Efficient Packet Scheduling Schemes with Built-in Fairness Control for Multiantenna Packet Radio Systems

Stanislav Nonchev and Mikko Valkama
Tampere University of Technology
Department of Communications Engineering
P.O. Box 553, FI-33101, Tampere, FINLAND
Email: stanislav.nonchev@tut.fi, mikko.e.valkama@tut.fi

Abstract – In this article, we propose fairness-oriented dual stream multiple-input multiple-output (MIMO) packet scheduling schemes with efficient utilization of channel quality indicator (CQI) feedback for emerging multiantenna packet radio systems. In general, multiuser multiantenna transmission schemes allow users to be scheduled on different parallel streams on the same time-frequency resource. Based on that, implementations of more intelligent scheduling schemes that are aware of the instantaneous state of the radio channel require utilization of time, frequency and spatial domain resources in an efficient manner. Stemming from the earlier advanced proportional fair (PF) scheduler studies, we extend the developments to dual stream MIMO packet radios with fairness-oriented scheduling metric and practical feedback reporting mechanisms, including the effects of mobile measurement and estimation errors, reporting delays, and CQI quantization and compression. Furthermore, we investigate the resulting fairness distribution among users together with the achievable radio system performance in terms of throughput and coverage, by simulating practical OFDMA cellular system environment with MIMO functionality in Micro and Macro cell scenarios. As a concrete example, we demonstrate that by using the proposed fairness-oriented multiuser scheduling schemes, significant coverage improvements in the order of 40% can be obtained at the expense of only 16% throughput loss for all feedback reporting schemes. Furthermore, the user fairness is also greatly increased, by more than 30%, when measured using Jain's fairness index.

Keywords - radio resource management; packet scheduling; proportional fair; channel quality feedback; fairness; coverage; throughput; multiantenna

I. INTRODUCTION

The advancement of new radio technologies for beyond third generation (3G) cellular systems continues steadily. This includes, e.g., third generation partnership project (3GPP) long term evolution (LTE) [2], worldwide interoperability for microwave access (WiMAX) [3] and the work in various research projects, like WINNER [4]. Some common elements in most of these developments are orthogonal frequency division multiple access (OFDMA) based air interface, operating bandwidths of at least 10-20 MHz, and the exploitation of multiple-input multiple-output (MIMO) techniques and advanced channel-aware packet scheduling principles [2]. MIMO in terms of *spatial multiplexing* (SM), possibly combined with pre-coding, is considered as one core physical layer technology towards increased link spectral efficiencies compared to existing radio systems. In addition, it also provides the packet scheduler (PS) with an extra degree of freedom (spatial domain), by offering a possibility to multiplex multiple data streams of one or more users on the same physical time-frequency resource. The two principal concepts widely analyzed in literature (see, e.g., [5]-[6] and the references therein) in this context are single user (SU) and multiuser (MU) MIMO. The SU-MIMO approach allows only the streams of one individual UE to be scheduled at the same time-frequency resource block (RB), while MU-MIMO provides additional flexibility so that streams of multiple users can be scheduled over the same time-frequency RB. Assuming relatively accurate channel state feedback in terms of channel quality indicator (CQI) reports from mobile stations (MS) to base station (BS), together with fast link adaptation mechanisms, advanced channel-aware packet scheduling schemes have major impact on the system-level performance optimization in terms of, e.g., throughput and coverage. Practical CQI reporting mechanisms in this context are described, e.g., in [7]-[13]. Another important feature of multiuser radio systems related to scheduling, in addition to throughput and coverage, is fairness, implying that also users with less favorable channel conditions should anyway be given some reasonable access to the radio spectrum. This is especially important in serving users at, e.g., cell edges in cellular networks.

Recently, multiantenna oriented packet scheduling principles have started to be investigated in the literature, see, e.g., [14]-[19]. New scheduling algorithms have been proposed and their performance been evaluated in different simulator environments in [1], [16]-[19]. In this article, we concentrate on the proportional fair (PF) principle, which in general offers an attractive balance between cell throughput and user fairness, and extend it with spatial domain functionality for the needs of SU- and MU-MIMO operation. More specifically, we extend our earlier studies in [1], [18]-[19] on algorithm development by deploying SM functionality to frequency domain (FD) PF scheduling schemes that can efficiently utilize the provided feedback information from all the user equipments (UEs), in terms of quantized CQI reports. A new packet scheduler is proposed, called MIMO modified PF (MMPF), with built-in fairness control in its scheduling metric, which is shown to improve the system performance considerably, in terms of cell-edge coverage and overall scheduling fairness, when compared to existing reference schedulers. For practicality, all the performance evaluations are carried out in 3GPP LTE system context, covering both Micro and Macro Cell scenarios, and conforming to the 3GPP evaluation criteria [2]. The used radio system performance measures are cell throughput distribution, average throughput, cell-edge coverage and Jain's fairness index [21].

In general, while the increased flexibility of channel-aware scheduling can offer great performance enhancements, compared to fixed resource allocation, it also has some practical disadvantages. This includes, e.g., relatively higher scheduling complexity, in terms of scheduling metric calculations and increased signaling overhead to facilitate CQI reporting. Keeping these at reasonable levels requires thus some constraints on the scheduling algorithm, so for simplicity we assume here that only one MIMO mode (SU or MU) and fixed modulation and coding scheme (MCS) is allowed per user within one time-frequency scheduling element (RB). For simplicity, we also assume that the BS as well as all the UE's are equipped with 2 antennas (dual antenna TX and RX).

The rest of the article is organised as follows: Section II describes the MIMO channel-aware scheduling principles and the proposed fairness-oriented scheduling scheme. Section III, in turn, gives an overview of different feedback reporting schemes in packet scheduling context. The overall radio system model and simulation assumptions are then presented and discussed in Section IV. The corresponding simulation results and analysis are presented in Section V, while the conclusions are drawn in Section VI.

II. Channel-Aware MIMO Scheduling

In general, the task of the packet scheduler is to select the most suitable users to access the overall radio resources at any given time window, based on some selected priority metric calculations. Typically the scheduler also interacts with other radio resource management (RRM) units such as *link adaptation* (LA) and *Hybrid ARQ* (HARQ) manager as shown in Figure 1. The scheduling decision is based on received users' signaling information in terms of acknowledgements (ACK/NACK) and channel state information (CQI reports) per given transmission time interval (TTI) [9] and per frequency domain physical resource block (PRB). More specifically, in this article in multiantenna radio system context, we assume that both single stream and dual stream CQIs are reported to BS by each UE. Depending on the selected CQI reporting scheme, the accuracy and resolution of the channel quality information can then easily differ considerably [7], [8], [11], [12], as will be explained in Section III. Moreover, the CQI information is not necessarily available for all the individual subcarriers but more likely for certain groups of subcarriers only [13], [22], [23]. Based on this information, the BS scheduler then decides whether the particular time-frequency resource is used for (i) transmitting only one stream to a specific UE, (ii) two streams for a specific UE (SU-MIMO) or (iii) two streams to two different UEs (MU-MIMO, one stream per UE).

