PERFORMANCE OF DOWNLINK FREQUENCY DOMAIN PACKET SCHEDULING FOR THE UTRAN LONG TERM EVOLUTION

A. Pokhariyal(1)
1) Aalborg University, CSYS
Aalborg, Denmark
ap@kom.aau.dk

T. E. Kolding(2), P. E. Mogensen(1,2)
2) Nokia Networks
Aalborg, Denmark
troels.kolding@nokia.com

ABSTRACT

In this paper we investigate the potential of downlink frequency domain packet scheduling (FDPS) for the 3GPP UTRAN long-term evolution. Utilizing frequency-domain channel quality reports, the scheduler flexibly multiplexes users on different portions of the system bandwidth. Compared to frequency-blind, but time-opportunistic scheduling, FDPS shows gains in both average system capacity and cell-edge data rates on the order of 40%. However, the FDPS performance is shown to depend significantly on the frequency-domain scheduling resolution as well as the accuracy of the channel state reports. Assuming Typical Urban channel profile, studies show that the scheduling resolution should preferably be as low as 375 kHz to yield significant FDPS gain with two-branch receive diversity and in 20 MHz. Further, to have convincing FDPS gain the std. of error of radio state reports needs to be kept within 1.5-2 dB.

I. INTRODUCTION

The ambitious design goal of the 3GPP UTRAN *long-term evolution* (LTE) is to provide spectral efficiency gains in the order of 3-4 compared to e.g. Release 6 *high-speed downlink packet access* (HSPDA) [1, 4]. For the LTE downlink OFDMA is considered to be the best access technology for providing high scalability up to large system bandwidths and to facilitate advanced frequency-domain scheduling methods. As LTE is optimized for packet data transfer only, the packet scheduler functionality assumes great significance. In this paper we study specifically the potential of frequency-domain multiplexing of users according to their instantaneous radio conditions. This is most often referred to as *frequency domain packet scheduling* (FDPS), although time-domain scheduling is inherent as well.

Optimal and sub-optimal sub-carrier based adaptation has been widely studied in the literature, see e.g. [7, 3, 2] and references therein. Most studies are conceptual in nature and disregard practicalities such as limited dynamic range, multi-user multiplexing aspects, amount of signaling overhead, adaptation uncertainties, etc. Such factors are, however, highly relevant in practical system design. Recent studies, e.g. [8, 10, 9], investigate the potential of frequency domain adaptation under less ideal conditions. In [10] the performance of FDPS in a 100 MHz OFDMA system is reported. Assuming a fixed scheduling resolution of 640 kHz and 10 active users, a FDPS capacity gain over time-domain *proportional fair* (PF) scheduling of around 60% is reported. Hence, FDPS appears to be an attractive method although the conditions in [10] are optimistic seen in relation to LTE; e.g. LTE bandwidth is limited to 20 MHz, flexible data rate adaptation per sub-band is hard to achieve due to signaling constraints, and the radio quality estimation errors may exceed the levels assumed in [10].

In this study we include those additional aspects and focus on the conditions required for high FDPS gain in LTE. In particular, the impact of scheduling resolution in frequency-domain, scheduling freedom, radio environment, and *channel quality indication* (CQI) estimation error on FDPS performance is evaluated. Further, the analysis is expanded to include both average cell-level throughput and coverage performance. We initiate the paper by describing the basic FDPS terminology and approach. This includes details related to the used scheduling algorithms and the operating conditions. Next, we present the simulation methodology before moving on to the simulation results and conclusions.

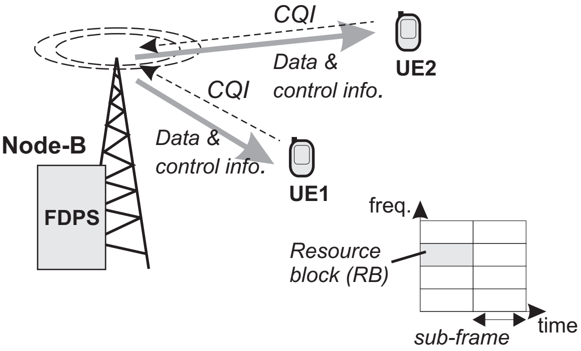

Figure 1: Basic FDPS concept and terminology.

