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Rosa, Claudio; Outes Carnero, José; Sørensen, Troels Bundgaard; Wigard, Jeroen; Mogensen, Preben Elgaard

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Combined Time and Code Division Scheduling for Enhanced Uplink Packet Access in WCDMA

Claudio Rosa [1], José Outes [1], Troels B. Sørensen [1], Jeroen Wigard [2], Preben E. Mogensen [1,2]

[1] Department of Communication Technology, Aalborg University, Denmark
[2] Nokia Networks, Aalborg R&D, Denmark

E-mail: `cr@kom.aau.dk`

Abstract— **This paper contains an evaluation of three different time and code division schedulers for data transmission on enhanced dedicated channel (E-DCH) in WCDMA uplink. Time scheduling on E-DCH is possible thanks to fast Node B scheduling operation on a Transmission Time Interval (TTI) basis. Time scheduling allows for allocating users for transmission with instantaneously high data rates, and possibly when they experience favourable channel conditions. The system capacity can therefore be increased, also because interference generated to other cells is reduced. We apply a combined time and code division scheduling strategy in three different cases: a "blind fair throughput" scheduler (BFT), a "maximise transmit power efficiency" scheduler (MTPE) and a "channel-state aware fair throughput" scheduler (CSAFT). The two latter schedulers utilise an appositely defined Uplink Channel Quality Indicator (UCQI) to exploit channel-state information in the packet scheduling procedure. While the MTPE scheduler maximises cell throughput at the cost of a low degree of fairness between users, the CSAFT algorithm is shown to offer an appealing trade-off between users' fairness and throughput maximisation. Under a specific outage constraint for the packet call throughput, the capacity gain of the CSAFT scheduler over a Node B code division scheduler is 17% and 30% for Vehicular A and Pedestrian A channel profile at 3 km/h, respectively. The estimated capacity increase compared to a reference RNC-based scheduler is estimated between 50% and 80%, also depending on the propagation scenario.**

I. INTRODUCTION

Enhanced performance of uplink transmission on dedicated channel (DCH) is currently a work item in 3GPP [1]. One of the candidate approaches for enhanced (E-) DCH is fast Node B scheduling for Non-Real Time (NRT) radio bearers. Moving the packet scheduler functionality from the Radio Network Controller (RNC) to the Node B has already shown some potential benefits [2] [3]. In this paper, we consider the possibility to perform fast Node B scheduling operation on a TTI basis so that users can be time-scheduled for data transmission on E-DCH. Time scheduling readily allows performing allocation of radio resources based on channel-state information. One of the first papers to address the issue of channel-dependent scheduling in wireless networks is [4].

Data scheduling in wireless networks is a widely studied topic due to the expected growth of high-speed wireless data services in third generation systems. Because of the asymmetry of traffic in the uplink and downlink of 3G systems, most of the previous research has focused on the downlink [6] [7]. However, an increase in uplink traffic is also expected due to the growth of services like ftp, image/data upload, interactive games with rapid response patterns, etc., which require high data rates on the uplink. These considerations have resulted in some research on the subject of uplink scheduling [9] [10] [11] [12]. Although formulated in different ways, the general goal presented in these papers is to define an optimum (or sub-optimum) power and rate allocation scheme that maximises throughput with respect to some fairness constraints. The main focus is on the scheduling gain achievable when a combined TDMA and CDMA approach is used, compared to a pure CDMA solution. However, the impact of time scheduling on the time variability of both uplink load and other-to-own cell interference has not been considered, as well as the interaction between time scheduling and fast power control operation. The main objective of the work presented in this paper is to assess the performance improvement of time and code division scheduling by also taking into consideration these issues. In particular, we present an evaluation of three different scheduling algorithms that perform time and code division scheduling for packet data traffic on E-DCH in WCDMA uplink. All three proposed allocation strategies improve radio resource utilisation by scheduling users based on their buffer state, and two of them furthermore take advantage of channel-state information.

