The Effects of Time and Frequency Domain Resource Partitioning in OFDMA Systems

Michael Einhaus, Ole Klein
Communication Networks, RWTH Aachen University, Faculty 6, D-52064 Aachen, Germany
Email: ein@comnets.rwth-aachen.de

Abstract – **A general problem in multi-cellular radio systems is the allocation of radio resource subsets to base stations. In OFDMA systems, the partitioning scheme, either time or frequency partitioning, directly affects the possibility to exploit diversity in scheduling algorithms. This paper provides a description of the effects of different resource partitioning schemes concerning the OFDMA scheduling of downlink connections in a multi user scenario. Further, a detailed performance analysis of an exemplary scenario is given. It is shown that there is a superposition of two effects. The first is the dependency of the OFDMA scheduler on the frequency diversity, depending on the number of usable subchannels, and the second effect is the influence of the power allocation for the subchannels. When the total transmission power is fixed, the mean power per subchannel increases with a reduced number of used subchannels. Simulation results show that the domination of the first or second effect depends to a great extent on the traffic characteristics in the system.**

Keywords – **OFDMA, resource partitioning, multi user diversity, power allocation**

I. Introduction

Recently, the concept of Orthogonal Frequency Division Multiple Access (OFDMA) has become a promising candidate for future broadband radio systems. That transmission scheme is for example currently deployed in the well known standard IEEE 802.16a [1]. Especially in combination with adaptive modulation and power allocation OFDMA has shown to be quite beneficial [2].
The subject of this paper is to provide a performance evaluation of a simple OFDMA scheduling algorithm for packet based data transmissions in a centrally controlled Medium Access Control (MAC) scheme. It is investigated how different resource partitioning schemes in multi-cellular environments affect the OFDMA scheduling.
In general, in multi-cellular environments the set of usable radio resources for the system, for example an 80 MHz frequency channel, has to be shared between the base stations in an efficient manner that provides both fairness and interference minimization. In a multi-channel scheme like OFDMA the according partitioning process can be conducted both in time and frequency domain. It is also possible to apply a partitioning via codes, but this is not considered here. Anyway, a subchannel or subcarrier pattern in an OFDMA system can be considered as a code.
With the application of Time Domain Resource Partitioning (TDRP), time slots are assigned to different base stations. Within these slots the base station can use the whole channel bandwidth for the scheduling. Frequency Domain Resource Partitioning (FDRP) denotes the subdivision of the channel bandwidth into subchannels that are assigned to different base stations. Therefore, the diversity in the frequency domain is reduced.
When the OFDMA scheduler exploits the diversity in the frequency domain, the difference between FDRP and TDRP will obviously affect the achievable diversity gain. At the same time, with FDRP and fixed total transmission power, the latter will be allotted to a reduced number of subchannels, resulting in an increased mean transmission power per subchannel. Hence, in general there is a superposition of two opposite effects that influence the performance in OFDMA systems that apply resource partitioning between base stations and scheduling algorithms that exploit the inherent subcarrier or subchannel diversity. The process of resource partitioning can be conducted in a centralized manner or based on distributed algorithms. Since this paper is focused on the effects of different partitioning schemes and not on the partitioning processes itself, fixed resource allocations for base stations are assumed in the analysis. An interference minimizing partitioning scheme which only assigns orthogonal resources to base stations is considered. Further, the base stations are perfectly synchronized both in time and in frequency. Therefore interference is neglected during the simulations and the performance evaluation can be conducted for a single cell scenario without loss of generality.
The remainder of the paper is organized as follows. In section II, the evaluated OFDMA system is described. The description comprises the Physical Layer, the MAC, and the OFDMA scheduling algorithm. The resource partitioning schemes and the impacts on the scheduling are explained in section III. Results of the thorough performance evaluation of an exemplary scenario are presented in section IV. Finally, the paper ends with a conclusion.

II. System Description

In this paper, a broadband OFDMA system with a centrally controlled MAC scheme is examined. The MAC structure is based on IEEE 802.16a, whereby the Physical Layer (PHY) significantly differs. In the following, the PHY parameters, the MAC, and the OFDMA scheduling algorithm are explained in detail.

