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Abstract

The UMTS enhanced uplink or high speed uplink packet access (HSUPA) provides efficient mechanisms for the radio resource management of radio bearers for best effort traffic. The resources available for the enhanced uplink users depend on several factors like the spatial configuration of the mobiles in the cells, the number of QoS users and the implemented RRM strategy. In this work, we provide a framework for the calculation of the resources assigned to the enhanced uplink users. It considers the maximum transmit power and down-grants for the reduction of the other-cell interference. We further show the impact of centralized and de-centralized radio resource management strategies on the feasible load region.

1 Introduction

The UMTS enhanced uplink or high speed uplink packet access (HSUPA) is a set of new transport and signaling bearers as well as functional entities which had been introduced in release 6 of the 3GPP UMTS standard [1]. The purpose of the enhanced uplink is to overcome certain limitations of the existing dedicated channel (DCH) transport bearers if used in conjunction with packet switched data. Packet switched data traffic can be roughly categorized in elastic traffic like web or p2p traffic, i.e. traffic originating from typical best-effor applications and traffic which requires certain quality of service guarantees like voice over IP (VoIP), video streaming or gaming. While DCH bearers are suitable for the transport of QoS traffic, the characteristics of elastic traffic require transport bearers which adapt to the traffic demand to avoid waste of resources. In the same time, elastic traffic also permits the downgrading of existing connections, since the don't have hard QoS requirements which have to be fullfilled.

The enhanced uplink meets this requirements by introducing two new main features: Shorter transport time intervals (TTI) of 2ms and a flexible resource allocation mechanism which is located mainly in the NodeB. Additional features are Hybrid ARQ and multi-code transmissions. An overview of the changes and additional features of the enhanced uplink is provided e.g. in [2]. The short TTIs and the fast rate control enables fast reactions on variations in traffic demand or resource availability and thus leads to a more efficient resource allocation than in Rel. 5 or Rel. 99. In contrast, the rate control mechanism in UMTS Rel. 99 and 5 which is responsible for the resource allocation is located in the RNC. This leads to long signaling delays and consequently to reaction times which are too long to adapt to fast channel condition fluctuations. Measurements have shown that in some imlementations changes of the radio bearer bit rate are a matter of at least seconds in Rel. 99 [3].

Additionally, the E-DCH standardization documents define a fine granularized set of possible bit rates or *transport block sizes* (TBS), which are the number of bits which can be transported within one TTI [4]. This and the fast allocation of these TBS enables theoretically to implement an RRM strategy which globally (in the sense of network-wide) tries to optimize the system for a certain utility function.

The fast rate control feature of the enhanced uplink is implemented by moving parts of the RRM entity from the RNC to the NodeB, which reduces signaling delay. However, the drawback is that the now distributed RRM has to work with ony local knowledge (i.e. local with respect to the NodeB) about the interference situation, since NodeBs do not know anything about the load in neighbouring NodeBs. This make the implementation of an RRM strategy which avoids load overshoots significantly more complex.

In this paper we want to investigate the influence of different RRM strategies on the so called feasible load region, which describes the region in which the resource assignments for the E-DCH users must be in order to meet the RRM constraints.

In the next section, an overview of papers in this field is given, followed by Sec. 3, which gives a short introduction to the principles of the enhanced uplink. In Sec. 4, the RRM for the enhanced uplink is introduced. In 5, we propose an interference and load model, and in Sec. 6, a model for the resource assignement is proposed. In Sec. 7 we present some numerical examples and finally we conclude our work with Sec. 8.

2 Related Work

In [5], the authors propose an analytical single cell model for the enhanced uplink, which is based on the assumption that the RRM always try to maximize the resource utilization by concurrently obeying a certain maximum load (or target load) and interference, resp. This strategy, which we call *greedy* in the remaining text, is also the base for this work. The greedy RRM strategy can be seen as the uplink equivalent of downlink best-effort bearers like the HSDPA or 1xEV-DO, since it allocates as much resources as possible to the users which are currently needing them, thus supporting the elastic nature of best-effort traffic (which one this could be in the uplink is beyond the scope of this paper, but one hint could be the expansion of peer-to-peer file sharing networks into the mobile domain [6]).

In the literature, several works exist which investigate the optimality and feasibility of centralized and decentralized RRM strategies. One of the first is [7], in which the author proposes a centralized optimising RRM strategy to maximize the system utilization and minimize the outage probability, which is defined as the probability that the required minimum *signal-to-noise-ration* (SNR) of a mobile cannot be reached.

In [8], some resource allocation algorithms are described with different degrees of knowledge about the total interference in the network. The system throughput for the different algorithms is calculated by solving the corresponding optimization problem.

In a more recent paper [9], some important results on the feasibility region of the CDMA uplink power assignment problem have been found. The authors show that the solution set of the problem is *log-convex* if the QoS-requirements for the link are convex in the log domain itself. This makes the problem solvable within reasonable time with standard algorithms like line search.

In [10], the authors use the results of the previous mentioned work for an optimization framework. Additionally, they propose a distributed RRM algorithm which is based on load factors at the base stations.

Similar approaches exist in the context of the uplink of CDMA 2000, one example is [11]. Here, the non-linear optimization problem is converted to linear optimization problem by restricting the feasibility region.

3 Introduction to the Enhanced Uplink

The enhanced uplink was officially as final specification introduced with Rel. 6 into the 3GPP standard suite. It introduces the Enhanced dedicated channel (E-DCH), which is designed to provide the users with a higher bandwidth and lower packet delay than with the conventional dedicated channel (DCH) radio bearers. The first goal is reached by introducing multi-code transmissions with up to 4 parallel orthogonal codes, which enables a maximum bit rate of around 5.7 Mbps. For reduced packet delays, the transport time interval (TT) between (sub)frames has been reduced to 2ms. Additionally, Hybrid ARQ (HARQ) has been introduced similar like for the high speed downlink packet access (HSDPA) for an increased link efficiency.

