HARQ Aware Frequency Domain Packet Scheduler with Different Degrees of Fairness for the UTRAN Long Term Evolution

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***Abstract*— In this paper we evaluate the performance of downlink channel dependent scheduling in time and frequency domains. The investigation is based on the 3GPP UTRAN long term evolution (LTE) parameters. A scheduler framework is developed encompassing frequency domain packet scheduling, HARQ management and inter-user fairness control. It is shown that by dividing the packet scheduler into a time-domain and a frequency-domain part the fairness between users can be effectively controlled. Different algorithms are applied in each scheduler part, and the combined performance is evaluated in terms of cell throughput, coverage, and capacity. We show that frequency-domain packet scheduling can provide a gain of around 35% in both throughput and coverage over opportunistic time-domain only scheduling. Furthermore, it is shown that by using an equal throughput scheduler, coverage can be improved by 100% at the expense of a 5% loss in average cell throughput in comparison with the proportional fair scheduler.**

I. INTRODUCTION

Orthogonal frequency division multiple access (OFDMA) has been selected as the downlink access technology for the 3GPP UTRAN *long-term evolution* (LTE) system [1]. It provides scalability, simple equalization and facilitates advanced frequency-domain adaptation techniques. In this paper we investigate the performance of various downlink *packet scheduling* (PS) algorithms that are able to exploit available multi-user diversity in both time and frequency domains. This is often referred to as *frequency domain packet scheduling* (FDPS).

Recent FDPS studies [2], [3], [4] have shown significant potential over time-domain only scheduling. Focusing on the LTE it was reported in [4] that FDPS can provide both cell throughput and coverage gain of around 40%. However, in [4] the impact of HARQ on the scheduling flexibility was not explicitly modeled and non-ideal serving cell selection was not included. Further, we extend the study to include also methods for controlling inter-user fairness. A two-layer scheduling framework is developed consisting of a *time-domain* (TD) scheduler followed by a *frequency-domain* (FD) scheduler. We show that this approach can effectively encompass the HARQ scheduling constraints as well as control the fairness among users. We evaluate the performance of the scheduling algorithms based on a detailed system model according to the 3GPP evaluation criteria laid out in [1]. Performance is reported in terms of average cell throughput, coverage and capacity, in the 3GPP macro-cell outdoor scenario. Capacity is defined as the number of users that can be supported at the target coverage data rate.

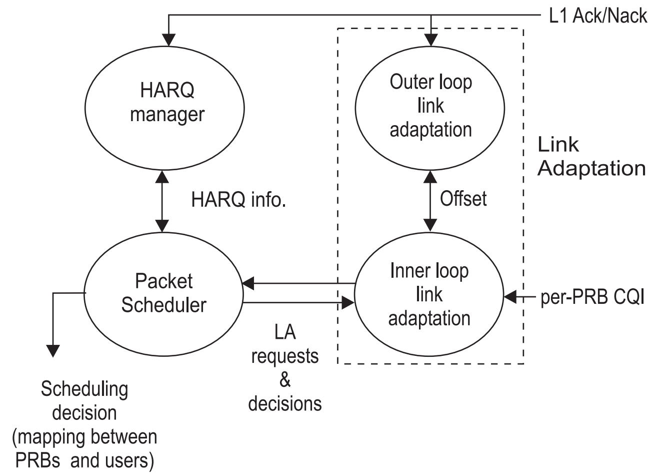

Fig. 1. Interaction between PS, LA & HARQ entities involved in dynamic resource allocation.

The paper is organized as follows. Section II presents the scheduler frame-work including detailed algorithm descriptions as well as inner and outer loop link adaptation. Section III presents the system model and the simulation assumptions, while Section IV covers the simulation results and analysis. Finally, the conclusions are presented in Section V.