The paper is organised as follows: First, in Section II the three proposed scheduling algorithms are described in detail. Section III presents the main simulation assumptions. The performance of the proposed scheduling policies is then assessed in Section IV. In addition, a discussion on the increased system complexity when introducing time scheduling in the uplink of real systems is presented in Section V. Finally, the concluding remarks are given in Section VI.

II. SCHEDULING ALGORITHMS

Besides some complexity issues that will be detailed in Section V, time scheduling presents some inherent advantages and disadvantages compared to a pure CDMA approach. First of all, with time scheduling very high data rates are momentarily allocated to data users; this has the potential for both improving round trip time performance over the air interface [1] and increasing system capacity. In fact, since each

scheduled user contributes more to the total received uplink power at the Node B, for a fixed noise rise (NR) value the same user will experience less interference from other users in the own cell. Moreover, time scheduling based on near instantaneous buffer state information can improve radio resource utilization, thus increasing cell throughput performance. Finally, as previously introduced, time scheduling allows users to be scheduled for transmission when they experience favourable channel conditions, thus minimising the interference generated to other cells. The main disadvantage is that the allocation of high data rates coupled with time scheduling is likely to introduce fast variability in other-cell interference, and consequently in the generated uplink load. This is expected to deteriorate the performance of the link adaptation mechanism based on fast power control and more importantly, to increase the required power headroom that the packet scheduler (PS) needs in order to meet specified NR outage criteria.

In the following, the three time and code division scheduling algorithms are described. A scheduler is defined 'fair resource' if in average it allocates the same amount of resources to all active users. In the uplink of WCDMA systems the resource to be shared is the total received wideband power at the Node B. A fair resource scheduler therefore allocates the same amount of received power to different users; since fast power control is assumed, that means the users are granted the same average throughput performance. The terms 'fair resource' and 'fair throughput' can in this case be used interchangeably.

A. Blind Fair Throughput (BFT)

Users in the scheduler queue are time scheduled for transmission on E-DCH in a round-robin fashion. This scheduling policy is based solely on User Equipment (UE) buffer state information (empty/non-empty). The scheduler is 'blind' because it does not take into account channel-state information, 'fair throughput' because it provides the users with the same channel access probability.

B. Maximise Transmit Power Efficiency (MTPE)

This scheduling strategy allocates uplink resources to those users that are estimated to experience the most favourable channel conditions with the scope to minimise the interference generated to neighbouring cells. This type of scheduler does not consider fairness issues and for this reason can be considered the uplink counterpart of the HSDPA maximum C/I scheduler [8]. In order to perform channel-dependent scheduling of radio resources, we introduce the *Uplink Channel Quality Indicator* (*UCQI*). The *UCQI* for user k at time instant n is defined as:

$$UCQI_k[n] = \frac{R_k[n]}{TxPw_k[n]} \cdot \frac{E_b/N_0^k[n]}{\rho_k} . \qquad (1)$$

In (1), $TxPw_k[n]$, $R_k[n]$ and $E_b/N_0^k[n]$ are the transmission power, the transmission rate and the received E_b/N_0 of user k at time instant n, respectively, while ρ_k is the target E_b/N_0 for user k. The quality measure defined in (1) can be interpreted as the

achievable transmission rate per transmission power unit (Watt) of user k at time instant n. The users in the scheduling queue are scheduled for transmission in descending order of the *UCQI* parameter. I.e., the MTPE algorithm first schedules those UEs that can support a given transmission rate with minimum power consumption. For the proposed study, we make the assumption that the Node B has exact knowledge of the UE transmission power at each WCDMA time slot. For the derivation of the instantaneous value of the received E_b/N_0, the PS can make use of signal-to-noise plus interference (SINR) estimations already available at the Node B to perform fast power control. Finally, $R_k[n]$ is known from the Transport Format Combination Indicator (TFCI) field transmitted by each UE on the dedicated physical control channel (DPCCH) [5].

