Impact of HSDPA Radio Resource Allocation Schemes on the System Performance of UMTS Networks

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***Abstract*— In UMTS networks, HSDPA users share radio resources like transmit power and OSVF codes with QoS-users, which use dedicated channels as primary transport method. Several options for the resource allocation for HSDPA exist, which center around the question whether resources should be exclusively reserved for HSDPA, or whether the resources for the HSDPA should be adapted to the requirements of the QoS users. We investigate the impact of three radio resource allocation schemes on the HSDPA and on the dedicated channel performance by means of a time-dynamic simulation. The numerical results show the trade-offs between dedicated channel and HSDPA performance and the sensitivity of the system against power and code reservation parameters.**

I. INTRODUCTION

The High Speed Downlink Packet Access (HSDPA) is either in deployment or in operation in most of the important mobile telecommunication markets. HSDPA is an enhancement of UMTS and has been introduced with Rel. 5 of the UMTS standard. One of the reasons which lead to the development of the HSDPA was the fact that “classical” dedicated channels (DCH) in Rel. 99 UMTS are inefficient for the transport of best effort traffic. DCH radio bearers follow a “circuit-switched” paradigm: Each user gets link with an agreed QoS level, i.e. bit rate, bit error rate, etc. Radio resource management (RRM) and the link layer takes care that this QoS level stays as constant as possible over time. Since best-effort traffic is typically bursty, this concept becomes inefficient since radio resources are occupied even in case of time periods without traffic, e.g. in case of web-browsing.

The concept of the HSDPA is to adapt the data rate to the instantaneous channel quality at the receiver by using channel quality information feedback. HSDPA uses a shared channel, the High Speed Downlink Shared Channel (HS-DSCH), which is used by all HSDPA users in a sector. The shared channel concept overcomes the drawbacks of dedicated channels regarding radio resource efficiency for bursty traffic, but a fixed QoS-level cannot be guaranteed anymore.

The HSDPA and the dedicated channels share two types of radio resources: Transmit power and OSVF codes. In the literature, two main approaches are proposed how to assign radio resources in a shared environment: The *adaptive* scheme assumes that the HSDPA consumes all radio resources which the QoS connections spare, while the *fixed* scheme assumes that a fixed amount of resources are reserved for both types of transport channels (see e.g. [1]). A variation is the *hybrid* scheme as a mixture between the adaptive and the fixed scheme. The *hybrid* scheme enables resource reservation for HSDPA, but allows additionally the HS-DSCH to consume resources spared by the DCH connections. The impact on the system stems directly from resource reservation on HSDPA throughput or DCH blocking probabilities, but also indirectly from the influence on the own- and other-cell interference.

Most literature on the performance of the HSDPA does not take into account resource sharing between DCH and HSDPA. An exception is [2] and [3]. In [2], a fixed number of OSVF codes is reserved for the HS-DSCH and the target transmit power is adjusted proportional to the HSDPA transmit power. In [3], an *adaptive* scheme is evaluated with simulations on packet level. Also, in [4], the impact of the (constant) HSDPA transmit power with 5 reserved codes in presence of DCH traffic is investigated. Finally, in [5], an analytical model for the adaptive scheme is introduced which assumes that the NodeBs always send with maximum power.

Our contribution is an investigation of the impact of resource allocation schemes with and without reservation on HSDPA and DCH performance. The performance evaluation is done with a time-dynamic simulation model which considers the complete interference situation of the network for the transmit power calculation for the different resource allocation schemes. The HSDPA throughput is calculated with an analytical bandwidth model which includes power and code restraints.

In the next section we give a very brief overview of UMTS radio resources. In Sec. III, we introduce the resource allocation schemes. In Sec. IV, the calculation of transmit powers is explained. Section V gives an overview of the HSDPA bandwidth model and the simulation model. The numerical results in Sec. VI show the impact of the allocation schemes on system performance. Finally, in Sec. VII, we give a conclusion and point out some further topics of research.

