Fair Channel-Dependent Scheduling in CDMA Systems

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ABSTRACT

In this study a scheduling algorithm for CDMA systems is presented which is a trade-off between two extreme ways of scheduling: C/I based and Round-Robin scheduling. The simulation results indeed display that the advantages of both these extremes have been combined in the new algorithm: a good fairness, comparable to that of the Round-Robin scheduling, together with almost the same power gain as reached in the C/I based scheduling.

I. INTRODUCTION

At present, we are beginning to experience the transition from second to third generation of mobile systems. UMTS and other third generation cellular systems will provide global access to voice and data services. One of the most important features which distinguishes UMTS from many previous generation cellular network technologies is the underlying CDMA principle that is being used. The same frequency resources are shared by many users at the same time. As a result, ongoing connections cause interference to each other which affects the capacity of the corresponding cell.

In this study we focus on a high-speed extension of UMTS that allows for higher data rates: High-Speed Downlink Shared Channel (HS-DSCH, also referred to as High-Speed Downlink Packet Access, HSDPA, [1, 2]). Its transmission time interval is smaller than that of the regular UMTS and the scheduling functionality no longer is in the RNC (Radio Network Controller) but in the Node B (Base Station) instead. As a result, the fluctuations in the fading characteristics can be tracked better. Different control mechanisms have been specified to enable Quality of Service (QoS) requirements. Among these, scheduling of data flows is a key mechanism to provide QoS on one hand, and to optimise resource efficiency on the other hand. Whereas the former objective is clearly most important to the user, the latter is essential for the operator.

In CDMA, the basic idea of power control is to guarantee equal power at the receiver, for all users. This prescribes that the transmit power is adapted such that the power signal received at the mobile units is approximately constant in time. In HS-DSCH the transmission power is no longer adapted by means of fast power control, but instead a fast link adaptation is applied. This involves a selection of the modulation and coding scheme. So, a bad channel condition does not result in a higher transmit power, but instead prescribes another coding and modulation scheme. Both measures have the same effect however: both give an indication of the current channel condition and can therefore be used for the scheduling process. The focus in HS-DSCH is best effort traffic. So, mainly the users in favourable channel conditions can benefit from the higher data rate of HS-DSCH. Related work involves other scheduling mechanisms described in [3, 4]. In the rest of this paper, Chapter II is used to describe the scheduling method studied in this work. In Chapter III the model for the propagation loss is given. Results are presented in Chapter IV and finally the conclusions are given in Chapter V.

II. SCHEDULING ALGORITHM

In this chapter we discuss some methods that can be used to schedule the traffic over shared resources. Because of the expected asymmetry in the traffic, we focus on the data transfer in the downlink, *i.e.*, from the base station (Node B) to the (mobile) user equipment (UE). Usually, the scheduling is based on either the current channel conditions (C/I based scheduling) or on simple Round-Robin mechanisms. While the latter is based on the principle of fair-share, channel-dependent scheduling mechanisms tend to be unfair because receiving nodes which are close to the sending node are served more often than others. This implies that those users that need least power, or that can send at the highest data rate, are scheduled for transmission. Sending at low power reduces interference and as a result increases system capacity. So does sending at higher data rate. So, users far away will hardly be served by the Node B. In Table 1 we summarize the scheduling methods studied in this paper and define the corresponding acronyms. The Fair Channel-Dependent Scheduling (FCDS) technique introduced in this paper forms a trade-off between the two other extremes in the

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* This work has been performed while the first two authors were working for Ericsson Eurolab Netherlands. Meanwhile both have changed employer and are now working for respectively the Twente Institute of Wireless Mobile Communications, and the University of Twente.

table as illustrated in Figure 1: low power use (system capacity) and fairness.

Table 1. Scheduling methods used in this paper.

Acronym	Optimization	Corresponding technique
MP	Minimum power	C/I based scheduling
FCDS	Relative power	FCDS scheduling
RR	Round Robin	Fair scheduling

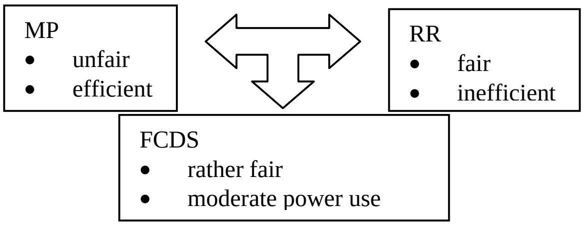

Figure 1. The FCDS scheduling is a trade-off between MP and RR scheduling.

