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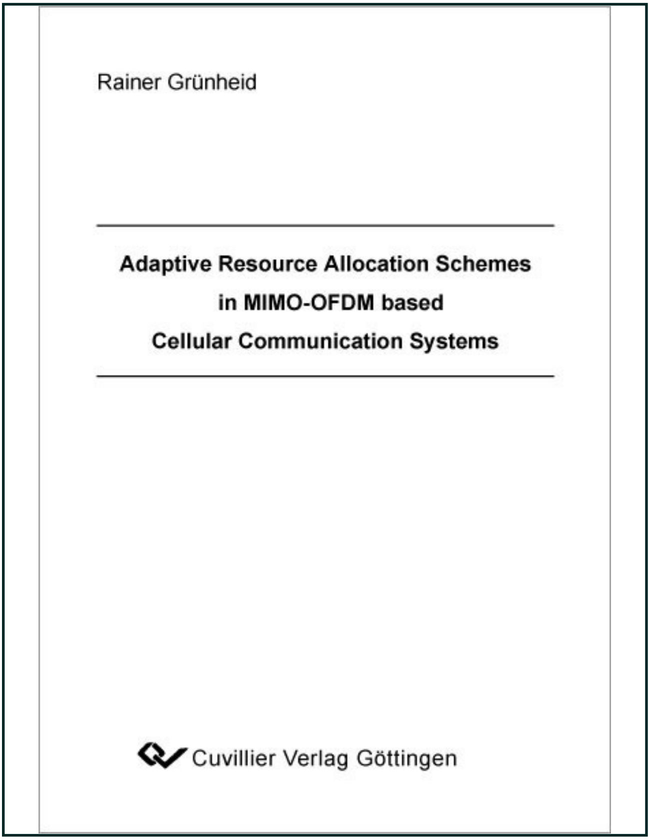

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1 Introduction and Scope

Mobile communication has become an integral part of everyday life in modern societies. The widespread use of mobile phones worldwide shows the significance of 2nd and 3rd generation systems which are in operation today. While the number of subscribers is still expected to grow, various new services, e.g. such as video streaming and web browsing, will most probably be requested more and more by the users in the future, in addition to the voice telephony service which is still dominating today.

From these observations, it can be concluded that certain challenges will have to be met in the research and development of 4th generation systems, which has already been underway for some years now. These new systems will have to be flexible enough to cope with requests for different and especially high data rates, depending on the specific service. Several other Quality of Service (QoS) demands, such as maximum delay or error rates, must be fulfilled, even in hostile multipath channels which are typically encountered in mobile scenarios. Thus, future systems must be adaptable in adjusting their transmission parameters in order to guarantee these QoS demands. It is a well-known fact that the required bandwidth constitutes a scarce, hence very expensive resource, consequently the allocation of resources to the users has to be organised in a very efficient way, in particular given the increasing need for data rates as mentioned above.

In reply to these challenges, some technical solutions are available and under discussion in various research projects. Compared to single-antenna systems, the use of multiple antennas at the transmitter and/or receiver side is termed *Multiple Input Multiple Output* (MIMO) and has the potential to boost data rates and improve link reliability. A lot of different MIMO techniques are proposed, which vary e.g. in the degree of channel knowledge needed at the transmitter and receiver.

For many years now, the multicarrier transmission technique called *Orthogonal Frequency Division Multiplexing* (OFDM) has proven to be very suitable in broadcast and communication systems. The main reasons are its robustness in multipath fading channels, its bandwidth efficiency, the offered flexibility in resource allocation, and the possibility of an efficient realisation in hardware. OFDM has already found its way into some broadcast and communication standards, such as DAB, DVB-T, IEEE 802.11a/g (WiFi), 802.16 (WiMax) and is widely regarded as being a strong candidate in 4th generation communication systems. Moreover, OFDM can be effectively combined with different MIMO techniques, which is an interesting research topic. Also, the application of OFDM in a cellular environment is currently considered by researchers. Here, the efficient distribution of the resources in an interference-limited system is of high relevance. Proposals for a self-organised concept are available which do not require a central coordination between the base stations.

In the described context, this thesis contributes to the above-mentioned aspects by considering methods of resource allocation in a MIMO-OFDM based cellular communication system. More specifically, a self-organised *beamforming* technique is chosen as MIMO technique, which constitutes a simple, yet effective means to add a Space Division Multiple Access (SDMA) component to the FDMA/TDMA-driven OFDM system under investigation. Besides the beamforming technique, the resource allocation to different users, i.e. *scheduling* concepts, are analysed in detail. It will be shown that the combination of both topics, beamforming and scheduling, can be beneficial in terms of system throughput. In this context, the idea of *cross-layer design* is considered and strongly supported here, which basically implies a more comprehensive information flow between the physical (PHY) and Data Link Control (DLC) layer.