II. UMTS RADIO RESOURCES

In the UMTS downlink, which we consider here, the OSVF-codes (orthogonal variable spreading factor codes) and the transmit power are of primary interest due to their capacity-limiting properties [6]. Each cell[1] has a number of codes and a certain maximum transmit power available. DCH connections normally require a fixed number of OSVF-codes (in most cases just one), and try to keep the received SIR at the UE (user equipment) constant. This means that the power demand of a DCH connection depends on the propagation loss between NodeB and UE.

The core of the HSDPA is the HS-DSCH (high speed downlink shared channel), which uses up to 15 codes with spreading factor (SF) 16 in parallel. The HS-DSCH enables two types of multiplexing: Time multiplex by scheduling the subframes to different users, and code multiplex by assigning each user a non-overlapping subset of the available codes. The latter requires configuration of additional HS-SCCHs (High Speed Shared Control Channel). Throughout this work we assume that one HS-SCCH is present, hence consider time multiplex only.

In contrast to DCH, where the transmit power is adapted to the propagation loss with fast power control and thus enabling a more or less constant bit rate, the HS-DSCH adapts the channel to the propagation loss with adaptive modulation and coding (AMC). The UE (user equipment) sends channel quality indicator (CQI) values to the NodeB. The CQI is a discretization of the received SIR at the UE and ranges from 0 (no transmission possible) to 30 (best quality). The scheduler in the NodeB then chooses a transport format combination (TFC) such that a pre-defined target BLER, which is often chosen as 10%, is fullfilled if possible. The TFC contains information about the modulation (QPSK or 16QAM), the number of used codes (from 1 to 15), and the coding rate resulting in a certain transport block size (TBS) that defines the information bits transmitted during a TTI. A number of tables in [7] define a unique mapping between CQI and TFC. This means that with an increasing CQI, the demand on code resources is also increasing. This leads to cases where a high CQI is reported at the NodeB, but the scheduler has to select a lower TBS due to lacking code resources.

III. RADIO RESOURCE SHARING BETWEEN DEDICATED CHANNELS AND THE HS-DSCH

Let us first introduce the following basic equations which hold true for all resource allocation schemes:

$$T_x = T_{x,d} + T_{x,c} + T_{x,h}, \quad \text{and} \tag{1}$$

$$C_x = C_{x,d} + C_{x,c} + C_{x,h}, \tag{2}$$

where T_x is the total transmit power of NodeB x, $T_{x,d}$ is the transmit power for DCH connections, $T_{x,c}$ is used by common channels and the pilot and $T_{x,h}$ is the HS-DSCH power. Analogously, the number of occupied code units C_x is the sum of code resources required for DCH, common channels and HS-DSCH. A code unit corresponds to an OSVF code with SF 512, which is the largest code used in UMTS. All other codes can be expressed in terms of a multiple of this code unit, such that the number of code units occupied by a code is $c_s = \frac{512}{\text{SF}_s}$. Accordingly, the number of SF 16 codes available for the HS-DSCH is $N_{x,h} = \lfloor \frac{C_{x,h}}{32} \rfloor$. Now we define the following radio resource allocation (RRA) schemes:

1) *Fixed*: A number $C^*_{x,h}$ of codes and a transmit power share $T^*_{x,h}$ are reserved for the HSDPA. If active, the HS-DSCH transmit power is equal to this reserved power. If allowed by the CQI reported for the currently scheduled mobile, the NodeB can always use the reserved codes:

$$T_{x,h} = T^*_{x,h} \quad \text{and} \quad N_{x,h} = \lfloor \tfrac{C^*_{x,h}}{32} \rfloor. \tag{3}$$