A. Physical Layer (PHY)

The channel bandwidth of the system is 80 MHz which is subdivided into 1024 subcarriers with a spacing of 78.125 kHz. Due to orthogonality, the total symbol length is 13.6 μs, including a guard interval of 0.8 μs to mitigate inter symbol interference in multipath environments. An OFDMA subchannels consists of 32 subcarriers, whereby 2 subcarriers per subchannel are reserved for the transmission of pilot signals. The subchannels are directly mapped onto a contiguous fraction of the frequency channel. This is in contrast to IEEE 802.16a, where the subcarriers of a subchannel are evenly distributed over the frequency channel in a pseudorandom manner to apply a kind of spreading scheme [3]. This obviously reduces the flexibility of the OFDMA scheduling since the subchannel diversity is lost.

Three different combinations of modulation and channel coding schemes are used for the performance evaluation, namely QPSK ¾, 16QAM ¾, and 64QAM ¾. These schemes are called PHY modes in the following.

An important feature of the OFDMA PHY is the possibility to exploit multi user diversity. That means that different terminals experience different fading levels on the same subchannel at the same time. When a scheduler for multi-channel schemes like OFDMA, is able to exploit that diversity, the system capacity can be significantly increased as performance evaluations have shown [4].

B. Medium Access Control (MAC)

The general MAC structure is based on a centrally controlled scheme like IEEE 802.16. The frequency channel is divided into MAC frames. In general, these frames consist of control and data phases. In the control phase, the messages of a resource request/grant scheme are transmitted [5]. Since only the downlink is considered in this paper, resource or bandwidth requests from the mobile terminals are not required. The resource or bandwidth grant message can be considered as a resource allocation table. This is required in an OFDMA system because each mobile terminal that is associated to a base station has to be informed prior to the transmission of user data which subcarriers or subchannels it may receive or transmit on in the data phase [6]. The latter in general consists of uplink- and downlink data transmissions.

Since the focus of this paper lies on the influence of different resource partitioning scheme on the OFDMA scheduling, a simplified MAC frame model is applied. The according structure is shown in Figure 1. The frame consists of 5 time slots. The first slot is reserved for the transmission of control data packets. These packets comprise messages for channel estimation and resource allocation. The resources of the remaining slots are used for downlink data transmissions. Overall, a fixed signalling overhead of 20% is assumed, independent of the amount of used resources. This means that the signalling for the data transmission one four time-subchannel elements requires one element.

A single MAC frame comprises several scheduling intervals. Within such an interval, time-frequency elements are allotted to connections based on an OFDMA scheduling algorithm. These elements are denoted Resource Elements (REs) in the following. One scheduling interval matches a single time slot. The latter has a length of 108.8 μs which corresponds to 8 symbols. Therefore, the MAC frame has a cumulative length of 5 x 108.8 μs = 544 μs.

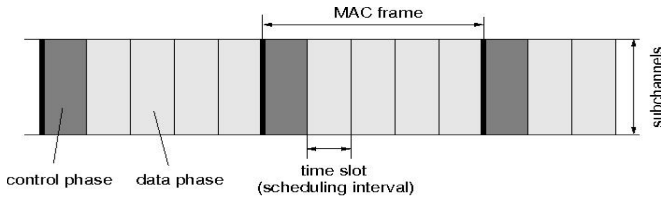

Figure 1 : MAC frame structure

Since data packet transmissions, and not bit streams, are investigated in this paper, a mapping of data packets onto REs is needed. This task is accomplished by a segmentation process. In that process, Network Layer Protocol Data Units (NPDUs) are segmented into MAC Protocol Data Units (MPDUs). The MPDUs have a fixed size of 45 bytes, whereby 5 Bytes (11.11 %) are considered as overhead (i.e. sequence number, connection ID, etc.). The application of that size has the advantage that the packets can be mapped onto REs without a waste of capacity due to clipping. That mapping is shown in Figure 2 for the PHY modes used in this work.

