Interference Averaging and Avoidance in the Downlink of an OFDMA System

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Abstract – In this paper, the effects of interference averaging techniques (e.g. Frequency Hopping) and interference avoidance are compared for the downlink of a synchronized OFDMA system. The aim is to exploit the rare resource frequency, represented by the subchannels in an OFDMA system, by means of an optimal reuse. Quantitative performance results are given for exemplary scenarios. The results indicate some general guidelines in the design of systems beyond 3G.

Keywords – OFDMA, interference avoidance, interference averaging, spread spectrum

I. Introduction

In recent years, OFDM (Orthogonal Frequency Division Multiplexing) has become the prominent transmission scheme in wireless communications due to its ability to combat inter-symbol interference (ISI) in multipath environments with large delay spreads. With OFDMA (Orthogonal Frequency Division Multiple Access) the concept of orthogonal subcarriers in the frequency domain has been extended to a multiple access scheme. In synchronized systems, sets of subcarriers can be assigned to terminals for parallel data transmission. In conventional OFDM (e.g. in IEEE 802.11a) all subcarriers are assigned to one terminal at a time. The frequency channel has to be shared between all terminals contending for resources in the time domain in a TDMA like manner. In addition to the time dimension, OFDMA offers the frequency dimension as a degree of freedom for the dynamic allocation of resources in wireless broadband systems. This provides an increased flexibility for the Medium Access Control (MAC). In this paper, we compare two distinct techniques for OFDMA to handle mutual interference in interference-limited quasi-cellular systems with reuse of transmission resources.

The paper is organized as follows. At first, a short description of OFDMA systems is given. Then, in section III the principles of Interference Averaging and Interference Avoidance and in section IV the effects of resource sharing are explained. Section V contains quantitative simulations results with respect to the packet delay in an exemplary scenario with Interference Averaging and Avoidance. The paper ends with concluding remarks.

II. OFDMA Systems

A Physical Layer

In OFDM systems, the frequency channel is divided into a set of a set of N subcarriers. Data is transmitted on all narrowband subcarriers in parallel. The length of the transmitted symbols on the subcarriers is chosen in a way that they are orthogonal to each other. In addition to data subcarriers, pilot carriers used for synchronization and channel estimation are distributed over the set of subcarriers. A detailed description of the OFDM transmission is given in [1]. When disjoint subsets of sub-carriers are assigned to different terminals for data transmission in parallel such the transmission scheme is known as multi-user OFDM or OFDMA. In OFDMA systems like IEEE 802.16a a subset of subcarriers is denoted subchannel [4]. Figure 1 depicts the difference in OFDM and OFDMA.

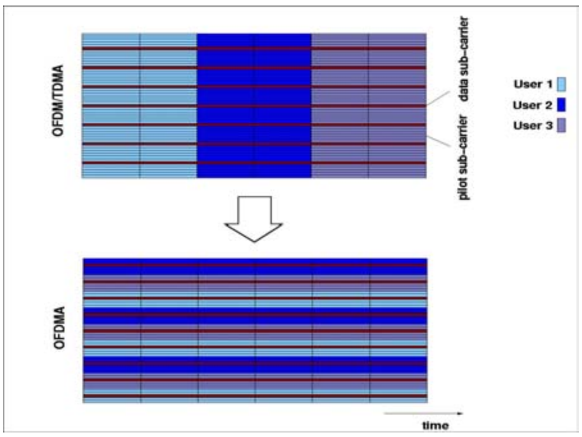

Figure 1 : OFDM/TDMA and OFDMA

B Medium Access Control

In this paper a centrally controlled OFDMA/TDMA MAC scheme with dynamic allocation of resources is assumed. The general structure of the MAC scheme is shown in Figure 1. The frequency channel, comprising M subchannels, is divided into MAC frames in the time dimension. Therefore two-dimensional resource elements (time and subchannel) are allocated for data transmission. Each MAC frame consists of a Control

Phase and a Data Phase which is used for data transmissions both in downlink and uplink direction. In the Control Phase, the central controller broadcasts the allocation of resources to terminals for the succeeding Data Phase. In IEEE 802.16a the description of the assignment of resources within the MAC frame is conveyed in a Frame Control Header [4].

