Performance Aspects of WCDMA Systems with High Speed Downlink Packet Access (HSDPA)

Troels E. Kolding, Frank Frederiksen, and Preben E. Mogensen
Nokia Networks, Aalborg R&D, Denmark

Abstract— **In this paper, we consider the link and network layer performance aspects of a WCDMA/UTRA system with high speed downlink packet access. The study considers packet scheduling and the tradeoff among user fairness and cell throughput. We show performance numbers for different network setups and study the applicability of proportional scheduling methods. Even with conservative system and traffic settings, the best effort methods produce high user data rates and cell throughput.**

I. Introduction

To facilitate a viable evolution of the WCDMA/UTRA system towards extensive packet data traffic, the Release'5 3GPP specifications introduce a new concept denoted *high speed downlink packet access* (HSDPA); see e.g. [1], [3]. The HSDPA concept introduces new adaptation and control mechanisms to enhance downlink peak data rates, spectral efficiency, and *quality of service* (QoS) control for packet services. As for the existing *downlink shared channel* (DSCH), high trunking efficiency for bursty data services is obtained by employing code as well as time multiplexing. As HSDPA may be viewed as an evolution of the DSCH, the radio bearer is denoted the *high speed* DSCH (HS-DSCH). The HSDPA overlay has previously been evaluated to yield a at least 50-100% spectral efficiency gain over previous WCDMA/UTRA releases as well as high support for *transmission control protocol* (TCP) applications, see e.g. [2], [3], [4]. In this paper, we focus on the impact of *physical layer* (L1) capabilities, hardware imperfections, traffic characteristics, and radio resource management policies on the HS-DSCH performance. The paper is initiated with a short description of the HSDPA concept including the basic operation principle. Next, performance related factors of the HS-DSCH are discussed and the employed simulation assumptions are presented. Finally, the performance of the HS-DSCH is demonstrated for different network assumptions and observations are discussed.

II. HSDPA Operation Principle

The simplified HS-DSCH operation principle is illustrated in Fig. 1. The critical issue is the determination of the downlink channel quality for the individual users; e.g. the available *symbol to noise energy*, E_s/N_0, and the individual UE detector performance. The Node-B can estimate the supported data rate for each UE by monitoring the *transmit power control* (TPC) commands sent on the associate *dedicated channel* (DCH) [5]. Additionally, the UE can be requested to periodically transmit an HSDPA specific *channel quality indicator* (CQI) on the uplink *high speed dedicated physical control channel* (HS-DPCCH) which also carries fast L1 based packet acknowledgment signaling (Ack/Nack) for each transport block. Having estimated the channel quality, the system shares the HS-DSCH power and code resources between the different users. The HSDPA *medium access control* (MAC) layer is located in the Node-B, thus enabling faster access to link measurements, faster and more efficient packet scheduling, as well as tighter QoS control. Compared to traditional CDMA methodology, the HS-DSCH does not operate with fast power control and the spreading factor is fixed to 16 [3]. Instead, the link adaptation is accomplished by continuously adjusting the modulation and coding parameters every 2 ms, corresponding to the basic HS-DSCH *transmit time interval* (TTI).

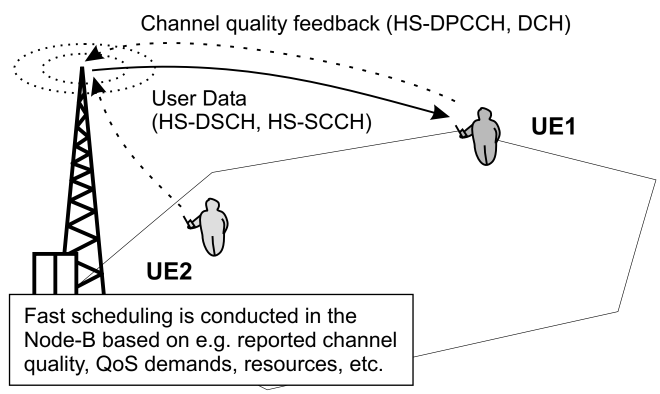

Fig. 1. Simplistic illustration of the HSDPA operation principle.