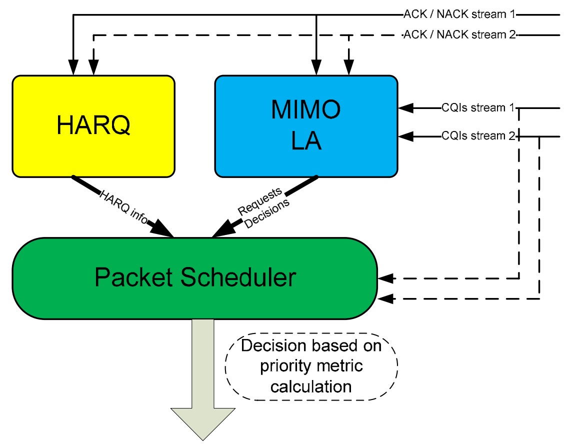

Figure 1: Joint time- and frequency-domain scheduling process.

A. *Proposed Scheduler at Principal Level*

In general, we use the well-known two-step PF approach with extended functionality in extra spatial dimension to enable MIMO operation [1], [5], [18]-[19]. The first step is time-domain (TD) scheduling in which the scheduler selects a sub-group of users in each TTI, called scheduling candidate set, based on the full bandwidth channel state information. More specifically, the TD step selects those I_{BUFF} UE's (out of the total number of UE's, say I_{TOT}) whose total instantaneous throughput, per TTI, calculated over the full bandwidth is highest [20]. In this stage, we also take the different spatial multiplexing possibilities (single stream, dual stream SU, dual stream MU) into account, in calculating all the possible full bandwidth reference throughputs.

The second step is then frequency-domain (FD) / spatial-domain (SD) scheduling in which the scheduler first reserves the needed PRB's for pending re-transmissions (on one stream-basis only for simplicity) and the rest available PRB's are allocated to the selected UE's of the scheduling candidate set obtained from the TD step. The actual metric in FD/SD allocation is based on the PRB-level and stream-wise channel state information, and the corresponding throughput calculations, as will be explained in more details below.

B. *Exact Scheduling Metrics*

Here we describe the actual scheduling metrics used in ranking users in the TD scheduling step as well as mapping the users to FD/SD resources in the second step. First a multistream extension of "ordinary" PF is described in sub-section II.B.1, used as a reference in the performance simulations, and then the actual proposed modified metric with increased fairness-control is described in sub-section II.B.2.

1) *Multistream Proportional Fair:*

For the PF scheduler, scheduling decision per TTI is based on the following priority metric

$$\gamma_{i,k,s} = \arg\max_i \left\{ \frac{R_{i,k,s}(n)}{T_i(n)} \right\} \tag{1}$$

in which $R_{i,k,s}(n)$ is the estimated instantaneous throughput of user i at sub-band k on stream s for the time instant (TTI) n (calculated based on the CQI reports through, e.g., EESM mapping [1]). $T_i(n)$, in turn, is the average delivered throughput to the UE i during the recent past and is calculated by

$$T_i(n) = \left(1 - \frac{1}{t_c}\right) T_i(n-1) + \frac{1}{t_c} R_i(n-1) \tag{2}$$

Here t_c controls the averaging window length over which the average delivered throughput is calculated [11]-[15] and $R_i(n\text{-}1)$ is the actually delivered throughput to user i at previous TTI n-1, calculated over all sub-bands k and possible streams s. In general, $1/t_c$ is also called the forgetting factor.

Considering the previous TD and FD/SD steps described earlier in Section II.A, the above metrics are used as follows:

a) TD: Metric (1) is evaluated over the full bandwidth and for different stream options to rank the I_{TOT} UE's. Out of these, $I_{BUFF} < I_{TOT}$ UE's with highest metric are picked to the following FD/SD stage. In the following, this subset is called scheduling candidate set (SCS), and is denoted by $\Omega(n)$.

b) FD/SD: The access to individual PRB and stream(s) is granted for the user(s) belonging to the above SCS with the highest metric (1) evaluated for the particular PRB and stream at hand.

2) *Modified Multistream Proportional Fair (MMPF):*

Stemming from the earlier work in [1], [11], the following modified multistream PF metric is proposed:

$$\overline{\gamma}_{i,k,s} = \arg\max_i \left\{ \left(\frac{CQI_{i,k,s}(n)}{CQI_i^{ave}(n)} \right)^{\alpha_1} \left(\frac{T_i(n)}{T_{tot}(n)} \right)^{-\alpha_2} \right\} \tag{3}$$

Here, α_1 and α_2 are scheduler optimization parameters ranging basically from 0 to infinity, $CQI_{i,k,s}$ is the CQI of user i at PRB k and stream s, and $CQI^{ave}{}_i$ is the average CQI of user i calculated using

$$\begin{aligned} CQI_i^{avg}(n) &= \left(1 - \frac{1}{t_c}\right) CQI_i^{avg}(n-1) \\ &+ \frac{1}{t_c} \frac{1}{K_{TOT}} \frac{1}{S_{TOT}} \sum_{s=1}^{S_{TOT}} \sum_{k=1}^{K_{TOT}} CQI_{i,k,s}(n) \end{aligned} \tag{4}$$

In above, K_{TOT} is the total number of available PRB's while S_{TOT} denotes the maximum number of streams which is here two (max two streams). In (3), $T_{tot}(n)$ is the average delivered throughput (during the recent past) to all I_{BUFF} users served by the BS and is calculated as

$$\begin{aligned} &T_{tot}(n) = \\ &\left(1 - \frac{1}{t_c}\right) T_{tot}(n-1) + \frac{1}{t_c} \frac{1}{I_{BUFF}} \sum_{i \in \Omega(n-1)} T_i(n-1) \end{aligned} \tag{5}$$

Intuitively, the proposed scheduling metric in (3) is composed of two elements affecting the overall scheduling decisions. The first dimension measures in a stream-wise manner the relative instantaneous quality of the individual user's radio channels against their own average channel qualities while the second dimension is related to measuring the achievable throughput of individual UE's against the corresponding average throughput of scheduled users. In this way, and by understanding the power coefficients α_1 and α_2 as additional adjustable parameters, the exact scheduler statistics can be tuned and controlled to obtain a desired balance between the throughput and fairness. This will be demonstrated later using radio system simulations. Considering finally the actual TD and FD/SD steps described at general level in Section II.A, the same approach as in sub-section II.B.1 is deployed but the metrics (1)-(2) are of course here replaced by the metrics in (3)-(5).

III. FEEDBACK REPORTING PROCESS

The overall channel state reporting process between UE's and BS is illustrated in Figure 2. Within each time window of length t_r, each mobile sends channel quality indicator (CQI) reports to BS, formatted and possibly compressed, with a reporting delay of t_d seconds [7] , [8], [11], [12]. Each report is naturally subject to errors due to imperfect decoding of the received signal. In general, the CQI reporting frequency-resolution has a direct impact on the achievable multiuser frequency diversity and thereon to the overall system performance and the efficiency of radio resource management, as described in general, e.g., in [12]. In our studies here, the starting point (reference case) is that the CQI reports are quantized SINR measurements across the entire bandwidth (wideband CQI reporting), to take advantage of the time and frequency variations of the radio channels for the different users. Then also alternative reduced feedback schemes are described and evaluated, as discussed below.

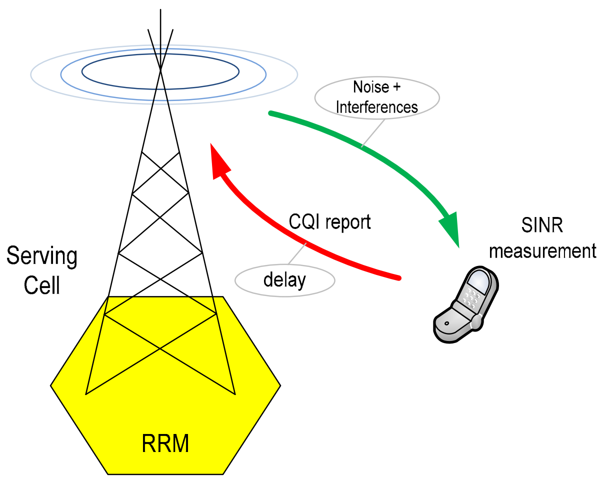

Figure 2: Reporting mechanism between UE and BS.

