

Erik Haas

Design, Evaluation and Implementation
of a Multi-Carrier Transmission System
for Aeronautical Communications

Herausgegeben von

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

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Chapter 1

Introduction

Digital wireless communications systems are gaining more and more influence in state-of-the-art technologies, where performance, mobility and safety are important issues. Using the Discrete Fourier Transformation (DFT) in combination with data transmission systems has first been proposed in [Wei71]. With modern technologies, Orthogonal Frequency Division Multiplexing (OFDM) using the Fast Fourier Transformation (FFT) to modulate multiple subcarriers at the same time has become an interesting option.

Like with single-carrier signals, coherent and differential coherent modulation techniques [Pro95] are applicable to OFDM and according standards are already in use for Digital Audio Broadcasting (DAB) [DAB95], Terrestrial Digital Video Broadcasting (DVB-T) [DVB99] or HIPER-LAN/2 [HIP00] to name only a few.

The strong focus on OFDM-based communications systems is related to the fact that this Multi-Carrier (MC) transmission technique in conjunction with M -ary mapping, where $M \gg 2$, shows a high spectral efficiency due to optimum Nyquist criteria application for the subcarriers. As can be seen from the prices that are asked for the current frequency bands of the third generation Universal Mobile Telecommunications System (UMTS), such a spectral efficiency has a high priority for future fourth generation and beyond systems.

Nowadays aeronautical communications systems are suffering a similar nuisance in the Very High Frequency (VHF) band. The applied analog Amplitude Modulation (AM) technique is more than fifty years old and the assigned frequency band between 118 and 137 MHz with a channel spacing of 25 kHz can only occupy a maximum of 760 channels worldwide, of which certain channels are fixedly assigned to aircraft authorities and airlines. The introduction of a new AM modulation with 8.33 kHz channel spacing did not solve the problem, since no data transmission is possible with this technique. Furthermore, the safety of the radio messages is not guaranteed due to the fact that everybody can listen to or even interfere the communication. The lack of digital data exchange and safety has led the aircraft authorities to investigate digital transmission techniques that were intended to solve these problems. The respective data links are known as VHF Data Link (VDL) Mode 2 [DDR01], VDL Mode 3 and VDL

Mode 4 [HHL99]. The drawback of all these data links is that they still operate in the VHF band with only 25 kHz bandwidth and therefore have a very poor performance considering the achievable throughput. This situation is worsened by the fact that the aforementioned aircraft authorities and airlines are not willing to give up their owned channels as long as it is not clear whether the new system(s) will be a success or not.

For that reason, the investigations in this work concentrate on a different frequency band. Since the allocation of frequency bands to aeronautical communications is a difficult task and the proposed systems will only be a success if they can be applied world-wide, a frequency band is used that is already reserved for aeronautical applications. It is the 5 GHz band in which the so-called Microwave Landing System (MLS) operates. Since the MLS has, due to a minor commercial success, not been introduced in all countries, but has on the other hand world-wide reserved frequencies, this frequency band is an ideal candidate for an Advanced aeronautical Data Link (ADL). The ADL can either occupy the full bandwidth or operate in parallel to an existing MLS system. For the case that the MLS frequency band will not be available to the ADL, it can be guaranteed that the ADL will also work in lower frequency bands.

In aeronautical communications, two different directions for the data link exist. One is the so-called ground-air link, forward link or downlink. In this case, the base station, normally at an airport, transmits information to a mobile receiver, normally an aircraft or a different mobile user, e.g. a follow-me car. The other link is the so-called air-ground link, reverse link or uplink. In this case, the information is transmitted from a mobile user to the base station. For the ground-air link, information is transmitted from one base station to several mobile users, whereas for the air-ground link, several mobile users transmit information to one base station. Please note the confusing standardized meaning of down- and uplink here.

The investigations in this work will focus on two different transmission techniques both using OFDM. The first technique is based on coherent modulation and demodulation and is commonly known as Multi-Carrier Code Division Multiple Access (MC-CDMA) [FaP93][YLF93]. As the name already suggests, it offers the possibility to transmit multiplexed information for several users, known as Multiple Access (MA). The reason for choosing MC-CDMA instead of a different MA techniques is justified with the facts that it offers a high flexibility and the possibility to exchange users versus data rates. Furthermore, MC-CDMA can be made extremely stable against worst case transmission channel conditions [Kai98]. The second technique is based on differential coherent modulation and demodulation applying Differential Phase Shift Keying (DPSK) [Pro95] on subcarrier level. It benefits from the fact that it does not need an explicit transmission channel estimation and equalization, compared to coherent transmission methods, and therefore is an interesting option for the air-ground link, where the channel conditions for each mobile user transmitting to the ground station vary. Despite the fact that the investigations concentrate on aeronautical communications, the proposed algorithms and techniques are also applicable for other wireless or wired communications areas.