In practise, the signal is fluctuating around a mean value that displays slow trends as well. This underlying slow fluctuation accounts for the distance from the base station. The time scale of so-called fading variations in the signal itself, due to multi-path reception and/or shadow fading, is much smaller than that of the variations of this so-called *local mean*. The scheduling is done based on the relative power, *i.e.* the instantaneous power relative to its own recent history. So, the transmission level of all mobile terminals is first translated with respect to their local means, and subsequently normalised with their local standard deviations. A transmission is scheduled to the UE that has the lowest value for this so-called relative power.

The idea of a relative power introduced above, needs the definition of a local mean, with *local* referring to the recent time history. Exponential smoothing weights past observations with exponentially decreasing weights in order to update the value for the local mean. It takes the local mean of the previous period and adjusts it up or down based on what actually occurred in that period. By the choice of a weighting factor, this procedure can be made sensitive to a small or gradual drift in the process. This method is simple and therefore has low data storage requirements and data processing since only the actual (instantaneous) value and the old local mean value are needed to update the new local mean value. Comparing with for example moving averaging, the low storage and higher weights on more recent samples are two properties in favour of the FCDS method. Before the algorithm is introduced, the variables used in this study are given in Table 2. Note that *t* either refers to the physical time unit or the corresponding integer index.

Table 2. Variables used in this study.

P_t	(instantaneous) transmission power at time t
μ_t	local mean of P_t based on the time interval $[t_0,t]$
v_t	local variance of P_t based on the time interval $[t_0,t]$
σ_t	local standard deviation, defined by $\sigma_t^2=v_t$
α_1	smoothing coefficient w.r.t. the local mean
α_2	smoothing coefficient w.r.t. the local variance

The local mean, introduced above, as well as the variance are updated each time unit according to the following algorithm [5]:

$$\mu_t = \alpha_1 \cdot P_t + (1-\alpha_1) \cdot \mu_{t-1},$$

$$v_t = \alpha_2 \cdot (P_t - \mu_t)^2 + (1-\alpha_2) \cdot v_{t-1}.$$

In other words: the new local mean (or variance) is a weighted average of the instantaneous contribution and the old mean (or variance). In the rest of this study, the parameter α refers to both α_1 and α_2 when not specified any further. As we will see later, extreme values of α (0 respectively 1) lead to the extreme variants in scheduling: C/I based scheduling respectively Round Robin scheduling (see Table 1).

The criterium that determines the optimal mobile node for the next downlink transmission at time *t*, is formulated as follows, where the superscript *i* is used to denote the situation at node *i*:

$$\min_i \left\{ \left(P_t^i - \mu_t^i\right) \Big/ \sqrt{v_t^i} \right\}.$$

Here, the data point, P_t, is translated with respect to the local mean, μ_t, and next normalised with the corresponding local standard deviation, σ_t. This subsequently translated and normalized transmission power is referred to as the scaled power, Ps. At each time *t*, the value for Ps is compared for all nodes *i* and the most optimal node is selected for the downlink transmission.

In the rest of this chapter, we give some definitions and related issues that are needed further on in this paper. The relative throughput vector is defined by the number of transmission moments allocated to each user, *alloc*, divided by the total number of time samples of the simulation. The resulting scalar fairness is defined as:

$$f = \left(\sum_i \frac{alloc_i}{fs_i} \right)^2 \Big/ Nu \cdot \sum_i \left(\frac{alloc_i}{fs_i} \right)^2$$

where fs_i denotes the fair-share value which is taken equal to the ratio of the total number of time samples in the simulation divided by the number of mobile terminals, *Nt/Nu*. Maximal fairness results in a *f* value of one, while minimal fairness results in a value of zero. Another interpretation of *f* is that it equals the ratio of b_1^2/b_2 with b_i the *i*-th moment of $alloc_i/fs_i$. Furthermore it should be stressed that the intuitive notion of fairness is strongly related to the time length to which respect it is considered. We come back to this issue when discussing the results.

III. PROPAGATION LOSS MODEL

Fading in mobile communication systems may be divided into two different types, fast and slow fading. In this chapter we give the formulas used to compute the transmit power at the Node B. The loss is defined as follows: $L = A + S + R$ with *A* the attenuation (path loss), *S* the long-term fading and *R* the short-term fading.

The attenuation is described by the Okamura-Hata propagation reference model for suburban areas:

$$A(x) = 129.4 + 10 \cdot \beta \cdot \log10(x),$$

with a path loss exponent of β=3.52 and x the distance to the Node B in kilometers. Here we assumed a base station antenna height of 30 m, a UE antenna height of 1.5 m and a carrier frequency of 1950 MHz [6]. Presumably, the influence of the attenuation on the fairness of the FCDS scheduling scheme is small because the signal is considered with respect to its local average.