2) *Adaptive*: The HSDPA uses the resources remaining from the DCHs. No resources are explicitly reserved for HSDPA. The NodeB assigns power to the HS-DSCH such that the total cell transmit power becomes equal to the desired total cell power T^*_x. Accordingly, HSDPA may use all the codes left over by the DCHs if the reported CQI allows for that:

$$\begin{array}{l} T_{x,h} = T^*_x - T_{x,c} - T_{x,d} \\ N_{x,h} = \lfloor \frac{C_x - C_{x,c} - C_{x,d}}{32} \rfloor \end{array} \tag{4}$$

3) *Hybrid*: As in *fixed*, a number of codes and power resources are reserved for HSDPA. However, if there are more resources available, the HS-DSCH may also use them as in *adaptive*.

$$\begin{array}{ll} T_{x,h} = T^*_x - T_{x,c} - T_{x,d}, & T_{x,d} \le T^*_x - T_{x,c} - T^*_{x,h} \\ N_{x,h} = \lfloor \frac{C_x - C_{x,c} - C_{x,d}}{32} \rfloor, & C_{x,d} \le C_x - C_{x,c} - C^*_{x,h} \end{array} \tag{5}$$

Note that the *adaptive* scheme can also be interpreted as a special case of the *hybrid* scheme. The *fixed* scheme is more or less a system with total segregation between HSDPA and DCH connections. However, both connection types do still influence each other indirectly by interference.

IV. CALCULATION OF TRANSMIT POWERS

A UMTS network is defined as a set $\mathcal{L}$ of NodeBs and with associated UEs, $\mathcal{M}_x$. A DCH user k corresponds to a RAB at NodeB $x \in \mathcal{L}$ that is defined by the code $C_{x,k}$, the information bit rate R_k, and a target bit-energy-to-noise ratio (E_b/N_0) ε^*_k. Furthermore, we define ν_k as the activity factor of the user which corresponds to the percentage of time the user is actually transferring data. Then, the transmit power requirement from NodeB x for a DCH user k is

$$T_{x,k} = \frac{R_k \varepsilon^*_k}{W} \cdot \left(\frac{W \cdot N_0 + I^{oth}_k}{d_{x,k}} + \alpha \cdot T_x \right), \tag{6}$$

where W denotes the system bandwidth of $3.84\,$Mcps, N_0 denotes the thermal noise spectral density of $-174\,$dBm/Hz, and $d_{x,k}$ is the average propagation gain from x to k. The other-cell interference I^{oth}_k is the total power received at mobile k from the surrounding NodeBs, and according to the most commonly used interference model [8] the own-cell interference is equal for all mobiles of the same cell:

$$I^{oth}_k = \sum\nolimits_{y \in \mathcal{L} \setminus x} T_y \cdot d_{y,k} \quad \text{and} \quad I^{own}_k = \alpha \cdot T_x \cdot d_{x,k} \tag{7}$$

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[1] Synonym to sector in this work

We are now able to determine the power required for DCHs which again determines the HSDPA power and, in particular, the interference for the HSDPA users. In order consider the different RRA schemes properly, we introduce the boolean variable $\delta_{x,h}$ that indicates whether NodeB x serves at least one HSDPA user or not. Furthermore, we follow [9] in defining the load of cell x with respect to cell y as

$$\begin{aligned}\eta_{x,y} &= \sum_{k\in\mathcal{M}_x} \omega_{k,y} \\ \text{with } \omega_{k,y} &= \tfrac{R_k\cdot\varepsilon_k^*}{W}\cdot\begin{cases} \alpha & \text{, if } \mathcal{L}(k)=y \\ \frac{d_{k,y}}{d_{k,\mathcal{L}(k)}} & \text{, if } \mathcal{L}(k)\neq y. \end{cases}\end{aligned} \tag{8}$$

