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A New Optimization Model for Dynamic Power and Sub-Carrier Allocations in Packet-Centric OFDMA Cells

By Mathias Bohge, James Gross, Michael Meyer, and Adam Wolisz

Abstract – It is well known that applying dynamic resource allocation to down-link transmissions of OFDMA systems provides a significant performance increase, by taking advantage of diversity effects. In order to quantify the maximum possible gain achievable by applying dynamic mechanisms, several optimization problems have been suggested for studying a dynamic system's optimal behaviour. However, so far these optimization approaches do not take sophisticated system requirements into account, as there are different packet-arrival processes, buffering constraints, scheduling policies, as well as QoS requirements per service class. In this paper we present a new optimization model that is based on a packet-centric system view and includes the system requirements mentioned above. We compare the performance results of the conventional and the new approach and study the impact of dynamic power allocation in both cases.

Index Terms – Wireless Networks, Multi-User OFDM, Optimization, Packet-Centric System Model

1. Introduction

The application of dynamic resource allocation mechanisms to down-link transmissions of cellular OFDMA (Orthogonal Frequency Division Multiple Access) systems has been proven to provide significant performance increases per terminal, simply by utilizing the given bandwidth more efficiently. This is mainly due to the fact that different sub-carriers of a broadband wireless system have a strongly varying attenuation, i.e. the system provides frequency diversity. As the attenuation of the sub-carriers for different terminals is statistically independent, an additional multi-user diversity per sub-carrier is present.

The given diversity is best exploited by *dynamic sub-carrier* allocation in an FDM (Frequency Division Multiplexing) fashion [1] and can be accompanied by *dynamic power allocation* as well [2]. By the use of these two dynamic mechanisms, a system can be adapted to the current channel state in order to either maximize the wireless channel's capacity for a given transmission power (*rate adaptive*) or to minimize the transmission power for a given rate per terminal (*margin adaptive*). Optimization methods such as linear programming have been considered for finding the best system configuration for a given channel state. This technique requires the precise definition of an optimization model.
So far, optimization has been done in system models, which emanate from persistent down-link data transmission, i.e. for each terminal endless data reserves are assumed that can be broken up into data pieces of arbitrary size (as in [3]-[5]). There is no notion of packetizing in those system models. Thus, none of the optimization models developed for these systems deals with balancing the resource scheduling decisions with the packet scheduling decisions to be made in a packet-centric system. As a result, a discrepancy between the packets that need to be sent and the amount of available resources at a certain terminal might arise, when those persistent data optimization models are applied to packet centric system models.

In this paper, we present an optimization problem formulation (Section III) that jointly optimizes resource and packet scheduling decisions and analyze (in Section IV) its performance in a packet-centric system model, which is described in Section II. We also show why conventional formulations do not suite the packet-centric architecture. In Section V, we conclude the paper[1].

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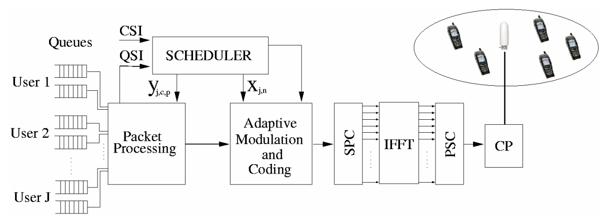

Fig. 1: The system model: a base station and terminals in a single cell.

2. System Model

We consider a single cell of a packet-centric cellular system according to [6] with radius r_{cell}. Within this cell, a base station coordinates all down-link data transmissions. Apart from receiving acknowledgements, we do not consider the up-link any further. J terminals are located within the cell (see Fig. 1). Each terminal receives streams of two different service classes c of data:

- a VoIP stream with rate and delay constraints,
- a best effort FTP stream,

where VoIP stands for *voice over IP* and FTP stands for *file-transfer protocol*. The base station holds two FIFO (first-in-first-out) QoS queues per terminal. Hence, each packet that is waiting for transmission at the base-station can be uniquely addressed by the triple $\{j,c,p\}$, where j is its destination terminal, c its type of data (*here:* VoIP or FTP), and p is its queuing position in the respective QoS queue. The packet's size is given by $sz_{j,c,p}$, its momentary delay (the difference in time between its arrival at the base station and the momentary simulation time) by $dl_{j,c,p}^{(t)}$. VoIP packets are assumed to arrive at the base-station according to the inter-arrival time ΔT_{voip}, where the first transmission per terminal is randomly chosen. FTP packets are available for transmission for each terminal at any point in time. Packets are delivered as a whole - fragmentation is not possible (this is the *packet centric approach*).

