Alexander Arkhipov

IFDMA for Uplink Mobile Radio Communication Systems

Herausgegeben von

Prof. Dr.-Ing. Jörg Eberspächer
Lehrstuhl für Kommunikationsnetze
Technische Universität München

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Chapter 1

Introduction

During the 1860s, Scottish physicist James Clerk Maxwell predicted the existence of radio waves. In 1886, the German physicist Heinrich Rudolph Hertz demonstrated that rapid variations of electric current could produce radio waves similar to those of light and heat.

In 1892, Serbian inventor Nikola Tesla delivered a widely reported presentation before the Institution of Electrical Engineers of London in which he noted, among other things, that intelligence would be transmitted without wires. Later, a variety of Tesla's radio frequency systems were demonstrated during another widely known lecture, presented to meetings of the National Electric Light Association in St. Louis, Missouri and the Franklin Institute in Philadelphia. According to the Institute of Electrical and Electronics Engineers (IEEE), ”the apparatus that he employed contained all the elements of spark and continuous wave that were incorporated into radio” [Cen06].

On May 7, 1895, the Russian scientist Alexander Popov demonstrated a wireless receiver consisting of a metal ”coherer” - a device that detected electromagnetic waves - an antenna, a relay, and a bell to signal the presence of these waves. Popov could send and detect them up to 64 meters away. Although not initially intended as a means of transmitting information, Popov's device proved that radio communication was feasible [Cen05].

The Italian inventor Guglielmo Marconi is generally recognized to have been the first to demonstrate the practical application of electromagnetic waves. In 1896, Marconi applied for a patent for his wireless work that gained him the credit for the invention of the radio.

In the next years, the development of the radio gives rise to television broadcasting, satellite and mobile radio communication systems. The latter are investigated in this thesis and basic principles of communication systems and their state of the art are shortly summarized in the following text.

Modern communication systems can be subdivided into two categories - single-carrier and multi-carrier systems. All these systems are characterized by the spectral efficiency

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which is the amount of information that can be transmitted over a given bandwidth in a specific time. A single-carrier system utilizes all available transmission bandwidth

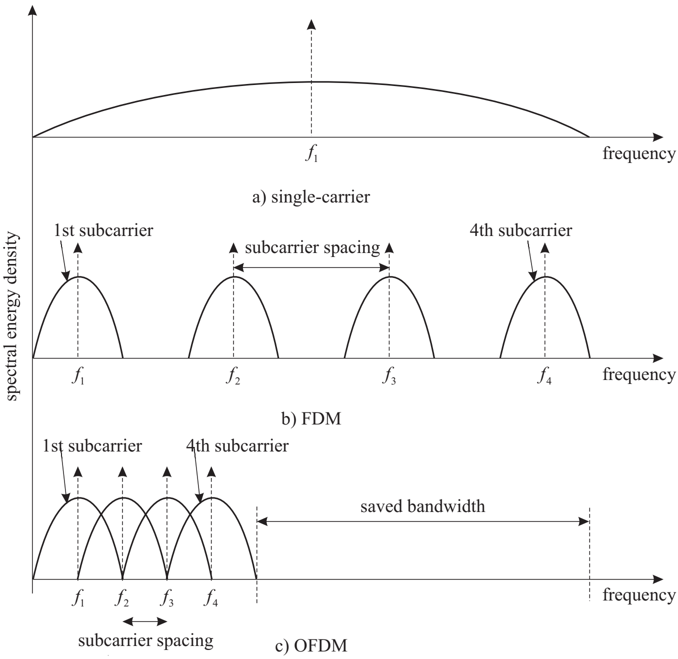

Figure 1.1: The spectral energy density of a) single-carrier, b) FDM, c) OFDM systems.

for one subcarrier and only one data stream can be transmitted. The spectral energy density (SED) of a single-carrier system is shown schematically in Fig. 1.1a.