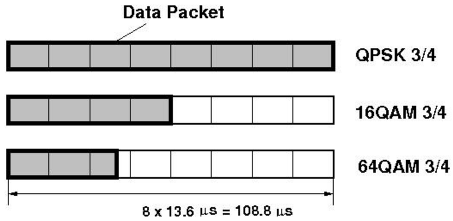

Figure 2 : Mapping of packets onto REs

The MAC capacity after the reduction of control and segmentation overhead depending on the PHY mode is shown in Table 1.

mode	*bits per symbol*	*packets per RE*	*net capacity*
QPSK ¾	60	1	2.35 Mbit/s
16QAM ¾	120	2	4.70 Mbit/s
64QAM ¾	180	3	7.06 Mibt/s

Table 1 : Capacity depending on modulation and coding schemes

A standard Selective Repeat Automatic Repeat Request (SR-ARQ) scheme is used on top of the MAC layer to provide reliable data connections due to packet retransmissions in the case of errors.

C. Scheduling Algorithm

The scheduling of data connections in OFDMA systems is a challenging task. It is required that the scheduler is able to exploit the multi user diversity and provide fairness at the same time. In the implemented basic scheduling algorithm, a simple adaptive modulation and power allocation scheme is deployed. To each allocated subchannel within the same scheduling interval (i.e. a time slot) is assigned the same fraction of the total transmission power. This power allocation scheme does not take into account current channel characteristics. Therefore it differs from the water-filling solution which is optimal from the information theoretic point of view [7]. After the power allocation, reasonable PHY modes are assigned to the subchannels based on SNR estimations.

The basic scheduling algorithm consists of a loop where each cycle comprises five steps:

1. *connection selection*
2. *subchannel selection*
3. *power adaptation*
4. *mode adaptation*
5. *requirement adaptation*

In the first step of the scheduling cycle, a connection is taken from the set of active connections. A connection is considered active if there is at least one packet to transmit. To provide fairness, that selection procedure is implemented as a round-robin scheme.
In the next step, the selected connection gets the subchannel with the smallest estimated fading loss from the set of the subchannels that have not been allocated yet. After that assignment, the transmission power and the modulation scheme are adapted for all already allocated subchannels. Then the number of data packets that can be transmitted for each connection is calculated. Based on that information, the resource requirements (i.e. the number of packets to transmit) for the next scheduling cycle are calculated. Here it has to be noted that it is possible that the requirements of a connection can increase during a cycle. That may happen when the modulation scheme for that connection changes within a cycle (e.g. from 64QAM ¾ to QPSK ¾) due to changes in the power allocation. The scheduling algorithm does not consider inter-cell interference. It is assumed that the resources are assigned to base station in a manner that the interference can be neglected. Sure, this OFDMA scheduling algorithm is suboptimal, but general effects due to the influence of different resource partitioning schemes can already be revealed.

III. RESOURCE PARTITIONING

The global set of resources available for the system consists of K OFDMA subchannels and L time slots. Therefore, subsets of the K x L resource elements must be allotted to the base stations in a multi-cellular environment. That partition can be done in the time and in the frequency domain. In the following, these schemes and the impacts on the OFDMA scheduling are explained in detail.

A. Time Domain Resource Partitioning (TDRP)

With the application of a TDRP scheme, the global resource set is subdivided into time slots. These slots are assigned to the base stations. Since each base station operates on the whole frequency channel, i.e. all subchannels, maximum diversity can be exploited by the OFDMA scheduling.
In TDRP schemes, the time slot pattern for a base station is the crucial design issue. Figure 3 shows the application of two possible allocation schemes. It is assumed that the frame structure of all base stations is synchronized.
In the first case, all slots of a frame are assigned to a single base station. Consecutive frames are used by different base stations. Therefore, it can be said that the resource partitioning is done on a frame level. This approach has one major drawback. With an increased number of base stations the time between two transmission phases of a base station also increases. In the case of transmission errors this may lead to unfavourable high retransmission delays.
In the second case, fractions of a single frame are assigned to different base stations. The advantage is here that the retransmission delay is bound to the frame length. Each base station has the possibility to transmit data packets in each frame. A drawback in this scheme is that the size of the frame fraction that is assigned to a single base station decreases with the number of base stations. This may result in an increased overhead due to preambles, etc. In this paper, only the second scheme is considered. This is done to have a fair comparison between TDRP and FDRP concerning the retransmission delay.