II. TIME AND FREQUENCY DOMAIN PACKET SCHEDULER

The interaction between the main entities involved in scheduling, i.e., packet scheduler, link adaptation (LA) and HARQ manager is illustrated in Fig. 1. These entities are located at the base station (eNode-B) in order to support fast adaptation to radio channel conditions. The controlling entity is the packet scheduler. The minimum resolution for scheduling in the frequency domain is one *physical resource block* (PRB), and its bandwidth is equal to 375 kHz [1]. 24 PRBs are available in 10 MHz bandwidth, each consisting of 25 neighboring sub-carriers. The packet scheduler can consult link adaptation to obtain an estimate of the supported data rate for certain users in the cell for different allocations of PRBs. Link adaptation is based on the channel quality indication (CQI) feedback from the users, as well as Ack/Nack's from past transmissions to ensure that the estimate of the supported data rate corresponds to a certain block error rate (BLER)

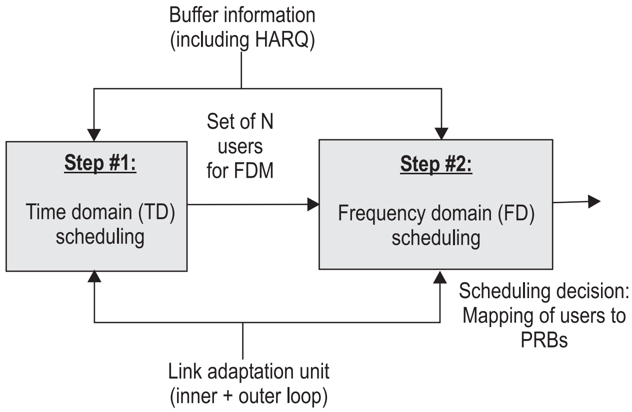

Fig. 2. Packet scheduler framework illustrating the split between the time and the frequency-domain scheduling parts.

target for the first transmissions. Outer loop link adaptation is used to stabilize the BLER performance [5]. The HARQ manager provides buffer status information as well as transmission format of the pending HARQ retransmissions.

The overall packet scheduling framework is illustrated in Fig. 2, where a simple two step algorithm is proposed. In step #1 the TD scheduler selects N users which are frequency-multiplexed by the FD scheduler in step #2. This framework is attractive from a complexity point of view, since the FD scheduler only has to consider frequency multiplexing of maximum N users per TTI. The value of N is set according to potential signaling constraints as well as the number of PRBs in the scheduling bandwidth. Assuming that the number of users in the cell, D, is larger than N ($D > N$), the TD scheduler provides the primary mechanism for controlling QoS of the users, while the FD scheduler mostly tries to optimize spectral efficiency per TTI, given the input from the TD scheduler. Note that the overall scheduler performance will be sub-optimum due to the limited user diversity order at the FD scheduler. It is worth noticing that although the scheduling framework consists of two successive steps, there is in many cases a dependency between the TD and the FD schedulers. This is especially the case for the TD schedulers which depend on average throughput delivered to users in the past (i.e., depend also on the FD scheduler). Given this scheduling framework, the QoS aware scheduling algorithms studied for WCDMA/HSDPA [6] are also applicable for the TD scheduler in Step #1 with minor modifications.

A. TD scheduling

The TD scheduler in Fig. 2 selects the N users with the highest scheduling priority for subsequent FD scheduling, where N is a parameter for the TD scheduler. Let us denote the instantaneously supported throughput of user m as $\hat{r}_m[n]$. It is obtained from the link adaptation unit assuming simple full bandwidth transmission with the eNode-B transmit power divided equally among the PRBs. For each TD scheduler variant we define a priority metric for user m, P_m, and the scheduler picks the N users that at the scheduling time have the highest value of this metric. The following TD scheduling priority metrics have been considered:

- Time-Domain Proportional Fair (TD-PF)

$$P_m = \frac{\hat{r}_m[n]}{T_m[n]} \quad , \tag{1}$$

  where $T_m[n]$ denotes the average delivered user throughput in the past, calculated by the recursive method outlined in [7] and n denotes the current scheduling interval.
- Time-Domain Maximum Throughput (TD-MT)

$$P_m = \hat{r}_m[n] \quad . \tag{2}$$

  This scheduler prioritizes users closer to the eNode-B.
- Time-Domain Blind Equal Throughput (TD-BET)

$$P_m = \frac{1}{T_m[n]} \quad . \tag{3}$$

  This scheduler aims at maintaining equal user throughput irrespective of user location. It does not require a priori knowledge of the radio channel.

The set of users considered by the TD scheduler includes both users with new data as well as those with pending retransmissions. Further, users with pending retransmissions are not prioritized by the TD scheduler.