By introducing variable-rate turbo encoding, 16QAM modulation, as well as extensive multi-code operation, the HS-DSCH supports peak data rates from 120 kbps up to and beyond 10 Mbps. The basic *adaptive modulation and coding* (AMC) process has a dynamic range on the order of 20 dB, further expanded by the available number of multi-codes [3]. This is typically sufficient to track the channel quality experienced at the UE. Table I shows the link between a possible *transport format and resource combination* (TFRC) and the corresponding user peak data rate. Since the AMC based link adaptation is slower than traditional fast power control and is associated with measurement errors, it is not possible to guarantee error-free detection without making the AMC very conservative. To facilitate more aggressive and spectrally efficient scheduling, a fast L1 based retransmission strategy is embedded in the HSDPA concept. Facilitated by the Node-B based MAC layer, soft-combining and *incremental redundancy* (IR) retransmission strategies ensure that past transmissions are effectively utilized. Due to the short retransmission delays it is possible to operate at 1st transmission *block error rate* (BLER) values around 10-30%, still maintaining a small relative delay jitter. This is a significant improvement compared to the radio link control layer retransmission method where delays are orders of magnitude higher [3]. To allow for processing and propagation delays, the retransmission scheme is based on the *stop and wait* (SAW) principle with several independent *hybrid automatic repeat request* (HARQ) processes per user [3]. Demodulation as well as HARQ instructions are sent to the UE on the *high speed shared control channel* (HS-SCCH).

TABLE I

PEAK DATA RATES FOR EXAMPLE TFRCS INCLUDING OVERHEAD.

TFRC	**Data rate** (1 code)	**Data rate** (5 codes)	**Data rate** (15 codes)
1. QPSK, rate 1/4	120 kbps	600 kbps	1.8 Mbps
2. QPSK, rate 1/2	240 kbps	1.2 Mbps	3.6 Mbps
3. QPSK, rate 3/4	360 kbps	1.8 Mbps	5.3 Mbps
4. 16QAM, rate 1/2	480 kbps	2.4 Mbps	7.2 Mbps
5. 16QAM, rate 3/4	720 kbps	3.6 Mbps	10.7 Mbps

III. EVALUATION METHOD AND HS-DSCH MODEL

In this section, the modeling and simulation assumptions are explained. As UE detector type, the single-antenna maximum ratio combining rake receiver is assumed. To model the receiver performance, *actual value interface* (AVI) tables are used which map the per-TTI (instantaneous) E_s/N_0 at the UE into an equivalent BLER for the different TFRCs and channel operating conditions [6]. Further, each link is dynamically represented by per-TTI E_s/N_0 traces obtained in a link level simulator for different environments. These traces include the effect of other traffic on the same Node-B (including common channels), the othercell interference adjusted to the *owncell to othercell power ratio* (I_{or}/I_{oc}), the UE speed, and the amount of time dispersion.

The Node-B conducts packet scheduling and link adaptation based on the estimated per-TTI E_s/N_0. This estimate is based on the actual E_s/N_0, denoted $\gamma(t)$, and is given as $\hat{\gamma}(t) = \gamma(t - \tau_{AMC}) \cdot \psi$, where τ_{AMC} is the inherent link adaptation/AMC delay and ψ denotes the uncertainty associated with the channel quality measurement. Even with negligible hardware, propagation, and scheduling delays, the AMC delay is still almost 2 ms owing to the required time offset between the HS-SCCH and the HS-DSCH [3]. The parameter ψ is assumed to be log-normally distributed with unity mean. Based on the estimated channel quality, the AMC algorithm selects the TFRC and multi-code setting that optimizes the throughput for the 1st transmission. The packet error rate is then evaluated through the AVI tables by exploiting the knowledge of the actual channel quality, $\gamma(t)$.