Using these variables we are able to formulate a compact equation of the total NodeB transmit power. However, we have to distinguish between the *fixed* power allocation scheme with

$$T_x = T_{x,c} + \delta_{x,h}\cdot T^*_{x,h} + \sum\nolimits_{y\in\mathcal{L}} \eta_{x,y}\cdot T_y \tag{9}$$

on the one hand, and the *adaptive* and *hybrid* power allocation schemes with

$$T_x = \delta_{x,h}\cdot T^*_x + (1-\delta_{x,h})\cdot\left(T_{x,c} + \sum\nolimits_{y\in\mathcal{L}}\eta_{x,y}\cdot T_y\right) \tag{10}$$

on the other hand, where DCH transmit power is given as

$$T_{x,d} = \sum_{y\in\mathcal{L}} \eta_{x,y}\cdot T_y. \tag{11}$$

In these equations, we neglected the thermal noise since it is by magnitudes smaller than the multiple access interference for a reasonable cell layout. Introducing the vectors

$$\begin{aligned} V_{\mathcal{F}}[x] &= T_{x,c} + \delta_{x,h}\cdot T^*_{x,h} \\ V_{\mathcal{A}}[x] &= \delta_{x,h}\cdot T^*_x + (1-\delta_{x,h})\cdot T_{x,c} \end{aligned} \tag{12}$$

and matrices

$$\begin{aligned} M_{\mathcal{F}}[x,y] &= \eta_{x,y} \\ M_{\mathcal{A}}[x,y] &= (1-\delta_{x,h})\cdot\eta_{x,y} \end{aligned} \tag{13}$$

for the *fixed* and *adaptive/hybrid* power allocation schemes, respectively, leads to a the matrix equation

$$T = V + M\cdot T \Leftrightarrow T = (I-M)^{-1}\cdot V, \tag{14}$$

that is valid for all three power allocation schemes. The matrix I is the identity matrix, and T is the vector with the cell transmit powers T_x. The DCH and HSDPA transmit powers are then calculated with Eq. (11) and Eq. (2).

V. HSDPA BANDWIDTH MODEL AND TIME-DYNAMIC SIMULATION MODEL

In each TTI the scheduler in the NodeB decides on behalf of the CQI feedback which transport block size (TBS) and which user should be scheduled. The relation between SIR and CQI given by the following formula which has been found in [10]:

$$\text{CQI} = \max\left(0, \min\left(30, \left\lfloor \tfrac{\text{SIR[dB]}}{1.02} + 16.62 \right\rfloor\right)\right). \tag{15}$$

The instantaneous SIR at an HSDPA UE after combining in the RAKE receiver is the sum of the received signal powers of the propagation paths divided by the interference. Let us define $\Delta_{T_x} = \frac{T_x}{T_{h,x}}$ as the ratio between total and HS-DSCH transmit power. Then, the received SIR at a position f is

$$\gamma_f(\Delta_T) = \Delta_T\cdot\sum_{p\in\mathcal{P}_{x,f}} \frac{\xi_p}{\frac{I_f^{other}}{T_x\cdot d_{x,f}} + \sum_{r\in\mathcal{P}_{x,f}\setminus p}\xi_r} \tag{16}$$

$$\text{with}\quad I_f^{other} = \sum\nolimits_{y\neq x} d_{y,f}\cdot T_y\cdot\sum\nolimits_{r\in\mathcal{P}_{y,f}}\xi_r, \tag{17}$$

where ξ_p is an exponential random variable with mean β_p that describes the instantaneous propagation gain on path $p\in\mathcal{P}$. In this work, we assume the ITU Vehicular A model with 6 propagation paths. By inspection it can be stated that the influence of the other-cell interference on the SIR grows as the location is closer to the cell border. Hence, we model the mean and standard deviation of the SIR distribution at location f as a function of the other-to-own-interference-ratio $\Sigma_f = I_f^{other}/(T_x\cdot d_{x,f})$ and introduce the *normalized* SIR $\Gamma_f = \gamma_f(1)$. By extensive simulations we have shown in [5] and in more detail in [11] that the dependency between Σ_f and mean and standard deviation of the normalized SIR distribution can be effectively approximated with a four-parametric Weibull function. Resulting from that, the location-dependent normalized SIR distribution is modeled in this work with an inverse Gaussian distribution.