A. Full CQI Reporting

In a general OFDMA radio system, the overall system bandwidth is assumed to be divided into v CQI measurement blocks. Then quantizing the CQI values to say q bits, the overall full CQI report size is

$$S_{full} = q \times v \tag{6}$$

bits which is reported by every UE for each TTI [2]-[4], [12]. In case of LTE, with 10 MHz system bandwidth and grouping 2 physical resource blocks into 1 measurement block, it follows that v = 25. Assuming further that quantization is carried with q = 5 bits, then each UE is sending 25x5 = 125 bits for every 1ms (TTI length).

B. Best-m CQI Reporting

One simple approach to reduce the reporting and feedback signaling is obtained as follows. The method is based on selecting only $m < v$ different CQI measurements and reporting them together with their frequency positions to the serving cell [9], [12]. We assume here that the evaluation criteria for choosing those m sub-bands for reporting is based on the highest SINR values (hence the name *Best-m*). The resulting report size in bits is then given by

$$S_{best-m} = q \times m + \left\lceil \log_2\left(\frac{v!}{m!(v-m)!}\right)\right\rceil \tag{7}$$

As an example, with v = 25, q = 5 bits and m = 10, it follows that $S_{best\text{-}m}$ = 72 bits, while S_{full} = 125 bits. Furthermore, on the scheduler side, we assume that the PRBs which are not reported by the UE are allocated a CQI value equal to the lowest reported one.

C. Threshold based CQI Reporting

This reporting scheme is a further simplification and relies on providing information on only the average CQI value above certain threshold together with the corresponding location (sub-band index) information. First the highest CQI value is identified within the full bandwidth, which sets an upper bound of the used threshold window. All CQI values within the threshold window are then averaged and only this information is sent to the BS together with the corresponding sub-band indexes. On the scheduler side, the missing CQI values can then be treated, e.g., as the reported averaged CQI value minus a given dB offset (e.g., 5 dB; the exact number is again a design parameter). The number of bits needed for reporting is therefore only

$$S_{threshold} = q + v \tag{8}$$

As an example, with v = 25 and q = 5 bits (as above), it follows that $S_{threshold}$ = 30 bits, while $S_{best\text{-}m}$ = 72 bits and S_{full} = 125 bits. The threshold-based scheme is illustrated graphically in Figure 3 [11].

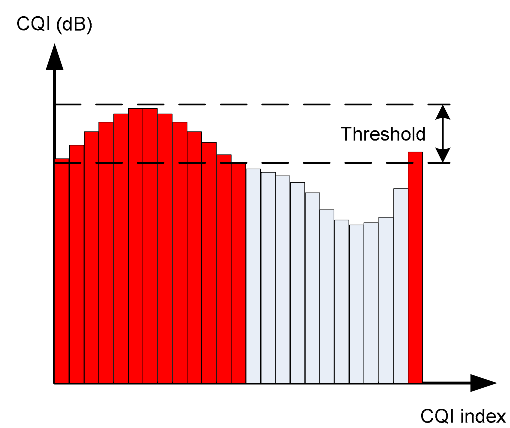

Figure 3: Basic principle of threshold-based CQI reporting.

IV. Quasi-Static Radio System Simulator

A. Basic Features

System-level performance of the proposed scheduling scheme is evaluated based on a quasi-static radio system simulator for LTE downlink, providing traffic modeling, multiuser packet scheduling and link adaptation [2]. As a practical example, the 10 MHz system bandwidth case of LTE is assumed, meaning that there are 50 physical resource blocks each consisting of 12 sub-carriers with sub-carrier spacing of 15 kHz. This sets also the basic resolution in FD/SD UE multiplexing (scheduling), i.e., the allocated individual UE bandwidths are multiples of the PRB bandwidth. The actual reported CQI's are based on received signal-to-interference-and-noise ratios (SINR), calculated by the UE's for each PRB. Here the UE's are assumed to deploy dual antenna linear MMSE (LMMSE) receiver principle, and utilize in the SINR calculations the actual radio channel response, the received noise level, and the structure of the detector (like described in more details below). Furthermore, like mentioned already earlier, the UE's always report single stream as well as both SU and MU dual stream SINR's (at the corresponding detector output).

In a single simulation run, mobile stations are randomly dropped or positioned over each sector and cell. Then based on the individual distances between the mobile and the serving base station, the path losses for individual links are directly determined, while the actual fading characteristics of the radio channels depend on the assumed mobility and power delay profile. In updating the fading statistics, the time resolution in our simulator is set to one TTI (1ms). In general, a standard hexagonal cellular layout is utilized with altogether 19 cell sites each having 3 sectors in Macro case and 1 sector in Micro case as show in Figure 4. In the performance evaluations, statistics are collected only from the central cell site while the others simply act as sources of inter-cell interference.

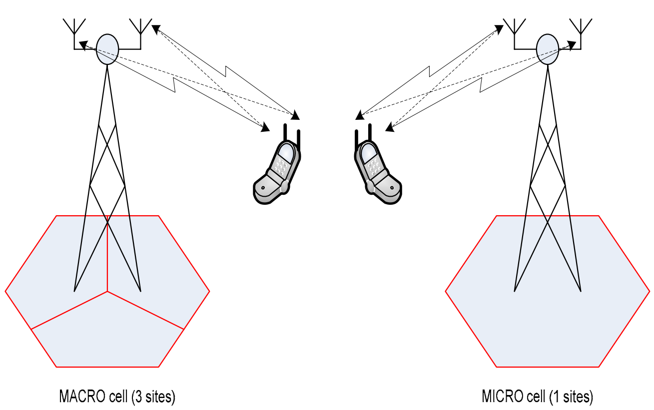

Figure 4: Macro and Micro cell scenarios.

The main simulation parameters and assumptions are generally summarized in TABLE 1 for both Macro and Micro cell scenarios, following again the LTE working assumptions. The used MIMO scheme is *per-antenna rate control* (PARC) with two transmit antennas at the BS and two receive antennas at the UE's and the receivers are equipped with LMMSE detectors. As illustrated in Figure 1, the RRM functionalities are controlled by the packet scheduler together with link adaptation and HARQ mechanisms. Notice that the maximum number of simultaneously multiplexed users (I_{BUFF}) is set to 10 here while the total number of UE's (I_{TOT}) is 15. In general, we assume that the BS transmission power is equally distributed among all PRB's. In the basic simulations, 15 UE's are uniformly dropped within each cell and experience inter-cell interferences from the surrounding cells, in addition to path loss and fading. The UE velocities are 3km/h, and the typical urban (TU) channel model standardized by ITU is assumed in modeling the power-delay spread of the radio channels. Infinite buffer traffic model is applied in the simulations, i.e. every user has data to transmit (when scheduled) for the entire duration of a simulation cycle. Exponential effective SINR mapping (EESM) is used for link-to-system level mapping (throughput calculations), as described in [2]. The length of a single simulation run is set to 5 seconds which is then repeated for 10 times to collect reliable statistics.