2.1. Physical Layer

The system under consideration uses OFDM as transmission scheme for down-link data transmission. It features a total bandwidth of B Hz at centre frequency f_c. The given bandwidth is split into S sub-carriers with a bandwidth of B/S each. In order to guarantee orthogonality between the sub-carriers, the symbol length T_s is identical for all sub-carriers and it is related to the sub-carrier bandwidth: $T_s = S/B$.

Together with the modulation type (out of a set of M available ones) per sub-carrier, an adequate code-rate per user is chosen by the base station's *adaptive modulation and coding* unit. Prior to the transmission of the time domain OFDM symbol, a cyclic extension (the *guard interval*) is added.

There is a transmit power budget P_t that limits the overall radiated energy in the cell. The budget is distributed among the terminals – the power-level l with which a terminal j is allowed to transmit on a certain sub-carrier s is determined by the scheduler. The power allocation l can be modelled as continuous parameter. However, in order to simplify the optimization model significantly, we consider only a discrete set of available power levels. In particular, exponential power-level spacing is used in order to allow large differences in power allocation with a comparatively low number of power-levels L. The computation of power value p_l is shown in Equation (1):

$$p_l = \frac{P_T}{S} \cdot \frac{2^l}{2^{\frac{L-1}{2}}} \tag{1}$$

2.2. Wireless channel model

We consider static terminals that are uniformly distributed over the cell. Still, due to reflecting and scattering objects within the cell that are moving with a maximum speed $v_{\max}$, the perceived signal quality per sub-carrier and terminal, i.e., their signal-to-noise-ratio (SNR), varies permanently. The instant SNR of sub-carrier s for terminal j at time t is given by:

$$v_{j,s}^{(t)} = \frac{p_s \cdot (h_{j,s}^{(t)})^2}{\sigma^2}, \tag{2}$$

where p_s denotes the chosen transmission power on sub-carrier s, $h_{j,s}^{(t)}$ denotes its channel gain value and σ^2 denotes the noise power per sub-carrier. The varying channel gain is primarily responsible for the variation of the perceived SNR; it varies due to path loss, shadowing and fading.

2.3. Medium Access Control Layer

We consider a time-division-duplex (TDD) system. Time is divided into alternating up- and down-link frames. A consecutive up- and down-link frame pair forms a transmission-time-interval (TTI) of duration T_{TTI}. OFDMA is applied to the down-link transmissions. In order to reduce the system's complexity, we define the smallest possible allocatable unit of frequency- and time-resources to be a *chunk* (shown in Fig. 2). In the frequency domain, a chunk consists of a well defined number of adjacent sub-carriers chn_{sub} with similar instant SNR values per frame. Thus, the same modulation type is applied to each of them. We define the chunk duration to be half the size of the TTI-duration $T_{\text{chn}} = T_{\text{TTI}}/2$.

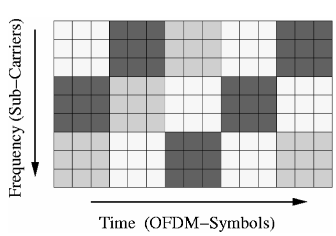

Fig. 2: Chunks consisting of 3x3=9 OFDM symbols.

The down-link SNR values per chunk are obtained at the base-station by tracing the channel states during the preceding up-link frame, exploiting the wireless channel's reciprocity. Since the TTI frame time is chosen smaller than the wireless channel's coherence time, these values are quite close to the real down-link values.

2.4. Scheduling Functionality

For each down-link phase, the scheduler needs to decide on two scheduling variables:

RESOURCE SCHEDULING:
The terminal/chunk/power mapping $x_{j,n,l}^{(t)}$, where

$$x_{j,n,l}^{(t)} = \begin{cases} 0\,, & \text{if } n \text{ is not mapped to } j \text{ using level } l, \\ 1\,, & \text{if } n \text{ is mapped to } j \text{ using level } l. \end{cases}$$

PACKET SCHEDULING:
The packet scheduling decision $y_{j,c,p}^{(t)}$, where

$$y_{j,c,p}^{(t)} = \begin{cases} 0\,, & \text{if packet } p \text{ in } j\text{'s queue } c \text{ is not scheduled,} \\ 1\,, & \text{if packet } p \text{ in } j\text{'s queue } c \text{ is scheduled.} \end{cases}$$