II. FREQUENCY DOMAIN PACKET SCHEDULING

The basic FDPS terminology and framework including the Node-B where the scheduler is based and the *user equipment* (UE) is illustrated in Fig. 1. To frequency multiplex users in OFDMA, the bandwidth (e.g. the number of OFDM sub-carriers) needs to be divided into separable chunks denoted as *resource blocks* (RBs). Chunk based adaptation and user multiplexing is preferred for LTE as it reduces the associated signaling overhead. Moreover, coherence bandwidth of the channel implies that fading is correlated over a group of OFDM sub-carriers. Two main ways of creating the RBs exist:

- *Distributed:* The RB is defined by sub-carriers distributed over the operating bandwidth. No or limited user/selection diversity exists in frequency domain since all resource blocks will experience approximately the same average conditions. Hence, it does not facilitate FDPS but supports full averaging frequency diversity.

1-4244-0330-8/06/$20.00

- *Localized:* The RB is defined as contiguous sub-carriers; e.g. isolated to a certain sub-band within the system bandwidth (see Fig. 1). The method supports full user/selection diversity in the frequency domain and thus FDPS. Depending on the scheduling algorithm, this method also supports significant averaging frequency diversity by allocating scattered RBs to the same user.

The basic terminology as well as multiplexing examples with four users are illustrated in Fig. 2. In LTE both multiplexing methods can be combined.

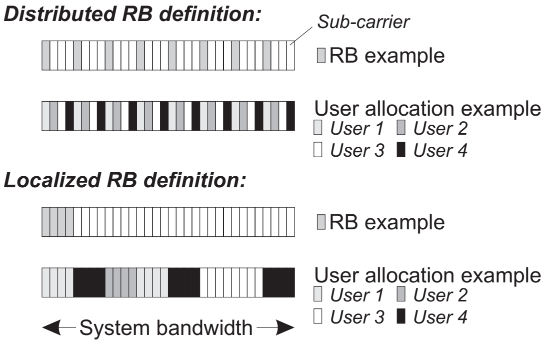

Figure 2: Distributed and localized resource block definitions including examples of user frequency multiplexing.

To yield a high gain of localized RB definition and FDPS the system must be able to (i) schedule with a resolution that is sufficiently small in terms of RB bandwidth and (ii) multiplex users with a large degree of freedom. Further, the Node-B needs accurate CQI reports for each RB in order to make optimal scheduling decision and achieve the gain from user multiplexing. Accuracy of a CQI report depends on two main factors (provided that reliable uplink transmission is available): Accuracy of the RB/CQI measurement and the signaling resolution of the CQI report. In WCDMA/HSDPA the CQI measurement is conducted over a 5 MHz bandwidth and a 2 ms period. Still, the equivalent CQI error in the SINR domain is often modeled as a lognormal error with a 1 dB standard deviation [6]. The CQI resolution for WCDMA/HSDPA is approximately 1 dB. For LTE with shorter sub-frame sizes we may expect significantly larger error levels when considering only a single RB. In this study we model the CQI error per RB as a log-normal SINR error in the dB domain with zero mean and a parameterized standard deviation. The basis of the considered CQI scheme is shown in Fig. 3. It provides high FDPS performance, but is not optimized for the lowest possible overhead.

As a basis for the study we consider the well-known PF algorithm which provides an attractive balance between gain in coverage and gain in average cell capacity [5, 10]. We assume that we know the equivalent and instantaneously supported throughput for each user k on each RB b, $\hat{r}_{k,b}[n]$. We can estimate $\hat{r}_{k,b}[n]$ based on the SINR of the RB (using Shannon-type relation), or the UE may report this value directly (CQI). Our FDPS then picks user k' for scheduling on RB b' which maximizes

$$k' \quad = \quad \arg\max_{k} \left\{ \frac{\hat{r}_{k,b}[n]}{T_k[n]} \right\}. \tag{1}$$

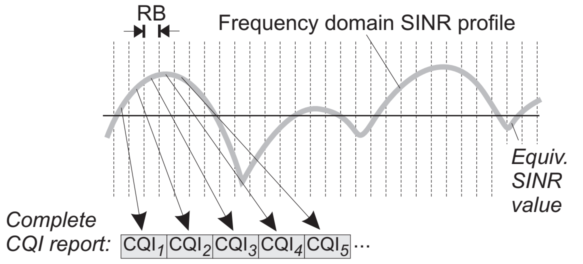

Figure 3: Pictorial illustration of the CQI scheme.