This leads directly to the distribution of the feedback CQI, $p_{\text{CQI},f}(q)$, which can be easily calculated by discretization of the normalized SIR distribution with (15). The mean TBS, i.e. the mean possible datarate at location f is then

$$E[\text{TBS}_f] = \sum\nolimits_{q=0}^{30} p_{\text{CQI},f}(q)\cdot\min\left(\text{TBS}^*, \text{TBS}(q)\right), \tag{18}$$

where TBS* is the maximum TBS that is possible with $N_{h,x}$ codes. The long-term bandwidth with round-robin scheduling, which we assume here, is then simply the mean value of the TBS corresponding to the CQI distribution, divided by the number of concurrently active HSDPA users:

$$R_f = \frac{1s}{N_h\cdot 2\text{ms TTI}}\cdot E[\text{TBS}_f] \tag{19}$$

Note that also MaxC/I scheduling or proportional scheduling can be modeled in a similar way by calculating additionally the probability that a user is scheduled. It should also be noted that the maximum possible bandwidth is due to the strong multipath component of the Vehicular A model around 2.3 Mbps, which means that more than 5 codes do not lead to any significant performance gain even for high HSDPA transmit powers.

The long term bandwidth is now used in a time-dynamic simulation which considers the HSDPA data traffic of a user k as a flow with data volume V_k. The network area is discretized into a set of quadratic area elements. The time axis is divided in inter-event times, in which we assume that the users stay roughly within an area element. Events can be arrival events of DCH or HSDPA users as well as departure events. At the beginning of each inter-event time, admission control is performed if necessary and for existing connections the DCH and HSDPA transmit powers as well as the number of codes available for HSDPA are calculated according to the specific RRA scheme. Then, the bandwidth and the expected new departure times of each HSDPA user are calculated. At the end of an inter-event time, the remaining data volumes $V_{k,r}$ of the users are decreased by the data amount which has been transmitted within the current inter-event time.

In our simulation, we assume both DCH users and HSDPA flows arrive according to a Poisson process with arrival rate λ_s and λ_H, respectively. Dedicated channel users have a exponentially distributed call time with mean $E[T] = 120\,\text{s}$, the HSDPA flow size is exponentially distributed with mean volume $E[V] = 100\,\text{kbyte}$ which is approximately the mean size of a web page.

Admission control for the DCH connection is performed on base of the maximum allowed transmit power and on the available code resources on each new DCH arrival. For the HSDPA we assume a count-based admission control which restricts the maximum number of concurrent connections to a fixed value.

VI. Numerical Results

For the numerical results the standard 19-cell network layout has been used, from which we only consider the middle cell. However, the complete network has been simulated such that the effect of the other-cell interference is properly captured. The distance between the NodeB antennas is $1.2\,\text{km}$. The maximum allowed transmit power per NodeB is $10\,\text{W}$, from which a constant share of $T_c = 2\,\text{W}$ is permanently reserved for the pilot and common channels. The arrival rate for the HSDPA flows is set to $\lambda_H = 1$ for all scenarios. The maximum number of HSDPA connections is 10.

A. Impact of DCH loads

In the first scenario, we keep the reserved resources for the HSDPA constant and increase the arrival rate of the DCH users, which can either use 384 kbps or 128 kbps radio bearers with a service mix of 0.4 to 0.6. Both for the *hybrid* and for the *fixed* scenario the reserved transmit power is set to $T_h^* = 4\,\text{W}$. Additionally, $N_h = 5$ codes are reserved. The impact on the HSDPA user throughput which is calculated as the weighted time-average over all connections is shown in Fig. 1. In the *adaptive* case, the user throughput decreases steeply with increasing DCH load. This trend increases with a DCH load of 0.3, since in this case the resource preemption by DCH users leads to lower peak rates in the cell middle and increases the probability that HSDPA users at the cell border get CQI values of 0, which means that no transmission is possible at all. The resource reservation of the *hybrid* strategy prevents this strong decline. The *fixed* scheme shows as expected a smaller sensitivity to the DCH load, but the HS-DSCH also is not able to exploit the spare resources from the DCH connections, which leads to a significant lower throughput if compared to the *hybrid* scheme. Notable is the influence of the interference in the *fixed* case, which leads to a decrease of 100 kbps over the total range of the offered loads.