Multi-carrier systems can be subdivided into frequency-division multiplexing (FDM) systems and orthogonal FDM (OFDM) systems. FDM subdivides the transmission bandwidth into multiple subcarriers and several data streams can be transmitted in parallel, each data stream on an isolated subcarrier. These subcarriers are non-overlapping, do not have any influence on each other and can be demodulated independently. However, to be able to separate different subcarriers at the receiver, large subcarrier spacings between adjacent subcarriers are required, hence reducing spectral efficiency of FDM systems in comparison to single-carrier systems. Fig. 1.1b illustrates the SED of the FDM modulation scheme.

OFDM makes it possible to increase the spectral efficiency of FDM by employing overlapping subcarriers as shown in Fig. 1.1c. The subcarrier spacing can be decreased and bandwidth is saved, that can be filled with additional subcarriers. Although the subcar-

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riers overlap, they do not interfere with each other since the subcarrier waveforms in OFDM are chosen to be orthogonal [WE71]. At the receiver it is possible to separate individual subcarriers due to their orthogonality, while keeping the complexity of the receiver at a tolerable level.

The mobile communication systems have a common cellular structure [Pro00], first introduced in the early 1980s, where each cell includes one base station (BSs) and several mobile terminals (MTs) also referred to as users. The BS is a central radio transmitter/receiver for a network within a given area with a known fixed location and MT is a portable electronic device for personal communications over long distances. The communication link between the BS and one MT is referred to as downlink. Whereas the communication link between several MTs and a BS is defined as uplink.

The topic of this thesis is focused on the uplink of future mobile communication systems. Modern communication systems are based on several multiple-access techniques which allow MTs to access BS in the uplink. These include the following:

- frequency-division multiple-access (FDMA)
- time-division multiple-access (TDMA)
- code-division multiple-access (CDMA)
- orthogonal FDMA (OFDMA)

FDMA was the initial multiple-access technique for mobile communication systems. FDMA utilizes FDM where each user occupies one or more isolated subcarriers and the signals of different users can be received independently.

In TDMA, users are separated in time, meaning that each user transmits its data over all available transmission bandwidths only during the assigned time slot. Different users use different time slots, thus making multiple-access possible [Pro00].

The CDMA technique allows many users to simultaneously access the available frequency band. User separation at the receiver is possible because each user spreads its transmit signal over the available bandwidth using unique spreading codes. As other users do not use completely orthogonal spreading codes, there is residual multiple-access interference (MAI) present in the receiver [Vit95]. Usually, the CDMA technique is combined with single-carrier systems, however, the combination of CDMA with multi-carrier possible.

OFDMA is based on OFDM, where each user occupies its own set of isolated subcarriers. In contrast to FDMA, OFDMA uses overlapping subcarrier spectra and utilizes the transmission bandwidth more efficiently.

The history of modern communication systems has started in 1979, when the first cellular communication system has been employed in Japan. Since then, three generations

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of such systems have been deployed and each generation resulted in improved capacity and quality of service. The short description and technical characteristics of the first two generations can be found in [Č05]. As already mentioned, this thesis is focused on the uplink of future mobile communication systems, therefore, the state of the art in the modern wireless communications is shorty described.

Third Generation of Mobile Communication Systems: Third generation cellular systems (3G) have been proposed with the goal of providing a seamless integration of mobile services into a single global network infrastructure. International Mobile Telecommunications-2000 (IMT-2000) is the global standard for 3G defined by the International Telecommunications Union (ITU) as a set of interdependent recommendations. IMT-2000 includes: Wideband CDMA (W-CDMA), CDMA-2000 and Time Division - Synchronous CDMA (TD-SCDMA). W-CDMA is used in Japan and Europe, CDMA-2000 is employed in America [TC99], whereas TD-SCDMA was launched in China. All these standards employ CDMA for multiple-access.

W-CDMA represents a part of the Universal Mobile Telecommunication System (UMTS) standard and operates with cells of different sizes. By using the radio spectrum in bands identified and provided by the ITU, 3G systems use uplink and downlink channels with a 5 GHz bandwidth to deliver 384 kbit/s for high mobility scenarios and 2 Mbit/s for low mobility scenarios.