B. HARQ aware FD scheduler

The FD scheduler is responsible for allocating the M available PRBs to the N selected users. In order to gain from the multi-user frequency diversity scheduling it is desirable to map users to those PRBs where they experience relatively good channel quality. This is a non-trivial optimization problem, which is further complicated by the additional constraint that pending HARQ retransmissions shall be transmitted on the same number of PRBs as the original transmission. However, the FD scheduler still has the freedom to select PRBs for a

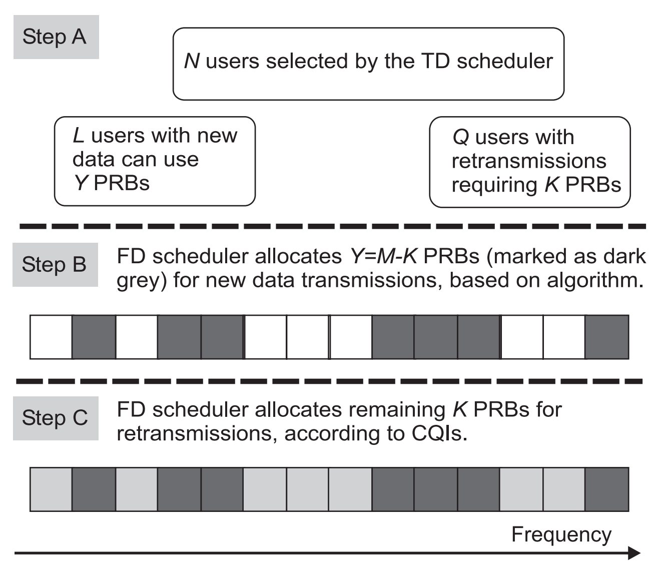

Fig. 3. Mechanism used by the FD scheduler to allocate PRB resources to 1st transmission and retransmission users.

retransmission as long as the number of PRBs is the same as for original transmission (*adaptive HARQ*). The steps involved in HARQ management are illustrated in Fig. 3. In order to limit the HARQ retransmission delays we choose to give priority to pending HARQ retransmissions in the FD scheduler. Hence, assuming that Q of the N users have pending retransmissions requiring allocation of K PRBs, this leaves $Y = M - K$ PRBs for transmission of new data from the remaining L users (Step A in Fig. 3). We begin by allocating up to Y PRBs to the L users with new data to transmit (Step B). This gives maximum flexibility in selecting PRBs for the users with relatively high channel quality, which tends to maximize the transmitted throughput for new data. The remaining K PRBs are subsequently allocated to the Q users with pending retransmissions (Step C). It means that there are less degrees of freedom for selecting good PRBs for retransmissions, as compared to new data. This approach is taken because it is less critical to have good channel quality for retransmissions, as these will most likely be correctly received due to the HARQ combining gain. The assumption is that the BLER for the first transmissions equals 20%.

Let use denote the instantaneous throughput of user m on PRB b by $\hat{r}_{m,b}[n]$. This throughput estimate is obtained from link adaptation based on the CQI report for the particular PRB and assuming equal power per PRB. Given this starting point we investigate the performance of the following FD scheduler options:

- Frequency-Domain Equal Resource (FD-ER) - The scheduler picks user m' for scheduling on PRB b which maximizes

$$m' = \arg\max_{m} \left\{ \hat{r}_{m,b}[n] \right\} \quad , \tag{4}$$

  subject to the constraint that a maximum of $\lceil Y/L \rceil$ PRBs are allocated to each user in Step B, i.e., equal PRB allocation per user.
- Frequency-Domain Proportional Fair (FD-PF)

$$m' = \arg\max_{m} \left\{ \frac{\hat{r}_{m,b}[n]}{T_m[n]} \right\} \quad . \tag{5}$$

- Frequency-Domain Throughput-to-Average (FD-TA) -

$$m' = \arg\max_{m} \left\{ \frac{\hat{r}_{m,b}[n]}{\hat{r}_m[n]} \right\} \quad , \tag{6}$$

  where $\hat{r}_m[n]$ denotes the instantaneous supported throughput based on full BW transmission using a single optimized MCS format.

C. Reference scheduler

In order to quantify the gain of FDPS, we also simulate the performance of a reference scheme with time-opportunistic scheduling. A single user is selected in each TTI based on the priority metric given by (1).