Considering MIMO functionality, every UE has an individual HARQ entry per stream, which operates the physical layer re-transmission functionalities. It is based on the stop-and-wait (SAW) protocol and for simplicity, the number of entries per UE is fixed to six. HARQ retransmissions are always transmitted with the same MCS and on the same PRB's (if scheduled) as the first transmissions in a single stream mode. The supported modulation schemes are QPSK, 16QAM and 64QAM with variable rates for the encoder as shown in TABLE 1.

Link adaptation handles the received UE reports containing the channel quality information for each PRB based on single and dual stream MIMO modes. The implemented link adaptation mechanism consists of two separate elements – the inner loop (ILLA) and outer loop (OLLA) LA's – and are used for removing CQI imperfections and estimating supported data rates and MCS. It is assumed that the CQI reporting errors are log-normal distributed with 1dB standard deviation.

B. *Detectors and SINR Modeling*

The actual effective SINR calculations rely on subcarrier-wise complex channel gains (estimated using reference symbols in practice) and depend in general also on the assumed receiver (detector) topology. Here we assume that the LMMSE detector, properly tailored for the transmission mode (1-stream SU, 2-stream SU or 2-stream MU) is deployed. The detector structures and SINR modeling for different transmission modes are described in detail below.

TABLE 1. Basic simulation parameters.

Parameter	Assumption
Cellular layout	Hexagonal grid, 19 cell sites, 3 sectors per site for Macro / 1 sector per site for Micro
Inter-site distance	500 m - Macro / 1732 m - Micro
Carrier frequency / Bandwidth	2000 MHz / 10 MHz
Number of active sub-carriers	600
Sub-carrier spacing	15 kHz
Sub-frame duration	0.5 ms
Channel estimation	Ideal
PDP	ITU Typical Urban 20 paths
Minimum distance between UE and cell	>= 35 meters - Macro >= 10 meters - Micro
Average number of UE's per sector	15
Max. number of frequency multiplexed UEs (I_{BUFF})	10
UE receiver type	LMMSE
Shadowing standard deviation	8 dB
UE speed	3km/h
Total BS TX power (Ptotal)	46 dBm
Traffic model	Full Buffer
Fast fading model	Jakes Spectrum
CQI reporting schemes	Full CQI, Best – m (with m=10), Threshold based (with 5dB threshold)
CQI log-normal error std.	1 dB
CQI reporting time	5 TTI
CQI delay	2 TTIs
CQI quantization	1 dB
CQI std error	1 dB
MCS rates	QPSK (1/3, 1/2, 2/3), 16QAM (1/2, 2/3, 4/5), 64QAM (1/2, 2/3, 4/5)
ACK/NACK delay	2 ms
Number of SAW channels	6
Maximum number of retransmissions	3
HARQ model	Ideal chase combining (CC)
1st transmission BLER target	20%
Scheduler forgetting factor	0.0025
Scheduling schemes used	Ordinary PF Modified PF (proposed)
Simulation duration (one drop)	5 seconds
Number of drops	10

1) *Single Stream SU Case*

In this case, only one of the two BS transmit antennas is used to transmit one stream. At individual time instant (time-index dropped here), the received spatial 2x1 signal vector of UE *i* at sub-carrier *c* is of the form

$$\mathbf{y}_{i,c} = \mathbf{h}_{i,c} x_{i,c} + \mathbf{n}_{i,c} + \mathbf{z}_{i,c} \qquad (9)$$

where $x_{i,c}$, $\mathbf{h}_{i,c}$, $\mathbf{n}_{i,c}$ and $\mathbf{z}_{i,c}$ denote the transmit symbol, 2x1 channel vector, 2x1 received noise vector and 2x1 inter-cell interference vector, respectively. Then the LMMSE detector $\hat{x}_{i,c} = \mathbf{w}_{i,c}^H \mathbf{y}_{i,c}$ is given by

$$\mathbf{w}_{i,c} = \sigma_{x,i}^2 (\mathbf{h}_{i,c}^H \sigma_{x,i}^2 \mathbf{h}_{i,c} + \mathbf{\Sigma}_{n,i} + \mathbf{\Sigma}_{z,i})^{-1} \mathbf{h}_{i,c} \qquad (10)$$

where $\sigma_{x,i}^2$, $\mathbf{\Sigma}_{n,i}$ and $\mathbf{\Sigma}_{z,i}$ denote the transmit power (per the used antenna), noise covariance matrix and inter-cell interference covariance matrix, respectively. Now the SINR is given by

$$\gamma_{i,c} = \frac{\left|\mathbf{w}_{i,c}^H \mathbf{h}_{i,c}\right|^2 \sigma_{x,i}^2}{\mathbf{w}_{i,c}^H \mathbf{\Sigma}_{n,i} \mathbf{w}_{i,c} + \mathbf{w}_{i,c}^H \mathbf{\Sigma}_{z,i} \mathbf{w}_{i,c}} \qquad (11)$$

The noise variables at different receiver antennas are assumed uncorrelated (diagonal $\mathbf{\Sigma}_{n,i}$) while the more detailed modeling of inter-cell interference (structure of $\mathbf{\Sigma}_{z,i}$) takes into account the distances and channels from neighboring base stations (for more details, see, e.g., [19]).

2) *Dual Stream SU Case*

In this case, both of the two BS transmit antennas are used for transmission, on one stream per antenna basis. At individual time instant, the received spatial 2x1 signal vector of UE *i* at sub-carrier *c* is now given by

$$\mathbf{y}_{i,c} = \mathbf{H}_{i,c} \mathbf{x}_{i,c} + \mathbf{n}_{i,c} + \mathbf{z}_{i,c} \qquad (12)$$

where $\mathbf{x}_{i,c}$ and $\mathbf{H}_{i,c} = [\mathbf{h}_{i,c,1}, \mathbf{h}_{i,c,2}]$ denote the 2x1 transmit symbol vector and 2x2 channel matrix, respectively. Now the LMMSE detector $\hat{\mathbf{x}}_{i,c} = \mathbf{W}_{i,c} \mathbf{y}_{i,c}$ is given by

$$\begin{aligned} \mathbf{W}_{i,c} &= \mathbf{\Sigma}_{x,i} \mathbf{H}_{i,c}^H (\mathbf{H}_{i,c} \mathbf{\Sigma}_{x,i} \mathbf{H}_{i,c}^H + \mathbf{\Sigma}_{n,i} + \mathbf{\Sigma}_{z,i})^{-1} \\ &= \begin{bmatrix} \mathbf{w}_{i,c,1}^H \\ \mathbf{w}_{i,c,2}^H \end{bmatrix} \end{aligned} \qquad (13)$$

where $\mathbf{\Sigma}_{x,i} = diag\{\sigma_{x,i,1}^2, \sigma_{x,i,2}^2\} = diag\{\sigma_{x,i}^2/2, \sigma_{x,i}^2/2\}$ denotes the 2x2 covariance matrix (assumed diagonal) of the transmit symbols. Note that compared to single stream case, the overall BS transmit power is now divided between the two antennas, as indicated above. Then the SINR's for the two transmit symbols are given by

$$\begin{aligned} &\gamma_{i,c,1} \\ &= \frac{\left|\mathbf{w}_{i,c,1}^H \mathbf{h}_{i,c,1}\right|^2 \sigma_{x,i,1}^2}{\left|\mathbf{w}_{i,c,1}^H \mathbf{h}_{i,c,2}\right|^2 \sigma_{x,i,2}^2 + \mathbf{w}_{i,c,1}^H \mathbf{\Sigma}_{n,i} \mathbf{w}_{i,c,1} + \mathbf{w}_{i,c,1}^H \mathbf{\Sigma}_{z,i} \mathbf{w}_{i,c,1}} \\ &\gamma_{i,c,2} \\ &= \frac{\left|\mathbf{w}_{i,c,2}^H \mathbf{h}_{i,c,2}\right|^2 \sigma_{x,i,2}^2}{\left|\mathbf{w}_{i,c,2}^H \mathbf{h}_{i,c,1}\right|^2 \sigma_{x,i,1}^2 + \mathbf{w}_{i,c,2}^H \mathbf{\Sigma}_{n,i} \mathbf{w}_{i,c,2} + \mathbf{w}_{i,c,2}^H \mathbf{\Sigma}_{z,i} \mathbf{w}_{i,c,2}} \end{aligned} \qquad (14)$$

3) Dual Stream MU Case

In this case, the transmission principle and SINR modeling are similar to subsection 2) above, but the two spatially multiplexed streams belong now to two different UE's, say *i* and *i*'. Thus the SINR's in (14) are interpreted accordingly.

