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Downlink Scheduling for QoS-Guaranteed Services in Multi-User MIMO Systems with Limited Feedback

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Abstract—**Significant throughput gains and system fairness can be obtained by employing scheduling schemes based on precoding techniques. However, QoS guarantee requirements are seldom taken into account. In this paper, we propose a downlink scheduling algorithm for QoS-guaranteed services in multi-user multiple-input multiple-output (MIMO) systems with limited feedback. The proposed algorithm combines stream selection with multi-user packet scheduling. To maximize the overall capacity and reduce co-channel interference, streams are selected in accordance with precoding matrices. In multi-user packet scheduling, the base station first determines the SDMA region size for the primary streams. In addition, packet scheduling for the secondary streams is performed to completely exploit spatial multiplexing gains. Numerical results show that, at the cost of slightly lower system fairness, the proposed algorithm can achieve higher spectrum efficiency, and have a noticeable improvement in guaranteeing QoS requirements in terms of data rates and delay.**

Keywords-stream selection; scheduling; QoS guarantee; MU-MIMO; precoding

I. INTRODUCTION

Multi-user multiple-input multiple-output (MU-MIMO) systems can exploit multi-user gains and multiplexing gains by leveraging multiple users as spatially distributed transmission resources. Spatial division multiple access (SDMA) permits multiple users to share the same time-frequency resource region, thus achieving higher spectral efficiency in MU-MIMO systems. However, it will introduce co-channel interference (CCI) [1]. MIMO precoding techniques are promising candidates to improve the total capacity of MIMO channels by utilizing the channel state information at the transmitter [2]. To reduce the feedback overhead for practical MU-MIMO systems with limited feedback, codebook-based precoding schemes are proposed. Unitary precoding is a typical linear precoding scheme which depends on limited feedback and allows the base station (BS) to allocate different antennas to various users.

Many scheduling schemes based on precoding techniques have been emerging recently. A MIMO scheduling and precoding scheme was performed in [3] according to feedback of the signal-to-interference-plus-noise ratio (SINR) to enhance system capacity. In [4], a multi-stage hybrid scheduling scheme, which applied varied scheduling methods at different scheduling stages for selecting users, has been proposed for precoding MIMO systems. Reference [5] proposed a joint multi-user scheduling and precoding scheme, which used the statistical information of CSIT errors to predict the relationship among precoding matrices, scheduling results and CCI, and utilized such information to achieve better CCI control.

On the other hand, system fairness is another crucial indicator of multi-user scheduling. With this indicator, a system is able to evaluate in what extent the scheduling can fairly treat and meet individual users' data rate requirements. Reference [6] introduced a proportional fair (PF) criterion which is a ratio of the maximum supportable data rate per slot to each user's average throughput. The original PF scheme has been extended to achieve a tradeoff between multi-user diversity and system throughput in precoding MU-MIMO systems in [7]. As can be seen from these existing algorithms, significant throughput gains, as well as system fairness, can be obtained by exploiting a combination of multi-user scheduling and spatial multiplexing using codebook-based precoding. However, these studies have not taken into account quality of service (QoS) requirements for QoS-guaranteed services.

In this paper, we propose a downlink scheduling algorithm for QoS-guaranteed services in MU-MIMO systems with limited feedback. Stream selection and multi-user packet scheduling are combined in downlink scheduling. To maximize the total capacity and reduce the CCI, streams are selected according to precoding matrices. In each SDMA resource region, packet scheduling for the primary streams is performed first, and then scheduling for the secondary streams may be performed several times to exploit all the degrees of freedom. Numerical results show that, the proposed algorithm can achieve higher spectrum efficiency, and has a noticeable improvement in guaranteeing QoS requirements.

The rest of the paper is organized as follows. Section II introduces the system model and the problem to be addressed. In Section III, the proposed downlink scheduling algorithm is described. Numerical results are presented in Section IV, which is followed by our conclusions in Section V.

II. SYSTEM MODEL

This paper considers the downlink of a multi-user MIMO-OFDM system with N_t transmit antennas at the base station (BS) and $N_{k,r}$ receive antennas at each user equipment (UE). There are L connections belonging to K UEs in the system. If a

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stream is defined as an information path output from a space-time coding (STC) block, then M_k denotes the number of streams intended for UE k in a SDMA resource region. Assume that $0 \le M_k \le N_{k,r}$ and $\sum_{k=1}^{K} M_k \le N_t$.

