

An Analytical Model for Best-Effort Traffic over the UMTS Enhanced Uplink

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Abstract—The next step in the evolution of UMTS is the Enhanced Uplink or high speed uplink packet access (HSUPA), which is designed for the efficient transport of packet switched data. One of the major novelties is the relocation of the scheduling control from the RNC to the NodeB which enables a faster reaction to cell load and radio condition variations. Our contribution is an analytic modelling approach for the performance evaluation of the UMTS uplink in a single cell with best-effort users over the enhanced uplink and QoS-users over dedicated channels. The model considers two different scheduling disciplines for the enhanced uplink: Parallel scheduling and one-by-one scheduling. The model also considers the effect of power control errors and other-cell interference fluctuations as well as multiple dedicated channel service classes.

Keywords: WCDMA, UMTS, Enhanced Uplink, HSUPA, radio resource management, radio network planning

I. INTRODUCTION AND RELATED WORK

The enhanced uplink (sometimes also referred to as high speed uplink packet access – HSUPA) marks the next step in the evolution process of the UMTS. Introduced with UMTS release 6 and specifically designed for the transport of packet switched data, it promises higher throughput, reduced packet delay and a more efficient radio resource utilization. A detailed overview can be found e.g. in [1] or [2]. The enhanced uplink introduces a new transport channel, the Enhanced-DCH (E-DCH) and three new signalling channels. The E-DCH can be seen as a "packet-optimized" version of the DCH. The major new features are: Hybrid ARQ, implemented similarly as in the high speed downlink packet access (HSDPA), NodeB-controlled fast scheduling, and reduced transport time intervals (TTI) of 2 ms.

The NodeB-based scheduling introduces a new flexibility into the UMTS air interface, since it enables the vendor or operator to implement a scheduling mechanism which is between two fundamentally different scheduling paradigms: One-by-one scheduling and parallel scheduling. In [3] it is shown that the best scheduling strategy in terms of throughput is to schedule users which cannot utilize the total radio resource due to transmit power constraints in parallel, and the rest in an one-by-one manner. A similar conclusion has been found in [4] by means of dynamic programming. Both works implicitly assume that an uplink synchronization mechanism exist which avoid that scheduled transmissions are interfering with each other.

The subject of this work is the performance evaluation of the enhanced uplink for a given network scenario. More

specifically, we try to answer the question: Which service qualities do the users get given a pre-defined network scenario? This means that we assume that the operator has chosen a scheduling strategy and knows the traffic demand in the network. We look at the system on flow level, which means that we consider data traffic regardless of the protocol and content as a continuous flow of data. We further assume that the E-DCH users use best effort applications which generate elastic traffic.

Related work which can be found in the literature is e.g. [5], where a queueing analysis for the CDMA uplink with best-effort services is presented. A similar approach has been taken in [6], which introduces a dynamic slow down approach for the best-effort users. Our contribution differs from the mentioned works by considering specifically the features of the enhanced uplink, and by including imperfect power control and log-normally distributed other-cell interference into the model. The radio resource management (RRM) model resembles the approach in [7], where an analysis for best-effort traffic over rate controlled dedicated channels on the UMTS downlink was done.

The rest of this paper is organized as follows: First we define in Sec. II a radio resource management strategy which provides the frame for our calculations. This forms the base for the interference and cell load model in Sec. III. In Sec. IV, we describe the rate selection and admission control mechanism, which is then used for a queueing model approach in Sec. V. In Sec. VI, we show some numerical examples and finally we conclude the paper with Sec. VII.

II. RADIO RESOURCE MANAGEMENT FOR THE E-DCH BEST EFFORT SERVICE

The scheduling of the E-DCH users is done in the NodeBs, which control the maximum transmit power of the mobiles and therefore also the maximum user bit rate. The NodeBs send scheduling grants on the absolute or relative grant channel (AGCH and RGCH, resp.), which either set the transmit power to an absolute value or relative to the current value. The mobiles then choose the transport block size (TBS) which is most suitable to the current traffic situation and which does not exceed the maximum transmit power. The grants can be sent every TTI, i.e. every 2 ms, which enables a very fast reaction to changes of the traffic or radio conditions. Grants can be received from the serving NodeB and from non-serving

NodeBs. However the latter may just send relative DOWN grants to reduce the other-cell interference in their cells. In our model, we consider grants from the serving NodeB only.