Finally, for link-to-system level mapping purposes, the exponential effective SINR mapping (EESM), as described in [2-4], is deployed.

V. Numerical Results

In this section, we present the results obtained from the quasi-static radio system simulations using the PS algorithms described in the article. The system-level performance is generally measured and evaluated in terms of:

a) *Throughput* – the total number of successfully delivered bits per unit time. Usually measured either in kbps or Mbps.

b) *Coverage* – the experienced data rate per UE at the 95% coverage probability (5% throughput CDF point).

c) *Fairness* – measures the resource allocation fairness among all UE's from the average throughput point of view. Evaluated using Jain's fairness index [21] which is calculated here as

$$fairness = \frac{\left(\sum_{i=1}^{I_{\mathrm{TOT}}} \overline{\mu}_i\right)^2}{I_{\mathrm{TOT}} \sum_{i=1}^{I_{\mathrm{TOT}}} \overline{\mu}_i^{\,2}} \tag{15}$$

where $\overline{\mu}_i$ denotes the average throughput value of user *i* across different simulation realizations (here ten). In single simulation run, the corresponding throughput of user *i* is given by

$$\mu_i = \frac{1}{N_{TTI}} \sum_{n=1}^{N_{TTI}} R_i(n) \tag{16}$$

where N_{TTI} denotes the length of a single simulation run in TTI's while $R_i(n)$ is the actually delivered throughput to user *i* at individual TTI *n*.

In the following, we illustrate the behavior of the proposed MMPF scheduler with using different power coefficients α_1 and α_2 as shown in TABLE 2. To focus mostly on the role of the channel quality reporting in the priority metric calculation in equation (3), α_2 is fixed here to 1 and different values are then demonstrated for α_1. More specifically, with large α_2 values, the effect of second term in priority metric calculation based on throughput estimation would be emphasized and the scheduling algorithm would behave like maximum throughput scheduler, which in turn would imply reduced fairness distribution. Consequently, the impact of the different CQI reporting schemes is seen now more clearly. For the cases of *Best–m* and *Threshold* based CQI reporting schemes, we fix the value of *m* equal to 10 and threshold to 5 dB, respectively. Similar example values have also been used by other authors in the literature earlier, see, e.g., [12]. Complete performance statistics are gathered for both Macro cell and Micro cell case scenarios.

A. Macro Cell Case

Figure 5 (left column) illustrates the average user throughput and coverage for the different schedulers. The power coefficient values from TABLE 2 are presented as index M, where M1 represents the first couple, etc. The obtained results are compared with the reference PF scheduler described also in Section II. By using the first term (M1) of the new metric calculation for MMPF, in combination with full CQI reporting scheme, we achieve coverage gain in the order of 63% at the expense of 20% throughput loss as shown in Figure 5 (a) and (b). This sets the basic reference for comparisons in the other cases. In the case of *Best-m* and *Threshold* based reporting schemes presented in Figure 5 (c) and (d), and Figure 5 (e) and (f), we have coverage increases by 69% and 74% with throughput losses of 15% and 20%, correspondingly.

Continuing on the evaluation of relative system performance using the proposed scheduler, we clearly see a trade-off between average cell throughput and coverage for different power coefficient cases. Furthermore, the remaining power coefficient values shown in TABLE 2 are used for tuning the overall system behavior together with the choice of the CQI reporting scheme. In the case of full CQI feedback and coefficient α_1 varying between 2 and 8 (M2 –M5) the cell throughput loss is decreased to around 7%, while the coverage gain is reduced to around 21%. Similar results are obtained for the other feedback reporting schemes as well. Consequently, an obvious trade-off between average cell throughput and coverage is clearly seen. In order to preserve the average sector throughput and still to gain from the coverage increase, coefficient values should thus be properly chosen. The exact percentage values for the coverage gains and throughput losses are stated in TABLE 3 at the end of the article.

Further illustrations on the obtainable system performance are presented in Figure 5 (right column) in terms of the statistics of individual UE data rates for the applied simulation scenarios. The slope of the CDF reflects generally the fairness of the algorithms. Therefore we aim to achieve steeper slope corresponding to algorithm fairness. This type of slope change behavior can clearly be established for each simulation scenario. Clearly, at 5% (coverage) point of the throughput CDF curves, corresponding to users typically situated at the cell edges, we observe significant data rate increases indicated by shift to the right for all CQI feedback schemes when the coefficient α_1 is changed in the proposed metric. This indicates improved overall cell coverage at the expense of slight total throughput loss.

Figure 6 (left column) shows the modulation and coding scheme (MCS) distributions for different schedulers and with applied feedback reporting schemes. The negligible decrease in higher order modulation usage (less than 3%) leads to the increase in the lower (more robust) ones for improving the cell coverage. In all the simulated cases, the MCS distribution behavior has a relatively similar trend following the choice of the power coefficients in the proposed packet scheduling. In general, the use of higher-order modulations is affected mostly in the case of *Best-m* and *Threshold* based reporting schemes.

Figure 6 (right column) illustrates the HARQ distributions for the different scheduler scenarios and reporting schemes. Clearly, the 20% BLER target rate is achieved in all simulated cases. Moreover, the MMPF scheduler provides slight increase in probability of successful first transmission of around 2% for the *Best-m* and *Threshold* based feedback cases.

TABLE 2. DIFFERENT POWER COEFFICIENT COMBINATIONS

Coefficient	Value				
α_1	1	2	4	6	8
α_2	1	1	1	1	1

B. Micro Cell Case

The performance statistics obtained for Micro cell case demonstrate similar trends, as in the previous Macro case, as shown in Figure 7. Starting from the primary case M1, with full CQI, we obtain a 17% loss in throughput and 92% coverage improvement. For the reduced feedback reporting schemes – *Best-m* and *Threshold* based – we have 21% and 19% throughput losses and 100% and 96% coverage gains, respectively. Furthermore, similar behavior is observed in the CDF's of individual UE throughputs, as well as MCS and HARQ distributions. The exact percentage values read from the figures are again stated in table format in TABLE 4 at the end of the article.