Downlink scheduling and signal processing in the BS are shown in Fig. 1. The UEs feed back the CSI including precoding matrix indices (PMI) and precoding vector indices (PVI). Depending on the CSI, the BS groups streams and selects appropriate connections to occupy these streams, and then performs multi-user packet scheduling. Transmit signals are precoded with the matrices indicated by the scheduler.

For the UE k, the received signal can be denoted as:

$$y_k = H_k \sum_{k}^{K} W_k x_k + n_k = H_k W_k x_k + H_k \sum_{k' \ne k} W_{k'} x_{k'} + n_k \qquad (1)$$

where y_k and x_k denote a $N_{k,r} \times 1$ received signal vector and a $M_k \times 1$ transmitted signal vector, H_k and W_k denotes a $N_{k,r} \times N_t$ channel matrix and a $N_t \times M_k$ precoding matrix, respectively, n_k is a $N_{k,r} \times 1$ noise vector. In the receiver, the UE k generates an estimate $\hat{x}_k$ by multiplying y_k with a decoding matrix B_k as:

$$\hat{x}_k = B_k y_k = B_k H_k W_k x_k + B_k H_k \sum_{k' \ne k} W_{k'} x_{k'} + B_k n_k . \qquad (2)$$

A minimum-mean-square-error (MMSE) criterion is employed in the receiver, so the B_k can be derived as:

$$B_k = \underset{k \in \{1,\ldots,K\}}{\arg\min}\, \mathrm{E}\left(\left\| x_k - \hat{x}_k \right\|^2 \middle| H_k \right). \qquad (3)$$

Based on (1) and (2), the total capacity C of the MU-MIMO system is then derived from the mutual information C_k between $\hat{x}_k$ and x_k as:

$$C = \sum_{k=1}^{K} C_k = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \log_2 (1 + sinr_{k,m}) \qquad (4)$$

where

$$sinr_{k,m} = \frac{\left\| b_{k,m}^H H_k w_{k,m} \right\|^2}{\left\| b_{k,m} \right\|^2 \sigma_n^2 + \sum_{(k',m') \ne (k,m)} \left\| b_{k,m}^H H_k w_{k',m'} \right\|^2} \qquad (5)$$

is the post-processing SINR for the stream m of UE k with $(\cdot)^H$ being the matrix conjugation transposition, $b_{k,m}$ and $w_{k,m}$ being the column m of B_k^H and W_k respectively.

Unitary precoding is used in the MU-MIMO system. Based on (4), the optimal system capacity can be obtained when each $sinr_{k,m}$ is maximum, so $w_{k,m}$ is selected from the unitary codebook in accordance with the following criterion:

$$w_{k,m} = \underset{\forall k,\, \forall m}{\arg\max} \{ sinr_{k,m} \}. \qquad (6)$$

For a UE occupying a single stream, the UE should feed back the PMI and PVI corresponding to $w_{k,m}$, as well as the maximum $sinr_{k,m}$, to the BS. For a UE occupying multiple streams, the UE should feed back the PMI and all the PVIs corresponding to $\{w_{k,1}, \ldots, w_{k,M_k}\}$, and the average SINR of multiple streams [8] which is calculated as:

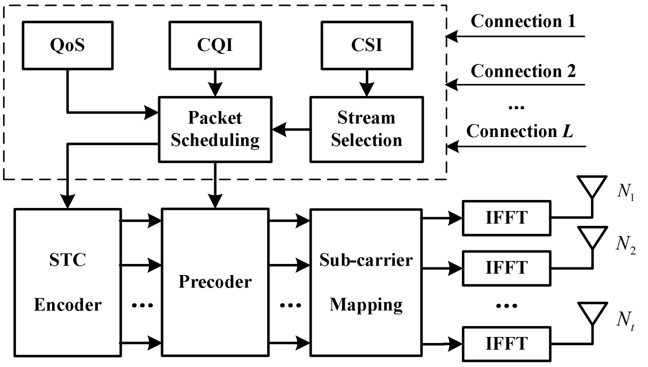

Figure 1. Downlink scheduling and signal processing in the BS

$$avg\_sinr_k = \left(\prod_{m=1}^{M_k} (1 + sinr_{k,m}) \right)^{1/M_k} - 1. \qquad (7)$$

We consider real-time services transmitting multimedia. The QoS requirements concerned include delay and data rates. The objective is to allocate the downlink resources in the MU-MIMO system to achieve a tradeoff among spectrum efficiency, QoS guarantee and system fairness.