The first commercial 3G service based on W-CDMA technology named Freedom of Mobile multimedia Access (FOMA) was launched in October 2001 in Japan. In April 2007, the number of FOMA subscribers exceeded 68.9 millions and corresponded to 67.5% of all mobile subscribers in Japan [Ono07].

Increasing demands on data rate have forced the development of transmission standards capable to provide higher data rates. A host of technologies enabling commercial mobile broadband services is known as 3.5G.

3.5G: The most significant 3.5G standards are: High Speed Packet Access (HSPA) and Evolution-Data Optimized (EV-DO) of Revision B and Revision C. HSPA is an extension of UMTS, whereas EV-DO is a part of the CDMA-2000 family of standards. Note that EV-DO Revision C is also known as Ultra Mobile Broadband (UMB).

Other commercial technologies such as FLASH-OFDM, and iBurst will have commercial traction in certain markets and applications [GSM07]. However, according to the research report of the ”Strategy Analytics”, there will be 518 million mobile broadband users worldwide by 2010. The competitors of HSPA and EV-DO will account for only 30 million of those [Str06].

EV-DO employs CDMA to maximize the throughput and supports a 9.3 Mbit/s downlink and a 5.4 Mbit/s uplink (EV-DO Revision B). HSPA is the set of technologies standardized by the 3rd Generation Partnership Project (3GPP) that defines the migration path for UMTS operators worldwide. HSPA includes High Speed Downlink Packet

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Access (HSDPA), High Speed Uplink Packet Access (HSUPA) and HSPA Evolved. These are also known as 3GPP Releases 5 through 8.

Both HSPA and EV-DO Revision C (or UMB) will introduce antenna array technologies such as beamforming and Multiple Input Multiple Output (MIMO). Beam forming can be described as focusing the transmitted power of an antenna in a beam towards the users direction. MIMO uses multiple antennas at the sending and receiving side. The deployment of HSPA and UMB is scheduled on 2008.

As an alternative to HSDPA, the new standard termed as High Speed OFDM Packet Access (HSOPA) is introduced, which uses OFDM. HSOPA is a technology under development for specification in 3GPP Release 8, which is called the Long Term Evolution (LTE) initiative. It aims to achieve data rates of up 200 Mbit/s for the downlink and 100 Mbit/s for the uplink.

1.1 Fourth Generation of Wireless Communication Systems

The ITU Recommendation ITU-R M.1645 ”Framework and overall objectives of the future development of IMT and systems beyond IMT-2000” [ITU03] defines the basic requirements to the systems beyond 3G. It is envisioned that development of such systems will proceed according to the following trends:

- Encompassing of the capabilities of the previously developed systems and standards.
- Developing of the new complementary multiple-access, fully packet based, wireless systems with hierarchical cell structure with an objective to provide global roaming of the mobile users according to the principle ”optimally connected anywhere, anytime”.
- Supporting of 100 Mbits/s between high mobility users with high speed on highways or fast trains (up to 250 km/h and more) and 1 Gbit/s for the low mobility users with a pedestrian speed.

Currently, many institutions and research consortiums are investigating possible technical solutions for the 4G radio interface. In the following, several different 4G initiatives are presented.

NTT DoCoMo Initiative: In May 2003, the NTT DoCoMo carried out a field trial of the 4G mobile communications system. The tests used Variable Spreading Factor Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) and Variable Spreading Factor CDMA (VSF-CDMA) technologies [AMAS02]. VSF-OFCDM, also known as Multi-Carrier CDMA (MC-CDMA) [Kai98] with variable spreading factor, enables downlink connections. The VSF-CDMA, also known as Multi-Carrier

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Direct-Sequence CDMA [FK00], realizes high-speed packet transmissions for the uplink. Note that for the small cells, Variable Spreading and Chip Repetition Factors CDMA (VSCRF-CDMA) known as Interleaved Frequency-Division Multiple-Access (IFDMA), is applied [AS03]. The proposed communication scheme uses adaptive modulation and coding scheme and MIMO. Recently, DoCoMo reports that 5 Gbits/s in the downlink is achieved at the MT speed equal to 10 km/h [Ono07].