3. Optimal Scheduling

There are several suggestions for solving the bandwidth and power allocation optimization problem in dynamic OFDMA systems. In [5] the authors present different linear program problem formulations for the *margin adaptive* transmit-power minimization (constraint to a certain required rate per terminal) and the *rate adaptive* throughput maximization (constraint to a certain total power budget) optimization goal. However, none of the linear programs presented so far includes the packet scheduling decision. Thus, instead of deciding on which packets will be sent during the next frame, for the frame the scheduler decides on the transmission power and the set of chunks allocated to each user only. Among the linear program formulation alternatives so far suggested, only the fair version of the rate adaptive approach [5] is of interest for our system model, as we need to supply all users with VoIP data and have to deal with an overall transmit power constraint $P_{\max}$:

MaxMin Capacity-based Optimization Goal:

$$\max \varepsilon \tag{3}$$

MaxMin Capacity Constraint:

$$\sum_{n,l} cp_{j,n,l}^{(t)} \cdot x_{j,n,l}^{(t)} \geq \varepsilon \quad \forall j \tag{4}$$

Exclusive Chunk Usage Constraint:

$$\sum_{j,l} x_{j,n,l}^{(t)} \leq 1 \quad \forall n \tag{5}$$

Restricted Power Constraint:

$$\sum_{j,n,l} x_{j,n,l}^{(t)} \cdot p_l \leq P_{\max}\,, \tag{6}$$

where $x_{j,n,l}^{(t)}$ is the terminal/chunk/power-assignment variable at time t and $cp_{j,n,l}^{(t)}$ is the capacity of chunk n for terminal j using power-level l at time t. $cp_{j,n,l}^{(t)}$ is determined using a function F that selects modulation and coding type based on the instant SNR values $v_{j,s}^{(t)}$ and a target bit-error probability (P_{BER}): $cp_{j,n,l}^{(t)} = F(v_{j,s}^{(t)}, P_{\text{BER}})$.

Finding a solution for the optimization goal (3) while complying with the *MaxMin capacity* constraint (4) leads to chunk and power allocations that maximize the minimum throughput per user ε. Constraint (5) assures that each chunk is assigned only to one terminal at a time, while constraint (6) restricts the total transmit power to the actual power bound P_{max}.

In other words, each user j is provided with a capacity of at least ε for packet delivery during the following down-link frame. The number of packets to be delivered per user is determined by the scheduler with respect to the user's allocated capacity. VoIP packets are always prioritized.

Instead of selecting the number of packets to be delivered based on the optimized capacity allocations, the scheduler *jointly* decides on the resources to be allocated *and* on the packets to be delivered in our alternative optimization problem formulation:

Packet Centric Optimization Goal:

$$\max \sum_{j,p} \left[\frac{sz_{j,ftp,p}^{(t)}}{tp_{j,k}^{(t)}} \cdot y_{j,ftp,p}^{(t)} + \frac{dl_{j,voip,p}^{(t)}}{\omega} \cdot y_{j,voip,p}^{(t)} \right] \tag{7}$$

QoS Constraint:

$$(1 - y_{j,voip,p}^{(t)}) \cdot (dl_{j,ftp,p}^{(t)} + T_{TTI}) \le dl_{voip,\max} \quad \forall j,p \tag{8}$$

Packet Size vs. Capacity Constraint:

$$\sum_{n,l} x_{j,n,l}^{(t)} \cdot cp_{j,n,l}^{(t)} \ge \sum_{c,p} \left\lfloor y_{j,c,p}^{(t)} \cdot sz_{j,c,p} \right\rfloor \quad \forall j \tag{9}$$

Exclusive Chunk Usage Constraint:

$$\sum_{j,l} x_{j,n,l}^{(t)} \le 1 \quad \forall n \tag{10}$$

Restricted Power Constraint:

$$\sum_{j,n,l} x_{j,n,l}^{(t)} \cdot p_l \le P_{\max} \,, \tag{11}$$

where $y_{j,c,p}^{(t)}$ is the packet-assignment variable at time t, $sz_{j,c,p}$ is the packet's size, $dl_{j,c,p}$ is the packet's delay, $dl_{\text{voip,max}}$ the maximum permitted VoIP delay, $tp_{j,k}^{(t)}$ is terminal j's throughput over the last k frames, and T_{TTI} the system's frame-time.