III. PROPOSED DOWNLINK SCHEDULING

Resource allocation in the MU-MIMO system needs to logically divide every downlink sub-frame into several SDMA resource regions, and determine the inter-relationship between the connections and streams in the same SDMA region. Hence, the proposed downlink scheduling algorithm consists of two parts: stream selection and multi-user packet scheduling.

A. Stream Selection

CCI may occur when multiple UEs share the same SDMA resource region. Stream grouping and selection is significant to maximize the total capacity and reduce the interferences among the co-channel UEs. In accordance with (5) and (6), inter-stream interference is taken into consideration in calculating SINR, and the UE tries each unitary preocding matrix and calculates the SINR on each of its PVIs, assuming that the other PVIs within the same precoding matrix as interferences.

Before selecting streams, the BS classifies UEs into different groups in accordance with their PMIs and PVIs:

$$\begin{cases} \mathrm{G}(k,m) = \mathrm{G}(k',m'), & \begin{array}{l} \mathrm{pmi}(w_{k,m}) = \mathrm{pmi}(w_{k',m'}), \\ \&\, \mathrm{pvi}(w_{k,m}) = \mathrm{pvi}(w_{k',m'}); \end{array} \\ \mathrm{G}(k,m) \ne \mathrm{G}(k',m'), & \text{otherwise}. \end{cases} \qquad (8)$$

In (8), G(k,m) represents the group index which the stream m of UE k belongs to, pmi($w_{k,m}$) and pvi($w_{k,m}$), respectively represent the PMI and PVI reported from UE k in stream m. If precoding codebook includes P precoding matrices and each precoding matrix includes N' precoding vectors, pmi($w_{k,m}$) $\in D = \{1, 2, \ldots, P\}$, pvi($w_{k,m}$)$\in F = \{1, 2, \ldots, N'\}$, $N' \le N_t$.

The streams which can be selected to share the same SDMA region are those whose feedbacks correspond to the different precoding vectors within the same precoding matrix:

$$\begin{cases} \mathrm{G}(k,m) \neq \mathrm{G}(k',m') \\ \mathrm{pmi}(w_{k,m}) = \mathrm{pmi}(w_{k',m'}) \end{cases} \qquad k \neq k', m \neq m'. \qquad (9)$$

B. Multi-user Packet Scheduling for the Primary Streams

Multi-user packet scheduling can be performed in two steps based on the result of stream selection, QoS and CQI. The first step is to schedule packets for the primary streams.

Definition 1. *The primary streams are those which occupy a SDMA resource region in the first place.*

Let R_i, D_i denote the data rate and delay requirements of connection i, and let μ, φ_i^q denote the frame duration, packet queue length of connection i, respectively. Assume that the frame number at which the last packet in the queue of connection i arrives, is denoted as T_a, and the current frame number is denoted as T_c. Then, the BS will preferentially select connection i of UE k to occupy the primary streams as:

$$\begin{aligned} i &= \arg\max_{i\in\{1,2,\ldots,L\}} \{p_1 \bullet p_2\} \\ &= \arg\max_{i\in\{1,2,\ldots,L\}} \left\{ \frac{\varphi_i^q R_i}{\exp\,(\lambda, T_a + D_i/\mu - T_c)} \bullet \frac{\mathrm{S}(k,m)}{\theta_i(t)} \right\}. \end{aligned} \qquad (10)$$

In (10), p_1 represents a QoS-urgent-degree coefficient which is directly proportional to a product of φ_i^q and R_i, and is inversely proportional to an ascending exponential function $\exp(\cdot)$ with base λ, $\lambda > 1$. The exponent $(T_a + D_i/\mu - T_c)$ reflects the delay sensitivity of connection i. Coefficient p_2 represents a proportional fair index [6] where $\theta_i(t)$ is the average throughput of connection i, and $\mathrm{S}(k,m)$ is the supportable data rate per slot of UE k in stream m.

Once the candidate connection is selected for the primary streams, the BS can determine the appropriate amount of bandwidth and the number of streams allocated to the connection. Denote by φ_i^b the lower-bound of bandwidth, and φ_i^r the remaining bandwidth available in the current frame. The bandwidth allocated to connection i is expressed as:

$$\varphi_i = \min\,\{\varphi_i^q, \varphi_i^b, \varphi_i^r\} \qquad (11)$$

where the average lower-bound of bandwidth φ_i^b is measured on a sliding window with a window length ΔT_w.