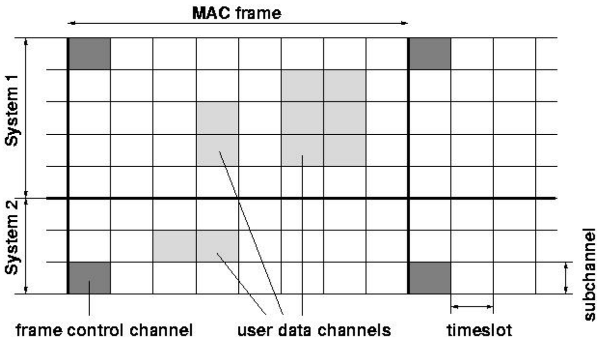

Figure 2 : Frame structure of an OFDMA/TDMA transmission scheme

The terminal which is responsible for the assignment of resources is denoted Central Controller (CC) and is normally placed in the Access Point (AP). All resources (time frequency elements) are assigned to Mobile Terminals (MTs) for either downlink or uplink transmissions by the CC. In IEEE 802.16a a two-dimensional resource element is named Data Regions. These Data Regions are assigned to terminals with a resource request/grant scheme based on demands [4].

III. Interference Averaging and Avoidance

In an OFDMA/TDMA system the resources comprise a set of $M \times L$ orthogonal resource elements, with M subchannels and L timeslots. These resources are assigned to T terminals for data transmissions. When the number of served terminals exceeds the amount of orthogonal resources, they have to be reused by terminals at the cost of mutual interference. The system is then said to be interference-limited [1]. To handle the mutual interference of terminals sharing a resource either Interference Averaging or Interference Avoidance schemes can be applied.

The subject of Interference Averaging is to mitigate interference with the help of spread spectrum techniques. The underlying principle is that of distributing a relative low dimensional data signal in a high dimensional environment [3]. Interferers with a fixed power constraint either spread that fixed power over all coordinates, thereby inducing just a little interference in all coordinates, or else place all of the power into a small subspace, leaving the remainder of the space interference free.

In the receiver, all dimensions of the spread data signal are combined, causing an averaging of the interference.

In OFDMA systems, spreading can be accomplished as a form of Frequency Hopping (FH). Every terminal transmits on a pseudo-randomly selected subset of subcarriers (see Figure 1). Interfering terminals in the same frequency (subchannel) do the same type of selection, but statistically independent. Therefore, the interfering systems constitute a form of Frequency Hopping Spread Spectrum (FHSS) system operating in the presence of a partial band jammer. The data from carriers with a low CIR level are corrected through interleaving and convolutional coding with a long constraint length [7]. Spreading based on pseudo-randomly selection of subcarriers is used in IEEE 802.16a [4].

Interference Avoidance describes the technique to exploit the diversity in the quality (interference/CIR level) of resources for different terminals. In environments where terminals are distributed over a relative large area the interference levels of a resource element in different terminals can be assumed to be uncorrelated to a certain extend. This means that resources with low quality for a terminal *a* can show an acceptable interference level for a terminal *b* in the same cell. In scenarios with diversity in the noise/interference levels of resources, water filling is know to be the optimal scheme for the dynamic allocation of carriers [11]. For the application of Interference Avoidance, knowledge of the interference situation on the receiver side of a connection is required. Therefore, interference measurement and estimation procedures must be supported. Based on that information, a transmitting terminal can allocate the subcarriers for data transmission which have low interference levels on the receiver side. In [8] and [9] it is shown that the capacity in Multiuser OFDM systems can be increased due to adaptive subcarrier allocation when the channel state information (CSI) is know on both receiver and transmitter side. The cost of Interference Avoidance is the overhead required for the acquisition of the channel quality of all subchannels. When a terminal *a* has to send data packets to a terminal *b,* at first it has to request the channel quality on the receiver side. The receiver has to propose appropriate resources for the data transmission.