The remainder of this thesis is organised as follows. Chapter 2 describes some general aspects of cross-layer design in mobile communication systems and their benefit. As already mentioned, the considered cellular system is based on MIMO-OFDM. Consequently, some basics of OFDM and MIMO are briefly summarised in Chapters 3 and 4, respectively. The concrete system under investigation is outlined in Chapter 5, together with the respective system and radio channel parameters. The main criteria applied for assessment of the system are also listed.

For the sake of studying the effects of beamforming and scheduling on the performance separately, two different chapters (6 and 7) are devoted to these aspects. The availability of Channel State Information (CSI) represents a major prerequisite for adaptive resource allocation. That is why some practical considerations concerning the generation and signalling of CSI are summarised in Chapter 8.

In accordance with the cross-layer design, a closer tying between beamforming and scheduling, i.e. PHY and DLC tasks, is expected to yield a performance gain. The respective strategies are outlined in Chapter 9. In this context, also QoS criteria are included which in turn are defined by the higher layers.

The quantitative simulation results of all above-mentioned topics and their discussion are presented in the respective subsections of Chapter 10. A summary highlighting the main aspects and results of this thesis is given in Chapter 11.

2 Aspects of a Cross-Layer Design in Mobile Communication Systems

The variety of complex tasks to be performed in mobile communication systems is commonly grouped in different *layers*, ranging from the application (highest layer) to the air interface (lowest layer). The well-known ISO/OSI-model [Pis93] consists of seven layers and is an example of such a hierarchical approach, which implies that a layer communicates exclusively with the layers directly above and below it, keeping the exchange of information between layers to a minimum.

Mobile communication systems in the past were primarily designed for supporting voice services. Consequently, the Quality-of-Service (QoS) parameters (such as tolerable delay and residual error rates) were mainly identical and fixed for all data streams. In contrast, future wireless systems beyond the third generation are expected to offer many different services, comprising video, voice, and data applications. This heterogeneous mix will entail the need to provide a wide range of QoS parameters. It is self-evident that a large degree of adaptivity and flexibility will be essential on different layers of the communication system in order to meet these requirements.

In the research field of mobile communication systems, many publications deal with a specific topic concerning an improvement in a particular layer, e.g. the design and optimisation of novel and flexible air interfaces or the development of new DLC protocols. In many cases however, the scope of these investigations is focused on one layer only, and the impact of certain techniques on protocols of other layers is mostly not considered. In recent years, in order to exploit the full potential of such new techniques, a “broader” view has been developed, taking into account also other layers of the ISO/OSI model. This aspect is termed *cross-layer design* and has been recently considered for resource allocation techniques to be applied to wireless systems, see e.g. [Ant06][Ber04][Gra06][Rea05]. It is also adopted for the analysis presented in this thesis.

In Figure 2.1, the conventional view of the ISO/OSI model is shown for the two lowest layers. The data link layer makes use of the service offered by the underlying layer, passing on the user data and only some small amounts of control information, since the choice of specific PHY layer parameters is mostly limited. Furthermore, the data link layer typically disposes of no or only very rough information about the radio channel behaviour, and consequently is not able to adapt well to the changing behaviour of the transmission medium, even if the underlying physical layer granted more flexibility.

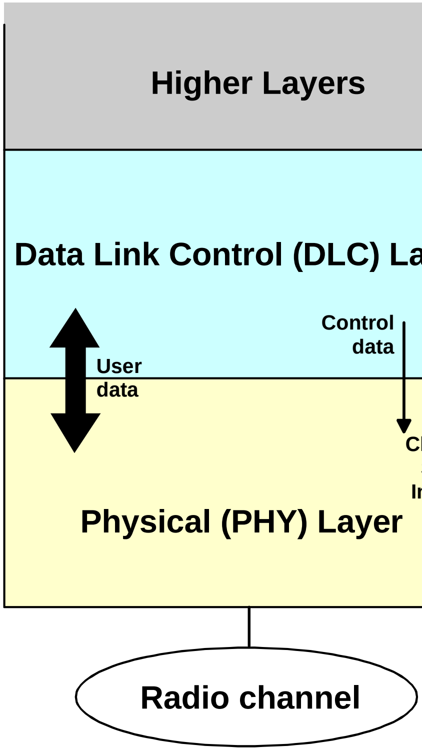

Figure 2.1: Conventional data flow in a wireless communication system based on a layered approach