4MORE Project: In January 2004, within the European Information Society Technology (IST) programme, 11 European partners have started the 4G MC-CDMA Multiple Antenna System on Chip for Radio Enhancement (4MORE) project [4MO06]. The 4MORE air interface is mainly based on a refinement of the MATRICE air interface proposal [MAT03].

The objective of the 4MORE project is to design the mobile radio system beyond 3G using multiple-antennas, adaptive modulation and coding schemes [BDN05]. The downlink is based on MC-CDMA, whereas the uplink is realized using OFDMA code division multiplexing (OFDMA-CDM) [KDL$^+$04] and IFDMA [Con06a]. The 4MORE demonstrator has a 50 MHz bandwidth. The peak data rates in downlink are 100 MHz and 20 MHz for the high and low mobility scenarios, respectively.

WIGWAM Project: In 2004, a consortium of partners led by Alcatel, DaimlerChrysler, Infineon, Nokia and Siemens launched a research project WIreless Gigabit With Advanced Multimedia (WIGWAM) [Wig07]. The goal of the WIGWAM consortium is to design a system concept with a peak data rate 1Gbit/s in the downlink, thus satisfying the ITU requirements and contributing to the standardization of 4G.

The system design considers different mobility scenarios [ZF04], scalable system bandwidth up to 100 MHz, MIMO and advanced scheduling [Fet03]. The WIGWAM air interface is based on MC-CDMA in downlink and OFDMA in uplink. The modulation schemes vary from binary phase shift keying (BPSK) to 256-quadrature amplitude modulation (QAM).

WINNER I and WINNER II Projects: The key objective of the WINNER I/II projects, described in [WIN03], is to develop a totally new concept in radio access. These projects are built on the recognition that developing disparate systems for different purposes is no longer sufficient in the future converged wireless world. This concept is realized in the ubiquitous radio system concept.

Both uplink and downlink use chunk based TDMA/OFDMA for all propagation scenarios. In the uplink, Block IFDMA (B-IFDMA) is chosen, whereas downlink uses Block Equidistant Frequency Division Multiple Access (B-EFDMA) [Con06b]. Several key technologies such as adaptive modulation and coding schemes, MIMO and enhanced radio protocols are defined.

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An analysis of industrial initiatives, European and international projects leads to the conclusion that OFDM based multi-carrier techniques are seriously considered as a basis for 4G air interface.

In the downlink, the tendency is to combine OFDM with TDMA/FDMA in different ways instead of using CDMA. The combination of OFDM and CDMA (known as MC-CDMA) has a serious drawback: it introduces MAI. However in some mobility scenarios, MC-CDMA has an advantage over conventional OFDM [Kai98]. From the practical point of view, the adaptive modulation and coding schemes, scheduling and MIMO make an additional bit error rate (BER) performance gain brought by the MC-CDMA over OFDM insignificant.

In the uplink, there is a clear tendency to use OFDMA schemes in order to assign to users separated subcarriers and avoid MAI. An absolute favorite for 4G uplink is IFDMA since it brings the advantages of OFDMA and has an additional code division multiplexing (CDM) component. It is shown in this thesis that IFDMA provides the lowest peak-to-average power ratio (PAPR) among all known multi-carrier systems.

1.2 State of the Art in the Field of IFDMA

The application of interleaved frequency-division multiple-access (IFDMA) for mobile communications has become an active field of research since 1998. IFDMA can be applied to the downlink and the uplink. However, special interest has been given to the uplink since other multi-carrier systems show some deficiencies for the uplink.

This section gives an overview on the state of the art in the field of IFDMA with respect to data detection, PAPR of multi-carrier systems and the effects of frequency time offsets. Contributions to these topics made by the author of the thesis are not mentioned in this section. These contributions will be presented in Chapters 2 to 5.