$T_k[n]$ is the average delivered user throughput in the past, and n denotes the current scheduling interval. The average delivered throughput to user k is calculated by the traditional recursive method [5]. It is assumed that the same number of resources (resource blocks and supported throughput) are available for the H-ARQ retransmissions. H-ARQ retransmissions are scheduled and are given same priority as other-user new transmissions. H-ARQ does not limit the effective user diversity order in our model.

For the studies we use the distributed multiplexing scheme (D+PF) as a reference, as it stabilizes the RB conditions for all users. We still use Eq. (1), but now it will only provide user selection diversity in the time domain since all RBs undergo approximately the same average channel conditions. As CQI scheme, only a single wideband CQI measurement is needed, and we assume that the error and reporting levels are the same as for WCDMA/HSDPA (in 20 MHz we have a wider bandwidth, but an equivalently shorter sub-frame interval).

III. SIMULATION METHODOLOGY

We base our evaluation on the UTRAN LTE downlink parameters and assumptions described in [1]. The simulator consists of a detailed link simulator with a quasi-static network overlay which provides traffic modeling, multi-user scheduling, and *link adaptation* (LA) including Chase Combining *hybrid ARQ* (HARQ). The link-level model is based on guidelines in [1]. Furthermore, the system is based on a simple *admission control* (AC) strategy which keeps the number of users per cell constant. Users download a fixed 2 Mbit packet, and when the session is terminated a new user is immediately admitted. Hence, the session time of a user depends on the received data rates. Users within the reference cell are simulated in detail, while othercell interference, path loss, and shadowing are modeled as AWGN adjusted to an equivalent G-factor[1] distribution corresponding to the macrocell environment in [1]. The average G-factor remains constant for a user during a session, thus assuming that the packet call is short compared to the coherence time of the shadow fading. The downlink control and pilot channel overhead is not considered in these studies.

When the PS has selected a certain set of RBs for transmission to a certain user, it assumes that each RB is allocated the same transmission power and transmits using a data rate cor-

---

[1] The G-factor is the ratio of totally received wideband Node-B/intracell power and othercell/noise interference at the UE, and is averaged over short-term fading but not shadowing.

Table 1: Default simulation parameters and assumptions.

Parameter	**Setting**
Physical parameters	See [1]
System bandwidth	20 MHz
Cell-level user distribution	Uniform
RB bandwidth	375 kHz
Number of users (UDO)	10 (default)
Traffic model	Single 2 Mbit packet
Power delay profile	ITU TU and Ped-A†
LA delay	2 ms
D+PF CQI error std	1 dB
FDPS CQI error std	1 dB (default)
CQI reporting resolution	1 dB
Modulation/code rate settings	QPSK 0.2-0.8 16QAM 0.5-0.9 64QAM 0.5-0.9
H-ARQ model	Ideal chase comb.
LA target	10% BLEP (1st TX)
UE speed	3 km/h
UE receiver	Freq. equalizer, 1x2
Channel estimation	Ideal
Carrier frequency	2 GHz
PF filter length (FDPS)	150
PF filter length (D+PF)	300
Initial T_k value	log2(1+$\hat{G}$/2.5)/UDO‡

