Analysis of packet scheduling for UMTS EUL - design decisions and performance evaluation

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***Abstract*—The UMTS Enhanced Uplink (EUL) provides higher capacity, increased data rates and smaller latency on the communication link from users towards the network. In this paper we present a performance comparison of three distinct EUL scheduling schemes (one-by-one, partial parallel and full parallel) taking into account both the packet level characteristics and the flow level dynamics due to the (random) user behaviour. Using a very efficient hybrid analytical and simulation approach we analyse the three schemes with respect to performance measures such as mean file transfer time and fairness. In UMTS, a significant part of the system capacity will be used to support non-elastic voice traffic. Hence, part of our investigation is dedicated to the effects that the volume of voice traffic has on the performance of the elastic traffic supported by the EUL. Finally, we evaluate the impact that implementation specifics of a full parallel scheduler has on these measures.**

Our main conclusion is that our partial parallel scheduler, which is a hybrid between the one-by-one and full parallel, outperforms the other two schedulers in terms of mean flow transfer time, and is less sensitive to volume and nature of voice traffic. However, under certain circumstances, the partial parallel scheduler exhibits a somewhat lower fairness than the alternatives.

I. Introduction

With the specification of the Enhanced Uplink (EUL) in 3GPP Release 6 of the UMTS (Universal Mobile Telecommunication Systems) standard [25.b] a next step in the evolution of WCDMA-based cellular networks has been made. As the uplink counterpart of the HSDPA (High Speed Downlink Packet Access) technology, standardised in 3GPP Release 5 [25.a] and already introduced by many mobile operators, EUL is primarily designed for better support of elastic data applications.

The enhanced uplink introduces a new transport channel called EDCH (Enhanced Dedicated CHannel), see e.g. [HT06]. Channel access is coordinated by the base stations via packet scheduling based on time frames of fixed length (2 or 10 ms, termed TTI: Transmission Time Interval). Fast rate adaptation with an enhanced dynamic range and efficient time multiplexing through appropriate scheduling schemes enable higher data transfer rates than usually provided on DCHs (Dedicated CHannel) in ‘plain’ UMTS. Other key benefits offered by the EUL technology are an enhanced cell capacity and a reduced latency. In contrast to HSDPA for the downlink, due to limited transmit powers of the user terminals, a single uplink user cannot always use the total available channel resource on its own when it is scheduled (which would optimize throughput, cf. [RH97]) depending on its distance to the base station. Hence, it makes sense to consider scheduling schemes with simultaneous transmissions on the uplink, see e.g. [HT06].

In the present research we compare the performance of different EUL scheduling schemes, as we are particularly interested in the influence of flow level dynamics due to flow (file) transfer completions and initiations by the users at random time instants, which leads to a time-varying number of ongoing flow transfers. We aim at quantifying performance measures such as file transfer times and fairness, expressing how the performance depends on the user’s location in the cell. In addition we examine the impact of certain modelling and design issues such as the particular implementation of the same scheduling class.

Most EUL performance studies in literature are based on dynamic system simulations, see e.g. [HEE+05], [LP05], [ROS+04]. The underlying simulation models incorporate many details of the channel operations and traffic behaviour, but running the simulations tends to require a lot of time. A very interesting study which applies a simulation-oriented approach is [VP07]. The authors evaluate the performance of several schedulers which combine knowledge on channel quality and desired service goal, e.g. realized minimum data rate. Although it offers broad evaluation base and is rather insightful, [VP07] does not provide specific mathematical derivations to evaluate performance.

Analytical modelling overcomes the time demand problem by abstracting from system details yet allowing the same qualitative insights into the system performance. Unfortunately, in order to keep analysis feasible, such studies make sometimes unrealistic assumptions. Interesting examples of studies with analytical modelling are [KQ06], [RH97]. In [RH97] the authors examine the co-existence of voice and data traffic on the uplink for two schedulers which allow parallel transmission of data traffic. Disadvantage of the research is the assumptions that the number of ongoing flows is fixed and that MSs have unlimited transmitted power. The same assumption of fixed number of users holds for [KQ06], which provides a very well worked out optimal scheduling solution with several simplified versions of it to keep the solutions practical. Still the proposed scheduling schemes might prove difficult to deploy.

Analytical studies on EUL performance capturing both packet and flow level dynamics of the system are rare. Interesting references here are [FT05], [MS06] and [MSLB07]. In particular, [MSLB07] presents a rather complete study on the feasible service region supported by EUL and it accounts for flow dynamics and several relevant interference sources. However, the main goal of the authors is to compare several resource management strategies, e.g. centralized vs. distributed, rather than particular scheduling schemes. On the contrary, [MS06] analyses two (rate-fair) scheduling disciplines with flow level performance metrics unfortunately assuming that the transmit powers of all mobiles are sufficient to reach the maximum bit rate.

The performance on the EUL is affected mainly by two factors - inter-cell interference and internal cell processes, i.e. scheduling. In [DvdBHL08b] and [DvdBH09] we have concentrated only on inter-cell interference and the various ways it influences performance. In particular, aspects such as the scheduler specific form of the interference pattern, e.g. [DvdBHL08b], and the full impact of (six) neighbouring cells transmissions on the performance of EUL flows, e.g. [DvdBH09], are discussed. However, due to the complex nature of inter-cell interference, it is rather challenging to additionally evaluate the impact of other factors such as intra-cell interference or scheduler specifics on performance.

On the contrary, our work in [DvdBHL08a] abstracts from inter-cell interference and investigates issues related to the internal behaviour of the cell. [DvdBHL08a] is related to the model proposed by [MS06] but it discusses the more realistic situation of limited transmit power of users and scheduling schemes which are not rate-fair per se but grant equal channel access period. The latter implies that users close to the base station may be favoured, due to better received powers, over users at the cell edge and hence affects performance. In particular, in a single cell setting, we discussed three packet schedulers, each scheme representing a distinctive scheduling choice of simultaneous transmissions. The examined system traffic consisted of EUL (EDCH) users generating elastic traffic and DCH users generating voice traffic. We were able to observe the performance of the elastic traffic and its interaction with the non-elastic voice traffic, i.e. intra-cell interference issues.

Compared to [DvdBHL08a], the current paper elaborates in more detail on both intra-cell interference and scheduling. More specifically, the novelty of the current research can be summarised in the following aspects: (i) investigating how design choices, e.g. implementation specifics, affect scheduling; (ii) providing insights on the impact that modelling decisions have on performance; and (iii) a more extensive performance evaluation including impact of flow sizes and duration of DCH calls.

Our modelling and analysis approach is based on time scale decomposition and consists basically of three steps. The first two steps take the details of the scheduler's behaviour into account in a given state of the system, i.e. the number of EDCH and DCH users and their distance to the base station. In particular, in the first step the data rate at which a scheduled EDCH user can transmit is determined. The second step determines the user's average throughput by accounting for the frequency at which the user is scheduled for transmitting data. In the third step these throughputs and the rates at which new DCH and EDCH users become active are used to create a continuous-time Markov chain describing the system behaviour at flow level. From the steady-state distribution of the Markov chain the performance measures, such as mean file transfer time of a user, can be calculated.

Due to the complexity of the resulting Markov model (transition rates are dependent on the full state) an analytical solution is not feasible; only for some special cases explicit expressions can be obtained for the steady-state distribution. When such closed-form expressions are not available, standard techniques for deriving the steady-state distribution can be used, e.g. numerical solution of the balance equations or simulation of the Markov chain. As the jumps in the Markov chain only apply to the initiation or completion of flow transfers (note that the packet level details are captured in the transition rates which are calculated analytically), simulation of the Markov chain is a very attractive option and does not suffer from the long running times of the detailed system simulations used in many other studies. The latter approach is applied in the current paper.