III. System Model

The performance evaluation is based on a detailed multi-cell system model, which follows the guidelines in [1]. The system bandwidth is fixed at 10 MHz with settings according to the LTE working assumptions. The main simulation parameters are listed in Table I, assuming macro case 1 deployment scenario. The link-to-system level mapping is based on the *exponential effective SNR metric* (EESM) model [1]. The location of users is randomly assigned with a uniform distribution within each cell. Further, each user experiences inter-cell interference from all surrounding cells. It is assumed that distance dependent path loss and shadow fading is constant during a packet call. Shadowing is fully correlated between cells of the same site, while the correlation is 0.5 between sites. Fast fading is updated in each TTI based on the ITU Typical Urban (TU) power delay profile. A finite buffer best effort traffic model is employed, where each user downloads a 2 Mbit packet. The session is terminated as soon as the download is completed and a new user is immediately added to the system. There are six HARQ stop-and-wait processes per user operating in an adaptive asynchronous scheme. The serving cell is selected randomly among the strongest cells within a cell selection margin of 2 dB.

TABLE I
DEFAULT SIMULATION PARAMETERS AND MODEL ASSUMPTIONS.

Parameter	**Setting**
System bandwidth	10 MHz
Sub-carriers per PRB	25
Cellular Layout	Hexagonal grid, 19 cell sites, 3 cells per site
Inter-site distance	500 m
Total eNode-B transmit power	46 dBm
Penetration loss	20 dB
Shadowing standard deviation	8 dB
Min. dist. between UE and cell	35 m
Avg. number of users per cell	20
Max. users multiplexed per sub-frame (N)	6
Traffic model	Single 2 Mbit packet
Power delay profile	ITU Typical Urban, 20 paths
Ack/Nack delay	2 ms
CQI log-normal error std.	1 dB
CQI reporting resolution	1 dB
CQI delay	4 ms
Pilot, control channel overhead	28.5% (2/7 symbols)
Modulation/code rate settings	QPSK (R= 1/3, 1/2, 2/3), 16QAM (R=1/2, 2/3, 4/5), 64QAM (R=1/2, 2/3, 4/5)
HARQ model	Ideal chase comb.
1st trans BLER target	20%
UE speed	3 km/h
UE receiver	2-Rx MRC
Channel estimation	Ideal
Cell selection margin	2 dB

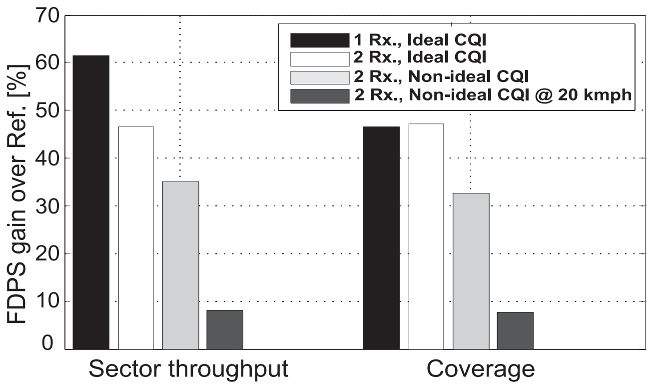

Fig. 4. FDPS (TD-PF/FD-PF) cell throughput and coverage gain over the reference scheme.

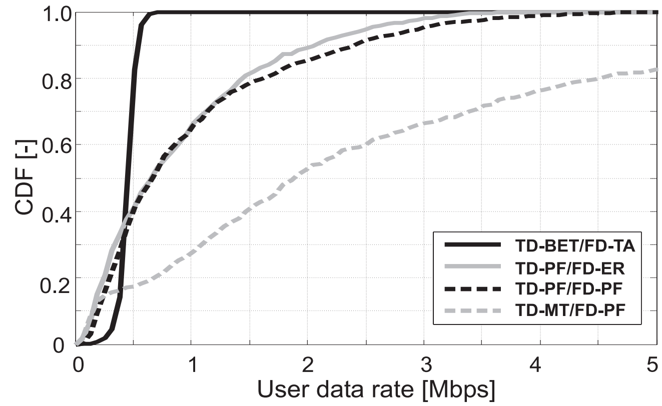

Fig. 6. CDF of user data rate for different scheduler combinations.