Finding a solution for the optimization goal (7) while complying with the *QoS* (8) and the *Packet Size vs. Capacity* constraint (9) leads to chunk and power allocations in combination with packet scheduling decisions that follow the scheduling goal:

``Maximize the proportional fair FTP throughput per terminal, while guaranteeing QoS for all VoIP packets."

4. Performance Analysis

According to the methodology described in [2], nr_{dl} down-link phases were simulated for each radius r_{cell} using a system-level simulator. Also, we use the same multi-path propagation wireless channel parameterization.

All other simulation parameters can be found in Tables 1 and 2.

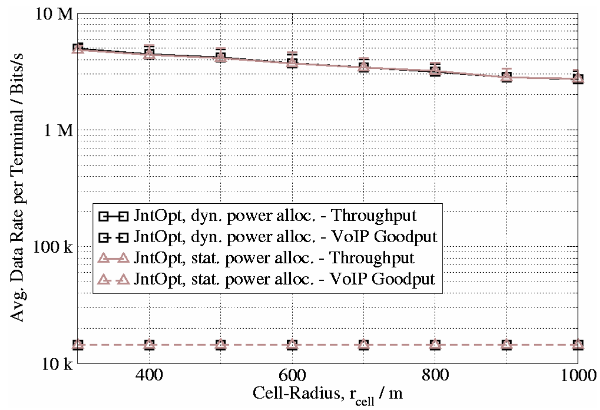

Fig. 3: Results of the packet centric *JntOpt* approach: 10 terminals.

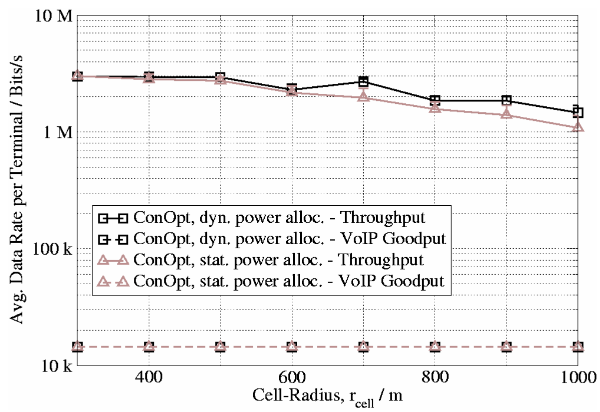

Fig. 4: Results of the conventional *ConOpt* approach: 10 terminals.

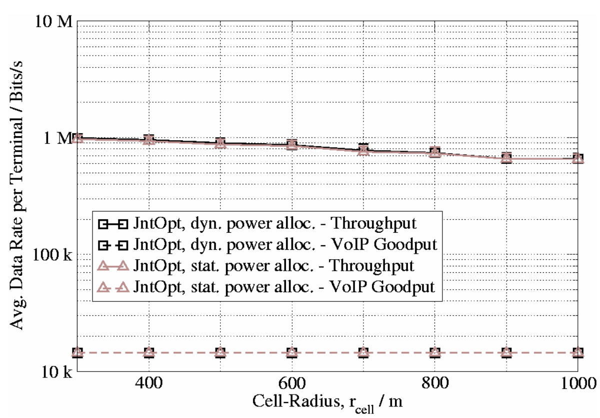

Fig. 5: Results of the packet-centric *JntOpt* approach: 50 terminals.

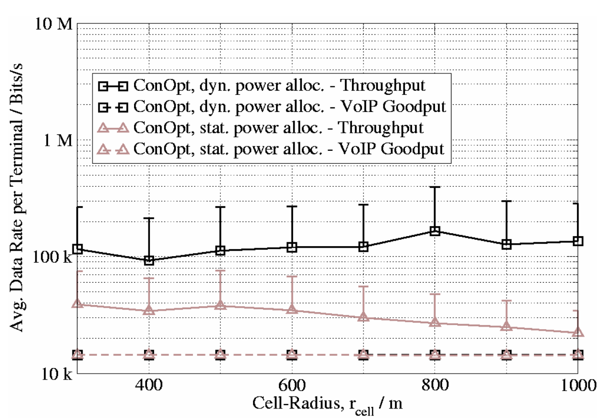

Fig. 6: Results of the packet centric *ConOpt* approach: 50 terminals.

Parameter		Value
VoIP packet sizes	sz_{voip}	36 Bytes
VoIP data rate per terminal	r_{voip}	14.4 kBit/s
VoIP inter-arrival-time	T_{voip}	20ms
VoIP max. delay	$dl_{voip,max}$	150ms
FTP packet size	sz_{ftp}	500 Bytes

Table 1: Packet stream parameters.