For the operator, the most important feature is probably the distributed RRM mechanism. In order to avoid long signaling delays, the majority of the RRM functionality has been moved from the RNC to the NodeB. This allows the rapid reaction on varying load conditions, decreasing the probability of load-overshoots and increasing resource utilization.

Figure 1 shows a graphical overview of the E-DCH RRM. The RRM entity of the radio network controller (RNC) defines the radio ressource policy which should be enforced by the NodeBs. This is done in two ways: First, the RNC restricts the set of possible transport format combinations (TFC) for the UEs. Second, the RNS sets the maximum tolerable interference (or received wideband transmission power, RWTP) and the maximum other-cell interference to own-cell interference ratio at the NodeBs.

The serving NodeB has the possibility to set the maximum transmit power of the E-DPDCH relative to the DPCCH on a 2ms basis via scheduling grants. Two kinds of scheduling grants are defined: Absolute grants and relative grants. While absolute grants set the absolute power of the E-DPDCH, relative grants of type UP, DOWN or HOLD are added to or substracted from the current transmit power. According to that and to the current buffer status, the UE may then select a transport format combination (TFC) with a corresponding transport block size (TBS). The TBS defines the number

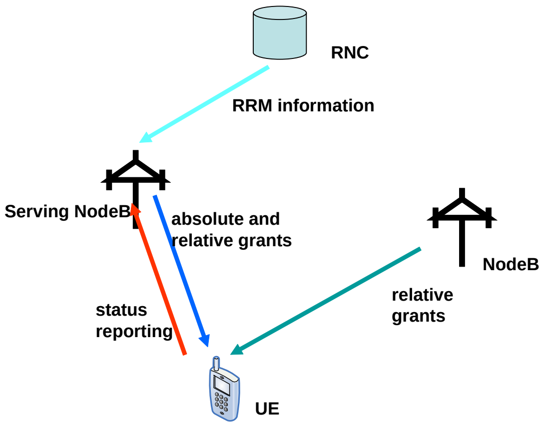

Figure 1: Overview of the rate control functionality of the E-DCH

of information bits which can be transmitted within one TTI. So if we assume that the UEs have always buffered data, the UEs will always choose the maximum TBS.

Additionally, the non-serving NodeBs may send DOWN or HOLD relative grants to the UE if the ratio between own- and other-cell interferences is below a certain threshold [1]. This is done to avoid the flooding of cells with other-cell interference, however, the impact of this mean is restriced to UEs which are in the soft-handover area of the flooded NodeB.

The UE may send information over its curent power consumption, power headroom and buffer occupancy back to the NodeB, which may use it for its scheduling and RRM decisions.

4 Radio Resource Management for the E-DCH Best Effort Service

How much resources resources are available for the enhanced uplink is in the hand of the operators, which can define a certain target load for their network corresponding to the maximum RWTP. The basic idea is to keep the uplink load in all cells as close as possible but below this target load, which we denote with η^*. A higher target load means more resources and higher bit rates for the enhanced uplink users, but also increases the probability of load overshoots which may lead to outage events in the worst case. A lower target load leads to a more stable system, but may also lead to insufficient resources for the best-effort users.

The uplink load consists of several parts, which reflect the different possible interference sources. We define the load at a NodeB x as

$$\eta_x = \eta_{x,D}^{own} + \eta_{x,E}^{own} + \eta_{x,D}^{oc} + \eta_{x,E}^{oc}. \tag{1}$$

In this equation, $\eta_{x,D}^{own}$ is the own-cell dedicated channel load generated by mobiles with DCH radio bearers which are power controlled by NodeB x, $\eta_{x,E}^{own}$ is the own-cell load coming from enhanced uplink best-effort users, $\eta_{x,D}^{oc}$ is the other-cell load originating

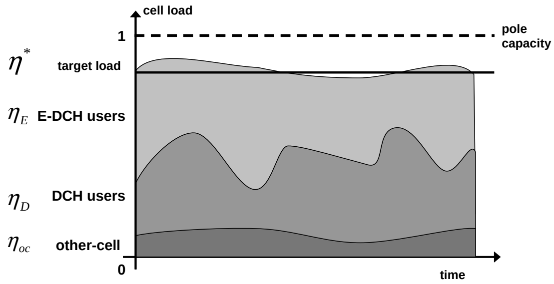

Figure 2: Load at a NodeB

from DCH users in surroundin cells and $\eta^{oc}_{x,E}$ is the other-cell load from enhanced uplink users in surrounding cells. The different loads are related to the interference by the common load definition as defined e.g. in [12], such that we can write

$$\eta_x = \frac{\hat{I}^{own}_{x,D} + \hat{I}^{own}_{x,E} + \hat{I}^{oc}_{x,D} + \hat{I}^{oc}_{x,E}}{\hat{I}_x + W\hat{N}_0}. \tag{2}$$

In this equation, the meaning of the different intereferences $\hat{I}$ correspond to their counterparts in Eq. (1). The interference $\hat{I}_x$ in the denominator is the sum of all interferences in the nominator.

The load which is available for the enhanced uplink users is then simply the difference between the target load and the remaining loads:

$$\eta^{own}_{x,edch} = \eta^{ast}_x - \eta^{own}_{x,D} - \eta^{oc}_{x,D} - \eta^{oc}_{x,E}. \tag{3}$$

5 Interference and Load Model

We consider a UMTS network with a set of NodeBs $\mathcal{L}$ and a set of user equipments (UEs) $\mathcal{M}$. Each UE is connected via a DCH or E-DCH radio bearer and controlled by one NodeB. So, corresponding to each NodeB x two sets $\mathcal{E}_x$ and $\mathcal{D}_x$ exist, the first containing the controlled DCH users and the second the E-DCH users. We write $k \in x$ with $x \in \mathcal{L}$ to denote a UE controlled by NodeB x, regardless of its bearer.