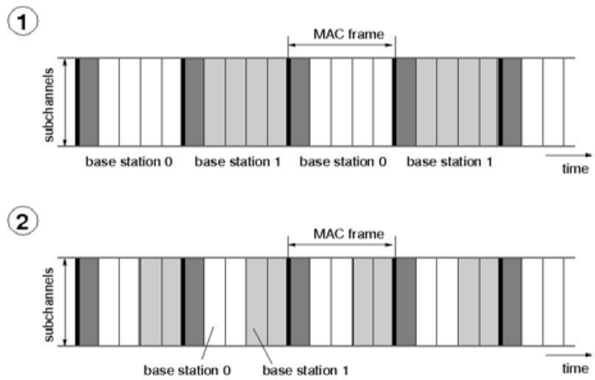

Figure 3 : TDRP MAC frame structures with two base stations

B. Frequency Domain Resource Partitioning (FDRP)

In this partitioning scheme, the subdivision of the global resource set is done in the frequency domain. In an OFDMA system this means the allotment of subcarriers sets to different base stations. The granularity of the FDRP is defined by a subchannel that comprises a defined number of subcarriers. Since a single bases station is not operating on the whole frequency channel, the diversity in the frequency domain is reduced. The amount of the diversity loss depends on the number of subchannels that are used by a base station for OFDMA scheduling. And this number in general depends on the number of base stations. A typical subdivision of the resources in an FDRP manner is shown in Figure 4. As in the second TDRP scheme, here the retransmission delay is determined only by the frame length and not by the number of base stations since a base station can transmit data in each frame. Another consequence of FDRP is influence on the power allocation for subchannel transmissions. When a fixed total transmission power is assumed, the mean power that can be allotted to a subchannel will increase with the reduction of the number of used subchannels. Hence, there is a superposition of a possible SNR loss due to reduced diversity in the frequency domain and an SNR gain due to the increased power density per subchannel. Which effect dominates depends to a great extent on the scheduling algorithm and the traffic characteristics.

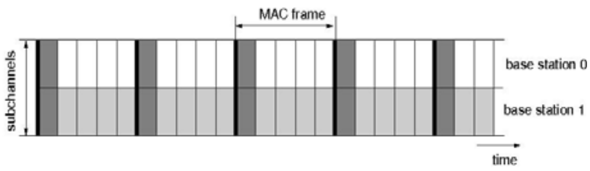

Figure 4 : FDRP MAC frame structure with two base stations

IV. Performance Evaluation

A. Simulation Model and Scenario

For the performance comparison of TDRP and FDRP, a single cell is evaluated. Since the application of an interference minimizing resource partitioning scheme is assumed, the interference from other cells is neglected. The global set of resources consists of 32 subchannels and 4 time slots for the transmission of data packets. The time slot, that is required for the control signaling, is shared between the different base stations, whereby the coordination scheme itself is not of interest in this analysis.

With TDRP, a fraction of the time slots is used for scheduling by the investigated cell. In the FDRP approach, a subset of all subchannels is used in all time slots as explained in section III. 32 mobile terminals, each with a single downlink connection, are associated the base station. The terminals are evenly distributed in an area with a radius of 300 m around the base station. The time interval between random terminal position updates is 0.01s. This corresponds to approximately 18 MAC frames. The downlink connections are modeled Poisson traffic with 100 byte packets. During the simulations, the same traffic load is used for all connections.

A one-slope model with a path loss exponent of 2.5 has been used for the calculation of the radio propagation. The subchannel fading is modeled as Rayleigh fading [8],[9]. Thereby, the fading processes of the subchannels are assumed to be uncorrelated in both time and frequency dimension. Due to the very short MAC frame length of 544 µs, constant fading levels and perfect channel knowledge is assumed at the base station for each MAC frame. In the simulator, the fading levels are updated every MAC frame. A fixed total downlink transmission power level of 30 dBm is used.

The critical point in each MAC level simulation that considers packet errors due to interference, fading and noise is always the mapping of SINR levels onto packet error rates. In this paper, a simple model is used to show the general effects of resource partitioning. The raw BER after demodulation has been calculated for an AWGN channel for different modulation schemes as explained in [10]. Further, channel coding is assumed, whereby the capacity reduction due to redundancy is considered and the coding gain is neglected. On the first sight, the latter might be considered as an unrealistic model, but this paper is focused on MAC scheduling in OFDMA systems and the aim is to show the general effects of FDRP and TDRP independent of the particular implementation of a channel coding scheme.