Parameter		Value
Center frequency	f_c	5 GHz
System bandwidth	B	20 MHz
Number of sub-carriers	S	1536
TTI-frame duration	T_{TTI}	1.34 ms
Chunk duration	T_{chn}	0.67 ms
OFDM symbol duration	T_s	76.8 µs
Guard-interval duration	T_g	6.95 µs
OFDM symbols per chunk	chn_{sym}	8
Number of chunks	N	96
Number of power levels	L	13
Prop fair – evaluated TTIs	k	J/2
Number of terminals	J	10, 50
Cell radius	r_{cell}	300m, … 1000m
Modulation types applied	M	4 (1,2,4, or 6 Bits)
No. of simulated DL-phases	nr_{dl}	1000

Table 2: System and simulation parameters.

Analyzing the performance result graphs, it can be stated that jointly optimizing resource and packet scheduling decisions in a packet-centric system (*JntOpt* - Fig. 3 and Fig. 5) delivers higher packet throughput results than optimizing the resource-allocations only (*ConOpt* - Fig. 4 and Fig. 6). Especially in the 50 wireless terminal scenario, the limits of the conventional approach become clear (Fig. 6): As the scheduler is forced to reserve a certain bandwidth (to assure the *MaxMin* rate) for each terminal in each frame, in most cases the resulting chunk capacity per terminal is too small to carry a large packet. As in the packet-centric system model fragmentation is not an option, the comparatively large FTP packets can not be delivered and the average throughput per terminal goes down. Additionally, the large confidence intervals of the throughput curves indicate that the FTP delivery is not fair (weak terminals don't receive any FTP traffic). On the other hand, the small VoIP packets are immediately forwarded to all terminals, which assures that the required VoIP rate is achieved. By applying dynamic power allocation, the power can be distributed in order to enable those terminals whose capacity almost suffices to carry a large packet in the static power case, to get the power they need.

Since the packet- and chunk-assignment decisions are jointly optimized in the packet-centric optimization model (*JntOpt*), chunk-capacity is assigned only to those terminals that have packets of adequate size to be delivered. The small confidence intervals indicate a fair system behaviour that is due to the proportional fair optimization goal formulation. No difference in average performance can be observed if the dynamic power allocation is switched on, which indicates efficient chunk capacity usage (i.e. low capacity wasting) even in the static power case. This is in contrast to the results for the conventional approach, where the power adaptation improves the FTP throughput significantly for the case of 50 terminals (while the performance of the VoIP delivery is not affected, as stated above). Why does power adaptation does not have any effect on the joint optimization approach (despite the significantly increased complexity of the problem with power adaptation)? In fact, the FTP throughput is improved for the terminals at the rim of the cell at the price of decreasing the FTP throughput for terminals close to the base station. On average though, the cell's FTP throughput does not increase in contrast to the conventional approach, where the additional dynamic power distribution leads to an overall FTP throughput improvement.

5. Conclusions & Future Work

Considering optimal performance in packet-centric dynamic OFDMA systems, it is necessary to include packet-scheduling decisions into the optimization process. In this paper, we have presented an adequate packet-centric optimization model that jointly delivers optimal resource and packet scheduling assignments depending on current sub-channel and individual packet states. As our simulations show that dynamic power allocations do not yield a significant average performance increase in our packet-centric system model, it is important to consider carefully the transmission scenario where dynamic OFDMA schemes are applied to. Our results show that only terminals at the rim of the cell benefit from dynamic power allocation - at the cost of a higher computational complexity and a lower FTP throughput for other terminals. Thus, dynamic power adaptation can improve the fairness without improving the overall throughput.

Further issues to be considered include a generalization of the specific packet-centric approach presented here, as well as the derivation of low-complexity schemes that deliver near-to-optimal performance under real-time constraints. Additionally, dismissing the packet-centric philosophy, the application of fragmentation at adequate signalling cost should be studied.

6. References

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Mathias Bohge, James Gross, Adam Wolisz
Einsteinufer 25, Sekr. FT-5
Telecommunication Networks Group (Fachgebiet TKN)
TU Berlin
10587 Berlin
Germany
E-mail: {bohge,gross,wolisz}@tkn.tu-berlin.de

Michael Meyer
Ericsson Allee 1
Ericsson Research, Corporate Unit
Ericsson GmbH
52134 Herzogenrath
Germany
E-mail: michael.meyer@ericsson.com