As mentioned, the HS-DSCH facilitates very high throughput to users having favorable E_s/N_0 conditions. Such users may very well be limited by the hardware imperfections rather than the interference and propagation conditions. In these simulations, a Node-B *peak code domain error* (PCDE) of -36 dB has been assumed according to recent discussions in 3GPP. The UE implementation margin is assumed ideal, but in the link simulations the channel phase and amplitude are estimated from a common pilot measurement (e.g. inaccuracies related to this measurement are included).

As the retransmissions take up a significant part of the overall transmission capacity, they require specific attention. As proposed in [7], the HARQ process is modeled using the individual E_s/N_0 values for each retransmission. We denote the available per-TTI received E_s/N_0 for transmission number n by $\gamma[n]$. The combined E_s/N_0 after N transmissions is calculated as [7]

$$\left(\frac{E_s}{N_0}\right)_{tot} = \varepsilon^{N-1} \cdot \eta(M,R) \cdot \sum_{n=1}^{N} \gamma[n] \ , \ \ \forall N \geq 2 \qquad (1)$$

where M is the modulation order, R is the code rate of the first transmission, ε is the chase combining efficiency, and η denotes the incremental redundancy gain which is assumed to be unity for other transmissions than the second. With this approach, the HARQ analysis is conducted with a single 1st transmission AVI table for each modulation, code rate, and multi-code setting.

The network performance characteristics, including shadowing, propagation loss, antenna characteristics, as well as cell size, are described by an I_{or}/I_{oc} *cumulative distribution function* (CDF). Since the HS-DSCH does not support soft handover, the I_{or}/I_{oc} performance near the cell edge is generally reduced compared to e.g. the DCH. In this paper, we assume the I_{or}/I_{oc} CDFs shown in Fig. 2 for the macrocell outdoor and the microcell indoor/outdoor scenarios [8]. The shown CDFs are in simulation truncated according to the desired coverage area. We further assume the ITU *Pedestrian A* (Ped-A) profile for the microcell case and the *Vehicular A* (Veh-A) profile for the macrocell case. The rake receiver is configured with one and four fingers for the Ped-A and Veh-A channels, respectively.

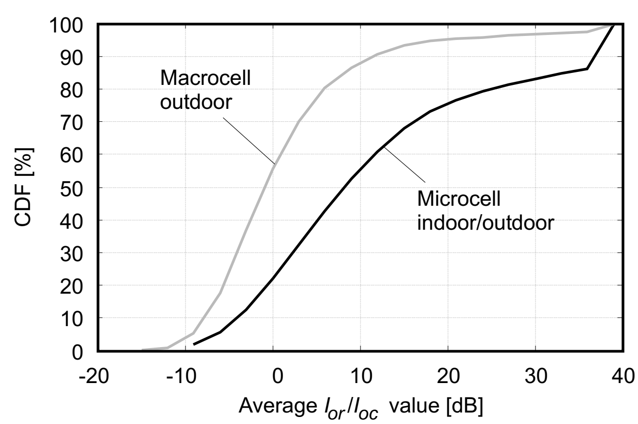

Fig. 2. Assumed I_{or}/I_{oc} CDFs for the microcell and macrocell scenarios (100% cell area coverage, no soft handover) [8].

When new users are generated, they are extracted randomly according to the I_{or}/I_{oc} CDF. The user arrival is modeled with a Poisson process adjusted according to an offered load, A_{offer}, and an arrival window of 10 ms. Each user requests a 100 kbit download with an assumed maximum allowed delay of 12.5 seconds. If this delay is exceeded it is assumed that the user is transferred to another radio bearer; e.g. is *dropped* from the HS-DSCH. For admission control, the dominating requirement is the limit of 32 simultaneously queued users. A "queued" user is defined as a user having data in the queue as opposed to an "active" user which is currently transmitting on the HS-DSCH. Users rejected through the admission control criterion are counted as *blocked users*. The default simulation parameters and their considered ranges are listed in Table II. The resource allocation is considered as the number of available multi-codes as well as the HS-DSCH/Node-B power ratio. For simplicity, we assume a fixed amount of power resources allocated to the HS-DSCH (HS-SCCH overhead not considered).