The received power $\hat{S}_{k,x}$ of a mobile k at it's controlling NodeB x depends on the target-E_b/N_0 requirement and the bit rate of the mobile. If we assume perfect fast power control it must hold:

$$\hat{\varepsilon}^*_k = \frac{W}{R_k} \frac{\hat{S}_{k,x}}{W\hat{N}_0 + \sum_{j \in \mathcal{M} \setminus k} \hat{S}_{j,y}}, \tag{4}$$

where $\hat{\varepsilon}^*_k$ is the target-E_b/N_0-values, W is the system chiprate (3.84 Mcps in UMTS FDD), R_k is the instanteneous bit rate and $\hat{N}_0$ is the one-sided thermal power density.

Solving for the received power $\hat{S}_{k,x}$ yields

$$\hat{S}_{k,x} = \omega_k \cdot \left(W\hat{N}_0 + \sum_{j \in \mathcal{M}} \hat{S}_{j,y} \right). \tag{5}$$

The term ω_k is an effective bandwidth measure of the load this mobile generates at it's controlling mobile. We will denote it as *service load factor* in the rest of the paper. It is defined as

$$\omega_k = \frac{\hat{\varepsilon}_k^* R_k}{\hat{\varepsilon}_k^* R_k + W} \tag{6}$$

and depends only on the target-E_b/N_0-value and the bit rate. The relation between the SLF and the cell load can be readily seen if we substitute the received power sum in (5) with the received interference $\hat{I}_x$ and calculate the load of one mobile according to (2):

$$\omega_k = \frac{\hat{S}_k}{W\hat{N}_0 + \hat{I}_x} = \frac{\omega_k \cdot (W\hat{N}_0 + \hat{I}_x)}{W\hat{N}_0 + \hat{I}_x}. \tag{7}$$

Specifically, it is true that the own cell loads defined in the previous section are formed as the sum of all SLFs of all users in the considered cell:

$$\eta_{x,D}^{own} = \sum_{k \in \mathcal{D}_x} \omega_k \quad \text{and} \quad \eta_{x,E}^{own} = \sum_{j \in \mathcal{E}_x} \omega_j \tag{8}$$

In E-DCH, the information bit rate is the number of bits which can be transported within one TTI. This quantity is given by the TBS which are defined in several tables in the MAC standardization document.

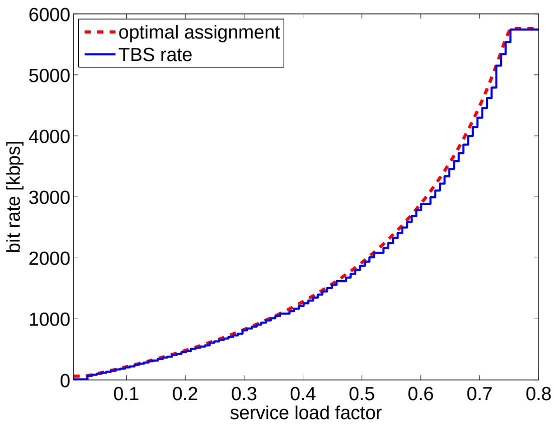

Figure 3: The service load factors and the corresponding bit rates

Fig. 3 shows the SLFs as function of the bit rate. The blue, solid line corresponds to the SLFs calculated form the TBS table in the standard. The red, dashed line is directly calculated from the SLFs as $R = \frac{\omega \cdot W}{\hat{\varepsilon}^* \cdot (1-\omega)}$. We see that both lines are very close to each other due to the fine granularity of the possible bit rates. In the rest of the paper we therefore use the direct relation between bit rate and SLF.

5.1 Multi-Cell Model

The sector interference in a unsynchronized CDMA system depends generally not only on the number of transmitting mobiles in the own sector, but also on the interference generated in surrounding cells and sectors, resp. This interference is called other-cell (or inter-cell) interference, since it originates from cells other than the cell we are currently looking on. With the same argument, the interference which is generated in other cells also depends on the interference of the own-cell. Fig. 4 shows an example with two mobiles. The first one is close to it's controlling NodeB and thus requires only a low transmit power to reach it's target-E_b/N_0. The second mobile, controlled by NodeB B, is close to the cell edge such that both NodeB A and NodeB B nearly recieve the same power from this mobile. The interference power $\hat{S}_{k,y}$ from one mobile to an none-

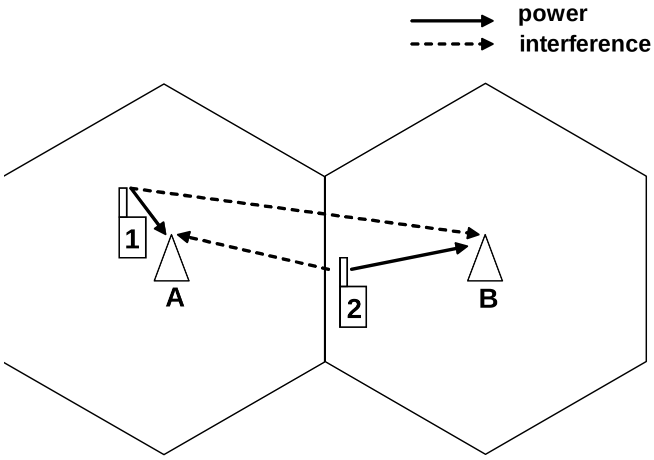

Figure 4: Simple example scenario with two mobiles

controlling NodeB is given by the ratio between the link gains between the mobile and the two NodeBs:

$$\hat{S}_{k,y} = \frac{\hat{d}_{k,y}}{\hat{d}_{k,x}} \hat{S}_{k,x} = \hat{\Delta}^{x}_{k,y} \hat{S}_{k,x}, \tag{9}$$

where x is the controlling NodeB, y is a non-controlling NodeB, $\hat{d}_{k,x}$ is the link gain between mobile k and NodeB x, and $S_{k,x}$ is the received power at NodeB x. Note that the link gain ratio $\hat{\Delta}^{x}_{k,y} = 1$ if $x = y$.