The corresponding link adaptation curves are shown in Figure 5. The dotted line therein represents the curve on which the maximum PHY level capacity can be achieved according to a known SNR, the bold line shows the achievable capacity under the constraint of a maximum tolerated PER of 0.01 for all PHY modes except the most robust one, i.e. QPSK½. In this case a lower PER is accepted so that also connections with a low SNR can be served. In general, the scheduler assigns a PHY mode for a subchannel allocation that provides the highest capacity under the given PER constraint. This is a rather simple model for the error mapping, but the general effects of TDRP and FRDP can be revealed anyway. Performance comparisons with more realistic models are planned for the future.

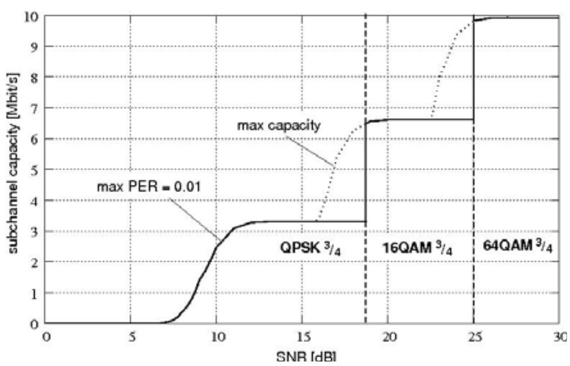

Figure 5 : Link adaptation curve

B. Simulation Results

In the first step, the performance of TDRP and FRDP is evaluated in the case of an assignment of 50 % of the total resources to the investigated base station. This accords 2 time slot in the case of TDRP and to 16 subchannels in the case of FRDP from the set of 32 x 4 resource elements.

Figure 6 and Figure 7 show the cumulative distribution functions of the SNR of a single downlink connection for 500 kbit/s and 200 kbit/s traffic load. The results exhibit that the SNR distribution obviously depends on the traffic load. In Figure 6, the two different effects of a reduced number of used subchannels in the FDRP approach can be clearly distinguished. In the left part of the diagram (lower SNR levels) the TDRP scheme provides a higher SNR compared to FDRP. This is due to the increased subchannel diversity since in the TDRP scheme the scheduler has more subchannels to choose from for an allocation compared to FDRP. In the area of higher SNR values, FDRP outperforms TDRP since the SNR gain due to an increased mean transmission power per subchannel is bigger than the possible SNR reduction due to the loss in diversity. Considering the results for 200 kbit/s traffic load, that are shown in Figure 7, it can be seen that with reduced traffic load the SNR gain due to increased frequency diversity in the TDRP scheme definitely exceeds the possible SNR loss due to a reduced transmission power per subchannel. The reason is that due to the burstiness of the packet arrival process not all subchannels have to be used to in parallel to serve all transmission demands in the case of TDRP.