C. Channel-State Aware Fair Throughput (CSAFT)

This scheduler is designed to offer a trade-off between user fairness and maximisation of cell throughput. Together with the instantaneous achievable transmission rate per transmission power unit ($UCQI_k[n]$), the Node B keeps track of the average value of $UCQI_k$ over a specified time period. The Node B then computes the *Relative UCQI* (*RUCQI*) as the ratio of the instantaneous *UCQI* to the average *UCQI*:

$$RUCQI_k[n] = \frac{UCQI_k[n]}{\langle UCQI_k \rangle} . \qquad (2)$$

The CSAFT scheduler allocates resources to those UEs that experience constructive fading in relation to their average channel quality [12] [13].

Figure 1 illustrates an example of the functioning of the three different scheduling algorithms in the case with only two simultaneously active UEs per cell. It can be seen how the BFT and the CSAFT are fair resource schedulers since they allocate the same amount of resources to each UE for an equal amount
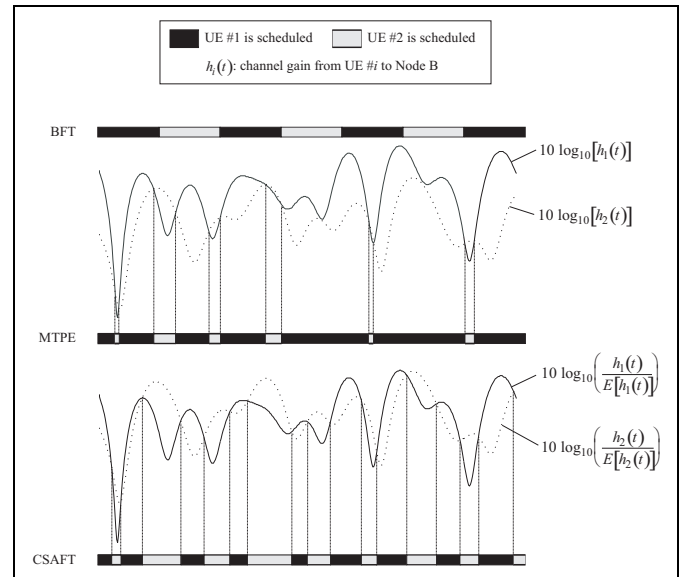

Figure 1: An example of the functioning of the three time and code division scheduling algorithms with only two simultaneously active users per cell.

of time. However, the CSAFT algorithm utilises information on both instantaneous and average channel quality to perform intelligent allocation of the radio resources. On the other hand, the MTPE is not a fair scheduler since it more often schedules for transmission users that in average experience better channel conditions.

III. SIMULATION ASSUMPTIONS

The scheduling performance of the proposed algorithms is evaluated by means of system level simulations; in this section, the main simulation assumptions are discussed. All the time and code division scheduling algorithms considered in this paper operate based on a TTI size of 2 ms. The common steps to all of the scheduling algorithms can be summarised as follows:

- At each TTI, the Node B PS estimates the reduction in the total received power from setting all current allocations to 0 kbps. The final value is the outset for the new allocations.

- Then the Node B PS constructs the scheduling queue based on information about the UE buffer state; a user is included to the scheduling queue only if its buffer is non-empty. The queue is then ordered according to the particular scheduling policy (BFT, CSAFT or MTPE). The Node B PS is assumed to have exact knowledge of the buffer state of each UE in the corresponding cells.

- Based on this order, the Node B PS schedules the total amount of available power (up to the planned target) starting form the first user in the scheduling queue. The PS always tries to allocate the maximum supportable data rate at the UE. In this sense, the Node B is assumed to have precise information on the available power margin at the UE. If there is not enough power available for scheduling, also data rates lower than the maximum supportable can be allocated. However, no allocation of data rates lower than 128 kbps is allowed. The maximum data rate that can be allocated by the PS is 384 kbps.