To prove the accurateness and operability of the proposed methods, a Digital Signal Processor (DSP) based demonstrator is built that features a wireless link in the 5 GHz band for outdoor

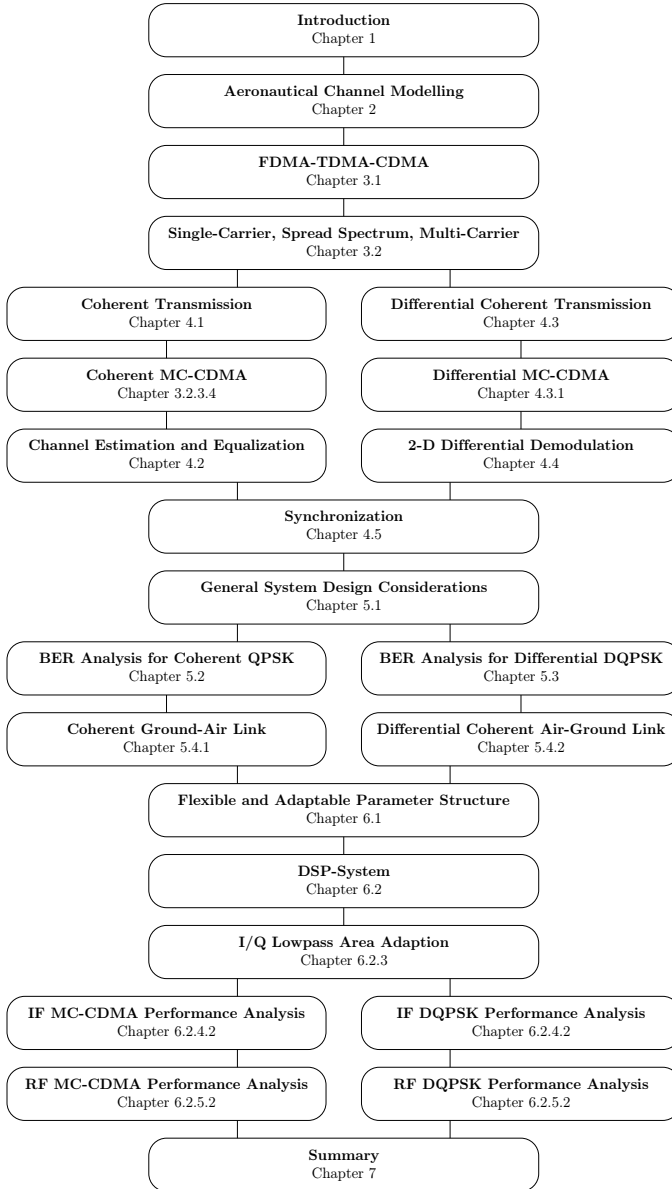


Figure 1.1: Synopsis

communications. It is the first known demonstrator world-wide that uses MC-CDMA transmission techniques. A benefit from this demonstrator is achieved by offering the possibility to investigate implementation aspects in a real-world system.

The outline of the contents of this work is shown in Fig. 1.1. The classification of the modulation technique into coherent and differential coherent aspects is reflected by the separation into a left- and right-hand side.

The introduction is followed in Chapter 2 by the presentation of a previously unknown class of aeronautical wideband channel models, featuring parking and taxi environments, take-off and landing situations, as well as en-route scenarios for ground-air and air-air links. Typical and worst case channel parameter sets, based on published measurement results and empirical data, are defined for the scenarios. They are used in conjunction with the system functions for a Wide Sense Stationary Uncorrelated Scattering (WSSUS) emulation of the aeronautical channel. Procedures are presented to implement the system functions on a digital signal processing system for simulation purposes in the time and frequency domain.

Chapter 3 first gives an overview about the differences between the available Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) multiplexing techniques. This is followed by a comparison of single-carrier, spread spectrum and multi-carrier modulation. Special attention is drawn onto the spectral identities of the transmitted signals with respect to the use of practical Digital-to-Analog (D/A) converter hardware of real-world systems. Measures for OFDM to overcome the resulting drawbacks related to real D/A-hardware are discussed and new hardware and software solutions are proposed. Finally, the basic MC-CDMA technique is explained and two modifications are presented to increase the maximum number of active users and the maximum data rate per user while keeping the complexity for each individual user low.