Based on the definition of primary streams and (7), one UE is able to occupy more than one stream, and the UE will feed back the average SINR if the UE has multiple streams. Hence, the number of slots Γ_i allocated to connection i is given by:

$$\Gamma_i = \left\lceil \varphi_i \Big/ \sum_{m=1}^{\mathrm{U}(\mathrm{S}(k,m),\,N_{k,r})} \mathrm{S}(k,m) \right\rceil \qquad (12)$$

where $\mathrm{U}(\cdot)$ is a function of MIMO mode selection determining the switch between spatial multiplexing and single antenna.

Let E denote a set for a specific SDMA resource region. Each element in set E indicates the stream index (i.e. PVI) that has been occupied in the same precoding matrix. Obviously, set E and its complementary set E^C satisfy $E \cup E^C = F$. If $E^C \neq \Phi$ and $\mathrm{pvi}(w_{k,m}) \in E^C$, for $\forall m$, stream m can still be occupied in the future. Let η_k denote the number of streams to be allocated to connection i of UE k, then η_k depends on the number of streams satisfying $\mathrm{pvi}(w_{k,m}) \in E^C$ for UE k or the number of elements in set E^C, whichever is smaller. The function of MIMO mode selection is given by:

$$\mathrm{U}(\mathrm{S}(k,m), N_{k,r}) = \begin{cases} \eta_k, & N_{k,r} > 1 \,\&\, \mathrm{S}(k,m) \geq \xi; \\ 1, & \text{otherwise.} \end{cases} \qquad (13)$$

In (13), ξ is a threshold of data rate per slot.

In this case, the BS can determine the target connection, SDMA region size and the number of primary streams in accordance with (10), (12) and (13). Henceforth, the PVIs of the occupied primary streams should be added into set E.

C. Multi-user Packet Scheduling for the Secondary Streams

Spatial multiplexing provides the system with more degrees of freedom to perform multi-user scheduling. After determining the SDMA region size, the BS can schedule packets for the secondary streams.

Definition 2. *The secondary streams are those which occupy the same SDMA region, following the primary streams, for the purpose of exploiting more degrees of freedom.*

The remaining available degrees of freedom are decided by the number of elements in E^C, so the secondary stream m' of UE k' should satisfy the sufficient condition as follows:

$$\mathrm{pvi}(w_{k',m'}) \in E^C, \quad k' \in \{1,\ldots,K\}, m' \in \{1,\ldots M_{k'}\}. \qquad (14)$$

On the basis of the result of stream selection, the BS needs to select the secondary streams by associating (9) with (14).

Let Z denote a set which matches

$$Z = \{j \,|\, \Gamma_i \geq \Gamma_j,\ j \in \{1,\ldots L\}\}$$

where Γ_i is the SDMA region size in terms of slot number and Γ_j is the number of slots occupied by connection j and calculated according to (12) and (13). The BS will allocate the secondary streams to connection j using the criterion:

$$\begin{cases} \{j, \Gamma_j\} = \arg\min\limits_{j\in\{1,\ldots L\}} \{\Gamma_i - \Gamma_j\}, & Z \neq \Phi; \\ \{j, \Gamma_i\} = \arg\min\limits_{j\in\{1,\ldots L\}} \{\Gamma_j\}, & Z = \Phi. \end{cases} \qquad (15)$$

The BS always offers opportunities to connection j which makes the best use of the SDMA region size. If each Γ_j is larger than Γ_i, $i \neq j$, the BS can only allocate Γ_i to connection j no matter what connection is selected. Otherwise, the connection whose Γ_j is closest to Γ_i has the opportunity to occupy the secondary streams. The number of secondary streams used by connection j depends on (13).

In each SDMA resource region, packet scheduling for the primary streams is performed once. However, packet scheduling for the secondary streams may be performed several times so as to exploit all of the degrees of freedom.

D. Overall Algorithm

The downlink scheduling algorithm for QoS-guaranteed services in MU-MIMO systems is summarized as follows:

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Proposed Downlink Scheduling Algorithm
1: Classify UEs into different groups using (8).
2: If there are slots available, select connection $i$ to occupy the primary streams in accordance with (10). Otherwise, go to end.
3: Determine the amount of bandwidth of connection $i$, the SDMA region size and the number of primary streams in accordance with (11), (12) and (13).
4: Add the PVIs of the occupied primary streams into set $E$.
5: If $E^C \neq \Phi$, select the secondary streams by associating (9) with (14). Otherwise, go to step 2.
6: Allocate the secondary streams to connection $j$ and its corresponding slot number using (15) and (12).
7: Determine the number of streams used by connection $j$, and update the PVIs of the occupied secondary streams into set $E$. Go to step 5.
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IV. NUMERICAL RESULTS