IFDMA was introduced in [SBS98, SBS99] as a special kind of a multi-carrier spread-spectrum scheme, where the property of a repeated data sequence has been used for multiple-access. The multiple-access capability is achieved by assigning to each user a different set of orthogonal subcarriers as in the conventional OFDMA. The next con-

Table 1.1: Contributions to fundamental IFDMA topics - invention, basic description, and equivalence to OFDMA-CDM

references	contribution
[SBS98] [SBS99]	IFDMA invention
[Bro03]	time-domain equalization, DFE
[Kai02] [Kai98] [FK00]	OFDMA-CDM, LE, SIC
[Bur01] [GR00] [XZG03]	equivalence between IFDMA and OFDMA-CDM

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tribution to IFDMA has been done in [Bro03], where maximum-likelihood (ML) and decision-feedback equalizers (DFE) have been compared.

Coincident with the first IFDMA publications, a novel multiple-access technique, named OFDMA-CDM, has been introduced in [Kai02] as a promising candidate for the 4th generation of mobile communications. In OFDMA-CDM, each user transmits its data on a fixed set of orthogonal subcarriers. Therefore, MAI is avoided. In contrast to conventional OFDMA, transmitted data symbols in OFDMA-CDM are spread with orthogonal Walsh-Hadamard (WH) codes, which provide additional robustness against non-ideal channels with frequency selective fading. However, this robustness is achieved at the cost of self-interference (SI) [FK00, Kai02, Kai98].

In [Kai02], different linear equalization (LE) techniques such as minimum mean square error (MMSE), equal gain combining (EGC), zero-forcing (ZF), and maximum ratio combining (MRC) have been investigated. In addition, an effective soft interference cancelation (SIC) technique has been proposed which allows the complete elimination of the SI.

Numerous contributions investigate different types of spreading codes for multi-carrier transmission systems. The WH spreading has been combined with pseudo-noise sequences in multi-carrier uplink [DK99], low-rate convolutional codes as spreading codes have been investigated in [Vit90] and Golay and Zadoff-Chu codes have been considered in [Bur01, NHM02]. Fourier codes have been proposed as spreading codes in [BR98]. In this contribution, the size of the spreading Fourier codes is chosen equal to the size of the inverse discrete Fourier transform (IDFT) operation at the transmitter. Thus, the resulting scheme is a single carrier system with cyclic extension and frequency domain linear equalizers, which has a PAPR of a single-carrier system. The

Table 1.2: Contributions to the field of PAPR and BER performance of multi-carrier systems with Fourier and WH spreading

references	contribution
[Bur01] [BL00] [NHM02]	PAPR and MAI reduction
[BEL03] [RD05]	BER performance
[BV98] [GA02]	signal space diversity

computationally efficient implementation of the more general case, where the Fourier spreading is performed over group of subcarriers which are interleaved equidistantly, is described in [Bur01, GR00, XZG03]. In this case, the Fourier codes for spreading and the rotation factors of the IDFT transform cancel out and the transmit time-domain signal reduces to a repeated data sequence.

Comparing the results obtained in [GR00] with [SBS98, SBS99], it may be concluded that IFDMA is equivalent to OFDMA-CDM with equidistant allocation of subcarriers and the Fourier spreading. Important contributions concerning IFDMA detection

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techniques and equivalence between OFDMA-CDM and IFDMA are summarized in Table 1.1.

The PAPR distributions for Fourier and WH spreading has been investigated in [BL00] for the up- and downlink. For both cases, Fourier spreading delivers a lower or equal PAPR. The superiority of Fourier spreading increases significantly for larger spreading factors.

The BER performance of multi-carrier transmission systems with Fourier and WH spreading is compared in [BEL03, RD05]. It is shown that the performance of the most commonly used WH transform is asymptotically bad for a high signal-to-noise ratio (SNR). The Fourier spreading as an alternative offers slightly better performance since it spreads transmitted data symbols more efficiently over the complex plane. In this case, the Fourier spreading efficiently exploits signal space diversity [BV98, GA02], thus providing better BER performance than the conventional WH spreading. However, if LE techniques are applied, an application of the Fourier codes for spreading improves BER performance only if the BPSK alphabet is used. In contrast, if modulation alphabet of higher cardinality is applied, e.g. quadrature phase-shift keying (QPSK), the achieved BER performance gain is remarkable only if ML equalizer is used. Important contributions to the fields of PAPR and BER performance of multi-carrier systems with Fourier and WH spreading are recapitulated in Table 1.2.