The rest of the paper is organized as follows. Section II introduces the three different scheduling schemes we will analyse in this paper. In Section III we describe the network scenario considered in this paper and state the modelling assumptions. Subsequently, in Section IV the analytical performance evaluation approach is described in general terms, while the details of the analysis for each of the three scheduling schemes are given in Section V. Preliminaries for the numerical study such as description of the cell scenario and implementation details are discussed in Section VI. Section VII presents and discusses numerical results illustrating schedulers' performance. Finally, in Section VIII, conclusions are drawn and our plans for future work are given.

II. Scheduling Schemes for Enhanced Uplink

In this paper we focus on a class of scheduling schemes for the enhanced uplink, where the users get fair channel access independent of the actual channel conditions ('channel-oblivious' scheduling). Three different scheduling strategies are investigated, termed one-by-one (OBO), partial parallel (PP) and full parallel (FP), which will be described in more detail below. The strategies mainly differ in the time scale on which the fair access is effectuated, in particular whether this is done within each TTI separately, or over a so-called scheduling cycle of multiple TTIs. Note, that fair channel access does not necessarily imply that each scheduling scheme yields equal bit rates to the different active EDCH users. The experienced bit rates depend on the modulation and coding schemes used. This in turn depends on the received powers which can be different for different users, e.g. based on distance to the serving base station.

A common notion in the three schemes is the available channel resource, termed total received power budget (B) at the base station. Expressed in linear units, B is the product of the noise rise target at the base station and the thermal noise. Part of the total budget B cannot be used by the EDCH users in a cell because of interference generated by other sources, e.g. intra-cell interference by DCH users and inter-cell interference by (E)DCH users in other cells. The budget left over to serve EDCH users (which varies over time) is termed the EDCH budget denoted by B'.

A. One-by-one (OBO) Scheduler

In this scheme, during a TTI, a single EDCH user is allowed to transmit and may use the entire available EDCH budget. The different EDCH users are selected for transmission in subsequent TTIs in a round robin fashion [MS06]. Figure 1(a) illustrates this scheme. Although it is generally beneficial to schedule only a single transmission during a TTI, due to high achievable instantaneous rate [RH97], there is also a downside, as a single EDCH user may not be able to fully utilize the available EDCH budget because of its power limitations. What part of the available resources is unused depends on the user's channel conditions. A user with good channel conditions, typically located close to the base station, is able to generate a relatively high received power level and hence leave less resources unutilised.

B. Partial Parallel (PP) Scheduler

The PP strategy attempts to optimize the strategy underlying the OBO scheme by selecting additional EDCH users for simultaneous transmission when the available EDCH budget cannot be fully utilised by a single transmission, see Figure 1(b). In fact, for a given TTI, EDCH users are added

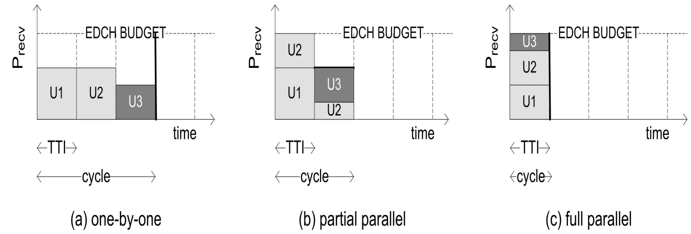

Fig. 1. Illustration of the packet handling of the considered EUL scheduling schemes.

for simultaneous transmission as long as the sum of their maximum received powers does not exceed the available EDCH budget; the remainder of the budget is filled up by an additional EDCH user whose transmission is split over two consecutive TTIs[1]. Overall, the user selection in consecutive TTIs is done in a round robin fashion yielding fair channel access for the users.

For both OBO and PP schemes, depending on the selected ordering of the users in the queue, several implementations of the same scheme are possible, such as descending or ascending order based on power levels or distance to the base station. We prove analytically in Section V-B that the ordering of the users is irrelevant for their service rates. Note that this conclusion is correct in the light of the made assumption that transmitting in one TTI at the maximum power delivers the same result as transmitting in two TTIs but at lower powers.

C. Full Parallel (FP) Scheduler

The last scheduling scheme considered in this paper is the FP scheme (see e.g. [MS06]), which, like the PP scheme, also aims at full utilization of the channel resource. In this scheme all EDCH users are given simultaneous channel access in a given TTI, see Figure 1(c). If the total amount of resources requested by the EDCH users (when transmitting at their maximum power) is larger than the available EDCH budget, then the transmit powers are decreased. What strategy to reduce the transmit powers is chosen depends on whether mean flow transfer times or fairness are given priority. For example, if we aim to provide fair service the strategy strives to assign the same power levels to all users, hence applying different power reductions depending on user's position. We propose several approaches towards power reduction in Section V-C and discuss their performance in section VII-F.

In a preliminary qualitative performance comparison of the three scheduling schemes we expect the PP scheduler to perform best. Which of the other two schedulers is best primarily depends on the available budget: if the budget is relatively low, the OBO scheduler is expected to outperform the FP scheduler

[1]Obviously, other possible strategies exist to deal with filling up the last part of the available budget, but the differences between various strategies appear to be very small.

since it experiences no interference from other EUL users; if the budget is high, the FP scheduler is likely to better utilize the available budget. In terms of operational complexity and computation the three schedulers differ - OBO being the least complex and PP the most. However, compared to other EUL functionality, e.g. power control, the level of complexity is relatively low. In the following sections the performance of the three schedulers will be investigated and compared in more detail. In fact, we will address the effect that practical traffic conditions, i.e. the variation in number of active users due to initiation and completion of flow transfers, on the performance experienced by users at different locations.

III. Modelling Assumptions

In this section we describe the modelling assumptions underlying the presented analysis. At the *system* level, we consider the uplink of a single cell with an omnidirectional base station, serving both DCH and EDCH calls. As illustrated in Figure 2, the considered cell is split in K concentric zones, where zone i is characterized by a distance d_i to the base station and a corresponding path loss denoted $L(d_i)$, $i = 1, \cdots, K$. Derived from an operator-specified noise rise target, the total received power budget at the base station is denoted B. This budget is partially consumed by the constant thermal noise level N, while the remainder is consumed by a varying amount of intra-cell interference originating from either DCH, e.g. voice, or EDCH calls. The DCH budget is the maximum part of the total budget that may be used by DCH calls. At any time, the EDCH calls may fully use that part of the budget that is not claimed by the thermal noise or on-going DCH calls: this is referred to as the EDCH budget, which is denoted $B'(n_D)$, where n_D denotes the number of existing DCH calls.