†*To prevent frequency correlation issues the TU channel uses a 20-tap model, while the Ped-A channel uses a 7-tap model.*
‡$\hat{G}$ *is based on the first available CQI for user.*

responding to the average CQI reports for the RBs. Hence, the FDPS scheme is sub-optimal compared to more advanced loading principles, but does not cause excessive signaling overhead in the downlink and uncontrollable interference issues in the frequency reuse-1 network. Furthermore, complexity and convergence of the algorithm is quite reasonable in comparison to the advanced loading algorithms. The FDPS decision is based on available CQI reports which are modeled with errors associated to (i) measuring inaccuracy modeled as a lognormal error in the SINR domain, (ii) error due to quantization using step size of 1 dB and (iii) a reporting delay corresponding to 2 ms (exact delay is not specified in [1] so we use the existing WCDMA/HSDPA delay scaled for a shorter sub-frame length in UTRAN LTE). LA is conducted according to a 1st transmission target BLEP of 10% extracted from link simulations. We use outer-loop link adaptation to stabilize the 1st transmission BLEP taking into account link adaptation errors due to incorrect CQI reports. The adaptation algorithm uses a target 1st transmission BLEP of 10% and is implemented by adding an adaptive offset to the available CQI report for each user. The offset is updated for each user using direct BLEP estimation when the UE is scheduled and uses a 0.05 dB step-size in the SINR domain. The "real" channel conditions are then used to extract the BLEP, and the associated packet error is then modeled. The HARQ process allows a maximum of three retransmissions before reformatting the data for transmission. Control channel signaling failure is not considered in these simulations. The default simulation assumptions are summarized in Table 1.

IV. RESULTS

A. *FDPS performance as a function of scheduling resolution*

As mentioned, the available scheduling resolution is important for the FDPS potential. In Fig. 4 the RB bandwidth has been adjusted by changing the number of RBs within the 20 MHz bandwidth, and the FDPS capacity and user data rate gains over the distributed (D+PF) scheme are reported. Both channel profiles are considered, and as expected less RBs are needed for high FDPS potential in the environment with the larger coherence bandwidth. The coherence bandwidth of the TU profile is 318 kHz and it is seen that most of the FDPS gain is achieved with a RB width of 375 kHz, i.e. in the order of coherence BW. Furthermore, the results in Fig. 4 show the ability of the PF principle to provide both capacity and coverage gain; the gain in user data rate at 5% outage is around 50%, while the similar capacity gain is about 45%.

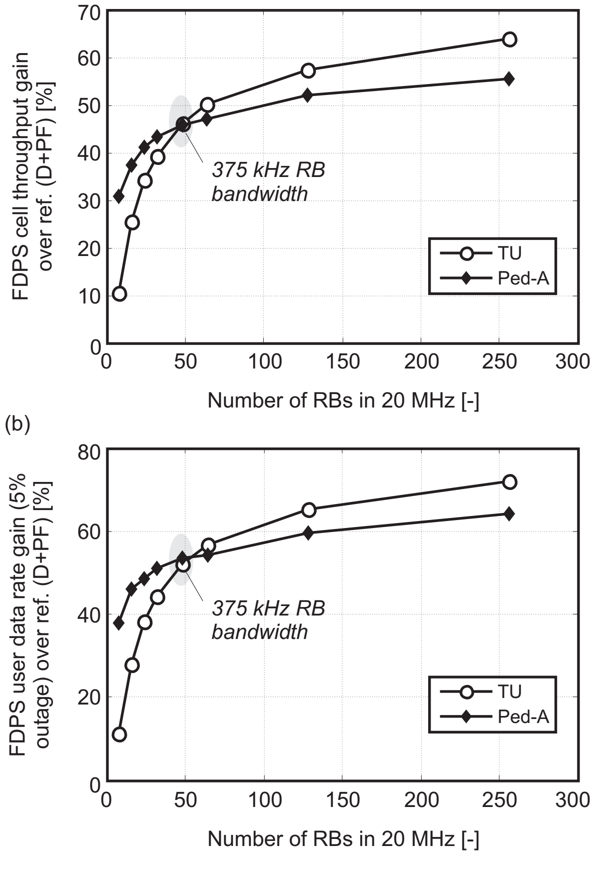

Figure 4: FDPS performance versus RB bandwidth.

To show in more detail the behavior of the schedulers, D+PF, FDPS as well as a maximum throughput scheduler (implemented by hard-coding the denominator in Eq. (1) to a constant for all users/RBs), we compare the average data rate statistics in Fig. 5. Although the wideband channel has limited SINR dynamics for a single user, the D+PF scheduler still provides more fairness than the maximum throughput scheduler. Getting another dimension of freedom, PF in the form of FDPS further enhances the trend and provides a large gain at the 5% cdf point.