Generally, the WCDMA uplink is interference limited. Therefore, following [8], we define the load in a cell as

$$\hat{\eta} = \frac{\hat{I}_D + \hat{I}_E + \hat{I}_{oc}}{\hat{I}_0 + W\hat{N}_0}, \quad (1)$$

with \hat{I}_D and \hat{I}_E as received powers from the DCH and E-DCH users¹ within the cell, \hat{I}_{oc} as other-cell interference from mobiles in adjacent cells, W as system chip rate, \hat{N}_0 as thermal noise power spectral density and $\hat{I}_0 = \hat{I}_D + \hat{I}_E + \hat{I}_{oc}$. It can be readily seen that this load definition allows the decomposition of the cell load after its origin, hence we define

$$\begin{aligned} \hat{\eta} &= \frac{\hat{I}_D}{\hat{I}_0 + W\hat{N}_0} + \frac{\hat{I}_E}{\hat{I}_0 + W\hat{N}_0} + \frac{\hat{I}_{oc}}{\hat{I}_0 + W\hat{N}_0} \\ &= \hat{\eta}_D + \hat{\eta}_E + \hat{\eta}_{oc} \end{aligned} \quad (2)$$

subject to $\hat{\eta} < 1$. The goal of the RRM is now twofold: First, the cell load should be below a certain maximum load in order to prevent outage. Second, the RRM tries to maximize the resource utilization in the cell to provide high service qualities to the users. The second goal allows also the interpretation of the maximum load as a target load, which should be met as close as possible. Since the DCH-load and the other-cell load cannot be influenced in a satisfying way, the E-DCH load can be used as a means to reach the target cell load. The fast scheduling gives operators the means to use the E-DCH best-effort users for "waterfilling" the cell² load at the NodeBs up to a desired target. This radio resource management strategy is illustrated in Fig. 1. The total cell load comprises the varying other-cell load, the load generated by DCH users and the E-DCH load. The received power for the E-DCH users is adapted such that the total cell load is close to the maximum load. However, due to the power control error and the other-cell interference there is always the possibility of a load "overshoot". The probability for such an event should be kept low. So, the cell load is a random variable due to fast

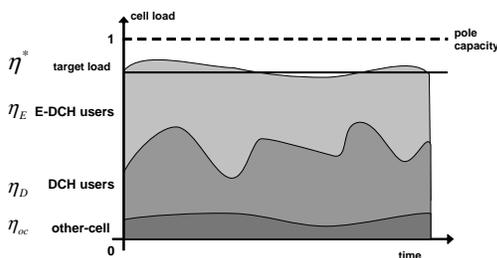


Fig. 1. Illustration of the RRM principles for the E-DCH best-effort service.

fluctuation of the received E_b/N_0 values. We define that the goal of the RRM is to keep the probability of the total cell load below a maximum tolerable probability p_t :

$$P\{\hat{\eta} \geq \hat{\eta}^*\} \leq p_t. \quad (3)$$

¹Note that variables \hat{x} are in linear and x are in dB scale

²corresponding to a sector in case of multiple sectors per NodeB

This means that the received signal power (i.e. the E-DCH interference) of the E-DCH users depends on the amount of dedicated channel and other-cell interference. More precisely, the E-DCH users are slowed down if the DCH or the other-cell load is growing, or are speed up, if more radio resources are available for the E-DCH users. If we now assume that the buffers in the mobiles of the E-DCH users are always saturated, we can use this relation to calculate the grade-of-service the E-DCH users receive depending on the scheduling strategy.

III. INTERFERENCE AND LOAD MODEL

Let us consider a NodeB in a UMTS network serving a single sector or cell, respectively. In the cell is a number of DCH users, each connected with a service classe $s \in \mathcal{S}$. The service classes are defined by bitrate and target- E_b/N_0 -value. Additionally, n_E E-DCH users are in the system. The state vector \bar{n} comprises the users per DCH service class, n_s , and the E-DCH users n_E :

$$\bar{n} = (n_1, \dots, n_{|\mathcal{S}|}, n_E). \quad (4)$$

Each mobile power controlled by the NodeB perceives an energy-per-bit-to-noise ratio (E_b/N_0), which is given by

$$\hat{\epsilon}_k = \frac{W}{R_k} \frac{\hat{S}_k}{W\hat{N}_0 + \hat{I}_0 - \hat{S}_k}. \quad (5)$$