In Chapter 4, coherent modulation/demodulation in comparison to differential coherent modulation/demodulation is considered. Novel aspects for the interpolation and filtering process of the channel estimation for coherent demodulation are obtained. It is shown that linear interpolation is an option worth considering for several cases, compared to other far more complex interpolation methods. For differential demodulation, no explicit channel estimation and equalization exists. Since the algorithms for coherent MC-CDMA require an equalized signal, these methods are not applicable for differentially modulated systems. Therefore, different methods based on spreading the data with a code before DPSK mapping are proposed. To overcome the degrading effects of differential demodulation, a completely new and formerly unknown two-dimensional algorithm is proposed and investigated. It makes use of the fact that even though the transmitted information is only differentially modulated in one direction within an OFDM frame, neighbouring symbols belong to the same symbol alphabet and thus can be used for the demodulation process without changing the transmitter or existing standards. With a mathematical analysis it is proved that this two-dimensional algorithm improves the Bit Error Rate (BER) performance of the DPSK system. The set-up of an OFDM demonstrator system further necessitates a freerunning synchronization. The interference ratios resulting from a

synchronization mismatch are investigated and the most commonly used algorithms illustrated. Some improvements for the chosen algorithm, that is implemented in the demonstrator system, are given.

Having the aeronautical channel parameter sets from Chapter 2 available, some general considerations about the OFDM system design are done in Chapter 5. These are followed by simulations of the chosen parameters for coherent Quadrature Phase Shift Keying (QPSK) systems and Differential Quadrature Phase Shift Keying (DQPSK) systems. The simulation scenarios enclose the simulated aeronautical channel models as well as non-linear transmitter power amplification effects, synchronization mismatches and CDMA. For DQPSK, the benefits with two-dimensional differential demodulation are investigated as well. It is shown that coherent MC-CDMA applying PSK further improves the system performance compared to normal coherent PSK. Moreover, it is proved that two-dimensional differential demodulation cannot only overcome degrading effects from additive noise, but also from synchronization mismatches, non-linear amplifying effects and fading channels. With the simulation results, parameter sets for a coherent and differential coherent demonstrator set-up are derived.

Chapter 6 deals entirely with the system implementation aspects of the OFDM DSP multi-processor demonstrator. To keep the system as flexible and adaptable as possible, generalized parameter structures are defined which make it possible to change the functionality completely by changing only a few definitions in the parameter list. This makes it possible to have a Software-Defined Radio (SDR) at hand that can be easily adapted to changing demands and new ideas. A detailed description of the transmitter and receiver hardware and software architecture is given next, followed by a description how the different tasks are distributed among the available processors. The investigation of the analog signal identities is done in several steps. First, the In-phase/Quadrature (I/Q) lowpass area is adapted by choosing the correct lowpass filter type and bandwidth and compensating DC gain, DC offset, filter bandwidth and subcarrier attenuation mismatches. In the next step, the Intermediate Frequency (IF) area is considered, where additional subcarrier compensation is necessary. The system improvement through accurate compensation is illustrated with corresponding performance results for coherent and differential coherent modulation/demodulation techniques and additive noise. In a final step, the Radio Frequency (RF) hardware is connected and additional measurements are investigated. The performances with and without freerunning synchronization are opposed. Received equalized subcarrier constellation diagrams for MC-CDMA applying QPSK are presented with varying numbers of active user.

A summary of all investigated results can be found in Chapter 7 which concludes this work.

Since OFDM symbols are generated in the frequency domain, but the equivalent time domain signal is transmitted, corresponding signals of both domains have to be distinguished properly. Throughout this work, capital letters are used for the frequency domain representation and small letters are used for the time domain representation of signals. Furthermore, the equivalent lowpass representation for signals is applied [Pro95].

Performance results are in most cases compared by the BER P_b versus the Signal-to-Noise Ratio (SNR) per bit γ_b . The overall SNR is $\gamma_c = C/N$, where C is the average received signal power and N is the noise power. For the case that the equivalent signal bandwidth B and the noise bandwidth are the same, γ_c can be rewritten as $\gamma_c = C/N = (E_s B)/(N_0 B) = E_s/N_0$, where E_s is the energy per modulation symbol and N_0 is the noise power density. Since modulation symbols can consist of several bits n , the SNR per bit $\gamma_b = E_s/(nN_0) = E_b/N_0$ is defined, where E_b is the energy per bit.

Unless otherwise noted, all calculations were done by hand and verified with Mathematica [Wol94].