One basic characteristic of Interference Averaging is that the interference is averaged over all subchannels. This reduces the degree of multi-user diversity in interference scenarios, which could be exploited with a resource allocation based on Interference Avoidance. In the latter case the frequency selectivity of the radio channel is exploited and subchannels are adaptively allocated to different users [12]. The general effect of spread spectrum techniques like Frequency Hopping (FH) in an OFDMA system on the interference reception process is shown in Figure 3. The interference caused by narrowband interferers, e.g. OFDMA terminals, which are transmitting on some narrowband traffic channels, is averaged over all traffic channels in the receiver, causing a loss of diversity in the interference as well as the CIR levels of different subcarriers which could be utilized by sophisticated resource allocation strategies.

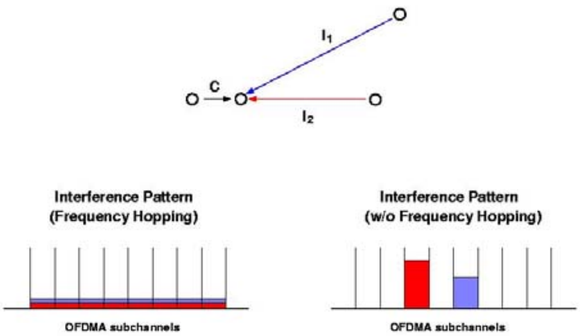

Figure 3 : Effects of Frequency Hopping in OFDMA

IV. Resource Reuse

With the reuse of resources the transmission capacity of a cell can be increased if the CIR level is sufficient. Figure 4 displays the achievable normalized throughputs (T_1,T_2) of two interfering data connections sharing a resource element in a symmetric scenario. In a symmetric scenario, both receivers work with the same CIR. The curves are calculated for uncoded 16QAM transmission of 54 byte packets over an AWGN (Additive White Gaussian Noise) channel, whereby the mutual interference is assumed as white noise and the thermal noise is neglected since we compare interference-limited systems. The equations for BER on AWGN channels are given in [10].

The curves in Figure 4 are based on the following equations for the achievable throughput:

$$T_1 = \eta_m \left(CIR_0 + \Delta P_{(1,2)} \right)$$
$$T_2 = \eta_m \left(CIR_0 - \Delta P_{(1,2)} \right)$$

The monotonic increasing function η_m maps a CIR level to the transmission capacity of a resource element. It depends on the modulation scheme and the channel coding scheme, whereby in the exemplary calculations presented in this paper, channel coding is omitted. CIR_0 denotes the CIR level for both interfering terminals when the transmission powers in the terminals are set in a way that both experience the same CIR level (fair resource sharing). $\Delta P_{(i,j)}$ is the difference of the transmission powers after the adjustment of CIR_0, which results in different throughput values for the two connections under investigation However, in all experiments the overall transmit power (sum of both transmitters) is constant, which allows a fair comparison of the different parameter settings. With this description, an asymmetric scenario concerning the CIR can be interpreted as symmetric scenarios with a power offset between the interfering connections.

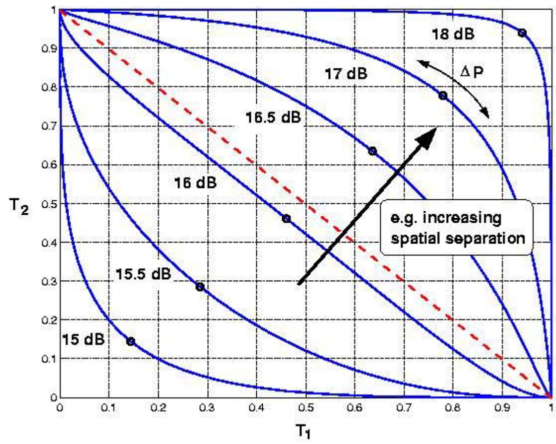

Figure 4 : Achievable throughputs in mutual interfering terminals (connections) depending on CIR_0

The dashed line in the picture represents the transmission capacity in the case of sharing the resource elements without mutual interference (e.g. with a TDMA approach). This corresponds to Interference Avoidance. As Figure 4 exhibits, the capacity of a cell can be increased with the reuse of resources when the according curve lies above the one concerning the sharing of resources in an orthogonal approach. This corresponds to an interference scenario where the CIR_0 of both connections is above a threshold, which depends on the selected modulation scheme. Higher CIR_0 values can be achieved, e.g., with an increasing spatial separation.