In this equation, W is the chip rate of 3.84Mcps, R_k is the radio bearer information bit rate, \hat{N}_0 is the thermal noise power density, \hat{S}_k is the received power of mobile k and \hat{I}_0 is the multiple-access interference (MAI) including the own- and other-cell interference. We assume imperfect power control, so the received E_b/N_0 is a lognormally distributed r.v. with the target- E_b/N_0 -value ϵ_k^* as mean value [9] and parameters $\mu = \epsilon_k^* \cdot \frac{\ln(10)}{10}$ and $\sigma = \text{Std}[\epsilon_k] \cdot \frac{\ln(10)}{10}$. The received power of each mobile is calculated from (5) as

$$\hat{S}_k = \hat{\omega}_k \cdot (W\hat{N}_0 + \hat{I}_0) \quad \text{with} \quad \hat{\omega}_k = \frac{\hat{\epsilon}_k R_k}{W + \hat{\epsilon}_k R_k}. \quad (6)$$

We define the r.v. ω_k as *service load factor* (SLF) depending on the bit rate and the E_b/N_0 -value. The sum of all concurrently received powers constitutes the received own-cell interference, i.e.

$$\hat{I}_D(\bar{n}) = \sum_{s \in \mathcal{S}} \sum_{k \in n_s} \hat{S}_k \quad \text{and} \quad \hat{I}_E(\bar{n}) = \sum_{j \in n_E^a} \hat{S}_j. \quad (7)$$

\hat{I}_D is the total received power of the DCH users and \hat{I}_E of the E-DCH users. Note that the number of currently active E-DCH users n_E^a depends on the scheduling discipline. For parallel scheduling, $n_E^a = n_E$, since all users are concurrently active. For one-by-one scheduling, $|n_E^a| = 1$ since in this case only one E-DCH user is transmitting at the same time.

The substitution of \hat{I}_D and \hat{I}_E in Eq. (2) with Eq. (7) gives us then the load definitions depending on \bar{n} :

$$\hat{\eta}_D(\bar{n}) = \sum_{s \in \mathcal{S}} \sum_{k \in n_s} \hat{\omega}_k \quad \text{and} \quad \hat{\eta}_E(\bar{n}) = \sum_{j \in n_E} \hat{\omega}_j, \quad (8)$$

and the total load as

$$\hat{\eta}(\bar{n}) = \hat{\eta}_D(\bar{n}) + \hat{\eta}_E(\bar{n}) + \hat{\eta}_{oc}. \quad (9)$$

We assume the service load factors as lognormal r.v.'s with parameters μ, σ derived from the mean and variance of the E_b/N_0 distributions. These parameters depend on the service class of the users, but are equal for all users within one class. So we can write $E[\hat{\omega}_k] = E[\hat{\omega}_s]$ for all mobiles k with the same service class s . The other-cell load η_{oc} is modelled as an independent lognormal r.v.

Since the total load $\hat{\eta}$ is a sum of independent lognormally distributed r.v.'s, we assume that the cell load $\hat{\eta}$ also follows a lognormal distribution [10]. We get the distribution parameters from the first moment and variance of the cell load which can be calculated directly from the moments of the SLFs. The accuracy of this approach is validated e.g. in [7].

Another novelty of the E-DCH is Hybrid ARQ (HARQ), which combines the automatic-repeat-request protocol with code combining techniques. The use of HARQ (either Chase-combining or incremental redundancy is possible) enables lower target- E_b/N_0 values due to reduced block error rates, but for the sake of an additional overhead due to more retransmissions. This trade-off is adjustable and can be characterized by the mean number of retransmissions. It can be modelled as a constant gain which is included in the target- E_b/N_0 of the E-DCH and with an additional overhead on the mean data volumes of the E-DCH.

IV. RATE ASSIGNMENT AND ADMISSION CONTROL

The available E-DCH load depends on the DCH and other-cell load. The task of the RRM is to assign each E-DCH mobile a service load factor ω such that the E-DCH load is completely utilized if possible. Due to the very flexible scheduling mechanism of the E-DCH, this can be reached in several ways. We consider two fundamentally different scheduling disciplines: The first one is parallel equal-rate scheduling, which means that every E-DCH user gets the same service load factor in every TTI. The second is equal-rate one-by-one-scheduling, where each E-DCH user gets the maximum possible service load factor in a round-robin-fashion. Note that we assume for the latter discipline that the E-DPDCHs (the enhanced dedicated physical data channels) are perfectly synchronized, hence do not generate any interference to each other.