TABLE II

DEFAULT SIMULATION ASSUMPTIONS (RANGES IN PARENTHESIS).

Parameter	Setting
HS-DSCH/Node-B power ratio	40%
Number of HS-DSCH multi-codes	7 (1-15)
Max. number of queued users in cell	32
Max. acceptable delay per 100 kbit	12.5 s
Download request	100 kbit
Offered load, A_{offer}	(250-3000 kbps)
HS-DSCH macrocell coverage area	80%
HS-DSCH microcell coverage area	100%
Macrocell power delay profile	ITU Veh-A
Microcell power delay profile	ITU Ped-A
AMC delay, τ_{AMC}	2 ms
AMC error standard deviation, ψ	1.5 dB
Chase combining efficiency, ε	0.95
$\eta(M,R)$, QPSK rate 1/4, 1/2, 3/4	0.0, 0.4, 1.4 dB [7]
$\eta(M,R)$, 16QAM rate 1/2, 3/4	1.6, 2.8 dB [7]
UE speed	3 kmph
Node-B PCDE at speading factor 256	-36 dB
UE receiver	Rake, ideal†
Pilot/Node-B power ratio	10%

†*Channel estimation based on common pilot measurement.*

The key to HSDPA operation and performance lies in the *packet scheduling* (PS) entity. In these simulations, the basic PS methods (and the used abbreviations) listed in Table III are considered. The pace of the scheduling divides the methods into two main groups. Traditional PS methods make scheduling decisions for a period of time based on averaged channel quality measurements. Fast PS methods track the user channel quality for each TTI and makes scheduling decisions "on the fly". Another issue is that of inherent fairness among users. The FT approach ensures that all simultaneously queued users receive the same average throughput, which means that users in bad conditions are given relatively more HS-DSCH resources. On the other end, the M-CI method only gives resources to the users in the most favorable conditions thereby enhancing cell throughput at the expense of inter-user fairness. In between, the FR method gives equal resources to all users so that all users will achieve a throughput corresponding to the channel quality. The proportional methods (P-FT and P-FR) attempt to give all users the same probability of being scheduled by using a *relative instantaneous channel quality* (RICQ); e.g. defined as the ratio between current and average user E_s/N_0. Ideally, this method will schedule users only during constructive fades thereby raising both the overall cell throughput and the user data rates. By weighting the RICQ with buffer statistics, the fairness of the proportional methods can be increased (e.g. P-FT type scheduling). Retransmission scheduling is also important to HS-DSCH performance evaluation. In this study, we reschedule the packet as soon as possible taking into account the basic signaling and AMC delays. Since the TFRC and multi-code parameters are maintained for the retransmissions, this ensures a minimal change in channel quality for successive transmissions. In this study we assume only one user per TTI; e.g. no code multiplexing on the HS-DSCH.

IV. PERFORMANCE RESULTS

The AMC performance for the considered UE type is illustrated in Fig. 3. The selected TFRC/multi-code setting (related to Table I) is shown together with the average 1st transmission throughput versus the instantaneous per-TTI averaged E_s/N_0. From a spectral efficiency viewpoint, it is better to first select a higher multi-code number before increasing the TFRC order.