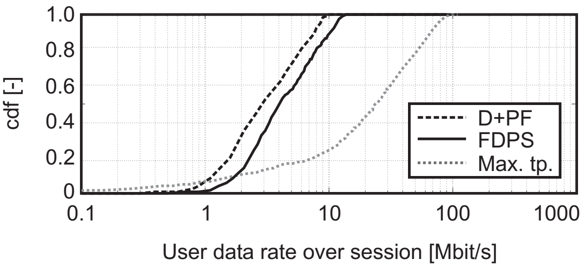

Figure 5: User throughput cdfs for D+PF, FDPS, and a maximum throughput scheduler (TU).

B. *Performance as a function of UDO*

As doubling the RB count immediately doubles the uplink CQI signaling and also impacts downlink allocation signaling needs, we are fixing the number of RBs to 48 in the following simulations; corresponding to an RB bandwidth of 25 subcarriers or 375 kHz. This is also consistent with progress in LTE [1]. Another condition for FDPS potential is to have a high number of users available for scheduling; typically denoted the *user diversity order* (UDO). The capacity results for both the reference scheduler and FDPS are shown in Fig. 6a. By increasing the UDO, the available PF gain in D+PF is about 20%, e.g. somewhat less than for WCDMA due to the larger inherent frequency diversity [6]. Even for low UDO, the available FDPS gain is significant since each user now offers optimization options in both time and frequency domains. The additional FDPS gain over D+PF is about 30-50% over the considered range. In Fig. 6b the user data rate (cdf 5% point) is plotted versus the UDO. As expected the data rate experienced by individual user reduces with increasing UDO. However, the gain in coverage performance improves with UDO. It is about 20-60% over the considered range. Looking at Fig. 6 it appears intuitively wrong that FDPS provides gain over D+PF for UDO=1. However, the FDPS is able to do so by averaging the available CQI reports to provide a very accurate wideband CQI estimate (now limited by the CQI reporting accuracy).

C. *Performance as a function of user multiplexing order*

To investigate the importance of scheduling freedom, the active number of users scheduled per sub-frame are plotted in Fig. 7a. Both channel profiles are considered in the simulation. For Ped-A, the available user diversity gain in the frequency domain is comparatively smaller than for TU due to a larger coherence to system bandwidth ratio. This is reflected in the results where optimally less users need to be scheduled per sub-frame. Further, a large number of users are scheduled per sub-frame on average. This is a non-trivial aspect to system design for FDPS since multiplexing a high number of users involves extensive signaling of allocation details. When a limitation of the multiplexing freedom is needed, this will thus impact the available FDPS performance depending on the environment (e.g. less impact for larger coherence bandwidth). To further investigate this issue we adjust the multiplexing freedom by limiting the number of users that may be multiplexed simultaneously per sub-frame to *N*. When selecting the number of users to schedule we take the *N* best users according to the instantaneous PF metric averaged over the complete system bandwidth. For the selected user subset we then use Eq. (1) to finalize the scheduling decision. The optimization problem is very complicated since individual scheduling decisions are mutually dependent. The used method is sub-optimum, but computationally simple. The results are shown in Fig. 7b. It is clear that limiting the multiplexing freedom impacts negatively the FDPS performance, but significant gain can be achieved even with 5-7 multiplexed users.