Generally, the user bit rate depends on the magnitude of the E-DCH cell load which may be generated without violating the RRM target in (3). The channel bit rate of the E-DCH is defined by the amount of information bits which can be transported within one TTI. This quantity is defined in [11] by the set of transport block sizes TBS . With a TTI of 2ms, the information bit rate per second follows as $R_{i,E}^I = TBS_i \cdot 500$, where $i = 1, \dots, |TBS|$ indicates the index of the TBS. We further define $R_{0,E}^I = 0$. With this interpretation we can map the E-DCH bit rate to a service load factor according to Eq. (6) as

$$\hat{\omega}_{i,E} = \frac{\hat{\varepsilon}_E R_{i,E}^I}{\hat{\varepsilon}_E R_{i,E}^I + W}, \quad (10)$$

where $\hat{\varepsilon}_E$ is the E_b/N_0 for the E-DCH RAB. Note that here we assume that the target- E_b/N_0 -values are equal for all rates. However, this restriction can be easily avoided by introducing individual target- E_b/N_0 -values for each rate (and ω), if they are available.

The next step is to select the information bit rate such that (3) is fulfilled:

$$R_E^I(\bar{n}) = \max\{R_{i,E}^I | P(\hat{\eta}_D(\bar{n}) + n_{E,E}^a \cdot \hat{\omega}_{i,E} + \eta_{oc} \geq \hat{\eta}^*) \leq p_t\} \quad (11)$$

The actual user bit rates are now calculated according to the scheduling mechanism under the condition that the rate is higher than a certain minimum bit rate $R_{\min,E}$: In case of parallel scheduling, the user bit rate is simply the information bit rate. In case of one-by-one scheduling, the user bit rate is approximated by dividing the information bit rate by the number of E-DCH users:

$$R_E(\bar{n}) = \begin{cases} R_E^I(\bar{n}), & \text{if } R_E^I(\bar{n}) \geq R_{\min,E} \text{ and par. sched.} \\ \frac{R_E^I(\bar{n})}{|n_E|}, & \text{if } \frac{R_E^I(\bar{n})}{|n_E|} \geq R_{\min,E} \text{ and o-b-o. sched.} \\ 0 & \text{else.} \end{cases} \quad (12)$$

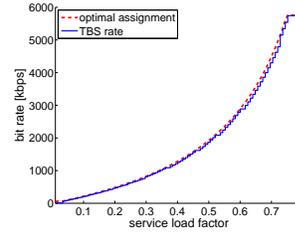


Fig. 2. Mapping of service load factors to bit rates

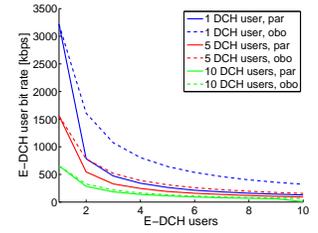


Fig. 3. Rate selection for varying DCH and E-DCH loads

Figure 2 shows the mapping of the service load factors to information bit rates in case of perfect power control and a target- E_b/N_0 of 3 dB. The optimal case indicated by the dashed line is calculated from the definition of the service load factors as $R_{\text{opt}} = \frac{\omega \cdot W}{\hat{\varepsilon}^*(1-\omega)}$. The solid line shows the corresponding rate calculated from the TBS. Both curves are very close to each other, and we see that for high SLFs, a small change means a large change on the bit rate. Figure 3 shows the E-DCH bit rate per user for different number of DCH and E-DCH users. The solid lines show the parallel scheduling case and the dashed the one-by-one scheduling. Different colors indicate different numbers of concurrently active DCH users. We see that for only one E-DCH user, parallel and one-by-one scheduling have naturally the same throughput. However, with more E-DCH users we see the gain of the one-by-one scheduling over the parallel scheduling increases, which is because for the first, the users do not interfere with each other and thus are able to utilize the radio resources more efficiently, i.e. get high SLFs and correspondingly also high bit rates. We see further that this gain depends on the number of DCH users in the system: With more DCH users, the gain shrinks such that with 10 DCH users, there is nearly no gain for the one-by-one scheduling. The reason is that in this case the available

resources for the E-DCH are already quite low and thus only enables SLFs with lower corresponding rates.