C. Jain's Fairness Index

Figure 8 illustrates the Jain's fairness index per scheduling scheme for Micro and Macro cell scenarios, calculated over all the I_{TOT} = 15 UE's. The value on the x axis corresponds to used scheduler type, where 1 refers to the reference PF scheduler, 2 refers to MMPF with index M1, etc. The value of Jain's fairness index is generally in the range of [0,1], where value of 1 corresponds to all users having the same amount of resources. Clearly, the fairness distribution with MMPF outperforms the used reference PF scheduler for both cases. The received fairness gains are in range of 13%-37% with *full* CQI feedback, 15-32% with *Best-m* CQI feedback and 17-35% with *Threshold* based CQI feedback in the Macro case scenario. The corresponding fairness gains in Micro case scenario are 25-46%, 32-41% and 34-43% for *full* CQI, *Best –m* and *Threshold* based reporting schemes, correspondingly. The exact percentage values read from the figures are again stated in table format in Table 5 in the end of the article.

VI. CONCLUSIONS

In this article, we have studied the potential of advanced multiuser packet scheduling algorithms in OFDMA type radio system context, using UTRAN long term evolution (LTE) downlink in Macro and Micro cell environment as practical example cases. New multistream proportional fair scheduler metric covering time-, frequency- and spatial domains was proposed that takes into account both the instantaneous channel qualities (CQI's) as well as resource allocation fairness. Also different practical CQI reporting schemes were discussed, and used in the system level performance evaluations of the proposed scheduler. Overall, the achieved throughput performance together with coverage and fairness statistics were assessed, by using extensive radio system simulations, and compared against more traditional proportional fair scheduling with multiantenna spatial multiplexing functionality. In the case of fixed coverage requirements and based on the optimal parameter choice for CQI reporting schemes, the proposed scheduling metric calculations based on UE channel feedback offers better control over the ratio between the achievable cell/UE throughput and coverage increase, as well as increased UE fairness. As a practical example, even with limited CQI feedback, the fairness in resource allocation together with cell coverage can be increased significantly (more than 40%) by allowing a small decrease (in the order of only 10-15%) in the cell throughput.

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REFERENCES

[1] S. Nonchev and M. Valkama, "Efficient packet scheduling schemes for multiantenna packet radio downlink," in Proc. Fifth Advanced Int. Conf. Telecommunications (AICT-2009), Venice, Italy, May 2009.

[2] "Physical Layer Aspects for Evolved UTRA", 3GPP Technical Report TR 25.814, ver. 7.1.0, Oct. 2006.

[3] WiMAX Forum™, http://www.wimaxforum.org, Aug. 2006.

[4] "Wireless World Initiative New Radio (WINNER)," IST-507581, European Information Society Technologies, Technical Report, Dec. 2006.

[5] N. Wei, B. Talha, T. B. Sørensen, T. E. Kolding, and P. E. Mogensen, "Spectral efficiency of closed-loop transmit diversity with limited feedback for UTRA Long Term Evolution," in Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications (PIMRC-2006), Helsinki, Sept. 2006.

[6] R. W. Heath, M. Airy, and A. Paulraj, "Multiuser diversity for MIMO wireless systems with linear receivers," in Proc. Asilomar Conf. Signals, Systems and Computers, Pacific Grove, CA, 2001.

[7] E. Dahlman et al., 3G Evolution: HSPA and LTE for Mobile Broadband, Academic Press, 2007.

[8] Y. Sun et al., "Multi-user scheduling for OFDMA downlink with limited feedback for evolved UTRA," in Proc. IEEE Vehicular Technology Conf. (VTC-2006 Fall), Montreal, Canada, Sept. 2006.

[9] S. Yoon, C. Suh, Y. Cho, D. Park, "Orthogonal frequency division multiple access with an aggregated sub-channel structure and statistical channel quality measurements," in Proc. IEEE Vehicular Technology Conf. (VTC-2004 Fall), Los Angeles, CA, Sept. 2004.

[10] I. Toufik and H. Kim, "MIMO-OFDMA opportunistic beamforming with partial channel state information," in Proc. IEEE Int. Conf. Communications (ICC-2006), Instanbul, Turkey, June 2006.

[11] T.E. Kolding, F. Frederiksen, A. Pokhariyal, "Low-bandwidth channel quality indication for OFDMA frequency domain packet scheduling," in Proc. IEEE Int. Symp. Wireless Communication Systems (ISWCS-2006), Valencia, Spain, Sept. 2006.

[12] K.I. Pedersen, G. Monghal, I.Z. Kovacs, T.E. Kolding, A. Pokhariyal, F. Frederiksen, P. Mogensen, "Frequency domain scheduling for OFDMA with limited and noisy channel feedback," in Proc. IEEE Vehicular Technology Conf. (VTC-2007 Fall), Baltimore, MD, Sept. 2007.

[13] P. Svedman, D. Hammarwall, B. Ottersten, "Sub-carrier SNR estimation at the transmitter for reduced feedback OFDMA," in Proc. European Signal Processing Conf., Florence, Italy, Sept. 2006.

[14] C. Wengerter, J. Ohlhorst, and A.G.E Von Elbwert, "Fairness and Throughput Analysis for Generalized Proportional Fair Frequency Scheduling in OFDMA," in Proc. IEEE Vehicular Technology Conf. (VTC-2005 Spring), Stockholm, Sweden, May 2005.

[15] T. E. Kolding, "Link and system performance aspects of proportional fair scheduling in WCDMA/HSDPA," in Proc. IEEE Vehicular Technology Conf. (VTC-2003 Fall), Orlando, FL, USA, Oct. 2003.

[16] P. Svedman, S.K.Wilson, L.J. Cimini, and B. Ottersten, "A simplified opportunistic feedback and scheduling scheme for OFDMA," in Proc. IEEE Vehicular Technology Conf. (VTC-2004 Spring), Milan, Italy, May 2004.

[17] I. Z. Kovács et al, "Effects of non-ideal channel feedback on dual-stream MIMO OFDMA system performance," in Proc. IEEE Vehicular Technology Conf. (VTC-2007 Fall), Baltimore, MD, Oct. 2007.

[18] S. Nonchev, J. Venäläinen and M. Valkama, "New frequency domain packet scheduling schemes for UTRAN LTE downlink," in Proc. ICT-MobileSummit, Stockholm, Sweden, 2008.

[19] S. Nonchev and M. Valkama, "A new fairness-oriented packet scheduling scheme with reduced channel feedback for OFDMA packet radio systems," Int. Journal of Communications, Network and System Sciences (IJCNS), vol. 2, No. 7, Oct. 2009.

[20] N. Wei, et al., "Performance of MIMO with frequency domain packet scheduling," in Proc. IEEE Vehicular Technology Conf. (VTC-2007 Spring), Dublin, Ireland, May 2007.

[21] D. Chui and R. Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks," Computer Networks and ISDN Systems, 1989.

[22] P. Svedman, L.J. Cimini, B. Ottersten, "Using unclaimed sub-carriers in opportunistic OFDMA systems," in Proc. IEEE Vehicular Technology Conf. (VTC-2006 Fall), Montreal, Canada, September 2006.

[23] S. Sanayei, A. Nosratinia, N. Aldhahir, "Opportunistic dynamic sub-channel allocation in multiuser OFDM networks with limited feedback," in Proc IEEE. Information Theory Workshop, San Antonio, TX, October 2004, pp. 182-186.