Some users in the scheduling queue might not be scheduled for transmission during one TTI if the available resources have already been allocated to others. While these users do not send any data on the dedicated physical data channel (DPDCH), they continue transmission on the DPCCH to perform fast power control.

Moreover, the scheduling is implemented to account for an allocation delay between the scheduling decision at the Node B and the application of the allocated data rate by the scheduled UE. It includes the processing delay at the Node B, the time taken to signal the allocation to the UE, and the processing delay at the UE. In the simulator, the default value for this delay is equal to 6 ms (see TABLE I).

The basic simulation assumptions are the same as in [2] and [3]. Traffic modelling is described in [1]. The performance of the proposed algorithms is compared to a reference RNC code division (CD) scheduler [2], as well as to a Node B CD scheduler [3]. The RNC scheduler is assumed to operate at a Block Error Rate (BLER) target of 1% to work with an RLC-based retransmission scheme. The Node B CD scheduler, on the other hand, operates at a BLER target for first transmission equal to 10% since L1 HARQ schemes with soft combining are introduced [3]. Fast L1 HARQ schemes are introduced also for the time and code division schedulers with the same 10% BLER target. The main assumptions for the simulation of the different scheduling concepts are reported in TABLE I. The modification period is the minimum time between two consecutive data rate modification commands from the PS to the same UE. All schedulers include soft handover (SHO) operation with the parameter setting reported in [3]. In the case of time and code division scheduling of users in SHO, the Node B with the best uplink signal is also the only scheduling Node B.

IV. SIMULATION RESULTS

As it has been previously introduced, time scheduling of users on E-DCH allows performing scheduling based on instantaneous channel conditions; the interference generated to neighbouring cells can be reduced, and cell throughput increased. This enhancement can be interpreted as multi-user diversity gain [8]. With code division schedulers, all uplink transmissions occur in parallel but at a low enough rate such that the desired total received power at the Node B is not exceeded; this kind of schedulers cannot exploit the individually fading channels. With time scheduling, on the other hand, the load budget is fulfilled as a result of the allocation of relatively high data rates to a limited set of users in each cell. The lower the numbers of users simultaneously scheduled, the higher the multi-user diversity gain. One of the main drawback is that time scheduling is also expected to increase the time variability of uplink load compared to more traditional code division schedulers. The time variability of uplink load is expected to grow when the number of users simultaneously scheduled at each Node B is reduced. Therefore, a trade-off seems to exist between multi-user diversity gain and time variability of uplink load. In this section, we aim at better illustrating this issue by means of extensive system level simulations.

Simulations have initially been run for a fixed average number of users per cell equal to 21 and for Vehicular A channel profile at 3 km/h [1]. All the results have been obtained for a 5% NR outage of 6 dB (i.e., the probability that the NR in the system exceeds 6 dB is in all cases 5%). Figure 2

TABLE I: MAIN SIMULATION ASSUMPTIONS.

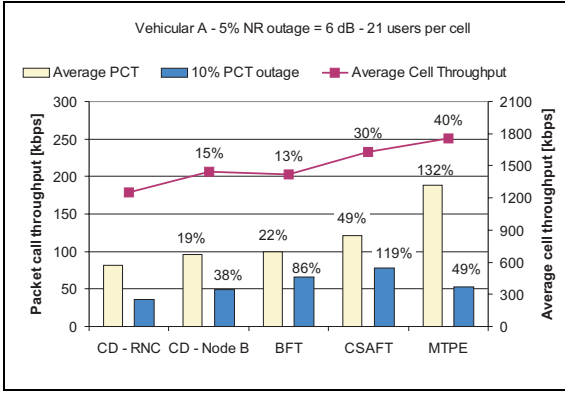|	SCHEDULER				
	RNC CD	Node B CD	BFT	CSAFT	MTPE
Modification period	600 ms	100 ms	2 ms	2 ms	2 ms
Allocation delay	120 ms	40 ms	6 ms	6 ms	6 ms
BLER target	1%	10%	10%	10%	10%
TTI	10 ms	10 ms	2 ms	2 ms	2 ms
L1 HARQ with soft combining	OFF	ON	ON	ON	ON

Figure 2: Average cell throughput, average PCT and 10% PCT outage for different scheduling scenarios - average number of UEs per cell = 21.

plots the average cell throughput, the average packet call throughput (PCT) as well as the 10% PCT outage (10% level of the cumulative distribution function) for the different scheduling concepts. The PCT is defined as the average throughput experienced by a user during an active packet data session.