The admission control (AC) is responsible for keeping the cell load below the maximum load. We model the AC on basis of the RRM target condition as follows: If a new connection is to be established to the network, the AC calculates the probability for exceeding the maximum load for the state vector $\bar{n} + \bar{1}_{s|E}$, where $\bar{1}_{s|E}$ denotes a single connection with service class s or an E-DCH connection. If the probability is higher than the target probability p_t , the connection is rejected, otherwise the connection is admitted. So, we calculate the parameters for the distribution of the expected cell load η_{AC} exactly as in (9), but with the *minimum possible* SLF for the E-DCH users which corresponds to the minimum bit rate $R_{\min,E}$:

$$\eta_{AC}(\bar{n} + \bar{1}_{s|E}) = \eta_D(\bar{n} + \bar{1}_{s|E}) + \sum_{j \in n_E^c} \hat{\omega}_{\min,E} + \eta_{oc}. \quad (13)$$

The Figures 4 and 5 illustrate the principle of the admission control and rate selection. Fig. 4 shows the mean and the p_t -quantile (here $p_t = 95\%$) of the cell load distribution for 5 DCH users and an increasing number of E-DCH users with parallel scheduling. The target load is $\hat{\eta}^* = 0.85$. Note that the results from a Monte-Carlo-simulation which uses random E_b/N_0 -values, denoted by dashed lines, are very close to the analytical results, which shows the accuracy of the lognormal approximation. Due to the discretization of the available rates, the p_t -quantile does not exactly meet the target-load, but stays just below. Since the variance of the cell load is decreasing with the number of users in the system, the mean load comes closer to the target load with an increasing number of E-DCH users. This is also well visible in Fig. 5, where the corresponding cell load pdfs are shown. Lighter colors indicate less E-DCH users. The vertical line indicates the target load.

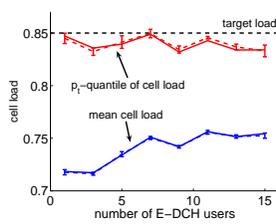


Fig. 4. Mean cell load and 95%-quantiles for parallel scheduling.

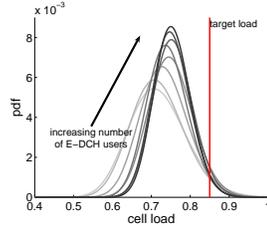


Fig. 5. Cell load pdfs for parallel scheduling.

V. CAPACITY MODEL

Now we assume that calls arrive with exponentially distributed interarrival times with mean $\frac{1}{\lambda}$. The users choose a DCH service class or the E-DCH with probability $p_{s|E}$, hence the arrival rates per class are $\lambda_{s|E} = p_{s|E} \cdot \lambda$. The holding times for the DCH calls are also exponentially distributed with mean $\frac{1}{\mu_s}$. For the E-DCH users we assume a volume based user traffic model [12] with exponentially distributed data volumes. The state-dependent departure rates of the E-DCH users are then

given by

$$\mu_E(\bar{n}) = n_E \cdot \frac{R_E(\bar{n})}{E[V_E]}, \quad (14)$$

where $E[V_E]$ is the mean traffic volume for the E-DCH users.

The resulting queueing system is a multi-service $M/M/n-0$ loss system with state dependent departure rates for the E-DCH users. Note that we here approximate the one-by-one scheduling case, which constitutes an $M/M/1-RR$ system with state dependent service times, with an $M/M/n-0$ system with state-dependent service times. We are now interested in calculating the steady-state distribution of the number of users in the system. Since the joint Markov process is not time-reversible which can be instantly verified with Kolomogorov's reversibility criterion, no product form solution exists. The steady state probabilities follow then by solving the matrix equation

$$Q \cdot \bar{\pi} = 0 \quad \text{s.t.} \quad \sum \pi = 1 \quad (15)$$

for $\bar{\pi}$, where Q is the transition rate matrix. The rate matrix Q is defined with help of the bijective index function $\phi(\bar{n}) : \Omega \rightarrow N$, which maps the state vector \bar{n} to a single index number. The transition rate $q(\phi(\bar{n}), \phi(\bar{n} \pm \bar{1}))$ in the rate matrix between states \bar{n} and $\bar{n} \pm \bar{1}$ is then