A number of additional assumptions are made at the *user* level. Calls are generated according to spatially uniform Poisson arrival processes with rates λ (EDCH calls) and λ_D (DCH calls). For the performance of EDCH calls it matters in which zone they appear. As a direct consequence of the uniformity assumption, the probability q_i that a generated EDCH call appears in zone i, is calculated as the ratio of the area of zone i and the total cell area, so that the EDCH call arrival rate in zone i is $\lambda_i = \lambda q_i$, $i = 1, \cdots, K$. EDCH calls are characterised by a file that needs to be uploaded, whose size is exponentially distributed with mean F (in kbits). All calls have the same maximum transmit power $P^{tx}_{\max}$ but different maximum received power at the base station $P^{rx}_{i,\max}$ due to the zone-dependent path loss. As no user mobility is considered, users keep their positions in the cell during the file transmission. The bit rate at which an EDCH call is served depends on the experienced signal-to-interference ratio C/I. Given a pre-fixed E_b/N_0 (energy-per-bit to interference-plus-noise-density ratio) requirement, the attainable bit rate is equal to $r = r_{chip} (C/I) / (E_b/N_0)$,

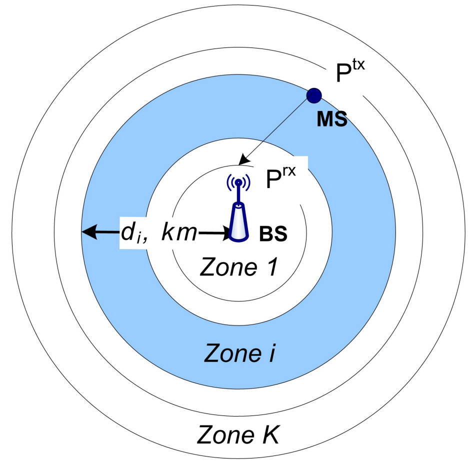

Fig. 2. Modelling approach - cell division into K concentric zones.

where $r_{chip} = 3840$ kchips/s denotes the system chip rate. The signal level C is determined by the call's transmit power and the zone-dependent path loss. The interference level I comprises several distinct components: *(i)* the thermal noise level N; *(ii)* the self-interference modelled by parameter ω, which is due to the effects of multipath fading; *(iii)* the interference $I_{EDCH}(\underline{n})$ originating from EDCH calls; and *(iv)* the interference $I_{DCH}(n_D)$ originating from DCH calls. DCH calls model e.g. speech telephony or video streaming calls and are characterised by a constant bit rate and hence a pre-fixed consumption P_D of the base station's received power budget, regardless of the specific location of the user. The applied value of P_D is based on a worst-case assumption that the noise rise target is fully utilised, which is indeed the objective of the EUL scheduler and hence a rather harmless assumption. Using P_D the above-mentioned DCH budget is readily translated to a maximum m on the number of admissible DCH calls, where m is increasing in the DCH budget and decreasing in the bit rate (which determines P_D). Also considering the single cell focus of our study, note that it suffices to keep track of the *aggregate* number of DCH calls in the cell. The DCH call duration is exponentially distributed with mean τ (in seconds). At a given time, the system state $\underline{n} \equiv (n_1, n_2, \cdots, n_K, n_D)$ is described by the number of EDCH calls n_i in zone i, $i = 1, \cdots, K$, and the total number of DCH calls n_D.

In the considered *traffic handling* scheme the fixed rate DCH calls are treated with priority within the DCH budget, while at any time the EDCH calls are allowed to utilise the remaining part of the uplink budget, including any part of the DCH budget that is not used by DCH calls. Consequently, the dynamics of the DCH calls can be described by an $M/M/m/m$ queuing model (Erlang loss model), which is independent of the EDCH dynamics. For this Erlang loss model explicit expressions are known that relate the traffic load and the channel capacity to the induced blocking probability.

IV. Generic Analysis

We now move on to present how the EDCH performance is analysed by applying our proposed three-step approach. The approach here is generic in the sense that it covers all proposed schedulers. In the next section, it will be 'filled in' with the specifics of the different scheduling schemes in order to complete the analysis.

A. Instantaneous Rate

In the first step of the analysis we determine the so-called instantaneous bit rate $r_i(\underline{n})$, i.e. the transmission rate a call in zone i can achieve *when* it is scheduled for transmission. The instantaneous rate is defined within the boundaries of a TTI and depends on the zone i where the user is located and the interference experienced from all other calls that are scheduled simultaneously, which in turn depends on the current state $\underline{n}$ and the scheduling scheme. We define $r_i(\underline{n})$ as a generalization of [HT01] eq. 8.4

$$\begin{aligned} r_i(\underline{n}) &= \frac{r_{chip}}{E_b/N_0} \cdot \frac{C}{I} \\ &= \frac{r_{chip}}{E_b/N_0} \cdot \frac{P_i^{rx}}{I_{EDCH}(\underline{n}) - \omega P_i^{rx} + I_{DCH}(n_D) + N}. \end{aligned} \quad (1)$$

Since $I_{EDCH}(\underline{n})$ is defined to include the reference call's own signal, a fraction $\omega (0 \leq \omega \leq 1)$ of the own signal must be subtracted from $I_{EDCH}(\underline{n})$ to model the effects of self-interference properly. Since P_i^{rx}, $I_{EDCH}(\underline{n})$ and $I_{DCH}(n_D)$ depend on the state $\underline{n}$ and/or the scheduling scheme, so does the instantaneous rate $r_i(\underline{n})$.

B. State-dependent Throughput

Knowledge of $r_i(\underline{n})$ is not sufficient to determine a call's throughput in system state $\underline{n}$ since a call often has to wait several TTIs between actual data transmissions (scheduling cycle; see also Figure 1). The result is a decreased effective transmission rate, which we term state-dependent throughput $R_i(\underline{n})$. More precisely, $R_i(\underline{n})$ is the average transmission rate an active call achieves during one scheduling cycle, given that the system is and remains in state $\underline{n}$. Denoting with $c(\underline{n})$ the cycle length, which depends on the number of ongoing EDCH calls and the applied scheduling scheme, we have

$$R_i(\underline{n}) = \frac{r_i(\underline{n})}{c(\underline{n})}. \quad (2)$$

C. Markov Chain Modelling

Now that the packet level analysis is completed we can introduce flow level dynamics. This is done in the third step of the analysis with the creation of a continuous-time Markov chain model describing the dynamics of EDCH and DCH call initiations and completions in the cell. The states in the Markov model are given by $\underline{n} = (n_1, n_2, \cdots, n_K, n_D)$, i.e. the distribution of the EDCH calls over the different zones in the cell and the total number of on-going DCH calls. Hence the Markov model itself has $K+1$ dimensions, with K dimensions representing the EDCH calls in the different zones and an additional dimension to represent the DCH calls in the cell. Each of the K 'EDCH dimensions' is unlimited in the number of admissible calls, while the 'DCH dimension' is limited to m simultaneous calls. The transition rates of the Markov model for the following events (i) data flow arrival; (ii) voice flow arrival; (iii) data flow completion and (iv) voice flow completion, are as follows:

$$\begin{array}{lll} \text{(i) } \underline{n} \rightarrow (n_1, ..., n_i + 1, ..., n_K, n_D) & \text{at rate} & \lambda_i \\ \text{(ii) } \underline{n} \rightarrow (n_1, ..., n_i, ..., n_K, n_D + 1) & \text{at rate} & \lambda_D \\ \text{(iii) } \underline{n} \rightarrow (n_1, ..., n_i - 1, ..., n_K, n_D) & \text{at rate} & \frac{n_i}{F} R_i(\underline{\text{n}}) \\ \text{(iv) } \underline{n} \rightarrow (n_1, ..., n_i, ..., n_K, n_D - 1) & \text{at rate} & \frac{n_D}{\tau} \end{array}$$

V. Scheduler Specific Analysis

The generic three-step approach described in Section IV can be used to analyse various schedulers. Applied to the three scheduling schemes of our interest the approach results in three different Markov models, which can be classified as complex processor sharing type of queuing models. The differences are a consequence of the different expressions of $r_i(\underline{n})$ and $c(\underline{n})$. Due to the specifics of the schedulers, the Markov chains generated here are too complex for the steady-state distribution to be obtained analytically. Therefore we have chosen to simulate the Markov model in order to find the steady-state distributions.