Being a special kind of a multi-carrier system, IFDMA inherits the sensitivity of the OFDMA to carrier frequency time offsets. The performance of the OFDMA uplink in the presence of the frequency offsets is studied in [TLP00, Ste00]. Three methods to combat MAI in the OFDMA uplink have been developed. The first method employs a frequency allocation scheme, where the data of a particular user is transmitted on a specific subset of adjacent subcarriers as described in [LH05]. The second method includes time-domain windowing [Mus96, MW01]. This method is developed for OFDM but can also be applied for OFDMA uplink systems and applies windowing at the receiver [BT07, SL05, YH03] in front of the discrete Fourier transform (DFT) operation. The third method makes it possible to correct the frequency offsets at the BS (reverse

Table 1.3: Contributions to the filed of frequency offsets in uplink of OFDMA and OFDMA-CDM

references	contribution
[TLP00] [Ste00]	analysis of influence of frequency offsets
[LH05]	sub-band transmission for OFDMA-CDM
[BT07] [Mus96] [MW01] [SL05]	windowing in the receiver side
[Mor04]	estimation of frequency offsets

link receiver). These estimates can be used to correct the sampling time instances at the BS receiver or can be sent back to the MT where they are used to pre-compensate the frequency offsets before transmission. Another algorithm for the frequency offset

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estimation in OFDMA was proposed in [Mor04]. The most important contributions to the field of frequency offset in uplink OFDMA and OFDMA-CDM are presented in Table 1.3.

1.3 Goals of the Thesis

The overview of the state of the art, given in Sec. 1.2, reveals that some aspects of IFDMA are thoroughly investigated and advantages of IFDMA are widely recognized. However, some issues are still open and further optimizations of the IFDMA receiver and the IFDMA transmit signal are necessary. The main goals of this thesis can be formulated as follows:

- The first objective of this thesis is to develop the IFDMA receiver with frequency domain equalization, low complexity and possibility to separate users in the frequency domain. Note that at the time the work on this thesis was started, efficient IFDMA receiver was not developed and the relationship between OFDMA and IFDMA systems were not yet understood.

- The BER performance of IFDMA and OFDMA systems should be compared in a frequency-selective channel with minimum-mean square error equalizer and self-interference in IFDMA systems to be understood, described analytically and compared to the self-interference of OFDMA-CDM. The closed form solution for the BER performance of uncoded IFDMA systems to be obtained.

- One of the most significant problems in IFDMA uplink are frequency offsets which cause SNR degradation of the received signal and MAI. Effective countermeasures against frequency offsets in the IFDMA uplink are required. Tradeoff should be found between minimization of the negative impact of frequency offsets and the complexity of the receiver. Moreover, identified countermeasures should keep the BER performance and spectral efficiency of IFDMA uplink systems at a tolerable level. An algorithm for the frequency offset estimation shall be developed and evaluated and its theoretical bounds shall be derived. In the presence of frequency offsets, the received signals of mobile users are not orthogonal to each other which complicates an estimation procedure. In order to reduce the estimation efforts and improve the quality of estimates, MAI should be suppressed.

- With the frequency offset, the inter-carrier interference in OFDM and OFDMA systems is reduced if one applies a window with better spectral characteristics than the rectangular one. By varying the window function, the spectrum of each individual subcarrier can be chosen so that it causes less interference to neighboring subcarriers. Other types of windows require, however, the introduction of

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cyclic prefix and postfix into time domain OFDM symbol. In its turn, an insertion of the prefix and postfix leads to losses in the spectral efficiency, since prefix and postfix do not transmit any information. The solution should be proposed which allows utilizing a power invested into the prefix and postfix.

- The PAPR distribution of IFDMA and OFDMA systems with pulse-shaping should be compared. The reduction of PAPR in OFDMA and IFDMA systems is one of the most significant problems, since high PAPR values require an expensive power amplifier at the MT. In practical amplifiers, the output power of the signal depends on the input power and this dependence is usually non-linear. Therefore, high PAPR values cause non-linear distortions of the signal. The spectral properties of an OFDMA uplink system can be improved if pulse-shaping filters of the high cost and complexity are applied. However, an application of the pulse-shaping filters lead to the higher PAPR.