We define the interference at a NodeB x as the sum of all received signal powers from all mobiles in the network. The interference is then from Eq. (9) given by

$$\hat{I}_x = \sum_{l \in \mathcal{L}} \sum_{k \in l} \Delta^{x}_{k,l} \cdot \omega_k \cdot \left(W \bar{N}_0 + \hat{I}_l \right). \tag{10}$$

With matrices, we formulate this equation as

$$\bar{I} = \widetilde{G} \cdot \left(\bar{N}_0 + \bar{I}\right), \tag{11}$$

where $\bar{I}$ is the $|\mathcal{L}| \times 1$-vector of interferences, $\bar{N}_0$ is a $|\mathcal{L}| \times 1$-vector with $(\bar{N}_0)_j = WN_0$, and $\widetilde{G}$ is an $|\mathcal{L}| \times |\mathcal{L}|$ matrix with the sum of the link-gain ratios multiplied with the corresponding SLF as elements, such that

$$(\widetilde{G})_{ij} = \sum_{k \in j} \Delta^i_{k,j} \cdot \omega_k. \tag{12}$$

Note that in our notation j is the set of mobiles which are connected to NodeB j. The interference at each NodeB is than the result of solving Eq. (11) for $\bar{I}$:

$$\bar{I} = \left(\widetilde{E} - \widetilde{G}\right)^{-1} \cdot \left(\bar{N}_0 \cdot \widetilde{G}\right), \tag{13}$$

where $\widetilde{E}$ is the identity matrix.

Up to now, our model does not make any distinction between DCH and E-DCH users. Both user types are characterized through their service load factor ω. However, in Sec. 4 we defined an RRM strategy for the E-DCH users which tries to maximize the resource utilization in each cell. Since the resource in our case is the interference and corresponding to that, the cell load, the remaining resources are distributed to the E-DCH users as in Eq. (3). Essentially this means that DCH users have fixed SLFs, while E-DCH users get the remaining load in a typical best-effort manner. We can express this by splitting the interference equation further up after the signal source:

$$\hat{I}_x = \hat{I}^{own}_{x,D} + \hat{I}^{oc}_{x,D} + \hat{I}^{own}_{x,E} + \hat{I}^{oc}_{x,E}, \tag{14}$$

which corresponds to the matrix form

$$\begin{aligned} \bar{I} = \tilde{G}^{own}_D(\bar{N}_0 + \bar{I}) + \tilde{G}^{oc}_D(\bar{N}_0 + \bar{I}) \\ + \tilde{G}^{own}_E(\bar{N}_0 + \bar{I}) + \tilde{G}^{oc}_E(\bar{N}_0 + \bar{I}). \end{aligned} \tag{15}$$

Here, the elements of the load matrices correspond to the set of users which generate interference. The matrices $\tilde{G}^{own}_D$ and G^{own}_E are diagonal matrices with elements $(\widetilde{G}^{own}_D)_{ii} = \sum_{k \in \mathcal{D}_x} \omega_k$ and $(\widetilde{G}^{own}_E)_{ii} = \sum_{k \in \mathcal{E}_x} \omega_k$. The matrizes for the other-cell interference contain zeros at the diagonal, and on the remaing entries the sum of SLFs multiplied with their link gain ratios, i.e. $(\widetilde{G}^{oc}_D)_{ii} = 0$ and $(\widetilde{G}^{oc}_D)_{ij} = \sum_{k \in \mathcal{D}_j} \hat{\Delta}^x_{k,j} \cdot \omega_k$ for all $i \neq j$.

6 Resource Assignment to E-DCH Users

In the previous section, we defined a general framework for the calculation of the interferences and loads at a NodeB. We now want to use this framework for obtaining the actual resources, which can be assigned to an E-DCH user. Let us for this reason first define some common constraints, within the assignment takes place.

1. The maximum load or interference should not be exceeded. The purpose is to guarantee a stable system, since if the cell loads get too high, the required transmit powers for the mobiles tend to infinity, which makes it impossible for them to reach their required target-E_b/N_0. Hence we define the constraint

$$\mathrm{C}_{\mathrm{load}}: \quad \eta_x \leq \eta_x^*. \tag{16}$$

2. All E-DCH users have a certain minimum bandwidth guarantee, which corresponds to a minimum TBS and thus to a minimum SLF ω_{min}. This condition avoids quasi-outage of users. Further, the maximum SLF ω_{max} is defined by the highest TBS, which corresponds to 5.74 Mbps. So it is mandatory that

$$\mathrm{C}_{\mathrm{SLF}}: \quad \omega_{min} \leq \omega \leq \omega_{max}. \tag{17}$$

3. The mobiles have a maximum transmit power $\hat{T}_{max}$, which is normally either 21 dBm or 24 dBm, so

$$\mathrm{C}_{\mathrm{pow}}: \quad \hat{T}_m \leq \hat{T}_{max}. \tag{18}$$

Note that ransmit powers can be easily calculated from the interference at the serving NodeB x and the pathloss as

$$\hat{T}_m = \hat{d}_{m,x}^{-1} \cdot \omega_m \cdot (W\hat{N}_0 + \hat{I}_x). \tag{19}$$

4. In [1] it is stated that DOWN grants are sent to mobiles in adjacent cells if the ratio between the E-DCH other-cell interference and the total interference from E-DCH users exceeds a certain, operator-defined threshold. This reduces flooding of cells from adjacent sites due to high-bitrate mobiles near the cell borders. Let $\mathcal{H}_x$ the set of UEs which are in the soft handover area but not controlled by NodeB x. The condition can then be expressed as

$$\mathrm{C}_{\mathrm{grant}}: \quad \frac{\sum_{h \in \mathcal{H}_x} \hat{S}_{h,x}}{\hat{I}_E} \leq t_{SHO}, \tag{20}$$

where t_{SHO} is an operator-defined threshold.