A. 'One-by-One' Scheduler

In case of OBO scheduling only one EDCH call may be scheduled per TTI. Hence the scheduled user may in principle utilise the entire EDCH budget but may very well be limited by its own maximum received power level: $P_i^{rx} = \min \left\{ P_{i,\max}^{rx}, B'(n_D) \right\}$. Having only a single active user per TTI yields a cycle length of $n \equiv n_1 + n_2 + \cdots + n_K$ (for state $\underline{\text{n}}$), hence, $c(\underline{n}) = n$. Under OBO scheduling the sources of interference are thermal noise, interference from DCH calls and self-interference. $I_{EDCH}(\underline{n})$ in this case consists only of the own signal power, which allows expression (1) to be rewritten and the resulting state-dependent throughput $R_i(\underline{n})$ is given by:

$$R_i(\underline{n}) = \frac{r_{chip}}{E_b/N_0} \cdot \frac{P_i^{rx}}{(1-\omega)P_i^{rx} + I_{DCH}(n_D) + N} \cdot \frac{1}{n}. \quad (3)$$

Expression (3) shows that $R_i(\underline{n})$ depends on the current state $\underline{n}$ only via $c(\underline{n})$ and n_D. Considering the third step of the analysis, in the special case where $\lambda_D = 0$, the Markov model for the OBO scheduler is effectively a multi-class $M/M/1$ processor sharing model, which is well examined and an explicit expression for the steady-state distribution is available, see e.g. [Coh79].

B. 'Partial Parallel' Scheduler

As the PP scheduler allows parallel transmissions of multiple EDCH calls in a single TTI, $I_{EDCH}(\underline{n})$ comprises the interference contributions from all scheduled EDCH calls in a TTI. Consequently, the instantaneous rate depends on $\underline{n}$, see (1). The opportunity for simultaneous transmissions also results in a shorter cycle than under OBO scheduling which can be expressed as the ratio of the aggregate resource requested by all present EDCH calls and the available EDCH budget $B'(n_D)$. The cycle length is then given by

$$c(\underline{n}) = \max\left\{1, \frac{\sum_{i=1}^{K} n_i P_{i,\max}^{rx}}{B'(n_D)}\right\}, \tag{4}$$

and hence the state-dependent throughput $R_i(\underline{n})$ is equal to

$$\begin{aligned} R_i(\underline{n}) &= \frac{r_{chip}}{E_b/N_0} \cdot \frac{P_{i,\max}^{rx}}{B'(n_D) - \omega P_{i,\max}^{rx} + I_{DCH}(n_D) + N} \cdot \\ &\cdot \frac{B'(n_D)}{\sum_{i=1}^{K} n_i P_{i,\max}^{rx}}, \end{aligned} \tag{5}$$

if $\sum_{i=1}^{K} n_i P_{i,\max}^{rx} \geq B'(n_D)$. In the alternative case that the sum of the power levels of the active users is lower than the budget, i.e. if $\sum_{i=1}^{K} n_i P_{i,\max}^{rx} < B'(n_D)$, each active user sends in each TTI and the cycle length is $c(\underline{n}) = 1$. That simplifies the state-dependent throughput expression to

$$\begin{aligned} R_i(\underline{n}) &= \\ &= \frac{r_{chip}}{E_b/N_0} \cdot \frac{P_{i,\max}^{rx}}{I_{EDCH}(\underline{n}) - \omega P_{i,\max}^{rx} + I_{DCH}(n_D) + N}, \end{aligned} \tag{6}$$

where $I_{EDCH}(\underline{n}) = \sum_{i=1}^{K} n_i P_{i,\max}^{rx}$.
The resulting flow level Markov chain model is a complex processor sharing type of queuing model with transition rates that depend on the detailed state distribution $(n_1, n_2, \cdots, n_K, n_D)$.

Looking at Equation (5), the state dependent throughput depends on the received power and the number of users for a state $\underline{n}$. Given that in a PP scheme a user always transmits on its maximum power level, the order of the users would not influence the received power just as it does not affect the number of users.

C. 'Full Parallel' Scheduler

Under FP scheduling, an active user transmits in each TTI and therefore the cycle length $c(\underline{n})$ is equal to 1 for all states $\underline{n}$. Hence the state-dependent throughput is equal to the instantaneous rate (calculated for the appropriate received power level), i.e. $R_i(\underline{n}) = r_i(\underline{n})$. In the expression for $r_i(\underline{n})$, $I_{EDCH}(\underline{n})$ comprises contributions from all EDCH calls. We distinguish between two cases. In the first case the number of EDCH calls is such that the sum of their (received) maximum powers is lower than the EDCH budget $B'(n_D)$. In that case the EDCH calls use their maximum transmit power and the state-dependent throughput is the same as under PP scheduling, see Equation (6). The second case is when the summed maximum received power from all users is higher than the EDCH budget. Since all users are assigned to transmit in parallel, the transmit power levels have to be decreased such that the summed received powers fit in the EDCH budget. The resulting received power levels P_i^{rx} are derived from the maximum received power via a proportional decrease:

$$P_i^{rx} = \frac{P_{i,\max}^{rx}}{\sum_{i=1}^{K} n_i P_{i,\max}^{rx}} \cdot B'(n_D), \tag{7}$$

so that $I_{EDCH}(\underline{n}) = \sum_{i=1}^{K} n_i P_i^{rx} = B'(n_D)$. Using P_i^{rx} we can rewrite Equation (1) for this second case of FP scheduling as

$$\begin{aligned} R_i(\underline{n}) &= r_i(\underline{n}) = \\ &= \frac{r_{chip}}{E_b/N_0} \cdot \frac{P_i^{rx}}{B'(n_D) - \omega P_i^{rx} + I_{DCH}(n_D) + N}. \end{aligned} \tag{8}$$

Since $R_i(\underline{n})$ depends on the full state information $(n_1, n_2, \cdots, n_K, n_D)$ the resulting Markov chain model for the FP scheme is also a complex processor sharing type of queuing model, for which we apply Markov chain simulation to obtained the performance results.

A full parallel scheme with proportional power division, referred in the rest of the paper to as FP, is only one possible implementation. We identify three additional power division approaches: FP with equal division (FP-ED), FP-ED with priority (FP-EDp) and FP-ED with equality (FP-EDe). All three schemes initially divide the budget in equal portions, whose size B_{EDCH}/n is determined by the number of active users n, and each user gets assigned one such portion. Depending on the match between the budget portion and the received power of a user two situations are possible. In the first case all users have received power such that they can fully used their assigned portion, i.e. $P_i^{rx} \geq B_{EDCH}/n$. In the second case this condition does not hold for at least one user, i.e. $P_i^{rx} < B_{EDCH}/n$, leaving part of the budget $U(\underline{n})$ unused. The size of $U(\underline{n})$ depends on how many users cannot fill up their portion and on their received powers. $U(\underline{n})$ can be derived as:

$$U(\underline{n}) = \frac{B_{EDCH}}{n} - \sum_{j=1}^{n} P_j^{rx}. \tag{9}$$

Each scheme adopts a different approach towards sharing $U(\underline{n})$ over the users. FP-ED leaves $U(\underline{n})$ as it is and by this does not exploit all available resources even if it would be possible. For example, users who can realize higher received power than their assigned portion and let us term them

TABLE I
DATA RATES CORRESPONDING TO ZONE NUMBER

zone	1	2	3	4	5
rate, kbps	4096	3584	3072	2560	2048
zone	6	7	8	9	10
rate, kbps	1536	1024	512	384	256

candidates. Both FP-EDp and FP-EDe apply a more advanced strategies and try to fully use the budget. In FP-EDp the candidate most far from the base station is given the whole $U(\underline{n})$ while FP-EDe equally divides $U(\underline{n})$ over all candidates. The redistribution of $U(\underline{n})$ in both schemes is in fact an iterative process.