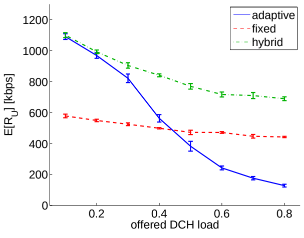

Fig. 1. HSDPA user throughput vs. offered DCH load

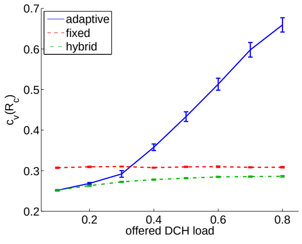

Fig. 2. Coeff. of var. of the HSDPA cell throughput vs. offered DCH load

Figure 2 shows the influence of the DCH load on the coefficient of variation $c_v(R_c)$ of the HSDPA cell throughput. The *adaptive* scheme lead to a significant higher variability which is mainly to the high code resource demand of the 384 kbps bearers. Especially if less than 5 codes are available, the maximum TBS size is significantly lower, which also explains why with reservation of 5 codes in the *hybrid* case the variability is much lower. On the other hand, the additional resources in case of *hybrid* RRA leads to an even smaller variability than in the *fixed* case, since HSDPA connections which profit from the additional resources can leave the system faster. Figure 3 clarifies the trade-off between HSDPA and DCH performance: Due to resource reservation, the total blocking probabilities, which comprise code and soft blocking, reach up to 40% for the 384 kbps service class. Note that the blocking probabilities for the *fixed* and *hybrid* RRA schemes are nearly identical.

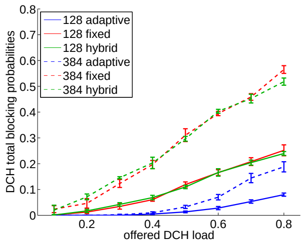

Fig. 3. Total DCH blocking probabilities vs. offered DCH load

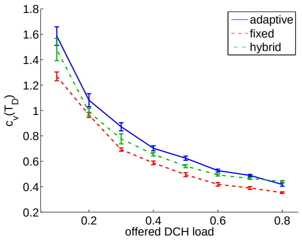

Fig. 4. Coeff. of var. of DCH transmit power vs. offered DCH load

The HSDPA blocking probabilities in the *fixed* and *hybrid* case are very close to zero. For the *adaptive* scheme, the blocking probability increases from 0.025 up to 0.2 for a DCH load from 0.3 to 0.8.

The impact of the allocation schemes on the coefficient of variation of the DCH transmit powers is shown in Fig. 4. Generally, a high variability of the transmit powers is malicious to the system, since large steps of the interference level (e.g. because of on-off-switching of connections) hast to be compensated by the inner loop power control, which has normally a step size of only $1\,\text{dB}$. So, a high variability may lead to increased target-E_b/N_0 values for DCH users. From this perspective, the *fixed* scheme has advantages over the other schemes.