In this section, we present numerical results to demonstrate performances of the proposed algorithm in terms of spectrum efficiency, QoS guarantee and system fairness. For comparison purposes, the pure PF algorithm [6] and Max-SINR algorithm [9] are extended to apply to the MU-MIMO system with limited feedback. In the pure PF algorithm, the criterion is employed to select connections for scheduling as follows:

$$i = \arg\max_{i \in \{1,2,\ldots,L\}} \left\{ \frac{\mathrm{S}(k,m)}{\theta_i(t)} \middle| k = \mathrm{user}(i) \right\}, \quad \text{for } \forall k, \forall m, \tag{16}$$

where user(i) represents the user index to which connection i belongs to, and

$$i = \arg\max_{i \in \{1,2,\ldots,L\}} \left\{ sinr_{k,m} \middle| k = \mathrm{user}(i) \right\}, \quad \text{for } \forall k, \forall m, \tag{17}$$

is employed by the pure Max-SINR algorithm. The spatial multiplexing PF (SM-PF) algorithm uses the scheduling framework proposed in this paper except for the replacement of (10), (15) by (16). Similar extensions are made for the spatial multiplexing Max-SINR (SM-Max-SINR) algorithm by the replacement of (10), (15) by (17).

Monte Carlo simulations are conducted with the simulation configuration as listed in Table I. The numerical results for a 4×2 MIMO configuration will be presented herein. The average SINRs of all UEs are assumed to be uniformly distributed. The EESM (Exponential Effective SINR Mapping) [10] model is employed to select the MCS (Modulation and Coding Scheme). In addition, the QoS parameters of real-time services are showed in Table Π where all the connections in the system randomly belong to one of the five types.

A. Spectrum Efficiency

Fig. 2 illustrates spectrum efficiency as the number of UEs increases. The average spectrum efficiencies achieved by the three algorithms are calculated 100 times with each time 10^3 scheduling cycles. The proposed algorithm takes into account the average throughput in p_2 of (10), and the best utilization of the SDMA resource region in (15), so its spectrum efficiency outperforms that of either the SM-Max-SINR or, SM-PF algorithm, when the number of UEs exceeds 75. When the number of UEs equals to 100, spectrum efficiency achieved by the proposed algorithm increases by 4.7% and 12.8%, compared with the SM-PF and SM-Max-SINR algorithms.

TABLE I. SIMULATION CONFIGURATION

Parameters	Values
Centre Frequency	2.3 GHz
Bandwidth	10 MHz
No. Subcarriers	1024
No. Slot Dedicated for Data	480
Frame Duration	5 ms
MIMO Antenna (N_t by $N_{k,r}$)	4×2
Estimated SINR Range	[0dB, 25dB]
Modulation and Coding	QPSK: CC-1/2, CC-3/4 QAM16: CC-1/2, CC-3/4 QAM64: CC-1/2, CC-2/3, CC-3/4
Precoding	Unitary precoding (codebook size 16)

TABLE II. QOS PARAMETERS

Connection Type	Data Rate	Delay
1	1000 kbps	300 ms
2	800 kbps	300 ms
3	650 kbps	300 ms
4	400 kbps	200 ms
5	250 kbps	200 ms

B. QoS Guarantee

Fig. 3 shows the comparison of the data rate satisfaction ratio (DRSR) which is a ratio of the number of connections satisfying their data rate requirements to the total number of connections. DRSR of the proposed algorithm does not decrease until the number of UEs is more than 85, benefiting from the consideration of packet queuing factor and data rate factor in (10). DRSRs of both the SM-PF and SM-Max-SINR algorithms decline when the number of UEs is more than 75. However, the decline of SM-Max-SINR is more noticeable.

The average packet loss ratio (APLR) is used to compare the abilities to guarantee the delay requirements. In Fig. 4, the advantage of the proposed algorithm is obvious because of the application of delay sensitivity factor in (10). SM-Max-SINR does not involve any QoS factor, so APLR increases rapidly when the system tends to be fully loaded. The maximum APLRs reach 15.0%, 11.8% and 2.5%, respectively for the SM-Max-SINR, the SM-PF, and the proposed algorithm.

C. System Fairness

System fairness reflects the extent to which the system can meet individual users' data rate requirements, and can be evaluated by a fairness index [11] expressed as:

$$\psi(\tau) = \left(\sum_{l=1}^{L} \tau_l \right)^2 \Bigg/ \left(L \sum_{l=1}^{L} \tau_l^2 \right). \tag{18}$$

In (18), τ_l is the utilization of connection l. A totally fair scheduling will have a fairness index of 1.