Accounting for the specific power assignment in the different FP schemes with equal division, we can write for the received powers:

$$P_i^{rx} = min(\frac{B_{EDCH}}{\sum_{i=1}^{K} n_i} + E(n), B_{EDCH}), \qquad (10)$$

where

$$E(n) = \begin{cases} 0 & \text{for FP-ED and FP-EDp} \\ U(\underline{n}) & \text{for FP-EDp, farmost user} \\ \frac{U(\underline{n})}{n_{cand}} & \text{for FP-EDe} \end{cases}$$

VI. PRELIMINARIES FOR NUMERICAL STUDIES

In this section we elaborate on several modelling issues which form the base for the numerical results presented later in Section VII. In particular, in Section VI-A all traffic and system parameters are set and the performance measures are introduced. Subsequently, in Section VI-B, we argue on the appropriate number of zones used for cell modelling. Finally, Section VI-C discusses our methodology to simulate Markov model in Matlab environment.

A. Parameter Settings

In the numerical experiments we assume a system chip rate r_{chip} of 3840 kchips/s, a thermal noise level N of -105.66 dBm and a noise rise target η at the base station of 6 dB. From these parameters the total received power budget B can be calculated: $B = \eta \cdot N$. A self-interference of 10% of the own signal is considered, i.e. $\omega = 0.9$. The assumed path loss model is given by $L(d) = 123.2 + 35.2 \log_{10}(d)$ (in dB).

The considered cell is split in $K = 10$ zones, see Section VI-B. Given an E_b/N_0 target of 1.94 dB for EUL transmissions, a maximum transmission power of $P_{\max}^{tx} = 0.125$ Watt and a worst case interference level (where the received power budget B is fully used), we applied straightforward link budget calculations to determine the zone radii corresponding to a set of ten bit rates between 256 kbit/s (zone 10) and 4096 kbit/s (zone 1) chosen to correspond to the EUL standard. The correspondence between rate and zone is given in Table I. EDCH calls consist of file transfers of mean size $F = 1000$ kbit; the aggregate rate at which new file transfers are initiated is $\lambda = 0.4$ calls/sec. Other than these default values are explicitly indicated.

DCH users are assumed to generate voice calls with requested bit rate of 12.2 kbit/s, an activity factor of 50% and an E_b/N_0 of 5.0 dB. The mean duration τ of the voice calls is 120 seconds. Given a noise rise target η of 6 dB, this translates to a P_D of $0.0729 \cdot 10^{-14}$ Watt. A DCH budget of 70% of the totally available channel resource B was used as a default value, implying a maximum of 77 simultaneous speech calls. Given a target blocking probability of 1%, this translates to a supported speech traffic load of about 62 Erlang, and hence $\lambda_D \approx 0.52$ calls/s. The DCH call arrival rate λ_D is always chosen such that the DCH call blocking probability equals 1%. The use of other than default values will be explicitly indicated where applicable.

The comparison of the three scheduling schemes is based on performance parameters such as mean file transfer time for zone i and fairness. The fairness is evaluated with the fairness index used by Jain; see [Jai91]:

$$F = \frac{(\sum_{i=1}^{K} D_i)^2}{K * \sum_{i=1}^{K} (D_i)^2}, \qquad (11)$$

where D_i denotes the mean flow transfer time for users in zone i, $i = 1, ..., K$

B. Cell Division in Zones

The cell separation in zones is an essential decision since it allows us to differentiate between user positions and achievable data transfer rates in order to model a realistic scenario. Just as important it is to decide on a representative number of zones K. We have performed experiments with 5, 10, 15, 20 and 40 zones and two different loads - medium and close to saturation - to find an optimal number of zones. A large number of zones provides for finer differentiation in the users' location and subsequently in the achievable data transfer rates. However, large number of zones also leads to increased modelling complexity and simulation time. Depending on the research goals, a trade-off between granularity and complexity of modelling is necessary. We performed several experiments to find the number of zones appropriate for our research.

As an evaluation parameter we have used the relative difference in mean flow transfer time. We prefer relative to absolute difference because we are interested in the improvement registered by each increase. An appropriate number of zones is found when further increasing K leads to negligible relative difference in the mean flow transfer times. The general trend is that increasing the number of zones leads to decrease in the relative difference. The initial improvement of 41.45% when changing from 5 to 10 zones reduces to only 3.15% when changing from 20 to 40 zones. We believe that further increase in the number of zones would not have a considerable contribution. The results show that 20 zones is an optimal choice for a wide range of loads - it achieves good granularity in location and the modelling is still manageable. We have chosen to work with 10 zones - the modelling and simulation efforts are considerably less and granularity level is satisfying unless very high loads are used.

C. Simulation of Flow Level Markov Chain

A Markov model with simple-form transition rates can be analytically described by explicit mathematical expressions and a steady state distribution. More complex models are challenging for purely analytical approach, in which cases simulation of the Markov model can be a solution. In order to obtain a steady state distribution we created a generic simulator for multi-dimensional Markov chains by using MatLab (`http://www.mathworks.com/`). We actually simulate state transitions taking into account the transition rates from the flow level Markov model, cf. [AvM05]. In particular, given the currently visited state $\underline{n}$, we calculate the total rate out of the state, denoted by $Q(\underline{n})$, as:

$$Q(\underline{n}) = \sum_i \lambda_i + \sum_i R_i(\underline{n}) + \lambda_D + R_D(n_D),$$

where $R_D(n_D) = \frac{n_D}{\tau}$. Subsequently, the transition probabilities are calculated as:

$$\begin{aligned} Pr\{\text{forward jump}\} &= \lambda_i / Q(\underline{n}), i = 1, \dots K, D, \quad (12) \\ Pr\{\text{backward jump}\} &= R_i(\underline{n}) / Q(\underline{n}), i = 1, \dots K, D, \end{aligned}$$

and an uniform sample is used to determine which transition takes place. Before moving to the newly chosen state the time spent in the current state, taken as a sample from an exponential distribution with mean $1/Q(\underline{n})$, and the state itself are recorded.

By applying this iterative process for 1 million state transitions and collecting data on the total time spent in each visited state, we derive the steady state distribution. Experiments showed that working with 1 million state transitions is sufficient to generate trustworthy results, i.e. 95% confidence intervals of about 1%. The combined approach of mathematical analysis and Markov model simulation allows us to perform fast performance evaluation. For example, our simulations take typically 2.5 minutes (and could be speed up).