The goal of the resource assignment procedure is that all this conditions are fullfilled. Under certain circumstances, this may not always be possible, which may lead to a load overshoot event. A load overshoot does not necessarily mean that a UE experiences outage, however it may affect the connection or system stability negatively, so it should be avoided if possible.

In our model, load overshoots corresponds to a resource assignment which is not in the feasibility reagion, which is defined by the constraints above. Depending on the

RRM strategy and the degree of knowledge that the executing entity on the global load situation has, the feasibility regions significantly differ from each other.

We distinguish between three kinds of RRM implementations: One with global knowledge of the system load, which constitutes the optimal case, one with global knowledeg but with a distributed implementation such that it has a reduced feasibility region and a totally decentralized one with only local knowledge, which corresponds to the single cell resource assignement scheme, i.e. with knowledge of the local load only.

Generally, load overshoots can occur because of two reasons: First, the load generated by the DCH users is so high, that the target load is exceeded. Normally, the admission control prevents such events. The second case is, that the RRM implementation is such that cells may be flooded with interference from adjacent cells. This may occur with the local RRM implementation.

Beneath load overshoots, it may also happen that the target load is not reached. This occurs if the RRM implementation decides to lower the load in some cells to prevent load overshoots, i.e. for the global RRM implementation.

Global Ressource Assignements

From Eq. (10) we see that the SLF and interference calculation can be interpreted as a non-linear optimization problem. In our model we try to optimize the cell load with a utility function $U(\cdot)$. In the literature, several options are mentioned to optimize for different fairness goals. The most straightforward utility function is to sum over all individual loads of the E-DCH users. However, this approach leads to unfair assignements in the sense that UEs close to the NodeB get as much load as possible, while the more distant UEs may only get the minimum SLF. An often mentioned generic fairness criterion is that of α-fairness, where the optimization converges to different fairness goals according to the setting of a parameter α, [13]:

$$U(\omega_m) = \frac{\omega_m^{1-\alpha}}{1-\alpha} \tag{21}$$

With this utility function, proportional fairness [14] can be achieved with $\alpha \to 1$ and max-min-fairness can be achieved in the limit $\alpha \to \infty$. The optimization problem, formulated as a non-linear program, is then:

$$\mathrm{OPT_{nlin}}: \quad \max. \quad \sum_{m \in \mathcal{M}} U(\omega_m) \tag{22}$$

$$\text{s.t.} \quad \mathrm{C_{load}}: \quad \eta_x \le \eta_x^* \tag{23}$$

$$\mathrm{C_{SLF}}: \quad \omega_{min} \le \omega_m \le \omega_{max} \tag{24}$$

We consider the load and SLF as the basic set of constraints. Later throught the paper we additionally take the power and the DOWN-grant constraints into account.

Linearized Feasibility Region

The non-linear constraint on the load lead to optimal assignements if the RRM entity has knowledge of the load situation in all cells. In practice, however, this is very difficult to implement since it would need a very high amount of signalling to a central point, which should be avoided. In [11] and [8] the authors therefore propose a RRM implementation which can be implemented in a distributed way. These proposals are based on the assumption that the feasibility region is linear, such that the distributed algorithm converges to a global optimum. The optimization problem is therefore in our model complemented with a linear constraint on the row sums of system matrix $\widetilde{G}$:

$$\begin{aligned} \mathrm{OPT_{lin}}: \quad & \max. \quad \sum_{m \in \mathcal{M}} U(\omega_m) && (25) \\ \text{s.t.} \quad \mathrm{C_{lin}}: \quad & \sum_{x} \sum_{k \in x} \Delta^i_{k,j} \cdot \omega_k \leq \eta^*_x && (26) \\ \mathrm{C_{SLF}}: \quad & \omega_{min} \leq \omega_m \leq \omega_{max} && (27) \\ & && (28) \end{aligned}$$

Note that with condition $\mathrm{C_{lin}}$ also condition $\mathrm{C_{load}}$ is fullfilled, see e.g. [11].

Constant Load Assumption with a Static Assignment Policy

In Sec. 4, we introduced a RRM strategy for the E-DCH which always tries to maximize the resource utilization up to a certain threshold, which we call the target load η^*. The target load relates to an equivalent target interference by $\hat{I}^* = \frac{\eta^*}{1-\eta^*}(W\hat{N}_0)$. Let us now assume, that the target interference is reached in all cells, i.e. $\hat{I}_x = \hat{I}^*_x$ for all NodeBs. The total interference term in Eq. (10) is then independent of the actual spatial user configuration. If we divide by the constant term $(WN_0 + \hat{I}_x)$, the left hand side is per definition the target load, and the rhight hand side are the sums of all SLFs times their link gain ratios, if we assume that $\hat{I}^*_x = \hat{I}^*_y$ for all $x, y \in \mathcal{L}$:

$$\eta^*_x = \sum_{l \in \mathcal{L}} \sum_{k \in l} \Delta^x_{k,l} \omega_k. \tag{29}$$

So under this assumption, we can calculate with the load factors only. If we split up the total load after the sources, Eq. (29) becomes

$$\eta^*_x = \eta_{x,D} + \eta^{own}_{x,E} + \sum_{y \in \mathcal{L} \setminus x} \sum_{j \in \mathcal{E}_y} \Delta^x_{j,y} \omega_j \tag{30}$$