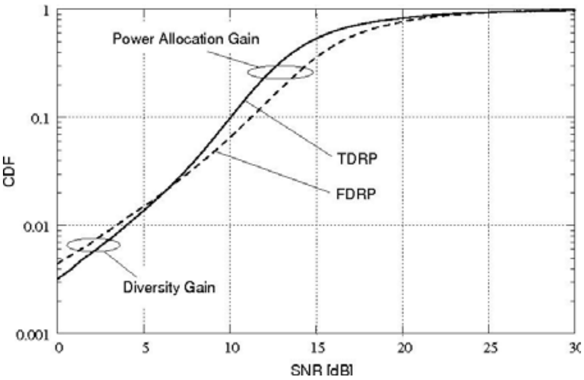

Figure 6 : Downlink SNR with 500 kbit/s traffic load

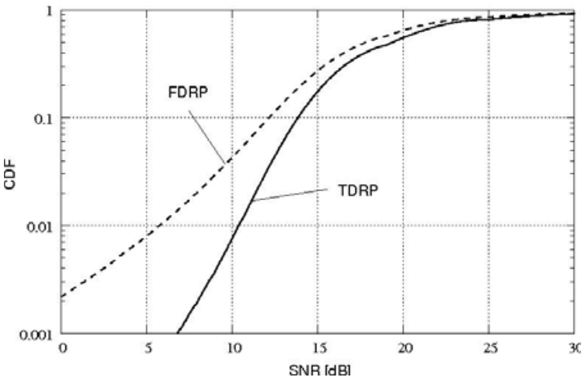

Figure 7 : Downlink SNR with 200 kbit/s traffic load

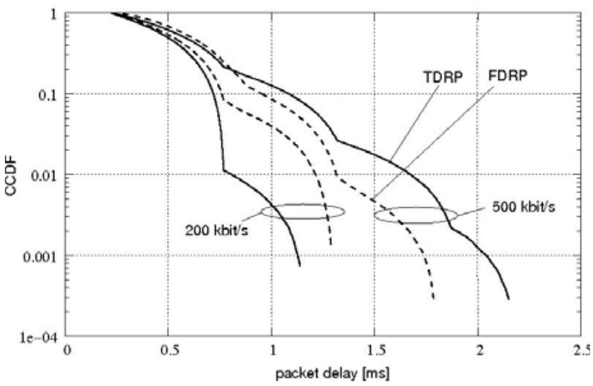

Figure 8 : Packet delay

The complementary cumulative distribution function of the packet delay distribution depending on partitioning scheme and traffic load is shown in Figure 8. As expected due to the SNR evaluation results, with 200 kbit/s traffic load TDRP outperforms FDRP. In the case of 500 kbit/s traffic load, FDRP in contrast provides the lower delay compared to TRDP. In this figure, the impact of the frame length (544 μs) can be clearly identified. Since the resource utilization is rather low for both traffic loads, the delay is here basically determined by the retransmissions due to packet errors.

Figure 9 shows the mean probability of QPSK ¾ and 64QAM ¾ usage depending on the downlink traffic load per connection. It is revealed that the usage of 64QAM ¾ in general decreases with higher traffic loads while the usage of QPKS ¾ increases. Concerning the comparison of TDRP and FDRP, with low traffic loads the system performs better with the TDRP scheme since the probability of 64QAM ¾ is higher than in the case of FDRP. In contrast, with higher traffic loads, the FDRP scheme performs better, i.e. the probability of high rate modulation schemes is increased and the probability of low rate schemes is reduced. This result corresponds to the SNR evaluation presented above since the PHY modes are dynamically adapted to the estimated SNR in the scheduling algorithm.

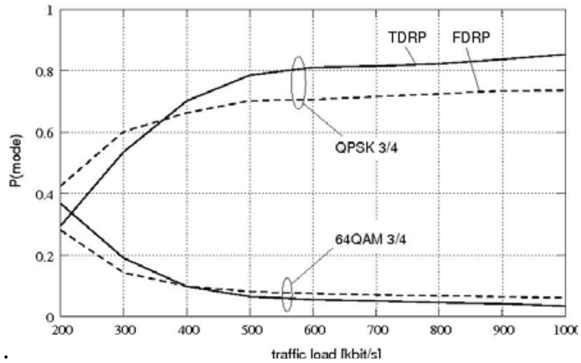

Figure 9 : PHY mode usage for resource fraction of 50 %

Figure 10 can be considered as the recapitulation result of the performance comparison of TDRP and FDRP in the case of a 50% resource usage by a single base station. The figure shows the throughput-delay characteristic. It is revealed that the capacity of the system is increased with the application of FDRP. But with low traffic loads the delay is lower when the TDRP scheme is deployed.