$$q(\phi(\bar{n}), \phi(\bar{n} + \bar{1}_s)) = \lambda_s \quad (16)$$

$$q(\phi(\bar{n}), \phi(\bar{n} + \bar{1}_E)) = \lambda_E \quad (17)$$

$$q(\phi(\bar{n}), \phi(\bar{n} - \bar{1}_s)) = n_s \cdot \mu_s \quad (18)$$

$$q(\phi(\bar{n}), \phi(\bar{n} - \bar{1}_E)) = \mu_E(\bar{n}) \quad (19)$$

for all valid states in the state space Ω and $q(\phi(\bar{n}), \phi(\bar{n} \pm \bar{1})) = 0$ otherwise.

VI. NUMERICAL RESULTS

In this section we give some numerical examples for our model. Our scenarios, if not stated otherwise, consist of two service classes: 64 kbps QoS-users (i.e. DCH users) with a target- E_b/N_0 of 4 dB and the E-DCH best effort users with a target- E_b/N_0 of 3 dB. The service probabilities are $p_1 = 0.4$ and $p_E = 0.6$.

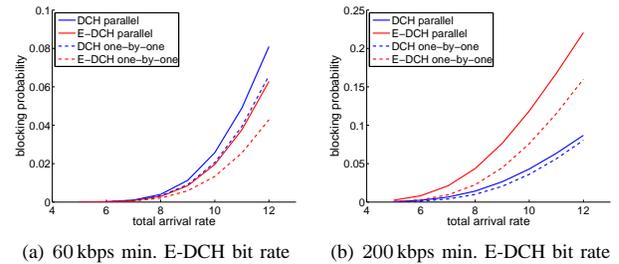


Fig. 6. Comparison of block. prob. for different minimal E-DCH bit rates

In the first scenario we compare the blocking probabilities between parallel scheduling and one-by-one scheduling. In Fig. 6(a), $R_{\min,E}$ is 60 kbps. $E[V_E]$ is 72 kbit. Red lines indicate the blocking probabilities for the E-DCH users, blue lines for the DCH users. We see that the blocking probabilities

for the DCH users are higher than for the E-DCH users. The reason is that due to the low minimum E-DCH bit rate and the resulting low minimal service load factor, E-DCH users may still connect to the system if DCH users are already blocked. The comparison of the parallel (solid lines) with the one-by-one scheduling case (dashed lines) shows that the throughput gain of the one-by-one users lead to lower blocking probabilities, and also to a higher difference between DCH and E-DCH users.

In Fig. 6(b), the scenario is equal to the previous with the exception that $R_{\min,E}$ is 200 kbps. In this case, the minimal service load factors for the E-DCH user is higher than the load requirements of the DCH users, which is the reason why the E-DCH blocking probabilities are now higher than the DCH blocking probabilities. We see further that the DCH blocking probabilities for both scheduling disciplines are now very close to each other.

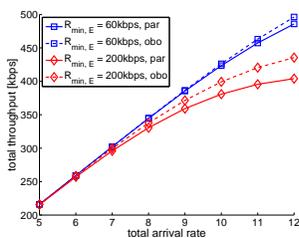


Fig. 7. Mean total E-DCH throughput

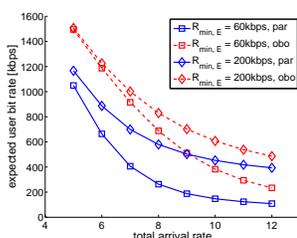


Fig. 8. Mean E-DCH bit rates per user

In Fig. 7, the total mean E-DCH throughput is shown, which is given by

$$E[R_{T,E}] = \lambda_E \cdot (1 - P_{b,E}) \cdot E[V_E]. \quad (20)$$

The throughput for the one-by-one scheduling is as expected always higher than for the parallel scheduling. The gain gets higher with increasing load due to the blocking probabilities, (c.f. Fig. 6). This also explains why the total throughput for a minimum E-DCH user bit rate of $R_{\min,E} = 200$ kbps is lower than with $R_{\min,E} = 60$ kbps, although the per-user-bit rate is higher, as we will see in Fig. 8. Here, the mean E-DCH bit rate of a random user is plotted, which is

$$E[R_E] = \sum_{R_E > 0} R_E \cdot \frac{\sum_{\bar{n} | R_E(\bar{n}) = R_E} n_E \cdot \pi(\bar{n})}{\sum_{\bar{n} | n_E > 0} n_E \cdot \pi(\bar{n})}. \quad (21)$$