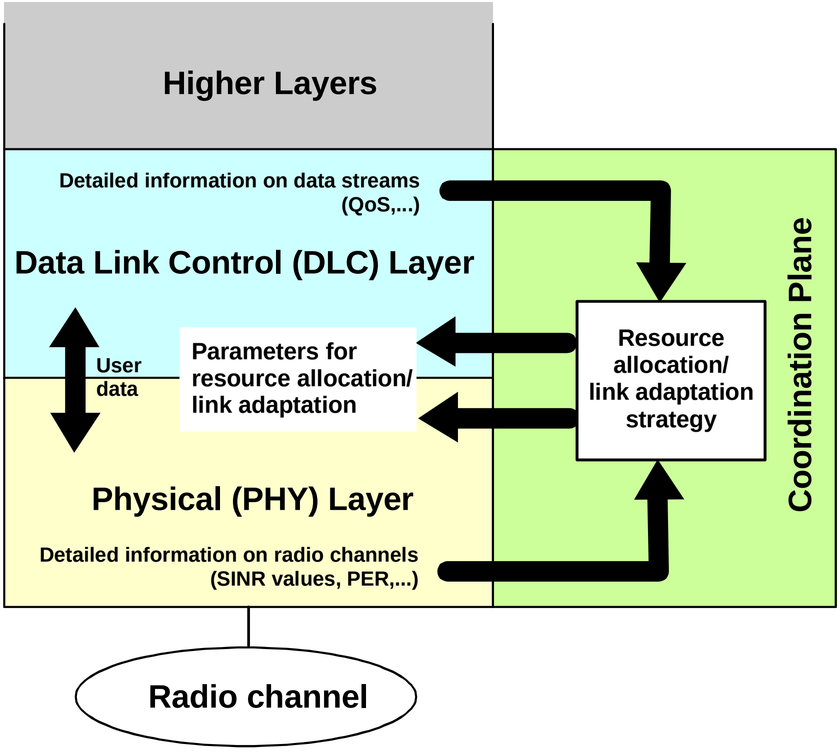

Figure 2.2: Modified protocol stack, introducing a coordination plane to support a joint design of data link and physical layer

Especially when considering new and highly sophisticated air interfaces, this lack of information flow between the two layers leads to a sub-optimum system concept.

As an alternative, Figure 2.2 illustrates a modified approach. Communication between the two layers is established via a so-called *coordination plane* spanning the physical and data link layer. Information on the characteristics and requirements of the incoming data streams is provided by the data link layer, while the physical layer passes on data about the current characteristics of the mobile radio channels. On the basis of these data flows, better strategies e.g. for resource allocation and link adaptation can be developed, taking into account information from both layers by following certain optimisation criteria.

Concerning the information flow from the DLC layer to the coordination plane, it can be expected that mainly Quality of Service (QoS) parameters for the different data packets (delivered from higher layers) can be provided. Parameters such as the required data rate, maximum tolerable delay of a packet, delay jitter or packet error rate are of importance since they are relevant for the transmission over the wireless link.

From the physical layer, in turn, information on the current state of the radio channel, the quality of the wireless link (“layer zero”) is expected. This can be accomplished by direct measurement results (e.g. received power, signal-to-interference-and-noise ratio, SINR). Alternatively, an “indirect” quality measure can be derived, e.g. in the form of a predicted Packet Error Rate (PER), to characterise the instantaneous channel behaviour in a compact way. This indirect measure needs to be associated with a set of transmission parameters offered by the physical layer (e.g. modulation/coding scheme, processing with multiple antennas etc.).

Finally, the definition of tasks for the coordination plane is a central aspect. With the knowledge of the requirements coming from the data streams (higher layers) on the one hand and the detailed information on the radio link qualities on the other hand, the coordination plane should fix the parameters for an allocation of the limited resources on the wireless link. In this respect, its tasks comprise the scheduling of incoming packets and generating a transmission frame (Medium Access Control [MAC] frame) as well as fixing the “physical” modes (modulation/coding etc.) which are used for transmission. The criteria for performing these tasks are numerous and can be realised by weighting the information from “both sides” appropriately.

These general remarks will be illustrated further in Chapter 9 for the concrete example of applying beamforming and scheduling in the considered cellular MIMO-OFDM system. For this purpose, first the topics of OFDM and MIMO are described in the next chapters.