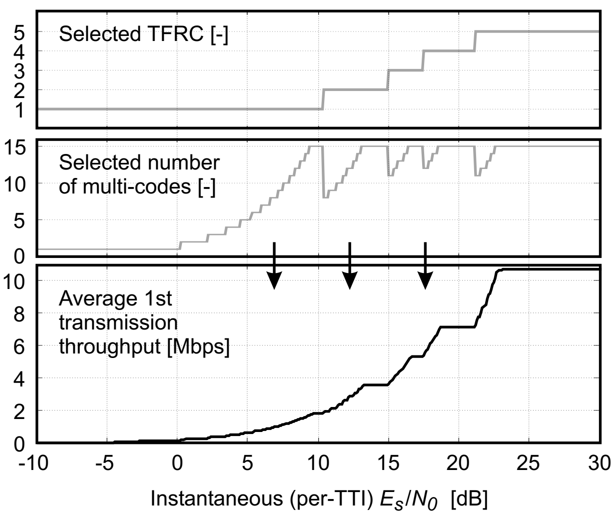

Fig. 3. HS-DSCH AMC performance with 15 available multi-codes (ITU Pedestrian A). See also Table I for TFRC definitions.

The basic scheduling mechanisms of Table III have been compared in terms of blocking probability, dropping probability, and achieved user data rates in Table IV. For the FT and FR methods, there is a large blocking probability caused by a low scheduling capacity compared to the offered load. However, once users are admitted to the system they are served with resource or throughput fairness which results in a relatively low drop rate (somewhat higher for the FR PS). As is seen from the user data rate distribution, the FT scheduler gives a more uniform throughput to all the users compared to the FR scheduler. The performance of the more aggressive schedulers (CI, P-FT, P-FR, and M-CI) is almost sufficient to support the offered load and this results in a relatively small blocking probability. However, as these schedulers employ user sorting, some users experience low data rates and are occasionally dropped. Hence, the dropping probability is quite high for cases when the offered load is comparable to the maximum HS-DSCH capacity.

As mentioned, the philosophy behind proportional scheduling is to serve users only during times with constructive fading.

TABLE III

COMPARISON OF FUNDAMENTAL PACKET SCHEDULING METHODOLOGIES, SEE E.G. [3], [9].

PS Method	Scheduling rate	Serve order	Allocation method
Fair throughput (FT)	Slow (averaged over e.g. 20-100 ms)	Round robin (random order)	Resources according to equal data amount for all users (up to maximum allowed allocation)
Fair resource (FR)	Slow (averaged over e.g. 20-100 ms)	Round robin (random order)	Same resources (power/codes/time) for all users
C/I (CI)	Slow (averaged over e.g. 20-100 ms)	Only user with maximum slow-averaged channel quality/throughput is served	Same resources (power/codes/time) per allocation time
Proportional fair throughput (P-FT)	Fast (per-TTI basis)	Only user with best relative instantaneous channel quality is served	Resources according to equal data amount for all users (up to maximum allowed allocation)
Proportional fair resource (P-FR)	Fast (per-TTI basis)	Only user with best relative instantaneous channel quality is served	Same resources (power/codes/time) for all users
Maximum C/I (M-CI)	Fast (per-TTI basis)	Only user with maximum instantaneous channel quality/throughput is served	Same resources (power/codes/time) per allocation time

TABLE IV

SIMULATION RESULTS FOR MICROCELL WITH $A_{\text{offer}} = 1.5$MBPS.

PS	Blocking/dropping probability	User data rates [kbps]			
		>16	>64	>512	>1024
FT	48%/1%	87%	4%	0%	0%
FR	38%/5%	91%	51%	0%	0%
CI	7%/16%	97%	96%	79%	65%
P-FT	13%/7%	97%	87%	61%	46%
P-FR	8%/12%	98%	88%	66%	55%
M-CI	4%/11%	97%	95%	77%	63%