Fig. 5 illustrates the system fairness as a function of the number of UEs. The system fairness of the three algorithms is well matched before the system is close to full load. SM-PF

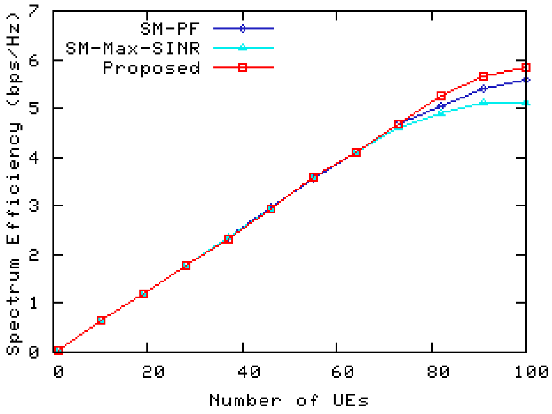

Figure 2. Spectrum efficiency versus the number of UEs

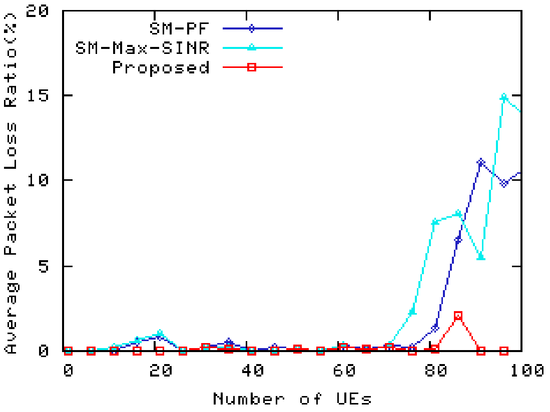

Figure 4. Average packet loss ratio versus the number of UEs

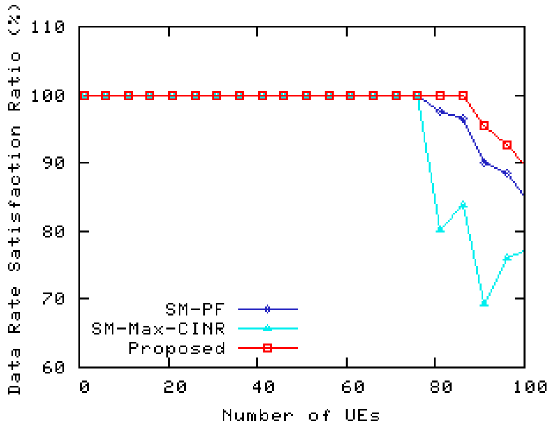

Figure 3. Data rate satisfaction ratio versus the number of UEs

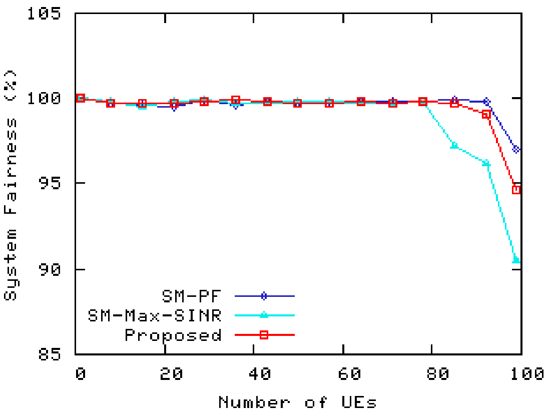

Figure 5. System fairness versus the number of UEs

achieves the best system fairness because it takes the PF index into consideration in packet scheduling for both the primary and secondary streams. Bringing the PF index into consideration in scheduling for the primary streams, system fairness of the proposed algorithm is lower than but close to system fairness of SM-PF.

V. CONCLUSION

In this paper, downlink scheduling based on precoding techniques in MU-MIMO systems with limited feedback has been studied. A joint stream selection and multi-user packet scheduling algorithm is proposed for QoS-guaranteed services. Streams are selected in accordance with precoding matrices to maximize the total capacity and reduce the CCI. The BS performs multi-user packet scheduling for the primary streams first, and then for the secondary streams to completely obtain spatial multiplexing gains. Numerical results show that, only at the cost of slightly lower system fairness, the proposed algorithm can achieve higher spectrum efficiency, and have a noticeable improvement in guaranteeing QoS requirements in terms of data rates and delay.

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