VII. Numerical Results

This section presents all performance evaluation scenarios we have examined. All results are based on the default

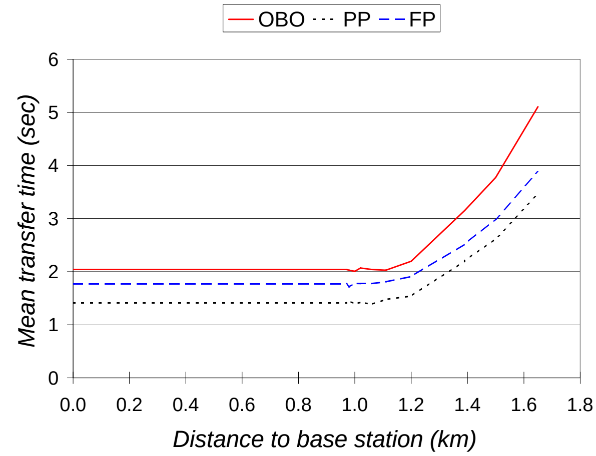

Fig. 3. Impact of the mobile station's location, i.e. distance to the base station, on the mean flow transfer times.

settings of Section VI-A. The first five sections present a comparison of the one-by-one, partial parallel and full parallel (with equal power division) in terms of mean flow transfer times (MFTT), see Sections VII-A to VII-D, and fairness, see Section VII-E. A final scenario, discussed in Section **??** shows the performance differences between the several proposed implementations of the full parallel scheduler.

A. Performance Impact of the User Location

Figure 3 shows, for each of the three schedulers, the mean flow transfer time as a function of the user's distance from the base station. The system and traffic parameters are set according to their default values indicated in Section VI-A. Note that, as consequence of the zone selection, the first zone ends at 0.96 km.

As expected, the partial parallel (PP) scheduling scheme outperforms the two other schemes, cf. the discussion at the end of Section 2; in the current situation the full parallel (FP) scheme performs second best and the one-by-one (OBO) scheme shows the worst performance. For all three schedulers, when moving away from the base station, the mean flow transfer times remain more or less constant until a distance of about 1.1 km. Apparently, in these central zones the combination of the available budget and the maximum attainable received power allows the same (maximal) data rates. At larger distances the effect of the increasing path loss, consequently lower attainable received powers and hence lower bit rates becomes clearly visible through rapidly increasing flow transfer times.

Note, that even for users close to the base station, which are able to fill up the whole EDCH budget on their own, the PP scheme performs considerably better than the OBO (and FP) scheme. This is due to the fact that the particular disadvantage

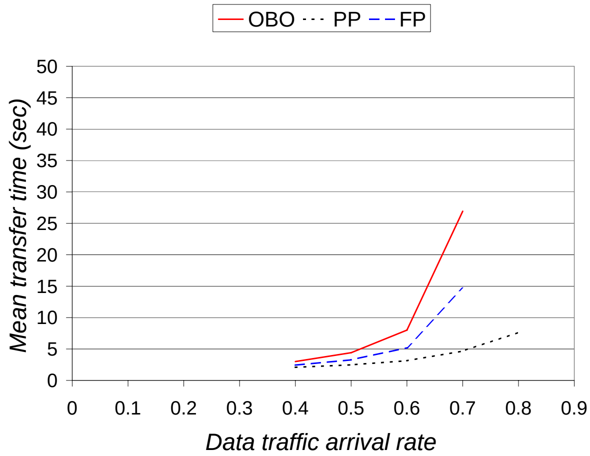

Fig. 4. Impact of the EUL arrival rate λ on mean flow transfer times. On the x-axis first the reserved B_E is given and after that, between brackets, is presented how much of the budget is actually used.

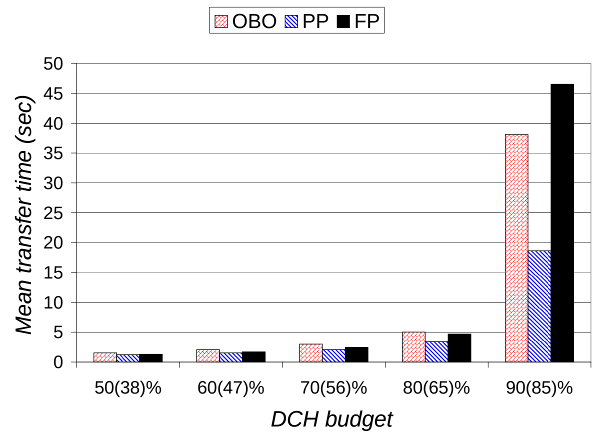

Fig. 5. Impact of the voice budget B_D, and implicitly on the avaialble EUL data budget B_{EDCH}, on mean flow transfer times.

of OBO for users at the cell edge (who cannot fill the budget on their own, and, hence, waste resources compared to PP) also has a disadvantageous effect on the throughputs obtained by the users at the centre of the cell (as the channel access is fairly shared among all users in the cell).

In the course of simulations we have also observed a particularly interesting tendency - with increasing system arrival rate (independently whether generated by DCH or EDCH users) OBO is the first scheme that will reach system instability, followed by FP and PP. This observation leads to two very important conclusions. First, since the three schedulers behave as three different system models there is not a single expression of the system load applicable to all three. Second, the relatively inefficient traffic handling in the OBO and FP schemes apparently leads to a considerable reduction of the cell capacity compared to the PP scheme.

B. Performance Impact of the Effective EDCH Load

In Figures 4 and 5 the effective EDCH load is varied in two distinct ways. In Figure 4, the aggregate EDCH flow arrival rate λ is varied directly. In Figure 5, the available capacity for EDCH transfers is varied (which effectively corresponds with an inverse variation of the EDCH load) by varying the DCH budget and load. As we will see, the key difference between these distinct approaches in varying the effective EDCH load is visible in the relative performance of the OBO and FP schedulers.

In Figure 4 the mean flow transfer time (appropriately averaged over all zones in the cell) is given as a function of λ. The other parameters are the same as in Figure 3. Observe that the performance difference between the schedulers shown by Figure 3 becomes even more pronounced when λ increases. In particular, the mean flow transfer time for the OBO (and also FP) scheme increases very rapidly when λ becomes larger than, say, 0.6 flow initiations/sec, while the system becomes saturated for λ's between 0.7 and 0.8. The growth of the mean flow transfer time under PP scheduling remains moderate.

As argued before, and illustrated by Figure 3 and Figure 4, the PP scheduling scheme performs always better than (or at least as good as) the OBO and FP schemes. It is however interesting to consider how the performance gain of PP over the OBO and FP schedulers depends on the available EDCH budget. In particular, it is expected that when the available EDCH budget is small enough to be filled up by a single user, OBO is more efficient than FP, since it yields lower intra-cell interference, higher signal-to-interference ratios and hence higher bit rates. In order to investigate this we have evaluated the scenario of Figure 3 under various DCH budgets/loads affecting the (remaining) EDCH budget available for the EDCH users. More specifically, we have varied the DCH budget between 50% and 90% of the total budget B and in each case determined the DCH arrival rate λ_D such that the DCH traffic experiences a blocking probability of 1%. Besides the available DCH budget, the horizontal axis indicates (between brackets) the (average of the) actually used budget by the DCH calls.

Figure 5 shows, for each of the schedulers, the resulting mean EDCH flow transfer time versus the DCH budget/load. Obviously, for all three schedulers, the mean EDCH flow transfer times increase when the DCH load increases, since the resources remaining for EDCH transfer decreases. For small values of the DCH load, the performance of the three scheduling schemes is quite similar, in particular for PP and FP. This is due to the fact that when the number of simultaneously ongoing flow transfers is small (typically when the overall system load is small) PP and FP (and to a lesser extent also OBO) handle them effectively in the same way. For higher

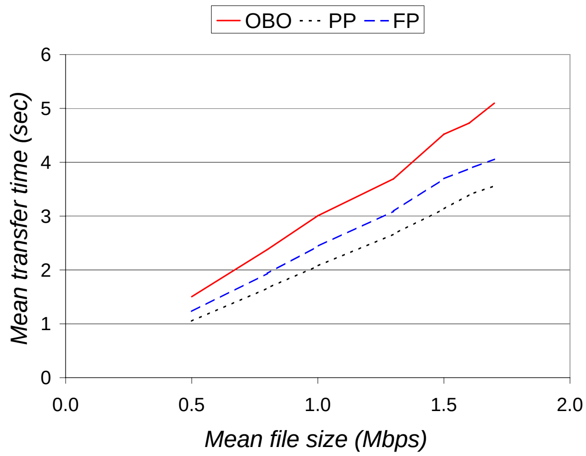

Fig. 6. Impact of EUL flow size on mean flow transfer times.