The BFT algorithm does not provide significant gains over the Node B CD scheduler. The reason is that the increased power headroom to meet the specified NR outage criteria is not balanced by any reduction in the interference generated to other cells. Figure 3 and Figure 4 plot the probability density function (PDF) of the NR in the system and the cumulative distribution function (CDF) of the other-to-own cell interference ratio i, respectively. In Figure 3, the longer tail distributions (and the consequently reduced average NR) for the time and code division schedulers make clear why a higher power headroom is required, compared to the Node B CD scheduler, to meet the specified NR outage constraint. This is mainly due to the increased time variability of the uplink load introduced with time scheduling. However, for the channel-dependent schedulers the reduction of the power headroom for scheduling is compensated by a significant reduction in the interference generated to other cells, as illustrated in Figure 4. Therefore, the total cell throughput increases compared to the Node B CD scheduler. While the MTPE algorithm maximises cell throughput at the cost of a low degree of fairness between users, the CSAFT scheduler offers an appealing trade-off between cell throughput maximisation and users' fairness, significantly reducing the difference between average and 10% outage PCT performance (see Figure 2).

In order to compare the different scheduling concepts under similar user performance constraints, simulations have been run so to obtain the same 10% PCT outage of 64 kbps. I.e., 90% of the packet data sessions experience an average data throughput of at least 64 kbps. Figure 5 reports the average cell throughput for all the considered scheduling concepts, for a 5% NR outage of 6 dB, a 10% PCT outage of 64 kbps and for Vehicular A channel profile at 3 km/h. When imposing a specific constraint on the minimum guaranteed user performance, the CSAFT algorithm takes advantage of its capability to make a fair distribution of the radio resources between users, while still exploiting instantaneous channel-

state information. It achieves the maximum cell throughput performance, with a gain over the RNC CD scheduler of 51%. The corresponding cell throughput increase compared to the Node B CD scheduler is 17%. Despite the additional complexity introduced (see Section V), the BFT algorithm does not provide any relevant gain compared to the Node B CD scheduler.

The same results are reported in Figure 6, but for Pedestrian A channel profile at 3 km/h. Also in this propagation environment the CSAFT algorithm is confirmed as the most performing, with a cell throughput increase of 78% and 29% with respect to the RNC CD and the Node B CD schedulers, respectively. Due to the lower diversity in the Pedestrian A channel profile, the gain from channel-dependent scheduling is more significant in the case of Pedestrian A. For the same reason, the effect of time scheduling on the time variability of uplink load is more significant in Pedestrian A, and the BFT algorithm therefore presents a slight performance decrease compared to the Node B CD scheduler.

V. ADDITIONAL COMPLEXITY

The introduction of time scheduling in the uplink of real systems brings about some practical concerns that are not so easy to quantify but might have great impact on system performance and cost. One of these issues is frame synchronisation, which requires additional complexity at the UE side due to frame asynchronous DCH transmission in the downlink direction. Moreover, time scheduling on a TTI basis require a significant signalling overhead both in uplink (UE
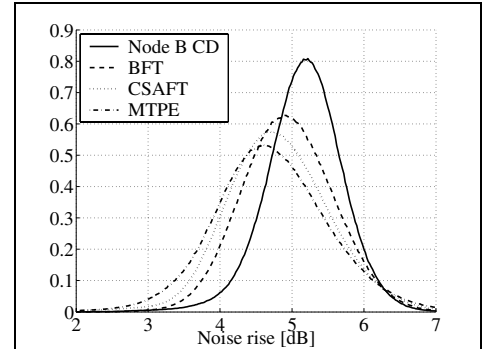