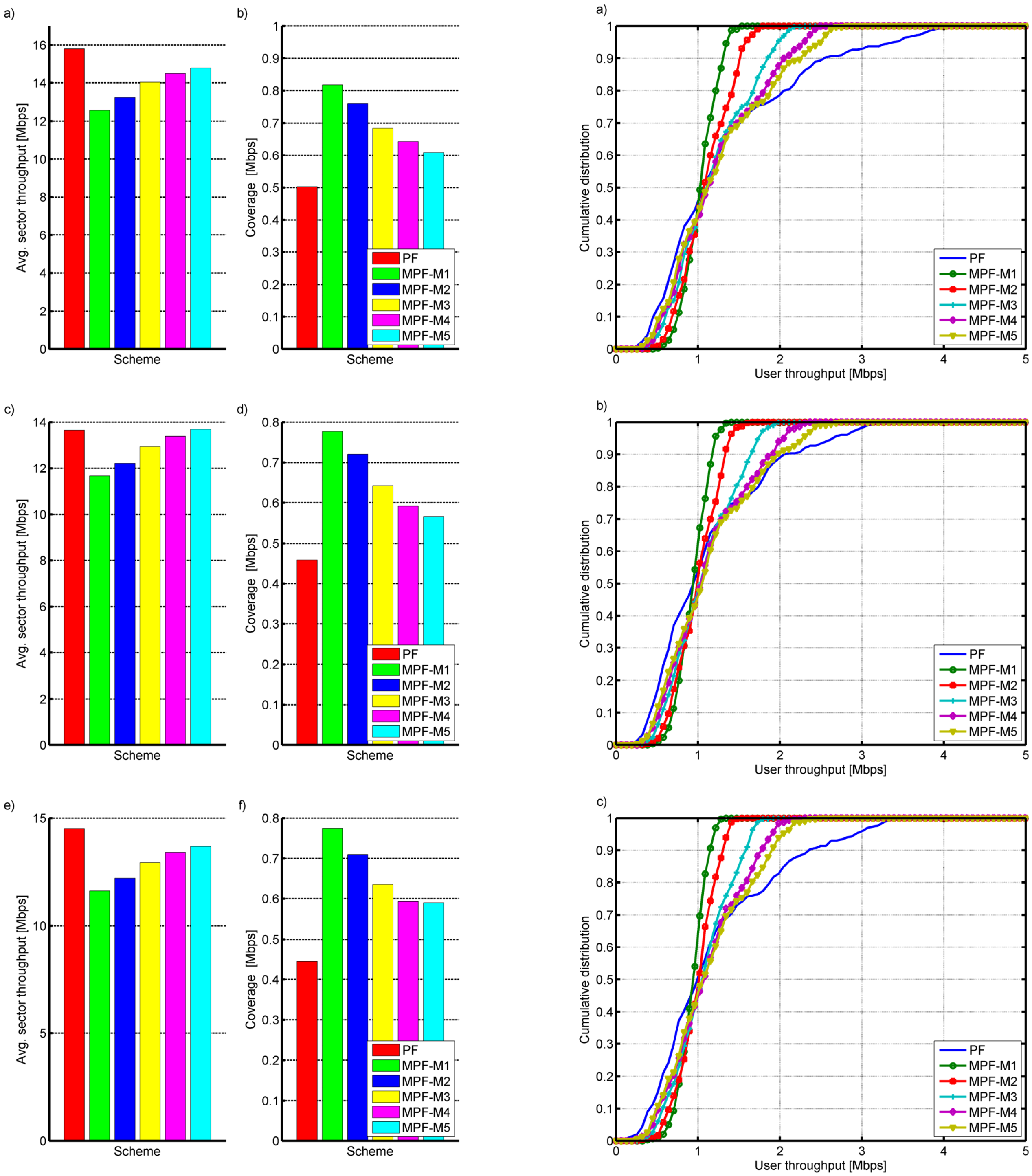

Figure 5: Left column: Average sector throughput and coverage for different scheduling schemes for Macro cell scenario with *full* CQI feedback (a, b), *Best -m* CQI feedback (c, d) and *Threshold* based CQI feedback (e, f). M1-M5 refer to the proposed scheduler with power coefficient values as given in TABLE 2. Right column: CDF's of individual UE throughputs for different scheduling schemes for Macro cell scenario with *full* CQI feedback (a), *Best -m* CQI feedback (b) and *Threshold* based CQI feedback (c).

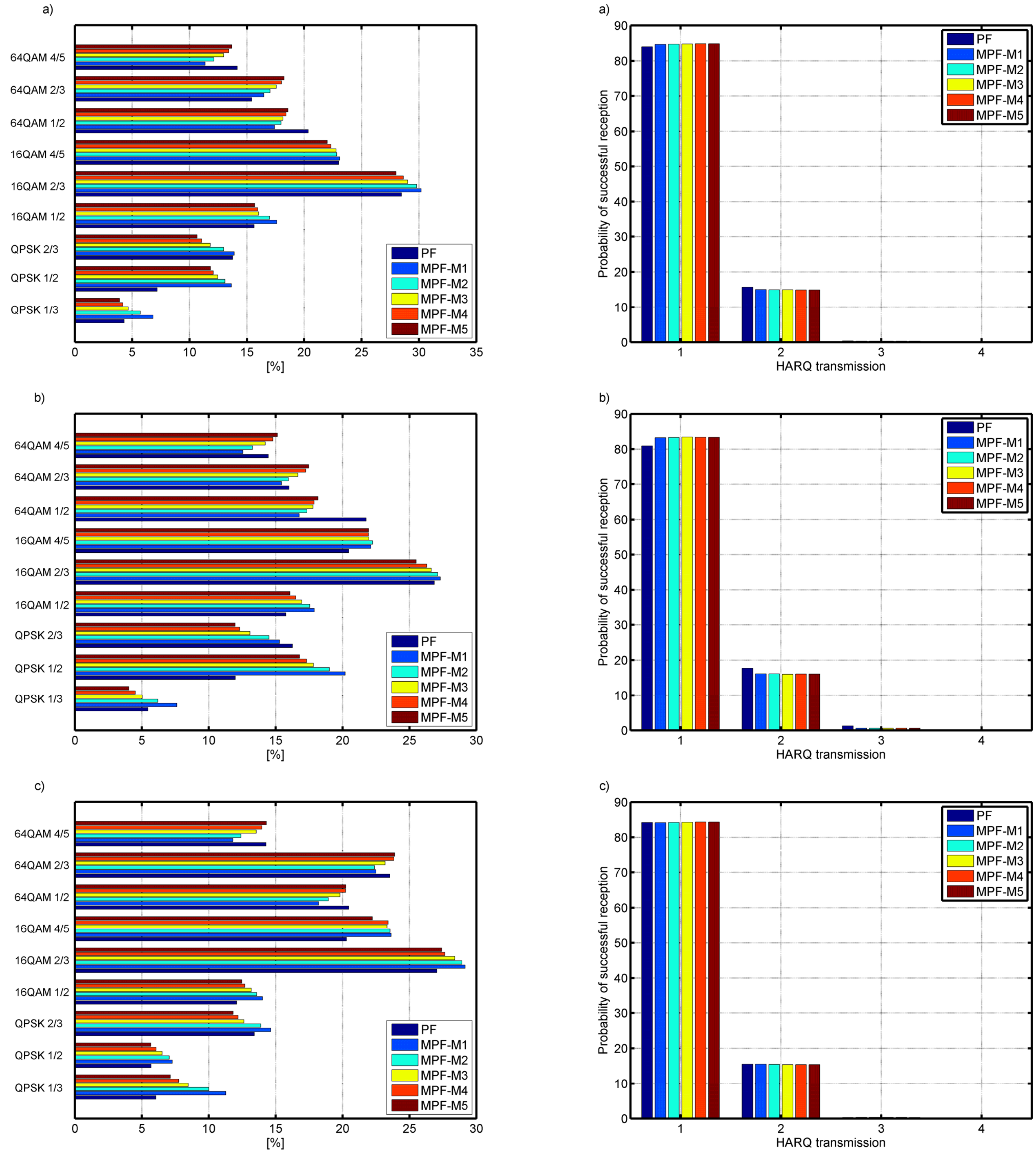

Figure 6: Left column: MCS distributions [%] for different scheduling principles for Macro cell scenario with *full* CQI feedback (a), *Best -m* CQI feedback (b) and *Threshold* based CQI feedback (c). Right column: HARQ distributions for different scheduling schemes for Macro cell scenario with *full* CQI feedback (a), *Best -m* CQI feedback (b) and *Threshold* based CQI feedback (c).