- In order to improve the spectral properties of IFDMA, the combination of IFDMA with continuous phase modulation schemes should be performed.

1.4 Contents and Important Results

The thesis consists of 7 Chapters. Chapter 1 and Chapter 7 are introductory and concluding chapters, respectively. The contents of Chapters 2 to 6 deal with the goals mentioned in Sec. 1.3.

In Chapter 2, the basic principles of multi-carrier systems are described and OFDM is introduced. The conventional OFDM model is extended in order to take into account the effects of pulse-shaping on the spectral properties of OFDM. The receiver structure proposed in Chapter 2 makes it possible to demodulate the OFDM signals with a variety of window functions without interference. The IFDMA technique is introduced as a special case of the OFDMA-CDM. The proposed transmitter does not have the computationally intensive DFT operation and thus is more preferable than the conventional OFDMA transmitter.

The concept of minimum shift keying (MSK) and Gaussian-shaped offset QPSK (GOQPSK) IFDMA is proposed. As a result of GOQPSK and MSK combination with IFDMA, the MSK/GOQPSK-IFDMA transmit signal is generated without phase transitions and has better spectral properties than the OFDMA transmit signal.

In Chapter 3, the PAPR of OFDMA, IFDMA and introduced GOQPSK- and MSK-IFDMA are compared. The cumulative distribution function of the PAPR is analyzed for the GSMK/MSK-IFDMA. As a reference, the conventional OFDMA and OFDMA-CDM systems are used. Finally, the circumstances under which PAPR distribution of

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GOQPSK-IFDMA outperforms the PAPR distribution of the conventional IFDMA are identified.

In Chapter 4, the effect of frequency offsets on the performance of IFDMA uplink system is investigated using raised cosine (RC) window. It is shown that MAI caused by the frequency offsets can be reduced significantly if RC window is applied instead of the conventional rectangular window.

Generally, frequency offset estimation in the uplink of multi-carrier systems is a complicated task, since the received signal at the BS comprises received signals from many users and each user can have its own frequency offset. Moreover, received signals from different users are distorted by different transmission channels which makes the problem of channel estimation complicated.

A frequency domain algorithm for frequency offset estimation is proposed and its performance is investigated in the mobile radio channel. This algorithm utilizes pilot symbols and provides joint frequency offset and channel estimation. A special construction of pilot symbols with additional spreading in time domain is proposed which allows reduction of the frequency offset estimation error.

A practical time domain algorithm is evaluated which uses the repetitive structure of the IFDMA transmit signal in time domain. The time domain algorithm is independent of the transmission channel and modulation alphabet. Statistical properties of the estimate are analyzed and proven analytically and by Monte-Carlo simulations. As a result, the obtained estimate is unbiased and is able to provide a reliable result at SNR values of practical interest. The proposed algorithm is compared with existing techniques and its superiority is proven.

In Chapter 5, the optimum equalization techniques for OFDM and IFDMA are presented. As shown in Chapter 2, the application of the window in the receiver changes the received spectrum of each individual subcarrier. Varying the roll-off factor of the DFT window function and, therefore, changing the length of the prefix and postfix, MAI caused by the frequency offset can be reduced. A method that allows demodulating the information transmitted on individual subcarriers without interference and by using the DFT of double size was proposed in [BT07].

In Chapter 5, we describe the MMSE algorithm which utilizes part of the energy invested into prefix and postfix for the equalization. As a result, the BER can be improved. Thus, the proposed algorithm improves the spectral efficiency of an OFDM system described in Chapter 2.

Additionally, the SI of IFDMA systems is investigated in an independent Rayleigh channel and it is shown that IFDMA has significantly less SI than conventional OFDMA-CDM.

In Chapter 6, an IFDMA uplink system with non-linear amplifier is investigated and compared with OFDMA and OFDMA-CDM techniques in terms of passband interfer-

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ence, out-of-band radiation and BER performance. Finally, the performance of IFDMA systems is simulated in the mobile radio channel.

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