex Sphere Detector (CSD) [176]. The algorithm proposed extends the potential range of applications of the CSD methods, as well as reducing the associated computational complexity, rendering the technique a feasible solution for implementation in practical systems. This technique allows the system to support a higher number of users than the number of antennas.

- **Chapter 11**: This chapter invokes the enhanced CSD of Chapter 10 and combines it with Genetic Algorithms (GA) for the sake of creating a powerful yet modest-complexity joint channel and data estimation scheme. It will be demonstrated that the proposed GA-aided iterative joint channel estimation and multi-user detection scheme generating soft outputs constitutes an effective solution to the channel estimation problem in multi-user MIMO SDMA-OFDM systems. Furthermore, the GA-JCEMUD is capable of exhibiting a robust performance in the so-called ’over-loaded’ scenarios, where the number of users is higher than the number of receiver antenna elements.

Chapter 12: The last in-depth chapter of the book introduces a new design paradigm, which aims for directly minimizing the BER at the output of the SDMA MUD, rather than minimizing the MSE. This results in a potentially complex optimization problem, which may be solved with the aid of GAs applied in the context of an SDMA OFDM system for determining the MBER MUD’s array weight vectors. We will demonstrate that the GA-aided system has an edge over the conjugate gradient algorithm-based system, because it does not require an initial SDMA array weight solution. Unlike the family of conventional MUDs, the MBER MUD is capable of supporting more users than the number of receiver antennas.

- **Chapter 13**: In this chapter we offer detailed conclusions and highlight a range of further research problems.

1.4 Chapter Summary and Conclusion

Here we conclude our brief introduction to OFDM and the review of its evolution since its conception by Chang in 1966 [1]. Numerous seminal contributions have been reviewed in chronological order in Tables 1.2–1.6, highlighting the historical development of the subject. These contributions reflect the state of the art at the time of writing in the context of the various OFDM system components, outlining a number of open research topics. Let us now embark on a detailed investigation of the topics introduced in this chapter.

Throughout this monograph we endeavour to highlight the range of contradictory system design trade-offs associated with the conception of OFDM and MC-CDMA systems. We intend to present the material in an unbiased fashion and sufficiently richly illustrated in terms of the associated design trade-offs so that readers will be able to find recipes and examples for solving their own particular wireless communications problems. In this rapidly evolving field it is a challenge to complete a timely, yet self-contained treatise, since new advances are being discovered at an accelerating pace, which should find their way into a timely monograph. Our sincere hope is that you, the readers, will find the book a useful source of information, but above all a catalyst for further research.