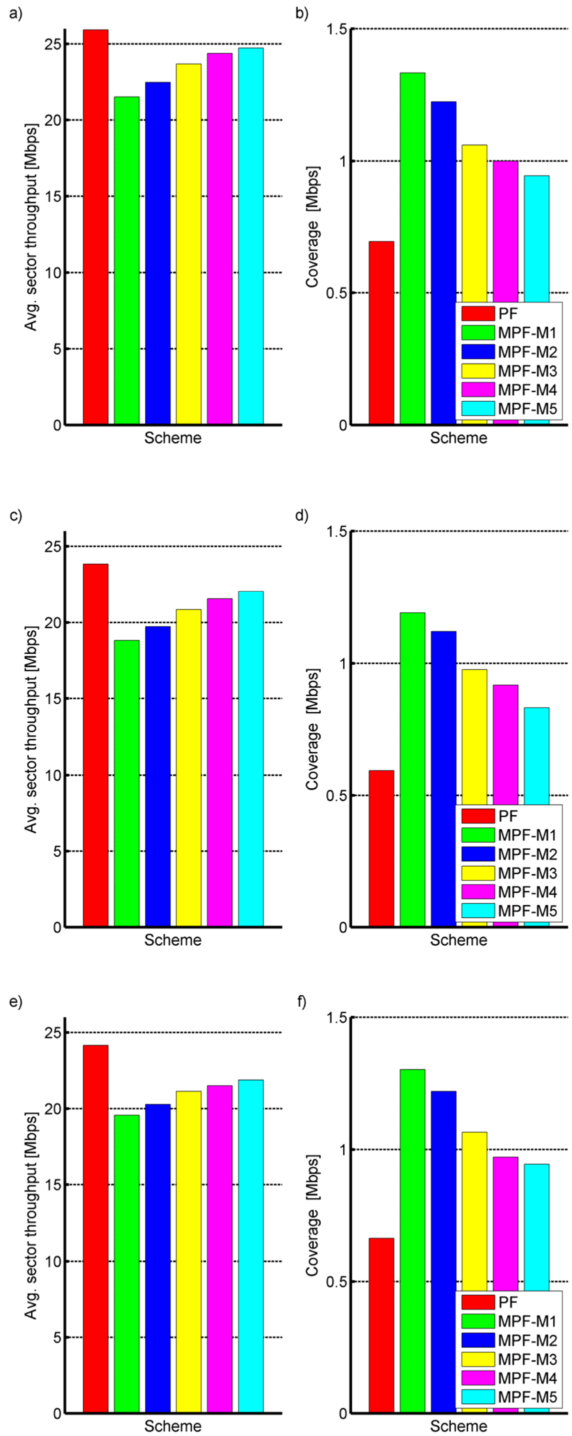

Figure 7: Average cell throughput and coverage gain over the reference PF scheduling scheme for Micro cell simulation scenario. The schemes M1-M5 refer to the new proposed scheduler with power coefficient values as given in TABLE 2.

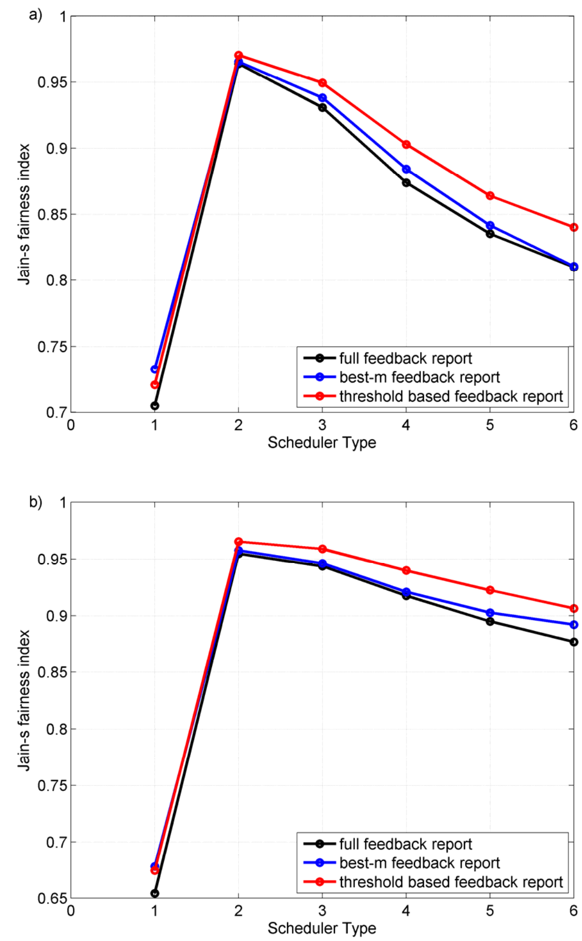

Figure 8: Jain's fairness index per feedback reporting scheme for the different simulation scenarios – Macro cell (a) and Micro cell (b). Scheduler type 1 means ordinary PF, while 2-6 means proposed modified PF with power coefficients as described in TABLE 2.

TABLE 3.
OBTAINED PERFORMANCE STATISTICS COMPARED TO ORDINARY PF SCHEDULER WITH DIFFERENT CQI REPORTING SCHEMES AND DIFFERENT POWER COEFFICIENTS (M1-M5) FOR THE PROPOSED SCHEDULER. MACRO CELL CASE SCENARIO.

	Coverage Gain [%]			Throughput Loss [%]		
	full	best-m	threshold	full	best-m	threshold
M1	63	69	74	20	15	20
M2	51	57	60	16	11	16
M3	36	40	43	13	6	12
M4	28	29	33	9	2	8
M5	21	24	32	7	0	6

TABLE 4.
OBTAINED PERFORMANCE STATISTICS COMPARED TO ORDINARY PF SCHEDULER WITH DIFFERENT CQI REPORTING SCHEMES AND DIFFERENT POWER COEFFICIENTS (M1-M5) FOR THE PROPOSED SCHEDULER. MICRO CELL CASE SCENARIO.

	Coverage Gain [%]			Throughput Loss [%]		
	full	best-m	threshold	full	best-m	threshold
M1	92	100	96	17	21	19
M2	76	88	84	13	17	16
M3	53	64	60	9	14	14
M4	44	54	46	6	11	12
M5	36	40	42	5	8	10

TABLE 5.
OBTAINED JAIN'S FAIRNESS INDEXES COMPARED TO ORDINARY PF SCHEDULER WITH DIFFERENT CQI REPORTING SCHEMES AND DIFFERENT POWER COEFFICIENTS (M1-M5) FOR THE PROPOSED SCHEDULER. MACRO AND MICRO CELL CASE SCENARIOS.

	Macro case Fairness Gain [%]			Micro case Fairness Gain [%]		
	full	best-m	threshold	full	best-m	threshold
M1	37	32	35	46	41	43
M2	32	28	32	44	40	42
M3	19	21	25	29	36	39
M4	16	15	20	27	33	37
M5	13	15	17	25	32	34