The most straightforward way to calculate the SLFs for the E-DCH users is to solve the load equation system for the E-DCH own cell load η^{own}_{edch}. This means, we assume that the load at each NodeB is constant and corresponds to the target load and solve for the own-cell load for the E-DCH users. This requires that, if we have more than one user per cell[1], we have to fix the partitioning of the E-DCH load to the individual SLFs with a *policy* factor g, such that

$$\sum_{j \in \mathcal{E}_x} g_j \cdot \eta_{x,E}^{own} = 1. \tag{31}$$

The policy factor can rely just on the number of E-DCH mobiles, such that $g_j = \frac{1}{|\mathcal{E}_x|}$ or can include distances or path gains to prioritize mobiles wich are close to the NodeB. Following Eq. (3), we can now calculate the own-cell E-DCH load directly:

$$\eta_{x,E}^{own} = \eta_x^* - \eta_{x,D} - \sum_{y \in \mathcal{L} \setminus x} \sum_{j \in y} \Delta_{j,l}^x g_j \eta_{y,E}^{own}. \tag{32}$$

In matrix formulation

$$\bar{\eta}_E^{own} = \bar{\eta}^* - \bar{\eta}_D - \tilde{F}_E^{\prime oc} \cdot \bar{\eta}_E^{own}, \tag{33}$$

where $\tilde{F}_E^{\prime oc}$ contains the link gain ratios as well as the policiy factor g_j:

$$(\widetilde{F}_E^{\prime oc})_{ij} = \begin{cases} \sum_{k \in \mathcal{E}_j} \Delta_{k,j}^i \cdot g_k, & \text{if} \quad i \neq j \\ 0 & \text{else} \end{cases} \tag{34}$$

Solving for $\bar{\eta}_E^{own}$ yields the own-cell E-DCH load at each NodeB and with the policy factor also the resource assignment for each individual E-DCH user:

$$\bar{\eta}_E^{own} = (\tilde{E} + \tilde{F}_E^{\prime oc})^{-1} \cdot (\bar{\eta}^* - \bar{\eta}_D). \tag{35}$$

This approach, which we will call “direct” in the reminder, leads to negative results for $\bar{\eta}_E^{own}$ if either $\bar{\eta}_D > \bar{\eta}^*$ for one element, which means that the DCH load is higher than the target load, or if the spatial configuration is such that the other-cell E-DCH load is higher than $\eta^* - \eta_D$. In this case, we assume that the SLFs for the E-DCH users in the specific cell is set to the minimum, which leads to a load overshoot.

6.1 Feasible Load Region and Boundarys

In this section, we want to clarify the feasibility region of the general problem and for the different RRM approaches and constraints. For this reason we consider a simple example with two cells, two E-DCH users (one per cell) and two DCH users. Let us consider the simple scenario from Fig. 4 with two NodeBs and four mobiles. The relevant parameters can be seen in Tab. 1. The values for Δ correspond to the path gain ratio between the non-serving and the serving NodeB. The first E-DCH user is close to the cell edge, which leads to an high Δ of 0.9. The second E-DCH user in the second cell is close to it's serving NodeB. The DCH user in the first cell has moderate distance to NodeB A. As fairness criterion for the global RRM schemes we chose max-min-fairness, since it is closest to the behaviour of the local RRM scheme with equal load assignemnts for all

[1]Note that we assume that at least one E-DCH user is in each cell

Table 1: Example scenario

	E-DCH 1	E-DCH 2	DCH 1	DCH 2
S-NodeB	A	B	A	B
ω			0.1	0.05
Δ	0.9	$6 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

E-DCH users in a cell.

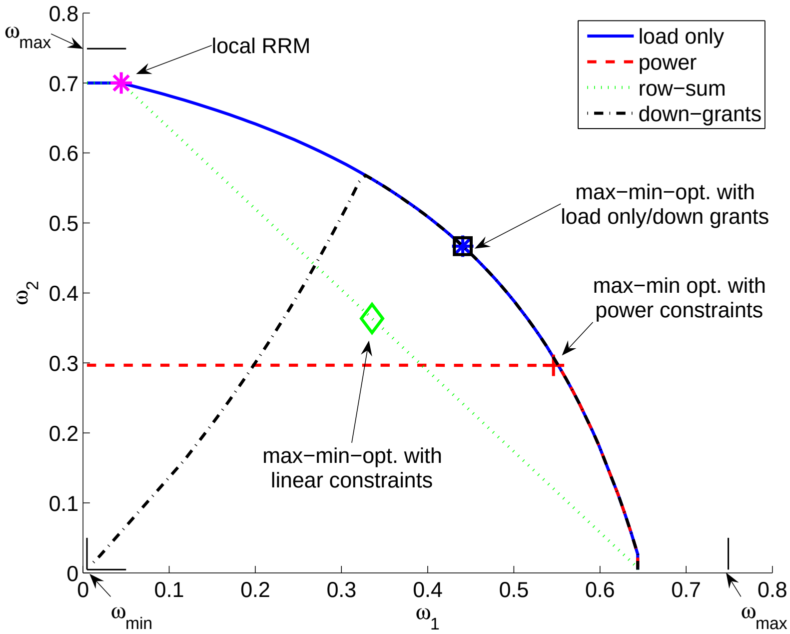

Figure 5: Feasible SLF region for the two-cell scenario.