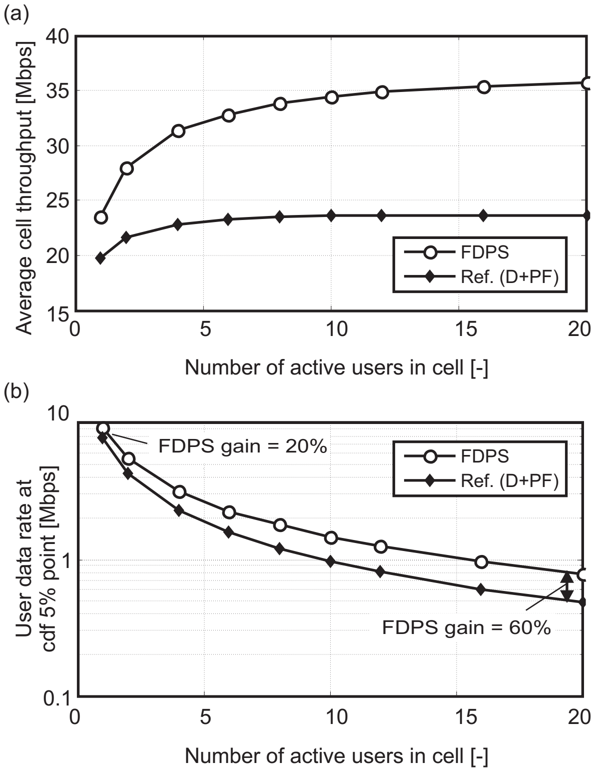

Figure 6: FDPS performance versus UDO (TU).

D. *FDPS performance as a function of std. of CQI error*

As mentioned earlier FDPS relies on the availability of accurate and timely CQI reports. In the previous results we have included a significant, but fixed error on each RB CQI report. As the reference D+PF system can employ a single wideband CQI measurement to represent the channel state, we assume that it can be maintained as accurate as originally assumed (lognormally distributed measurement error in SINR domain with zero mean and 1 dB standard deviation. Reporting accuracy is set at 1 dB). However, the measurement of a narrow RB over a short time interval may be associated with a large error. As measurement accuracy requirements are not yet addressed in LTE, we sweep here the standard deviation of the error model on each RBs CQI measurement. We maintain the 1 dB reporting ac-

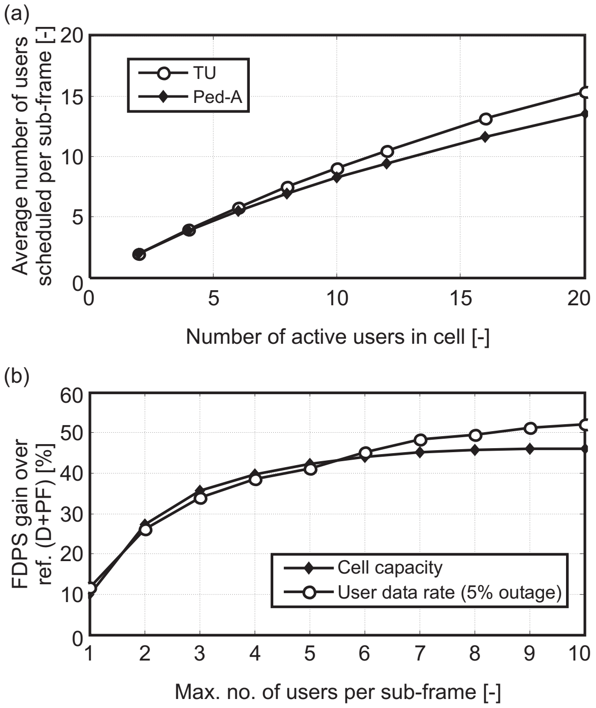

Figure 7: Illustration of FDPS multiplexing behavior and the performance impact of limited multiplexing freedom.

curacy per RB. The FDPS gain over the reference is shown in Fig. 8 considering both the capacity and the user data rate gain at 5% outage. It can be seen that both capacity and coverage performance is highly sensitive to CQI estimation inaccuracies, e.g., the cell-level gain is halved if the std. of error is 2 dB. As the error is increased further, FDPS potential diminishes quickly until a value of around 3-4 dB, where the gain is practically lost. This gives a clear indication of the requirement for accurate CQI reports, and that associated signaling errors must be included in the assessment of FDPS.

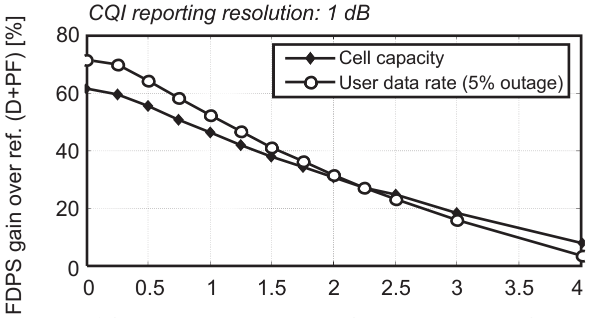

Figure 8: Sensitivity of FDPS performance to CQI error.