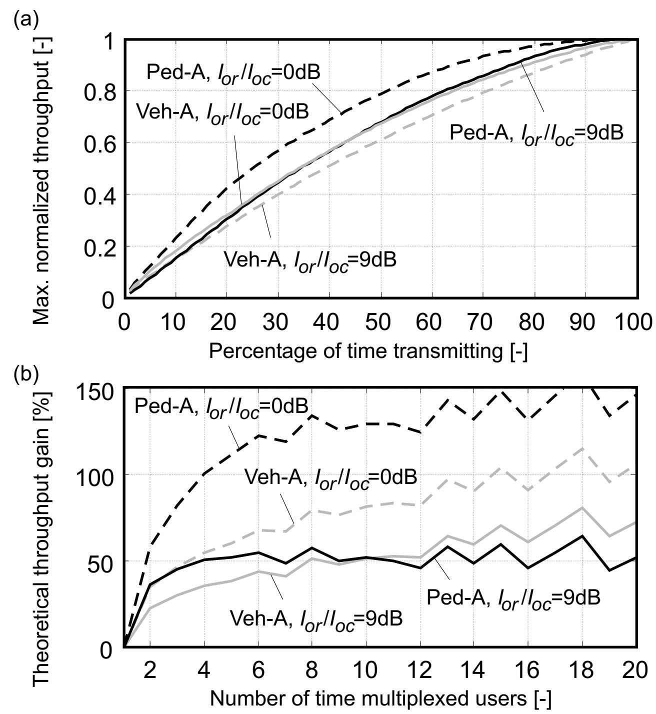

Fig. 4. Time dependence of user throughput and maximum obtainable gain from proportional scheduling and multiplexing.

To illustrate the gain potential, consider the curves for single user throughput versus the percentage of time transmitting in Fig. 4a. To exemplify, the results for the Ped-A case with a 0 dB I_{or}/I_{oc}-factor are considered. It is seen from Fig. 4a that 80% of the maximum achievable throughput (when transmitting 100% of the time) can be achieved in only 50% of the time if we schedule the user only when the channel quality is the best. If we time multiplex the channel evenly between two such users, we could in theory achieve a maximal gain of 1.6 or 60%. The gain curves for a different number of multiplexed users are shown in Fig. 4b. As can be seen there is a large potential gain, and especially when the maximum to minimum throughput ratio is high (e.g. Ped-A and low I_{or}/I_{oc}-factor). With more user diversity, the potential gain increases further.

In practice, the gain values shown in Fig. 4 are of hypothetical nature. Statistically speaking, users will not always fade constructively at different time instances thereby reducing the potential. Additionally, the UE velocity must be high enough to achieve sufficient short-term dynamics and low enough to prevent inherent AMC delays to severely damage the channel tracking ability. The studied case of 3 kmph appears to be a best-case situation for the proportional methods. Finally, link stabilizing features such as open loop transmit diversity may potentially reduce the available amount of user diversity. The P-FR scheduler has been compared to the FR scheduler in Fig. 5 in terms of carried load on the HS-DSCH versus the offered load. The maximum observed gains are on the order of 30-40%, e.g. reduced significantly compared to the initial gain analysis. As seen, the M-CI scheduler only marginally outperforms the P-FR scheduler which is due to a somewhat aggressive definition of the RICQ for the proportional methods as well as the assumed traffic characteristics (all users request same data).

One of the main advantages of the HSDPA concept is the flexibility to utilize available code and power resources. If the system is mainly code limited, the HSDPA concept can map any available power into higher throughput by use of higher order modulation and coding. If the system is mainly power limited,

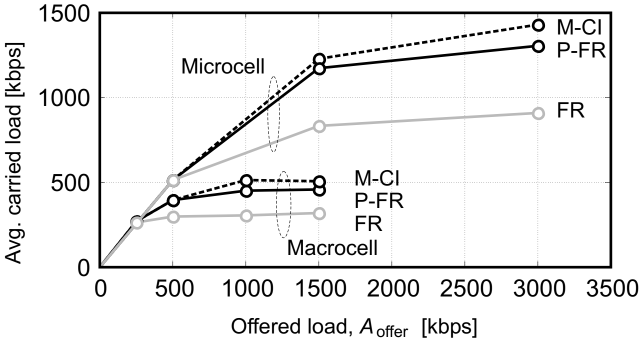

Fig. 5. Comparison of packet scheduling methods.