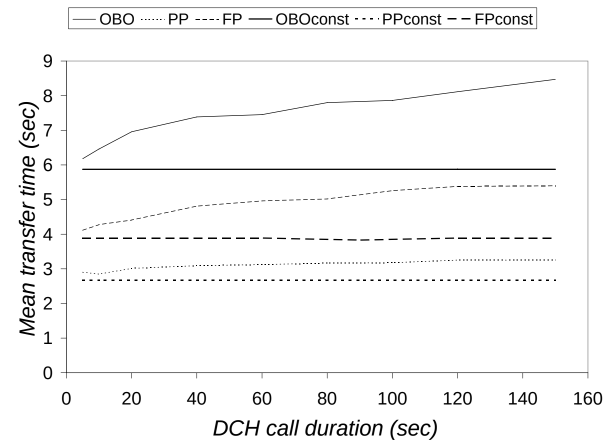

Fig. 7. Impact of voice flows durations on mean flow transfer times.

DCH budgets/loads the performance gain of PP (compared to FP and OBO) increases, while for the highest considered DCH budget/load, the OBO scheme indeed performs better than FP.

C. Performance Impact of EDCH File Size

We have observed the schedulers' behaviour for a range of mean file sizes - from 0.5 to 1.7 Mbps. As we can expect, and Figure 6 shows, increasing the file size leads to increase in the mean flow transfer time due to the bigger amount of data that has to pass through the system. OBO, as the most inefficient scheme in terms of budget utilization, shows fast degradation in the mean flow transfer time. Its curve in Figure 6 is the steepest and displays fast tendency towards infinity, which is an indication of the system approaching instability. The same process but to a lesser degree can be observed for the FP scheme. The optimal combination of transmission opportunity and achievable transmission rate for place PP again as the best performing scheme.

D. Performance Impact of DCH Flow Duration

Theory on processor sharing queuing systems shows that a constant service rate C is more beneficial for system performance than a varying service rate with mean C, e.g. [NBM99]. Furthermore, fast variations are preferable since they lead to system performance close to the optimal value realized under constant rate. Slow variations have stronger negative effect on performance. Hence, we could expect that mean flow transfer times increase when the duration of the DCH flows increases.

In order to examine this phenomenon we compared performance in terms of mean flow transfer times aggregated over the whole cell, for two scenarios. In the first scenario we set the number of DCH flows fixed (infinitely long DCH flows) such that 70% of the total budget is used by the DCH flows. In the second scenario we ran simulations with finite flow length λ_D ensuring on average 70% of the total budget is occupied. As DCH flows we took 12.2 kbit/s voice calls and set the call duration at (5, 10, 20, 40, 60, 80, 100, 120, 150) seconds. For each of these settings we ran extensive simulations of one million state changes, i.e. flow initiations or completions, of DCH flows.

Figure 7 shows the results for each of the three schedulers with the two examined scenarios. Indeed, as we expected, the graphs for constant and variable service rate lay close to each other for short DCH calls and further apart for long DCH calls. Note that in fact in the case of constant number of DCH flows, i.e. *const* graph, there is a single value but we have represented it as a line in order to ease comparison with the variable rate scenario.

The general trend in performance is the same for all three scheduling schemes but the specific impact of the DCH flow duration on each scheme is different. Recall that OBO and FP have longer mean flow transfer times than PP, therefore long periods of low service rate. Hence, long DCH flows have stronger negative influence on a OBO and FP scheme than on PP scheme.

The same observations are applicable when we repeat the experiment with an extended set of DCH applications - voice and video calls. Although each application has a specific service rate requirement, which leads to different mean flow transfer times, still within one service the mean flow transfer time increases in the flow duration.

E. Fairness Issues

For the same scenarios as consider in Figure 5, we investigate in some more detail the fairness of the three schedulers with respect to their performance as observed by users at

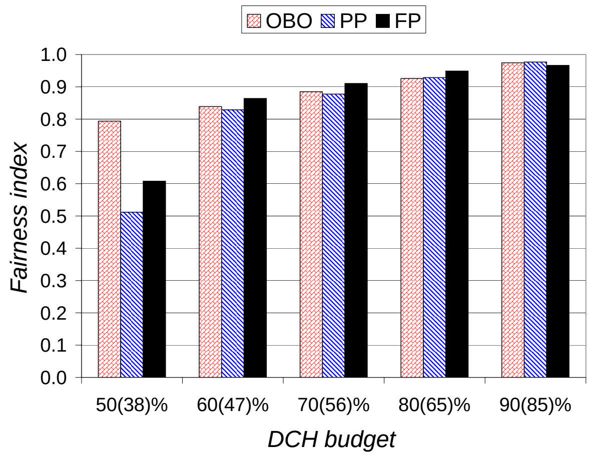

Fig. 8. Fairness index

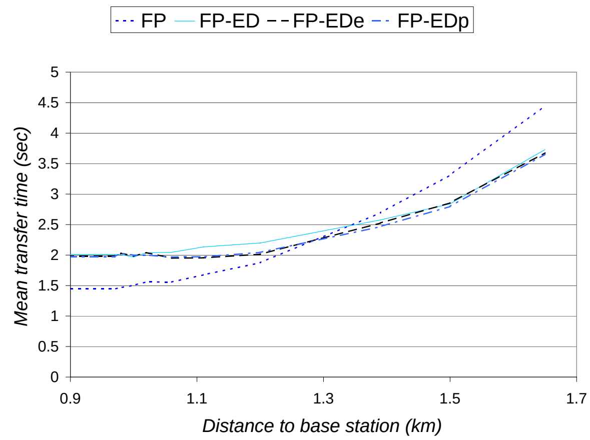

Fig. 9. Performance of implementations of FP scheme

different locations in the cell, cf. Figure 3. The fairness can be defined in different ways. We have used the fairness index applied by e.g. Jain [Jai91], which, in the present context, is defined in Equation (11). The maximum value of the fairness index equals 1, which refers to a perfectly fair scenario in which the mean flow transfer times are the same for all zones. The smaller the fairness index the larger the (relative) differences among the mean flow transfer times in the different zones.

Figure 8 shows the fairness results for the three schedulers. The general impression is that the fairness performance is more or less the same for the three schemes. However, for the case that the DCH budget/load is small (i.e. the available EDCH budget is relatively large) the OBO scheme appears to be significantly more fair than the two other schemes, in particular when compared to the PP scheme. This can be explained as follows. Under PP scheduling, users near the base station (with a high maximum received power) are more likely to be served alone compared to users at the cell edge, which are mostly served in parallel with others (because they are unable to utilise the available EDCH budget on their own). Consequently, remote users experience lower signal-to-interference ratios and hence lower bit rates. This will lead to relatively large differences between the throughputs observed by users close to the base station and users at the cell edge. Under OBO scheduling, all users are scheduled in a one by one fashion avoiding intra-cell interference among data flows. In a FP scheme however intra-cell interference occurs and differs per user, i.e. close by users are affected by remote users and vise versa. Despite the proportional power decrease, which soothes the effect, still remote users are in the more disadvantageous position the lower fairness index for the FP scheme. Observe that the fairness of the schedulers improves when the DCH budget/load increases (i.e. available EDCH budget decreases). This is due to the fact that when the available EDCH budget becomes smaller, the maximum (received) power that can be achieved by the users (i.e. their mobile equipment) at different locations is less and less a limiting factor for remote users, and hence the disadvantageous effect that remote users suffer from added intra-cell interference vanishes.