The gain in transmission capacity is acquired at the cost of a higher BER due to the increased interference compared to the use of orthogonal resources if the distance between the interfering connections (and therefore the CIR_0) is not sufficiently large. In the scenario in Figure 4, this means that in the case of a CIR_0 level of 17 dB the capacity can be increased but at the same time the BER is increased, too, resulting in retransmissions of data packets. With a CIR_0 of 15 dB the reuse of resource would constitute a loss of capacity. With the application of spread spectrum techniques, CIR_0 is directly affected by the processing gain G_P.

V. Simulations

A Scenario

To evaluate the impacts on the packet delay in OFDMA systems with Interference Avoidance and Interference Averaging the downlink of two interfering cells sharing a set of resources has been investigated. Since the QoS of a data connection mainly depends on the CIR level of the allocated resources, the distribution of the downlink CIR in the cells with mutual interference has been calculated. The scenario is shown in Figure 5.

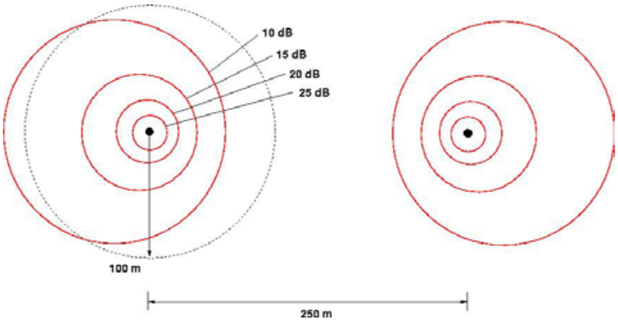

Figure 5 : Downlink CIR ranges in interfering cells

The probability distribution of the CIR level in a cell of the scenario in Figure 5 with uniform user density was determined with the help of Mont-Carlo simulations. Figure 6 show the results for cell radii of 100 m and 125 m and a distance of 250 m between the centers (APs) of the interfering cells.

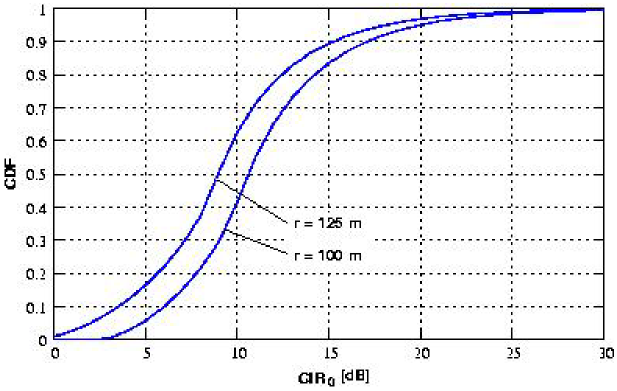

Figure 6 : Downlink CIR distribution

Based on the preceding analysis the scenario displayed in Figure 7 was chosen for the simulations. 8 terminals are associated to each AP. Between each terminal and the according AP a downlink connection is established. All connections carry the same traffic load. For the comparison of Interference Averaging and Avoidance fixed resource are assigned to the downlink connections. Fixed transmission power is assumed for each connection.

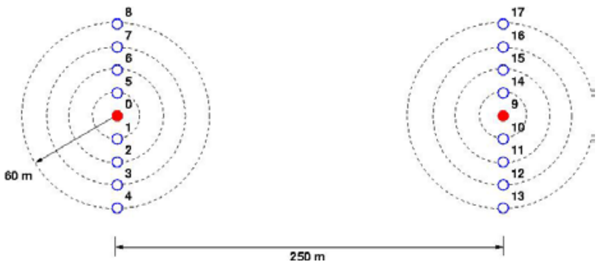

Figure 7 : Simulation scenario

In Table 1, the calculated downlink CIR values of terminal 1-4 are listed. Considering the CIR CDF in Figure 6 the simulated terminals are representative for 35% of terminals with the highest CIR when uniform distribution is assumed within a radius of 100m.