Figure 3: PDF of the noise rise for different scheduling scenarios - Vehicular A at 3 km/h - average number of UEs per cell = 21.
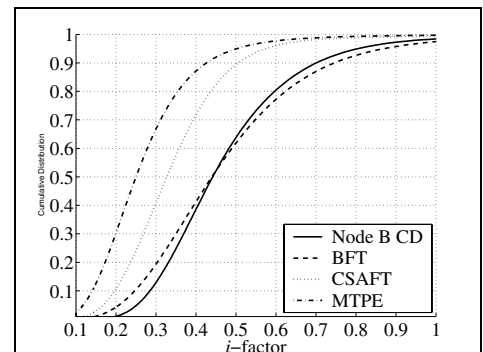

Figure 4: CDF of the other-to-own cell interference ratio (i-factor) for different scheduling scenarios - Vehicular A at 3 km/h - average number of UEs per cell = 21.
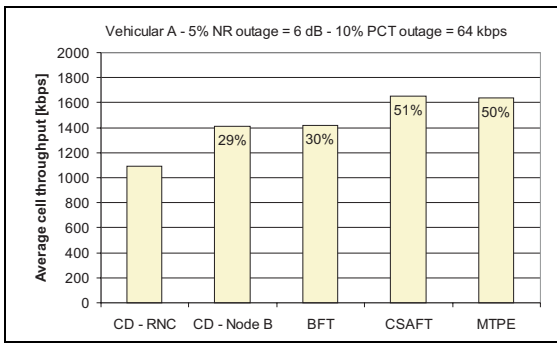
Figure 5: Average cell throughput for different scheduling scenarios - Vehicular A at 3 km/h - 10% PCT outage = 64 kbps.
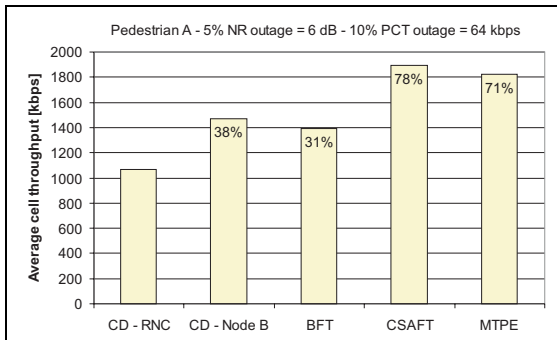

Figure 6: Average cell throughput for different scheduling scenarios - Pedestrian A at 3 km/h - 10% PCT outage = 64 kbps.

must send information on its buffer occupancy and some kind of channel quality indicator) and in downlink (Node B must signal every TTI which UEs are scheduled for transmission and at which rate). The required signalling overhead is more significant in the case of 2 ms TTI. Another potential drawback of time scheduling is related to measurement accuracy at the Node B, where instantaneous and accurate measurements of the received power must be available in order to keep the uplink load as close as possible to the planned target. Finally, time scheduling requires the UE to continuously switch from no data transmission to data transmission with high instantaneous data rate. At the UE this can introduce significant uncertainty in the selection of the transmission power to be used at the beginning of each TTI [14]. All these issues have been neglected in the results presented in this paper.

VI. CONCLUSION

In the presented paper we have proposed three time and code division scheduling algorithms for WCDMA uplink packet access on E-DCH. The performance of the algorithms has been assessed by means of system level simulations, which allow to include the impact of time scheduling on the time variability of both uplink load and other-to-own cell interference, on fast power control performance, etc. Despite of an inherent increase in the power headroom required to meet specified NR outage criteria, the time and code division schedulers can take advantage of channel information to schedule users when experiencing favourable channel conditions. In this perspective, the CSAFT algorithm has been shown to guarantee an attractive trade-off between throughput

maximisation and users' fairness, resulting the most performing scheduling strategy when a constraint is considered for the minimum guaranteed user performance.