F. Performance Impact of FP Implementation

In order to evaluate the importance of implementation details on performance we compare the mean flow transfer times for the four implementations proposed in Section V-C, namely full parallel with proportional division (FP), full parallel with equal division (FP-ED), full parallel with equal division and priority (FP-EDp) and full prallel with equal division and equality (FP-EDe). Figure 9 shows that there is negligible difference between FP-ED, FP-EDp and FP-EDe. Recall that all three schemes initially assign the same budget portion to all active user. However, the inequality between assigned portion and achievable received power can result in effectively unused budget, which each scheme manages differently. A closer look of the numerical results (TTI based evaluation) showed that the effective unused EDCH budget is in fact negligibly small, which explains why the schemes exhibit similar behaviour.

Furthermore, from the steepness of the graphs in Figure 9 we can implicitly evaluate fairness. It appears that FP with proportional division delivers the least fairness, i.e. steeper graph, which is explained by the fact that FP favours users located closer to the base station in order to maximise data rates. The schemes with equal division however try to serve all users equally, i.e. they are more fair. Therefore far away users in the equal division schemes improve in performance but at the cost of close by users the result of which is a less steep graph. The choice of implementation should be based on the desired goal by the operator - providing the best possible service or keeping fairness among the MSs. It is still worth noting that, although there are difference in performance between all full parallel schemes, these are not radical.

VIII. Conclusions

We have discussed three groups of uplink scheduling schemes for UMTS EUL termed One By One, Partial Parallel and Full Parallel. The schemes differ in the number of users served in parallel in one TTI; OBO serves only one user, PP several and FP all users. A single cell scenario is considered with a broad range of system and traffic parameters, i.e. proportion of EUL data taffic and 'plain' UMTS DCH (voice) traffic. The performance of the schemes is evaluated by a three-step modelling and analysis approach. In the first two steps of our approach the system behaviour at packet level is captured; next, in the third step, based on the packet level behaviour, a Markov chain is created which describes the system behaviour at flow level. From the steady state distribution of the Markov chain we determine flow level performance measures. The main performance measures in our study are the mean flow transfer times and fairness offered to users from different locations in the cell.

Our results lead to several major conclusions. Firstly, the results show that the PP strategy has the lowest mean file transfer time. This can be explained by the fact that PP has higher transmission power than FP and exploits the available radio resources more efficiently than OBO. Secondly, we examined the coexistence of UMTS DCH uplink users and EUL users. On the one hand we show that keeping a small resource reservation for EUL users can significantly improve their mean file transfer times without seriously degrading the service of UMTS DCH uplink users. On the other hand we observed that the service offered to EUL users degrades in the duration of the UMTS DCH users. Furthermore, the three schedulers do not differ much in fairness although the FP scheme seems to slightly outperform the other two schemes. Finally, we showed that the particular implementation of a PP or FP scheme does not affect significantly the performance and can be therefore considered irrelevant.

A major advantage of the analysis methodology proposed in this paper is its technology independent character. Technological specifics are captured by relatively simple calculations on packet level, calculations which can be easily modified according to the considered technology. Hence, it becomes attractive to apply the same methodology to 4G LTE (Long Term Evolution) networks.

IX. Acknowledgements

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References

[25.a] 3GPP TS 25.308. High Speed Downlink Packet Access (HSDPA); Overall Description.

[25.b] 3GPP TS 25.309. FDD Enhanced Uplink; Overall Description.

[AvM05] B. Abendroth, J.L. van den Berg, and M. Mandjes. A multiple time-scale model for TCP bandwidth sharing under user heterogeneity. NETWORKING 2005, Ontario, Canada, 2005.

[Coh79] J.W. Cohen. The multiple phase service network with generalized processor sharing. In *Acta Informatica*, volume 12, pages 254–284, 1979.

[DvdBH09] D. C. Dimitrova, H. van den Berg, and G. Heijenk. Scheduler dependent modeling of inter-cell interference in UMTS EUL. NGMAST '09, Cardiff, Wales, UK, 2009.

[DvdBHL08a] D. Dimitrova, H. van den Berg, G. Heijenk, and R. Litjens. Flow-level performance comparison of packet scheduling schemes for umts eul. Springer, 2008.

[DvdBHL08b] D. Dimitrova, H. van den Berg, G. Heijenk, and R. Litjens. Impact of inter-cell interference on flow level performance of scheduling schemes for the UMTS EUL. In *WiMob '08*, Avignon, France, 2008.

[FT05] G. Fodor and M. Telek. Performance analysis of the uplink of a CDMA cell supporting elastic services. Networking 2005, Waterloo, Canada, 2005.

[HEE+05] K.W. Helmersson, E. Englund, M. Edvardsson, C. Edholm, S. Parkvall, M. Samuelsson, Y-P.E. Wang, and J-F. Cheng. System performance of WCDMA enhanced uplink. IEEE VTC '05 (Spring), Stockholm, Sweden, 2005.

[HT01] H. Holma and A. Toskala. *WCDMA for UMTS*. John Wiley & Sons Ltd, 2001.

[HT06] H. Holma and A. Toskala. *HSDPA/HSUPA for UMTS*. John Wiley & Sons Ltd, 2006.

[Jai91] R. Jain. *The Art of Computer Systems Performance Analysis: techniques for experimental design, measurement, simulation, and modeling*. John Wiley & Sons Ltd, 1991.

[KQ06] K. Kumaran and L. Qian. Uplink scheduling in CDMA packet-data systems. In *Wireless Networks*, volume 12, pages 33–43, 2006.

[LP05] C. Li and S. Papavassilious. On the fairness and throughput trade-off of multi-user uplink scheduling in WCDMA systems. IEEE VTC '05 (Fall), Dallas, USA, 2005.

[MS06] A. Mäder and D. Staehle. An analytical model for best-effort traffic over the UMTS enhanced uplink. IEEE VTC '06 (Fall), Montreal, Canada, 2006.

[MSLB07] Andreas Mäder, Dirk Staehle, Tuo Liu, and Hans Barth. Feasible load regions for different RRM strategies for the enhanced uplink in UMTS networks. In *LNCS Volume 4369, Wireless Systems and Mobility in Next Generation Internet*, jan 2007.

[NBM99] Rudesindo N´u nez Queija, J. L. Berg, and Michel R.H. Mandjes. Performance evaluation of strategies for integration of elastic and stream traffic. Technical report, Amsterdam, The Netherlands, The Netherlands, 1999.

[RH97] S. Ramakrishna and J. M. Holtzman. A scheme for throughput maximization in a dual-class CDMA system. ICUPC '97, San Diego, USA, 1997.

[ROS+04] C. Rosa, J. Outes, T.B. Sorensen, J. Wigard, and P.E. Mogensen. Combined time and code division scheduling for enhanced uplink packet access in WCDMA. IEEE VTC '04 (Fall), Los Angeles, USA, 2004.

[VP07] J. Voigt and K. Pannhorst. Optimizations on scheduling strategies for enhanced uplink on wcdma. In *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pages 1172–1176, April 2007.