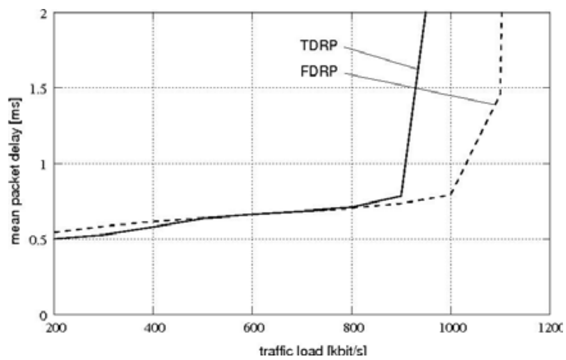

Figure 10 : Throughput-delay characteristic

In the second step of the performance evaluation, the influence of size of the resource fraction that is assigned to the base station has been evaluated for TDRP and FDRP. The probability of QPKS ¾ and of 64QAM ¾ usage have been compared with 500 kbit/s traffic load per downlink connection. The results are shown in Figure 11. With the application of the FDRP scheme, it can be seen that an increased size of the resource fraction for the base station, i.e. the number of subchannels, leads to an increased probability of QPKS ¾ usage, and the probability of 64QAM ¾ is decreased. With TDRP, the probabilities are rather constant except the case of a resource usage of 25%. This is based on the increased number of parallel used subchannels for the downlink data transmission in the FRDP case. Due to this, the power per subchannel is reduced and therefore more robust PHY modes have to be used. The probability distribution at 0.5 corresponds to the results shown in Figure 9.

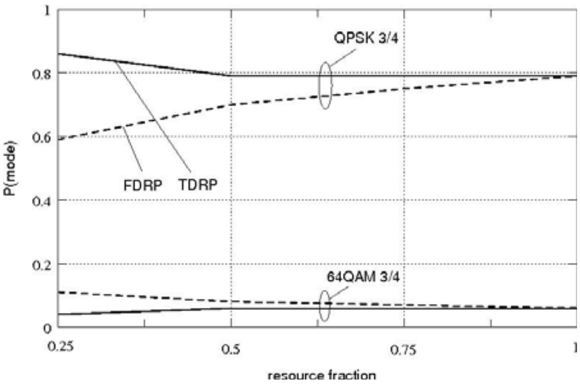

Figure 11 : PHY mode usage for 500 kbit/s traffic load

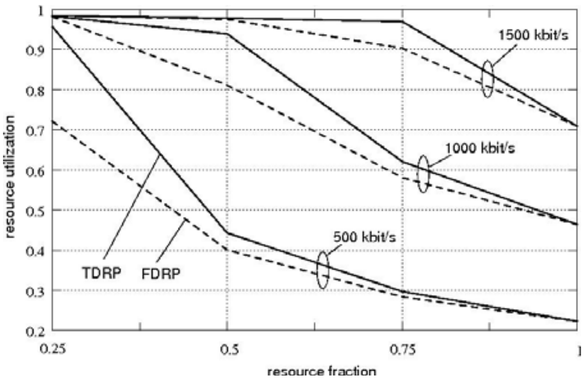

Figure 12 : Utilization

The resource utilization depending on the assigned resource fraction is shown in Figure 12 for different traffic loads. When the resource utilization approaches 1 the packet delay increases significantly. The figure reveals that FDRP reduces the resource utilization for all simulated traffic loads, i.e. 500, 1000, and 1500 kbit/s. The reduced utilization is based on the increased usage of high rate PHY modes like 64QAM ¾ and the reduction of low rate modes like QPSK ¾ as it is shown in Figure 9. The correlation between resource utilization and the delay can be seen in Figure 10 which corresponds to a resource fraction of 50%.

V. CONCLUSION

In this paper, resource partitioning schemes for the allocation of radio resource to base stations in multi-cellular environments have been investigated for an OFDMA system. A subdivision of resources in the time domain and in the frequency domain has been considered. The focus of the investigation was on the influence of the partitioning schemes on the OFDMA scheduling. In general, there is a superposition of two opposed impacts, the influence on the subchannel power allocation and the diversity of the subchannel fading levels. For the performance evaluation, a single base station with different downlink traffic loads and a fixed total transmission power has been analyzed in detail. The results show that the performance of the different partitioning schemes in combination with OFDMA scheduling depends to a great extent on the traffic characteristics. For low traffic loads, a resource partitioning in the time domain outperforms the partitioning in the frequency domain, due to an increased diversity gain. The ODMA scheduler has more subchannels to choose from during a channel allocation. When the traffic load increases, more resources have to be used by the base station to meet the demands. In the case of time domain resource partitioning, this means that more subchannels have to be used in parallel and that results in a reduced mean transmission power allocation per subchannel. It has been shown that the according SNR loss exceeds the possible SNR gain due to increased frequency diversity in the case of high traffic loads.

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