3 The OFDM Transmission Technique

The system considered throughout this thesis is based on the OFDM transmission technique (Orthogonal Frequency Division Multiplexing), a special form of a multicarrier transmission. That is why in the following, a brief overview of the OFDM technique is given. This description includes the motivation for applying OFDM in mobile radio channels as well as the mathematical formulation of OFDM processing in the transmitter and receiver. The discussion in this chapter assumes a single antenna (SISO) system. However, the extension to MIMO-OFDM is straightforward and is covered in Chapter 4.

3.1 Motivation and Principle of OFDM

In contrast to a single-carrier transmission, which uses one broadband carrier, the multicarrier technique is based on transmitting the information on many narrowband subcarriers which are closely spaced in frequency. While the principles of multicarrier concepts have been known for 40 years [Sal67][Wei71], an efficient implementation of this principle has only become possible in the last 10-15 years due to the rapid progress in microelectronics. One form of multicarrier transmission is the OFDM technique, which is considered exclusively in the analysed approach. In OFDM, narrowband subcarriers, which have a sinc-shaped spectrum, are applied (see Figure 3.1). Although their spectra overlap, the subcarrier signals are orthogonal. The transmit signal is produced by using an inverse FFT, while the correlation at the receiver side is done by an FFT.

In comparison to a single-carrier technique, the symbol duration is increased by a factor of N_{SC} (N_{SC} being the number of subcarriers). This fact represents one of the main motivations for using OFDM in mobile radio channels, since the detrimental effects of multipath propagation, namely inter-symbol interference (ISI), can be considerably reduced. ISI can even be completely eliminated in case a guard interval of appropriate length is used as a prefix of each OFDM symbol. In this case, the orthogonality of the subcarrier signals is preserved also at the receiver side. An equalisation can be performed easily due to the entailed cyclic nature of the channel influence, and a one-tap equaliser per subcarrier is sufficient.

Some of the main advantages of OFDM can be briefly summarised as follows:

- Robust behaviour in frequency-selective radio channel, simple equalisation
- Bandwidth efficient transmission due to overlapping subcarrier spectra
- Efficient realisation of transmitter and receiver

- Fine frequency granularity for adaptive resource allocation/link adaptation
- Possibility of a single-frequency network (cluster size of one) in a cellular environment

Especially the last two characteristics of OFDM are exploited in the scope of this thesis.

On the other hand, the following drawbacks of the OFDM can be mentioned:

- High requirements for frequency synchronisation
- Sensitivity to non-linear distortions

The strengths of OFDM and the feasibility of efficient hardware realisation have led to several standards which are based on this form of transmission technique. While in the first phase, OFDM has been standardised for broadcast systems (DAB, DVB-T), in recent years mobile communication and WLAN standards have emerged which are based on multicarrier transmission, such as DAB, DVB-T, IEEE 802.11a/g und 802.16. Generally, OFDM is also regarded as a strong candidate when it comes to the standardisation of future (4G) communication systems.

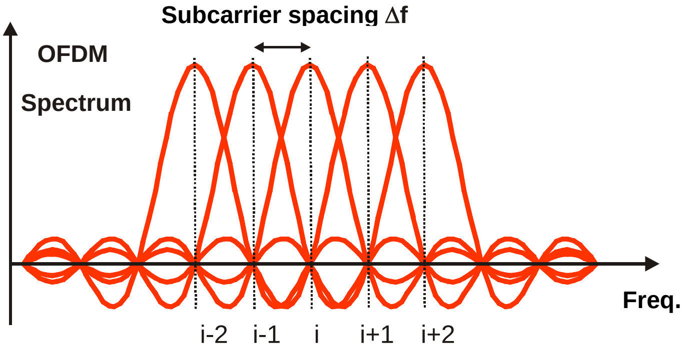

Figure 3.1: Schematic sketch of an OFDM spectrum with overlapping subcarriers

3.2 Mathematical description

In this section, the principles of OFDM are described in more detail by providing a mathematical framework.

An OFDM signal is composed of N_{SC} complex waves of frequency $i\Delta f$. One OFDM symbol, spanning the interval $[nT, (n+1)T]$, is described as

$$\begin{aligned} s_n(t) &= \sum_{i=0}^{N_{SC}-1} S_{n,i} \cdot g_i(t-nT) \\ g_i(t) &= e^{j2\pi i\Delta f t} \cdot rect\left(\frac{t-T/2}{T}\right) \end{aligned} \tag{3.1}$$