IV. Simulation Results

The performance of scheduling algorithms is evaluated in terms of average cell throughput and coverage. Coverage is defined as the per-user experienced data rate at the 95% coverage probability. Fig. 4 illustrates the relative gain of FDPS over the simple reference scheduler described in Section II-C as a function of the receive diversity order, CQI error and speed. The TD-PF/FD-PF scheme can provide throughput gain of around 60% for 1x1 deployment case and 45% for receive diversity case, when CQI without imperfections is used and at 3 km/h. With CQI imperfections, as given in Table I, the FDPS throughput gain is reduced to around 35% for the receive diversity case and $N = 6$. The sensitivity of FDPS performance to speed is clearly visible as the gain drops to below 10% at a speed of 20 km/h. Link adaptation is not able to track channel conditions accurately at this speed. Further, the time-domain channel variations are superimposed on top of the frequency-domain variations which cause the experienced SINR to deteriorate.

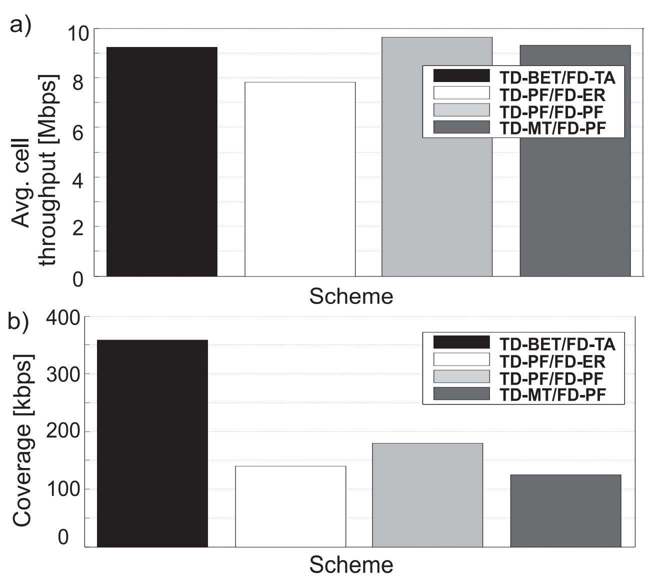

Fig. 5. Throughput and coverage performance of different TD and FD scheduler combinations.

The results in Fig. 5 show the trade-off between average cell throughput and coverage for the different scheduler combinations. For comparison purposes we use the popular proportional fair scheduler in both time and frequency (TD-PF/FD-PF) as our reference. By using the combination of TD-BET and FD-TA schedulers the coverage is increased by approximately 100%, while average cell throughput only decreases by around 5%. This gain/loss imbalance is due to the cell throughput being determined mainly by users experiencing less favorable conditions (due to the completely data-fair traffic model). Since the TD-BET scheduler greatly enhances performance of such users, the negative impact on cell throughput due to loss in data rate of users close to the eNode-B is not significant. On the contrary it is observed that the TD-PF/FD-ER scheduler looses in both cell throughput and coverage as compared to the TD-PF/FD-PF scheduler. This behavior is seen as a result of the constraint on the FD-ER scheduler to allocate an equal number of PRBs to all users (equal scheduling bandwidth), which clearly limits the gain potential of multi-user frequency diversity.

Fig. 6 shows the cumulative distribution function (CDF) of user experienced data rate for different scheduler combinations. The TD-BET scheduler is able to tightly control fairness among users, while the TD-MT scheduler can provide high data rates to users with good channel conditions, at the cost of users close to the cell edge.

The characteristics of different schedulers are analyzed in detail in Fig. 7. Fig. 7(a) shows that the TD-BET/FD-TA combination allocates a higher proportion of PRBs to users whose G-factor[1] is within -3 dB to 13 dB. When the G-factor is outside this range, the ratio in (6) becomes small ($\approx \frac{1}{M}$), due to the limited MCS range. However, within the specified G-factor range the ratio can be even greater than one, which results in the comparatively larger PRB allocation for such users. As expected the FD-ER scheduler allocates the same number of PRBs irrespective of the G-factor. Fig. 7(b) illustrates the potential of TD-BET scheme to tightly control

[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.