V. CONCLUSIONS

In this paper we have studied the potential of *frequency domain packet scheduling* (FDPS) within the framework for UTRAN long-term evolution. We have shown that FDPS needs a scheduling resolution in the order of coherence bandwidth in the frequency domain; preferably down to 375 kHz for the TU profile assumed here. The proposed value does not consider the overhead in associated channel quality signaling, which needs to be carefully studied. The FDPS algorithm considered here is based on the proportional fair principle extended to both the time and frequency domains. A gain of around 40-50% is available in cell throughput even for a relatively low user diversity order and for 1 dB std. error in the channel quality reports. In these conditions around 50-55% gain in user data rates (at 5% outage point) was found. Designing the channel quality state scheme with sufficient accuracy becomes a challenge in the system, as we have shown that the FDPS potential is very sensitive to such errors and should be kept within 1-2 dB. It was shown how FDPS gain depends on the multiplexing freedom and that the system should support simultaneous multiplexing of at least 5-7 users to achieve significant gain.

ACKNOWLEDGMENTS

The authors thank the Aalborg University colleague Na Wei for her assistance in providing detailed link level results and the Nokia colleague Klaus I. Pedersen for useful discussions.

REFERENCES

[1] 3GPP Technical Report 25.814, version 1.0.3. *Physical Layer Aspects for Evolved UTRA*, February 2006.

[2] F. F. Digham and M. O. Hasna. Performance of OFDM with M-QAM Modulation and Optimal Loading over Rayleigh Fading Channels. In *Proceedings of Vehicular Technology Conference (VTC)*, volume 3, pages 1717–1722, Orlando, Florida, USA, October 2003.

[3] A. J. Goldsmith and S.-G. Chua. Variable-Rate Variable-Power MQAM for Fading Channels. *IEEE Transactions on Communications*, 45(10):1218–1230, October 1997.

[4] H. Holma and A. Toskala, editors. *WCDMA for UMTS – Radio Access for Third Generation Mobile Communications*. John Wiley & Sons Inc, 3rd edition, 2004.

[5] A. Jalali, R. Padovani, and R. Pankaj. Data Throughput of CDMA-HDR High Efficiency-High Data Rate Personal Communication Wireless System. In *Proceedings of Vehicular Technology Conference (VTC)*, volume 3, pages 1854–1858, Tokyo, Japan, May 2000.

[6] T. E. Kolding. Link and System Performance Aspects of Proportinal Fair Packet Scheduling in WCDMA/HSDPA. In *Proceedings of 58th IEEE Vehicular Technology Conference (VTC)*, volume 3, pages 1717–1722, Orlando, Florida, USA, October 2003.

[7] B. S. Krongold, K. Ramchandran, and D. L. Jones. Computationally Efficient Optimal Power Allocation Algorithms for Multicarrier Communication Systems. *IEEE Transactions on Communications*, 48(10):23–27, October 2000.

[8] Y. Ofuji, A. Morimoto, H. Atarashi, and M. Sawahashi. Sector Throughput Using Frequency-and-Time Domain Channel-Dependent Packet Scheduling with Channel Prediction in OFDMA Downlink Packet Radio Access. In *Proceedings of IEEE Vehicular Technology Conference (VTC)*, volume 3, pages 1589–1593, Dallas, Texas, USA, September 2005.

[9] A. Pokhariyal, T. E. Kolding, F. Frederiksen, P. Olives, T. B. Sørensen, and P. E. Mogensen. Investigation of Frequency-Domain Link Adaptation for a 5-MHz OFDMA/HSDPA System. In *Proceedings of IEEE Vehicular Technology Conference (VTC)*, volume 3, pages 1463–1467, Stockholm, Sweden, May 2005.

[10] C. Wengerter, J. Ohlhorst, and A. G. E. v. Elbwart. Fairness and Throughput Analysis for Generalized Proportional Fair Frequency Scheduling in OFDMA. In *Proceedings of IEEE Vehicular Technology Conference (VTC)*, volume 3, pages 1903–1907, Stockholm, Sweden, May 2005.