ID	carrier distance	interferer distance	CIR_0
1	15 m	250.4 m	24.4 dB
2	30 m	250.8 m	18.4 dB
3	45 m	254.0 m	15.0 dB
4	60 m	257.0 m	12.6 dB

Table 1 : Downlink CIR levels of simulated scenario (fixed transmission power)

B Parameter

For the simulations an OFDM scheme with 1024 subcarriers is used. The subcarriers are subdivided into 32 subchannels, each comprising 4 pilot subcarriers and 28 data subcarriers. As the modulation scheme for all connections 16QAM is used. For channel coding a convolutional code with code rate ¾ and a coding gain of 2 dB is assumed. Due to orthogonality, the symbol length is 10 µs, including a guard time to combat ISI. Further, following assumptions are made concerning the radio channel:

- The maximum excess delay of the radio channel is always smaller than the guard time (ICI = 0)
- The background noise and interference is interpreted as AWGN
- The energy of a single data symbol is evenly spread over all subcarriers in a subchannel

The raw BER after demodulation can be calculated analytically for an AWGN channel as explained in [10]. The achievable throughput per subchannel with uncoded modulation and a packet size of 54 byte, corresponding to a HiperLAN/2 Long Channel (LCH) [5] is shown in Figure 8. In the simulation user data packets are segmented into 54 byte packets (LCHs). The packets are transmitted in form of packet trains preceded by a preamble with a length of 10 µs.

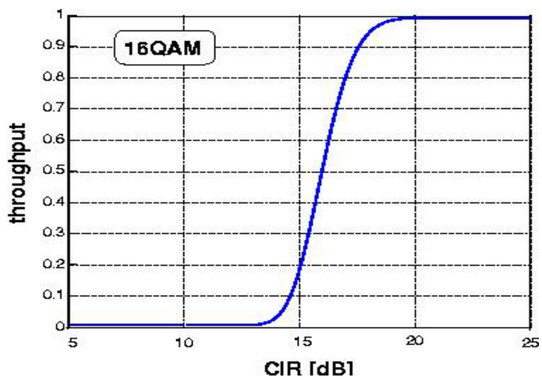

Figure 8 : Achievable throughput with uncoded 16QAM

The system is synchronized on the MAC layer, meaning that the control phase (i.e. FCH) coincides in both interfering cells. The MAC frame has a fixed length of 2 ms. For the Control Phase a length of 0.1 ms is assumed (5 % of the MAC frame). A Convergence Layer based on HiperLAN/2 is running on top of the MAC Layer [6]. In all simulations, a fixed packet size of 1000 bytes is used. The packets are generated by a poisson process.

The degree of freedom in resource assignment within the Data Phase of a MAC frame is determined by the set of all subchannels. Due to a total transmit power constraint in a terminal the power has to be distributed over the parallel transmissions on different subchannels. Uniform power distribution is assumed in the simulations (i.e. no Power Control). Scheduling in the time dimension is not considered in this paper, each downlink connection is assigned a fixed set of OFDMA subchannels and a fixed transmission power at the simulation setup. Therefore, the packet transmissions, i.e. the composition and sending of packet trains, in all downlink connections of an AP can be regarded as independent. Based on the MAC frame structure in the time dimension, within each Data Phase (see Figure 2) for each downlink connection a packet train consisting of packets from the according transmission queue is transmitted on the assigned subchannels. SR-ARQ with bitmap acknowledgments is used as the retransmission protocol.

C Results

In the first exemplary simulations, both APs use all 32 subchannels for downlink data transmission, 4 for each connection. The fixed total transmission power is 30 dBm. Frequency Hopping due to pseudo-randomly selection of subcarriers for an OFDMA subchannel is applied. The traffic load per connection is 8 Mbit/s. Figure 9 shows the CDFs of the CIR levels in MTs 1-4, the dotted lines represent the calculated levels from Table 1.These CIR levels appear when in the interfering AP all subchannels are used for data transmissions in parallel (none of the downlink transmission queues are empty). Otherwise, the CIR level comprises only a fraction of that maximum level when at least one transmission queue is empty (because of the assumed fixed power allocation for each connection). Comparing the range of CIR of Figure 4 in which 16QAM is working plus the assumed code gain of the convolutional code, the downlink connections to terminal 4 and 3 will be affected by retransmissions of data packets.