The resulting feasible SLF regions for the two E-DCH users are shown in Fig. 5. For the global RRM strategies, we considered the power, the linear and the DOWN-grants constraints individually, i.e. we considered only one constraint additionally to the load and SLF constraint, which are always considered. The max-min-optimal points for the global RRM differ significantly from the direct approach, which yields a very unbalanced result between the two E-DCH users but still lies within the feasible region. The power constraints in this scenario leads to a SLF configuration which favors the first E-DCH user, while for the load-only and the DOWN-grant constraint as well as for the linear constraint the SLF values are balanced. Since the direct approach for the local RRM leads to an pareto-optimal solution for the own-cell load, it corresponds in this scenario to the linear constrained RRM with sum-optimal utility function. The feasible region does not reach the maximum possible SLF ω_{max} due to the load from the DCH users. The optimal solution for the DOWN-grant constraint correspond in this case to the

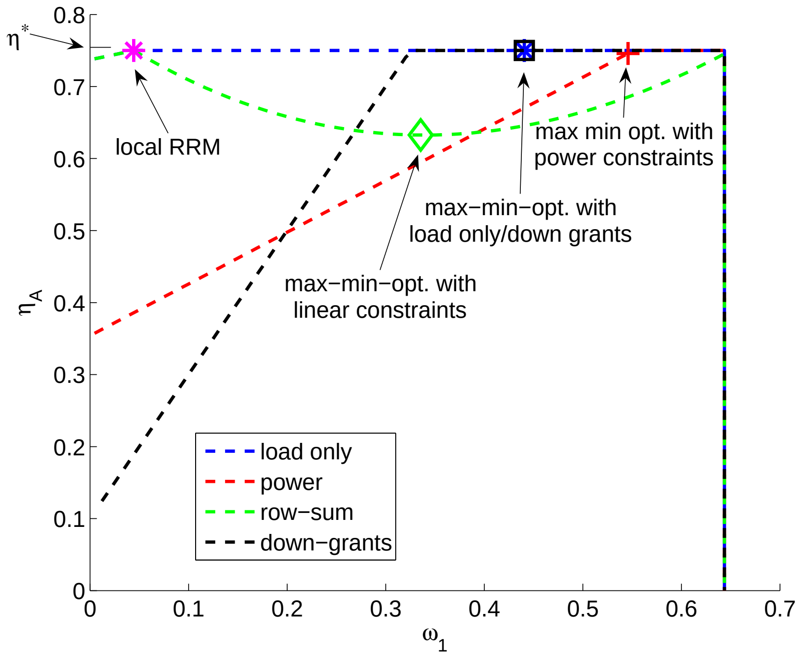

Figure 6: Cell loads at NodeB A.

solution with load constraints only, however this would change if the maximum allowed ration between own-cell to total E-EDCH load is set to a lower value.

The corresponding load η_A at the first NodeB is shown in Fig. 6. The loads for the non-linear and linear case begin to diverge on the solution point for the direct approach. The effect of the linear constraint on the load is that the target load is not reached for a large range of the feasible SLF region. Further, the max-min-optimal point in this case is significantly lower than for the non-linear case. The direct approach naturally reaches the target load at both NodeBs, but for the sake of a very low SLF for the first E-DCH UE. It should be mentioned that this scenario is quite extreme, which is the reason for the different results of the approaches. As we will see in the next section, with more users the results get more close to each other.

7 Numerical Example

In order to get a better idea of the impact of the RRM strategies on the resource assignments, we simulated a example scenario with a Monte-Carlo simulation. To see the influence of the power and DOWN-grant constraints better, we chose a layout with seven cells and a large distance between the NodeBs, 2 km. The layout follows a hexagonal 7 cell scheme. For the results we consider only the cell in the center. The pathloss is calculated from the COST-231 small urban Hata model, and the target load is set to $\eta^* = 0.75$, which corresponds to a target interferencec of -103 dBm. For each run,

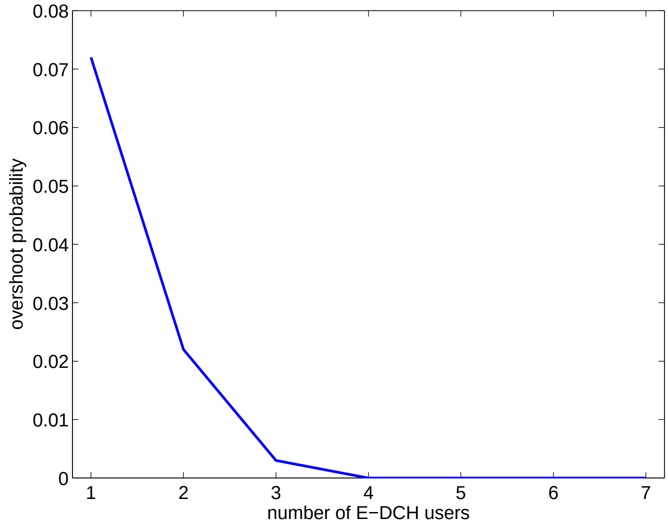

Figure 7: Probability of load overshoot

the simulation generates the position of each UE new and then calculates the loads and interferences according to the RRM implementation. To see the influence of the number of E-DCH and DCH users, the total number of the users in each cell is fixed to 10, while the fraction of E-DCH user grows from 2 users to 8 users. The rest are DCH users with a bit rate of 64,kbps. For the local RRM we consider an equal-rate scheme, i.e. all E-DCH users in a cell get the same SLF. The users' locations follow a spatial poisson process. Since it is not practical to let go $\alpha \to \infty$ in Eq. (21), the utility function for the optimization problem is defined as the reciprocal sum of the SLFs, which corresponds approximately to a max-min-fair ressource assignement [15]:

$$U(\omega_m) = \sum_m \omega_m^{-1}. \tag{36}$$

In Fig. 7 the load overshoot probability for the loccal RRM is shown. For two E-DCH users the overshoot probability is around 7%, but with an increasing number of E-DCH users the overshoot probability falls to nearly zero. Remember that a load overshoot occurs if the E-DCH SLFs in a cell are set to ω_{min}, but the target load is nevertheless exceeded because of a two high other-cell load. This explains why the load overshoot probability decreases with an increasing number of E-DCH users: Although the probability that some UEs are close to the cell border is higher with more users, the fact that the E-DCH UEs may get very high SLFs for a lower number of users outweights this effect. With a higher number of E-DCH users some UEs must have locations close to each other on the cell border to act as an "equivalent" E-DCH user with a high SLF.