B. *Sensitivity against Resource Reservation*

In the next scenario, we investigate the sensitivity of the *fixed* and *hybrid* RRA against code and power reservation. We keep either the number of reserved codes constant and vary the power reservation or vice versa. The range for the resource reservation is in both cases from 1 to 6, i.e. 1 code to 6 codes or 1 Watt to 6 Watt. The constant resource is set to 3 codes and $3\,$W power, resp. The DCH offered load is set to 0.4, and only one service class ($128\,$kbps) is considered. Figure 5 shows the impact of resource reservation on the mean HSDPA cell throughput. As in the previous scenario the *hybrid* RRA has a significant performance gain due to the exploitation of spare resources. The *hybrid* scheme in this scenario is not very sensitive against reservation, only in case of $6\,$W power reservation an increase is notable. This is in contrast to the *fixed* scheme, where especially code reservation up to 5 codes leads to an increased bandwidth. More than 5 codes cannot be used due to the multipath profile. The insensitivity of the *fixed* scheme against power shows that with 3 codes, $3\,$W transmit power are sufficient. However, we see in Fig. 6 that the resulting bandwidth with 3 codes leads to quite high HSDPA blocking probabilities, but 4 and 5 codes with $3\,$W power show acceptable results. The HSDPA blocking probabilities for *hybrid* RRA are with values around 10^{-4} very low, so we did not show them in this figure. The DCH blocking probabilities show in both cases a strong sensitivity against power reservation, as shown in Fig. 7. More than $4\,$W power reservation leads to soft blocking probabilities higher than 5%. Code reservation naturally leads to higher code blocking probabilities, however, the curve progression is not such steep as for soft blocking with power reservation. We can state here that 4 reserved codes do still lead to an acceptable performance for both schemes. The soft blocking probabilities for both schemes are nearly identical, which indicates that interference does not have a large influence here.

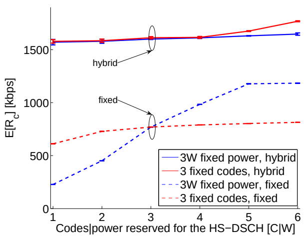

Fig. 5. HSDPA cell throughput vs. code or power reservation

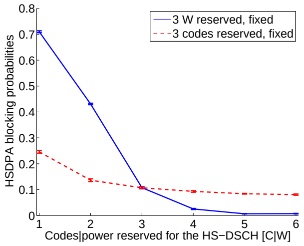

Fig. 6. HSDPA block. prob. for *fixed* RRA vs. code|power reservation

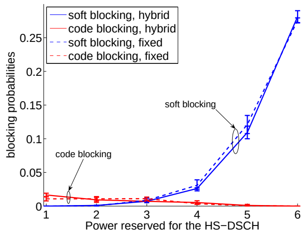

Fig. 7. DCH block. prob. for *fixed* and *hybrid* RRA with fixed power

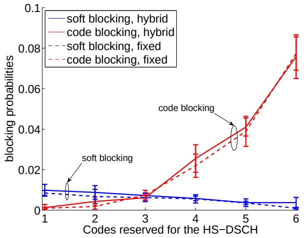

Fig. 8. DCH block. prob. for *fixed* and *hybrid* RRA with fixed codes

VII. CONCLUSION

We investigated the impact of resource allocation schemes for the HSDPA on the system performance of a UMTS network. The evaluation was done with a time-dynamic simulation which considers code and power resources for the DCH and HSDPA connections. The HSDPA data rate is calculated with a long-term model which calculates the location-dependent SIR-distribution depending on the mean other-to-own-interference-ratio. The numerical results show that in case of the *adaptive* scheme the HSDPA throughput is quite sensitive against the DCH load, which is mainly because of missing code resources. The HSDPA throughput for *hybrid* is generally less sensitive against both code and power reservation for moderate DCH loads due to the exploitation of spare resources. The *fixed* scheme is generally difficult to configure since it affects both the DCH and HSDPA performance directly. Generally, the DCH blocking probabilities are a crucial point for the HSDPA resource reservation since reservation does always lead to higher blocking probabilities. Finally, it can be stated that finding HSDPA resource reservation parameters is a difficile task which requires exact knowledge of scenario parameters like DCH offered load, multipath propagation profile, traffic profile of HSDPA users. Further points of research are the impact of different multipath propagation models as well as the impact of more heterogeneous networks.

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