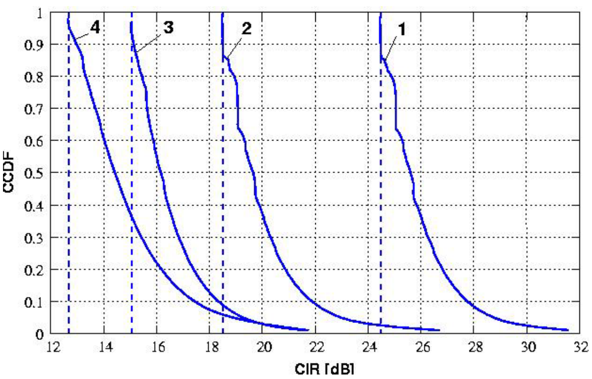

Figure 9 : CIR evaluatiuon

Figure 10 displays the CCDF of the packet delays for the downlink connections to MTs 1-4 in the simulated scenario. Additionally, the delay measurement with the assignment of orthogonal resources without frequency hopping is shown (dashed line). The set of 32 orthogonal subchannels is divided into two subsets each with a magnitude of 16 subchannels. Each of these subsets is assigned in a fixed manner to an AP. Within the APs, 2 subchannels are assigned to each downlink connection. This simulation setup represents an application of Interference Avoidance in the assignment of resources on the cell level. Since the same amount of mutually orthogonal resources and the same transmission power level are used for all connections, all connections in the scenario experience the same distribution of the packet delay. Since the noise level in the receiver is very low compared to the interference, with the assignment of orthogonal resources nearly no retransmissions appear. At the same time, the overall transmission capacity per downlink connection is reduced because of the reduced number of allocated subchannels.

The results exhibit that the packet delay for MT3 and MT4 can be reduced with the assignment of orthogonal resources. In connection 4, with the use of 4 subchannels and frequency hopping, 10 % of the transmitted data packets (1000 bytes) experience a delay of more than 12 ms, corresponding to 6 MAC frames. With the fixed allocation 2 interference–free subchannels per connection, representing Interference Avoidance, the delay is decreased in an extent that 10 % of the packet transmissions only take more than 3.5 ms.

For MT1 and MT2 the delay is increased in a minor degree. In comparison with the calculations for the probability distribution of CIR levels in a cell with uniform distribution of terminals, it is revealed that in the investigated scenario more terminals are affected by a reduced packet delay than by an increase delay. Therefore, with the application of Interference Avoidance, the mean packet delay of all connections can be reduced in the simulated scenario.

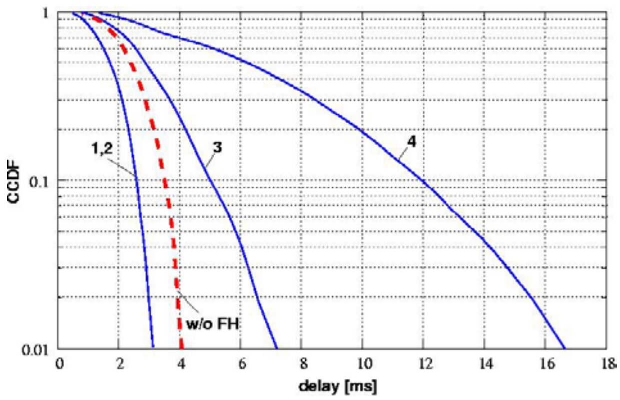

Figure 10 : Packet delay evaluation

Due to the limited space of this paper, only exemplary results for the described parameter setting are presented. Nonetheless, the general effects of Interference Averaging and Avoidance are shown.

VI. Conclusion

In this paper, the techniques to handle interference in an interference-limited OFDMA system are illustrated.

Interference Averaging based on Spread Spectrum techniques is compared with resource allocation schemes based on Interference Avoidance. Further, the effects of the reuse of resources are outlined. For quantitative performance evaluation of the impacts concerning packet delays, an exemplary multiuser scenario has been analyzed with stochastic simulations. Concerning the performance evaluation, it has to be noted that the measurement results presented in this paper are exemplary with a fixed setting of transmission parameters. Further research regarding interference aware allocation of resources in OFDMA systems is conducted. Especially the dynamic allocation of resources in combination with an adaptive selection of modulation, coding and transmission is promising task.

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