Under the considered traffic model, 5% NR and 10% PCT outage constraints, the CSAFT time and code division scheduler provides a capacity increase of about 50% for Vehicular A channel profile at 3 km/h compared to a reference RNC-based scheduler. The gain is as large as 78% for Pedestrian A channel profile at the same UE speed. However, it must be noticed that these gain numbers reduce to approximately 17% and 30% when compared to the performance of the Node B CD scheduler in [3]. Therefore, the complexity issues discussed in Section V must be carefully considered before time and code division scheduling on DCH can be considered as an applicable solution for the enhancement of WCDMA uplink performance.

REFERENCES

[1] 3GPP TR 25.896, "Feasibility Study for Enhanced Uplink for UTRA FDD", version 6.0.0, March 2004. Available at: www.3gpp.org.

[2] Dimou K., Rosa C., Sørensen T. B., Wigard J., Mogensen P. E., "Performance of Uplink Packet Services in WCDMA", VTC Spring 2003, vol. 3, pp. 2071-2075, April 2003.

[3] Rosa C., Outes J., Dimou K., Sørensen T. B, Wigard J., Frederiksen F., Mogensen P. E., "Performance of Fast Node B Scheduling and L1 HARQ Schemes in WCDMA Uplink Packet Access", VTC Spring, 2004, May 2004.

[4] Bhagwat P., Bhattacharya P., Krishna A., Tripathi S.K., "Enhancing Throughput over Wireless LANs Using Channel State Dependent Packet Scheduling", in Proc. INFOCOM 1996, vol. 3, pp. 1133-1140, March 1996.

[5] Holma H. and Toskala A. (Editors), "WCDMA for UMTS - Radio Access for Third Generation Mobile Communications", John Wiley and Sons, Third Edition, 2004.

[6] Jalali A., Padovani R., Pankaj R., "Data Throughput of CDMA-HDR a High Efficiency-High Data Rate Personal Communication Wireless System", VTC Spring 2000, vol. 3, pp. 1854-1858, May 2000.

[7] Elliot R.C., Krzymien W.A., "Scheduling Algorithms for the cdma2000 Packet Data Evolution", VTC Fall 2002, vol. 1, pp. 304-310, September 2002.

[8] T. E. Kolding, K. I. Pedersen, J. Wigard, F. Frederiksen, P. E. Mogensen, "High Speed Downlink Packet Access: WCDMA Evolution", IEEE Vehicular Technology Society (VTS) News, vol. 50, no. 1, pp. 4-10, February 2003.

[9] Ramakrishna S., Holtzman J.M., "A Scheme for Throughput Maximization in a Dual-Class CDMA System", IEEE Journal on Selected Areas in Communications, vol. 16, issue 6, pp. 830-844, August 1998.

[10] Haddad E.C., Mermelstein P., Despins, C., "A Transmit Assignment Algorithm for Uplink Flow Control in WCDMA Networks", VTC Fall 1999, vol. 1, pp. 416-420, September 1999.

[11] Ulukus S., Greenstein L.J., "Throughput Maximization in CDMA Uplinks Using Adaptive Spreading and Power Control", IEEE Sixth International Symposium on Spread Spectrum Techniques and Applications, vol. 2, pp. 565-569, September 2000.

[12] Krishnan Kumaran, Qian L., "Uplink Scheduling in CDMA Packet-Data Systems", in Proc. INFOCOM 2003, vol. 1, pp. 292-300, April 2003.

[13] Berggren F., Jäntti R., "Asymptotically Fair Transmission Scheduling Over Fading Channels" IEEE Transactions on Wireless Communications, vol. 3, issue 1, pp. 326-336, January 2004.

[14] 3GPP TS 25.101, "UE Radio Transmission and Reception (FDD)", version 6.4.0, March 2004. Available at: www.3gpp.org.