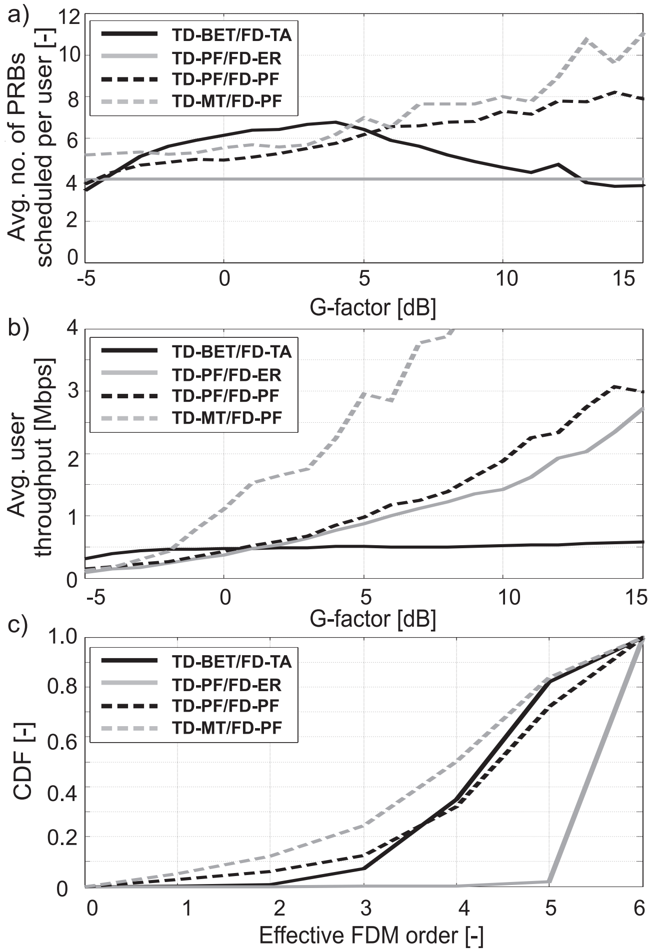

Fig. 7. Comparative performance of scheduler combinations.

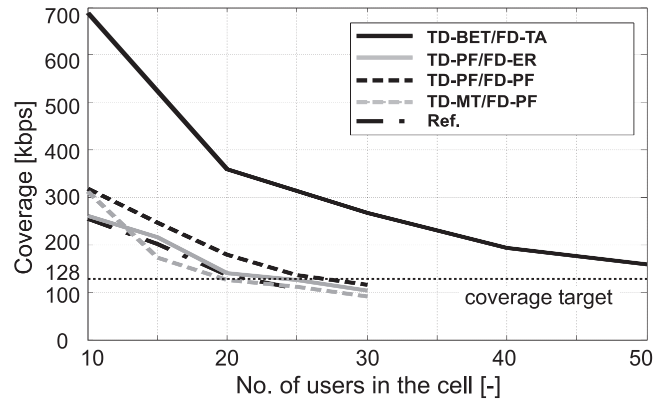

Fig. 8. Coverage performance as a function of the number of users in the cell.

user throughput over the entire cell area. In Fig. 7(c) we observe the effective frequency division multiplexing (FDM) order, defined as number of users multiplexed per sub-frame after FD scheduler processing. It is seen that the FD-ER algorithm schedules more users, close to the maximum FDM order (N). As expected the TD-MT/FD-PF combination tends to multiplex few users with relatively good channel quality.

Fig. 8 illustrates the cell capacity in terms of number of simultaneous users that can be supported at 128 kbps with 5% outage. Here we also include the reference case. The coverage enhancing potential of the TD-BET/FD-TA scheduler is clearly visible as it can almost double the number of users at the target coverage rate in comparison with the TD-PF/FD-PF scheduler.

V. Conclusions

In this paper we have evaluated the performance of downlink channel dependent packet scheduling for the UTRAN Long Term Evolution (LTE). Several practical system aspects such as imperfect frequency selective *channel quality indication* (CQI), link-to-system mapping and HARQ limitations are included in the analysis. A two-layer scheduler framework is devised consisting of a time-domain part followed by a frequency-domain part. We have shown that this approach is suitable for managing HARQ retransmissions and inter-user fairness. Various combinations of time and frequency-domain scheduling algorithms are investigated, which provide a trade-off between coverage and throughput. Results show that FDPS can provide a gain of around 35% in both throughput and coverage over time-domain opportunistic scheduling. Furthermore, it is shown that an equal throughput scheduler can improve coverage by 100% at the expense of around 5% loss in cell throughput, compared to the proportional fair scheduler. The results indicate that inter-user fairness can be effectively controlled by the time-domain scheduler.

Acknowledgment

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