Next, we have the shadow (slow) fading, denoted by *S*. This type of fading is caused by obstacles in the propagation path between the UE and the Node B. In wireless channel modeling, a common assumption is that shadowing is independent from one location to another. Unfortunately, this assumption is not valid in a dynamic model with mobile users, where location dependent correlation must be accounted for in order to provide continuity. In this study, we include the correlation model for shadow fading developed in [7]. The correlated slow fading contribution to the total loss is constructed from the following algorithm:

$$S(x+\Delta x) = a \cdot S(x) + b \cdot \tilde{\sigma} \cdot N$$

with Δx the distance between two subsequent time samples and N a random variable that satisfies the standard normal distribution. The parameter b is usually taken such that the standard deviation of the vector containing all realisations equals $\tilde{\sigma}$. This prescribes that $b^2 = 1 - a^2$. The remaining parameter, a, is determined by the following demand which concerns the auto-correlation function of S:

$$E[S(x) \cdot S(x+\Delta x)] = E[a \cdot (S(x))^2 + b \cdot \tilde{\sigma} \cdot N] = a \cdot \tilde{\sigma}^2 .$$

This expression should be equal to $\exp(-\Delta x / D) \cdot \tilde{\sigma}^2$ and results in the demand that $a=\exp(-\Delta x/D)$ with D the correlation distance which is taken equal to 40 m in the current study, in between the values coming from references [8] and [9]. For a pedestrian (3 km/h), the correlation distance taken here corresponds to a correlation time of fifty seconds, while it is only one second for a car (120 km/h). A typical value for the standard deviation in suburban areas is $\tilde{\sigma} = 8\,\mathrm{dB}$ [10, 11].

For the fast fading contribution, denoted by *R*, the Rician distribution is assumed. Fast fading is caused by multipath propagation. The statistical properties of multipath fading have been studied extensively in literature [10]. Now that all three contributions to the propagation loss have been introduced, we come to the way this prescribes the transmission power at the Node B. For the downlink, the wideband carrier to interference ratio, *C/I*, is expressed in terms of the influences of the whole system, taking into account influences from other channels, users and cells. This results in the following expression for the transmit power from Node B j to UE i:

$$P_{i,j} = \left(\frac{C}{I}\right)_{i,j} \cdot \left(\left(N_{th} + \sum_{k \neq j} g_{i,k} \cdot P_k \right) \cdot l_{i,j} \right).$$

In the rest of this study, we take the following values for the remaining constants: $(C/I)_{i,j}$ = -4 dB (the typical value of 6 dB often mentioned in literature [6] in combination with an antenna gain of 10 dB), thermal noise $N_{th} = -108\,\mathrm{dBm}$, an influence from other Node B's of -100 dBm based on an attenuation loss of 140 dB (attenuation formula, using a distance of 2 km). As a result, $P_{i,j}$ only has a linear dependence on the downlink total loss, $l_{i,j}$.

IV. SIMULATION RESULTS

A. Reference case

We start this section with a description of the reference setting that will be used throughout the rest of this study. In Table 3 several parameters are specified. First of all, the parameters used for the attenuation and shadow fading are recalled in this table. The number of active users is denoted by *Nu* and equals eight. In most studies on HS-DSCH, the user scenario of pedestrians is assumed, which corresponds to a mobile speed of 3 km/h. At this relatively low speed, fluctuations in the transmission power can still be tracked and next used as input information to the scheduling mechanism. The values of both α's are chosen based on the transmission time interval (TTI) of 2 ms used in HS-DSCH, corresponding to the 500 Hz frequency.

Table 3. Parameters used in the reference case.

Parameter / symbol	Value
Path loss exponent, β	3.52
Distance from Node B	200-475 m
Correlation in shadow fading	40 m
Standard deviation in shadow fading	8 dB
Number of active users, *Nu*	8
Mobile speed	3 km/h
Exponential smoothing, α_1, α_2	0.001
Exponential smoothing frequency	500 Hz
Number of time samples, Nt	100,000
Total simulation time	200 s
Total simulation distance	167 m
Time delay in scheduling	15 ms

The number of time samples in the simulation is *Nt*=100,000 and corresponds to a time interval of 200 seconds, or 167 meter. With the correlation length of 40 m, only about four shadow fading correlation lengths are simulated. As a result, the shadow fading part of a specific UE may for example reduce the total loss that one would expect for that UE based on the path loss, since the shadow fading part on average adds gain to the system. Finally a small time delay which accounts for the fact that the actual transmission is based on measurements and input which have been done a while ago is taken into account as well. As a result, the final evaluation of the scheduling algorithm is done by incorporating a time shift. Of course this only influences the average transmission power and not the scores in throughput.