the use of excessive multi-code operation and low code rates makes the HS-DSCH very power efficient. As an example of high code efficiency, consider the case in Fig. 6. As seen, a high level of throughput can be achieved using relatively few codes although having more codes generally increases the spectral efficiency. For a case with higher offered load but maintained HS-DSCH power allocation, the availability of a higher and more balanced code allocation becomes more important.

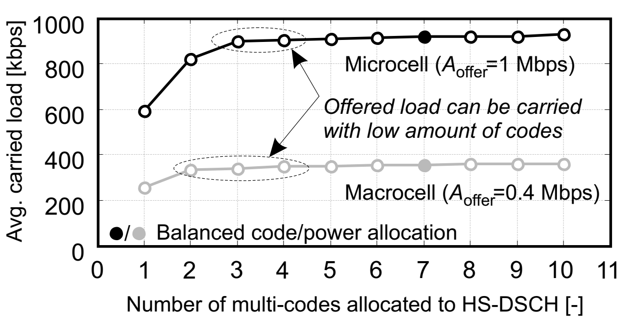

Fig. 6. Average carried load versus multi-code allocation for M-CI PS.

As mentioned previously, users at the cell edge do not benefit from a soft handover gain when transmitting on the HS-DSCH. As the overhead associated with control signaling is also highest at the cell edge, it may be desirable to limit the coverage area of the HS-DSCH. In a FR PS microcell simulation with a 3 Mbps offered load, the carried load increases from 1.2 Mbps to 2.0 Mbps when the coverage level is reduced from 100% to 80% (40% HS-DSCH power allocation). Hence, the cost in carried load can be very high when supporting the full cell area.

V. Discussion

The optimization of a packet scheduler involves considerations related to e.g. desired blocking/dropping, retransmission prioritization, application/protocal properties, as well as network dimensioning. Hence, it is difficult to achieve clear-cut and absolute performance numbers as well as a distinct comparison of different PS types. From consertive to optimistic traffic conditions, there is easily a factor of 2-4 in cell performance difference. The traffic characteristics and QoS requirements in particular have significant impact to the performance of the different schedulers. For instance, in the single-user case there is no scheduling flexibility and all PS methods perform equally. If there are many simultaneous users, the "best effort" schedulers (e.g. CI, M-CI, P-FR) perform the best due to more "user selection diversity". In this study, we have assumed that all users, regardless of their channel conditions, require the same amount of data. When operating with a maximum user limit, the bad-quality users tend to pile up in the system when aggressive scheduling is used. As there may be a tendency that users experiencing higher data rates will also request more data, this can facilitate much higher absolute cell throughput numbers than shown in this paper; especially for the M-CI scheduler type. Tight throughput and latency requirements will also override the basic operation of the packet scheduler and this reduces the difference between different approaches. Generally speaking, the HSDPA concept produces the highest user data rates and cell throughput when there is a large degree of scheduling flexibility. The main benefit of the HSDPA concept is that it facilitates flexible scheduling strategies with fast user and service differentiation. It should also be mentioned that further enhancements are discussed in 3GPP for operation with the HSDPA concept. One basic technique is transmit diversity which will generally improve the HS-DSCH performance further. Any link enhancing scheme can be mapped into higher throughput with the HS-DSCH due to its high inherent code efficiency.

VI. Conclusions

In this paper, it has been demonstrated that the performance of the HS-DSCH depends significantly on a large number of parameters ranging from the propagation environment over traffic characteristics to resource allocation policies. Six distinct "prototype" packet schedulers, including the proportional schedulers, have been considered and the inherent tradeoff among cell capacity and user fairness has been illustrated.

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