The total loads, shown in Fig. 8, reflect the load overshoot probalities for the local RRM. With a decreasing number of E-DCH users, the mean total load decreases from

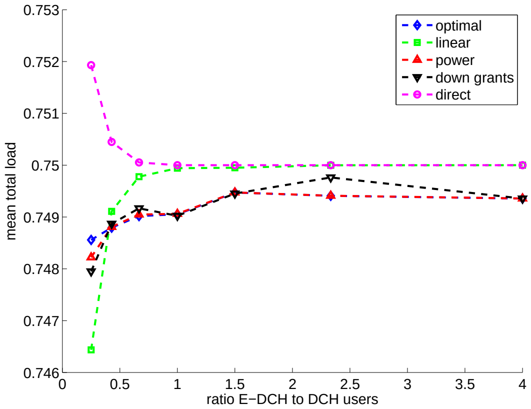

Figure 8: Mean total load η

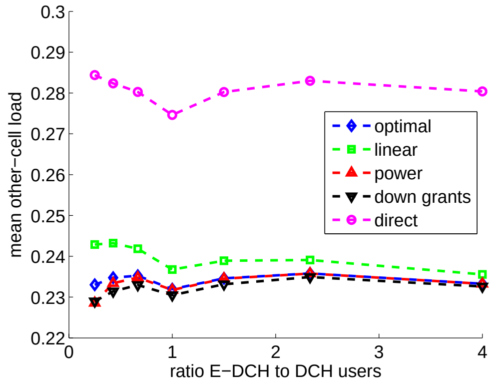

Figure 9: Mean other-cell load η^{other}

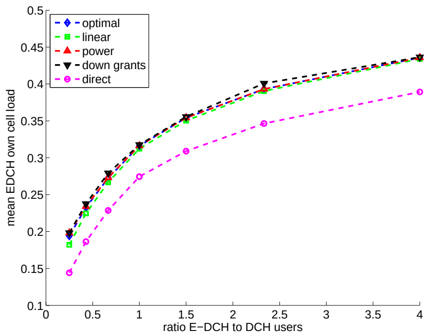

Figure 10: Mean E-DCH own cell load

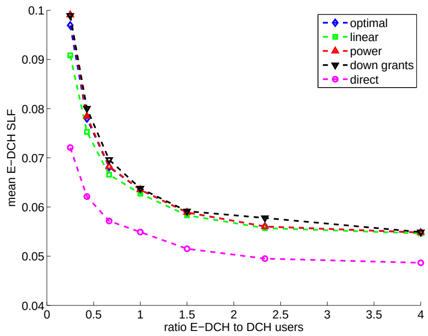

Figure 11: Mean E-DCH SLFs

0.752 to the target load of 0.75. Correspondingly, the the loads for linear (or distributed) RRM increase until the target load is reached. The total loads for the global RRM with different constraints stay all below the target load but are close to each other. Only in the case of two E-DCH users it can be observed that the DOWN-grants and the power constraints lead to a lower load than with load and SLF constraints only. The peak for the DOWN-grant curve at a ratio of 2.3 (corresponds to 7 E-DCh users and 3 DCH users) is probably an artefact. At a ratio of 1, however, a "break" in the curves for the global RRM is visible, which is also the case for the mean other-cell loads shown in Fig. 9. While this "break" is not visible for the total load curves for the local and linear RRM, it is visible for all RM implementations for the other-cell load. The other-cell load for the local RRM is significantly higher than the loads for the global approaches, and the distance between the curves is more or less constant for all considered E-DCH to DCH ratios. As expected, the linear RRM as the highest other-cell loads for the global RRM implementations, and the DOWN-grant constrained RRM has the lowest, although the difference to the other non-linear approaches is not very high.

This is leads also the highest own-cell E-DCH load as shown in Fig. 10, although the difference is even smaller between the different global RRM approaches. The local

RRM yields, corresponding to the highest other-cell load, the lowest E-DCH loads with a nearly constant difference to the global RRMs of 5%. Note that the own cell E-DCH grows linear with the number of E-DCH users. Corresponding to the E-DCH own cell load the mean assigned SLFs are shown in Fig. 11. The highest SLF is 0.1 for the global RRM, which corresponds to a bit rate of approximately 220 kbps. For two E-DCH users the SLFs for the local RRM are around 0.07, which corresponds to a bitrate of 150 kbps.

8 Conclusion and Outlook

The goal of this paper was to show the influence of different radio resource managment strategies on joint power and rate controlled CDMA systems like the UMTS Enhanced Uplink. We considered three kinds of strategies: Global with knowledge of the whole load situation in the network, global with linear constrained feasibility region and a local with knowledge about the load in the local cell only. We further investigated the impact of several constraints like transmit power and DOWN grants from non-serving NodeBs.

The results show that the local RRM strategy, which allows a direct calculation of the assigned resources to the users, lies on the boundary of the feasibility region of the global approach with linear constraints. Accordingly, the results for the total load of both approaches converge to each other if the probability for load overshoots decreases. The resource assignements, however, tend more to the results for the global approach, which yields the best results. Generally, we have seen that there is a significant difference between the global and local approaches in terms of resource efficiency.

In this work we only considered static or instanteneous scenarios, but not the influence of flow sizes or mobility on the system. So a next step would be to extend this work in this direction.

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