The distance between the mobile users and the base station, that determines the attenuation *A*, is further explored in Table 4. As is clear from the table, the users 1, 2, 5 and 6 are modeled as moving in concentric circles, but this could be interpreted as well as users standing still since it is only the distance to the base station which counts for the attenuation contribution to the propagation loss. On average, UE's 1 and 3 are relatively close to the base station while UE's 6 and 8 are far away from it. In the rest of this section we first present and discuss some results of the reference simulation specified above. Based on that, it is determined which parameters should be changed in the sensitivity analysis that follows in the next section.

Table 4. Way of movement for all 8 UE's with respect to the base station.

UE	Way of movement with respect to the Node B
1, 2	Circles of radius 200 m, respectively 350 m
3	Along the radius, between 225 and 308 m
4	Along the tangential of the 308 m radius circle
5, 6	Circles of radius 400 m, respectively 475 m
7	Along the radius, between 325 and 408 m
8	Along the tangential of the 400 m radius circle

Next, the impact of the FCDS scheduling is considered. In Figure 2 we have included results of both the MP and the FCDS scheduling. It is clear that in the left plot at each time the most favourable transmission signal is chosen. It displays a preference for UE 1. The right plot is the result for the FCDS case. A UE is chosen when its transmission level is low compared to its own recent history. All UE's are chosen frequently. This distribution of the available resources is much closer to general fairness than the MP alternative. The value of f (see Chapter II) is 0.27 for the MP case whereas it is 0.998 for the FCDS alternative which thereby is almost equal to the perfect fairness of 1 as in the RR case. The mean of the transmission power Pt is respectively 2.7, 11.8 and 28.7 dBm for the MP, FCDS and RR scheduling alternatives. The idea to minimise the transmission to users in unfavourable propagation conditions but at the same time to transmit when the circumstances are not too bad does apply to this scheduling technique.

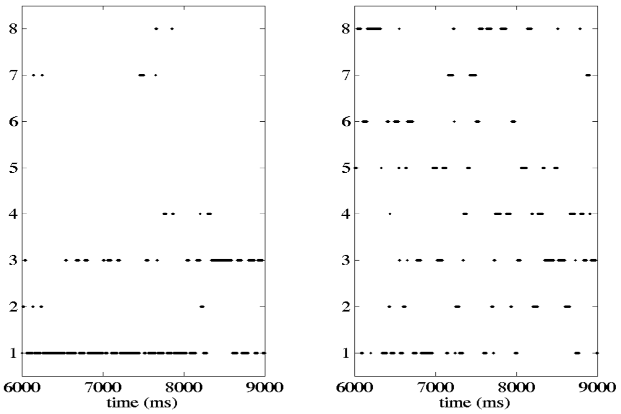

Figure 2. Comparison of the MP (left) and FCDS (right) scheduling technique. The plots display the scores by means of a symbol at the corresponding user index each time it is chosen.

We next define the outage probability as a measure for the waiting time to the next sending moment. It is computed in the following way:

$$Pout_{X,i} = \frac{1}{Nt} \cdot \sum_{t=1}^{Nt} P(t)$$

with $P(t)$=0 if the i-th UE is *not* scheduled in the time interval [t, $t+X$] and $P(t)$=1 otherwise. It is a measure for the average gap length in the information stream, prescribing a certain buffer size at the receiving mobile terminal. It is intuitively clear that the outage probability with respect to longer time intervals is getting smaller. In the relative power case, given a certain time interval [t, $t+X$], all users have the same outage probability. This supports the goal of developing a scheduling algorithm that only takes advantage of favourable propagation conditions in a local sense, thereby conserving the fairness of Round Robin scheduling. In the MP case, a clear difference exists between the outage probability of the users separately. Being in favourable transmission conditions, UE 1 displays the lowest outage probability. More findings are included in the sensitivity study presented below.

B. Sensitivity study

In this section, relevant parameters are systematically varied in order to infer the (in)sensitivity of the reference case described in the previous section. To start with, we consider the impact of taking more time samples: Nt is increased from 100,000 to 1,000,000. For each UE, the throughput of the FCDS becomes closer to the perfect fairness value of $1/Nu$. The FCDS mean transmit power changes from 11.8 to 11.7 dBm. For comparison purposes we also mention the Round Robin value for this property: 28.7 dBm for the small value of Nt and 28.9 dBm for the large one. These numbers are very close to each other, just like both equivalent values for the FCDS case. Also the outage probability is only slightly changed when the number of samples is increased.