At the beginning, the bit rates for $R_{\min,E} = 60$ kbps and $R_{\min,E} = 200$ kbps are close. This changes with an higher load, then the AC prevents the decline for the 200 kbps case stronger than in the case of 20 kbps minimum E-DCH bit rate. We see further that the gain of the one-by-one scheduling over the parallel scheduling shrinks with a higher load. This is due to the effect of the concurrently increased DCH load, as already seen in Fig. 3.

VII. CONCLUSION

We proposed an analytical model for the UMTS enhanced uplink for a single cell. The model considers two fundamental different scheduling mechanisms or multiple access techniques: Parallel scheduling, i.e. classical CDMA, and one-by-one scheduling, i.e. a mixture between TDMA and CDMA. The model considers the effects of imperfect power control and varying other-cell interferences. Because of these effects the bit rate selection for the E-DCH users and the admission control is based on a probabilistic metric, which states that a certain maximum cell load should not exceeded with a certain probability. In the numerical results, we showed that the one-by-one scheduling has the biggest performance gain over the parallel scheduling if the number of DCH users is low, i.e. if the own-cell interference level in the cell is low. We further saw the effect of a minimum allowed bit rate for the E-DCH users on the blocking probabilities and on the user bit rates. In future work, the model will be extended to multiple cells, which enables the investigation of the relative DOWN grants from adjacent NodeBs. Further extensions are e.g. the inclusion of transmit power restrictions of the mobiles, more sophisticated fairness schemes or admission control schemes.

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REFERENCES

- [1] 3GPP, "3GPP TS 25.309 V6.4.0 FDD enhanced uplink; Overall description; Stage 2," 3GPP, Tech. Rep., June 2005.
- [2] S. Parkvall, J. Peisa, J. Torsner, M. Sagfors, and P. Malm, "WCDMA Enhanced Uplink – Principles and Basic Operation," in *Proc. of VTC Spring '05*, Stockholm, Sweden, May 2005.
- [3] K. Kumaran and L. Qian, "Uplink Scheduling in CDMA Packet-Data Systems," in *Proc. of INFOCOM '03*, 2003.
- [4] R. Jantti and S.-L. Kim, "Transmission Rate Scheduling for the Non-Real-Time Data in a Cellular CDMA System," *IEEE Communication Letters*, vol. 5, no. 5, pp. 200–202, May 2001.
- [5] E. Altman, "Capacity of Multi-Service Cellular Networks with Transmission-Rate Control: A Queueing Analysis," in *Proc. of MobiCom '02*, Atlanta, Georgia, USA, Sep 2002, pp. 205–214.
- [6] G. Fodor and M. Telek, "Performance Analysis of the Uplink of a CDMA Cell Supporting Elastic Services," in *Proc of NETWORKING 2005*, Waterloo, Canada, May 2005, pp. 205–216.
- [7] D. Staehle, K. Leibnitz, K. Heck, P. Tran-Gia, B. Schröder, and A. Weller, "Analytic Approximation of the Effective Bandwidth for Best-Effort Services in UMTS Networks," in *Proc. of VTC Spring '03*, Jeju, South Korea, 4 2003.
- [8] H. Holma and A. T. (Eds.), *WCDMA for UMTS*. John Wiley & Sons, Ltd., Feb 2001.
- [9] A. Viterbi and A. Viterbi, "Erlang Capacity of a Power Controlled CDMA System," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 6, pp. 892–900, Aug 1993.
- [10] L. F. Fenton, "The Sum of Log-Normal Probability Distributions in Scatter Transmission Systems," *IRE Transactions on Communication Systems*, vol. 8, no. 1, pp. 57–67, Mar 1960.
- [11] 3GPP, "3GPP TS 25.321 V6.6.0 Medium Access Control (MAC) protocol specification," 3GPP, Tech. Rep., Sep 2005.
- [12] T. Hossfeld, A. Mader, and D. Staehle, "When do we need Rate Control for Dedicated Channels in UMTS?" in *Proc. of VTC Spring '06*, May 2006.