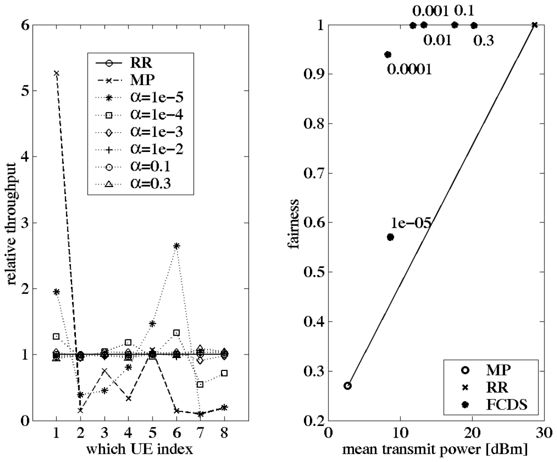

Figure 3. Relative throughput for several values of the smoothing parameter α as a function of the user index (left). Also the extreme values for the MP and RR scheduling mechanisms are included. Fairness and mean transmit power for several values of the smoothing parameter α (right).

The next part in this sensitivity study involves the dependence on the parameter used in the exponential smoothing, α. In Figure 3 (left) the results for several values of α (here, still $\alpha_1=\alpha_2=\alpha$) are collected. Except for some values of the α=1e-5 results, where the initial effects have a relatively strong impact on the local mean and thus on the scheduling algorithm as well, the FCDS results are already very close to the RR level corresponding to perfect fairness. The right figure is included to display the impact of the smoothing parameter on the resulting scalar value of the fairness. It is clear from here as well that the fairness in the FCDS case is close to that of RR for most values of α.

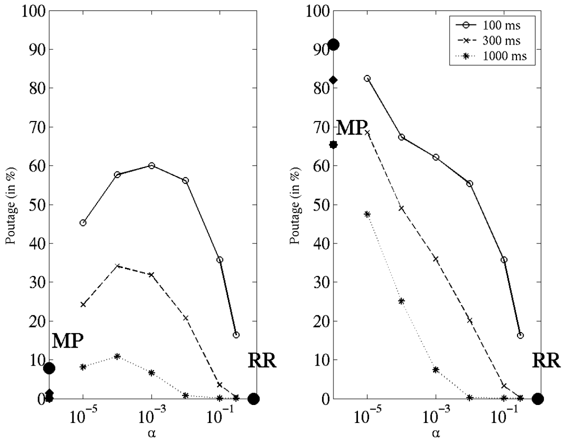

Figure 4. Outage probability for UE's 1 (left) and 2 (right) with respect to three time intervals (100, 300 and 1000 ms) as a function of the smoothing parameter α. Also the extreme values for the MP and RR scheduling mechanisms are included (separate symbols).

Next the influence of the smoothing parameter α with respect to a quantity that measures the instantaneous behaviour of the scheduling algorithm is considered. In Figure 4 we have collected the outage probability defined in Section IV.A. Its behaviour as a function of α is very much depending on which UE is considered. Since UE 1 most of the time has favourable transmission conditions, the MP values of $Pout_{X,1}$ are small. The results at extreme values of α also are relatively small. For UE 2, we note that the right hand side of the plot is close to that of UE 1, which supports the idea of a high level of fairness. The left side of Figure 4 is different however because of the fact that UE 2 has not too favourable transmission conditions.

Finally it turned out that the second step in the exponential smoothing, the normalisation of the local mean, is not important. Taking a ten times higher or lower smoothing parameter α_2 as well as the omission of this step does hardly affect the results.

V. CONCLUSIONS

In this study we have extensively evaluated the FCDS scheduling algorithm. It was introduced as a trade-off between the two extreme ways of scheduling: C/I based and Round-Robin scheduling. Based on the simulation results, we can indeed conclude that the advantages of both these extremes have been combined in the new algorithm: a good fairness, comparable to that of the Round-Robin scheduling, together with almost the same power gain as reached in the C/I based scheduling. The latter result of course is important because it determines the interference caused to other simultaneous transmissions. Also the sensitivity-study performed in this paper displayed that in particular the FCDS scheduling algorithm results are not very sensitive to the reference setting, implying that the conclusions are valid for all kind of related settings.

Throughout this study we have been focusing and the results are evaluated in the HS-DSCH context. Although it is a first analysis of FCDS scheduling, the results are promising enough to continue this study. In future research we will incorporate the interaction with higher-layer protocols such as radio link protocols and TCP (transmission control protocol).

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