Comparative Investigation on MU-MIMO Schemes for TDD MIMO OFDMA Uplink

Guangyi LIU, Jianhua Zhang
Beijing University of Posts & Telecoms, Beijing, P.R.China, 100876
Email: lgy@buptnet.edu.cn

***Abstract*-CSI can be ultilized at the transmitter to implement close loop multiuser MIMO and obtain both full spatial multiplexing and multiuser diversity gain in uplink. In this paper, Multiuser Per Antenna Rate Control (MU-PARC) and Multiuser Singular Value Decomposition (MU-SVD) for Spatial Divison Multiplexing (SDM) of MIMO OFDM are investigated and a novel joint spatial frequency Proportional Fairness (PF) scheduling is proposed to guarantee the user fairness. MU-SVD is expected to achieve better system throughput since it can achieve full transmission and reception diversity and multiuser diversity gain, while MU-PARC can only achieve reception diversity and multiuser diversity gain. From the simulation results, the throughput of MU-SVD is 31% higher than that of MU-PARC for 4×2 MIMO and 8×4 MIMO scenario when SNR at receiver antenna is set as 10dB without path loss and shadowing.**

I. INTRODUCTION

By configuring multiple antennas both at Node B and User Equipment (UE), Multiple Input and Multiple Output (MIMO) channel capacity can be improved to be proportional to the minimum number of the antennas at UE and Node B [1]. Meanwhile, multiuser MIMO transmission, like DPC [2], THP [3] is found to be able to improve the multiuser capacity greatly.

Since UE can't estimate the MIMO channel experienced by the other UE, the coordinated transmission at UE is impossible, and the DPC and THP is not feasible for multiuser MIMO uplink. On the other hand, the joint processing of multiuser MIMO at the Node B is feasible since all the users' signal arrive at the Node B and all users' MIMO channel information is estimated at Node B. So Multiuser Per Antenna Rate Control (MU-PARC) [4] and Multiuser Singular Value Decomposition (MU-SVD) [5] is suitable for multiuser Spatial Division Multiplexing (SDM) in uplink.

In this paper, the MU-PARC and MU-SVD based SDM is proposed to enhance the multiuser uplink performance of MIMO OFDM TDD system. Since the Channel reciprocity of TDD system can be utilized to obtain the channel Status Information (CSI) at the transmitter conveniently, the joint spatial-frequency subcarrier and antenna scheduling with AMC is very feasible to be implemented at the Node B to achieve multiuser diversity gain in frequency and spatial domain. To guarantee the user fairness required in a practical cellular system, a joint spatial frequency proportional Fairness (PF) scheduler is proposed to achieve the tradeoff between the user fairness and the throughput gain by multiuser diversity in spatial and frequency domain.

This work is funded by Chinese NSF under grant No. 603025.

Since MU-SVD achieves full MIMO diversity gain and multiuser diversity gain, and MU-PARC only achieves reception diversity and multiuser diversity gain, MU-SVD is expected to achieve better system throughput than MU-PARC. From the simulation results, the throughput of MU-SVD is 31% higher than that of MU-PARC for 4×2 and 8×4 MIMO scenario when SNR at Node B receiver antenna is set as 10dB without path loss and shadowing.

II. SYSTEM MODEL

Combined MIMO with OFDM, the frequency selective fading MIMO channel can be separated into many flat fading MIMO channel in parallel, and thus the complicated MIMO detection in frequency selective fading channel can be simplified as that in a flat fading channel. In this section, the processing of MIMO OFDM system is described on a subcarrier, and the OFDM modulation and the subcarrier index is ignored. Since TDD system is considered, the CSI is assumed to be known perfect at the transmitter and receiver.

For multiuser MIMO uplink, MU-PARC and MU-SVD is suitable since all the users' signal arrive at the Node B simultaneously and all users' MIMO channel information can be obtained at Node B, and the joint processing of multiuser MIMO is feasible. In this section, the principle of MU-PARC and MU-SVD is presented.

1. MU-PARC

For MU-PARC, the receiver antenna number is required to be not less than the transmitter antenna number selected from UEs. Several UEs can share the same sub-channel in frequency domain to make full use of the spatial dimension. Every selected UE can transmit independent data streams to Node B from its selected antennas. At Node B, the joint detection like ZF is adopted to cancel the interference and recover the original data symbol. By exploiting the CSI at the transmitter, AMC can be applied on every data stream to maximize the system transmission efficiency.

The Channel Impulse Response (CIR) experienced by user i is presented as:

$$\mathbf{H}^i = \left[H^i_{m,n} \right]_{M_R \times M_T} \quad (1)$$

Where M_T and M_R are the transmitter and receiver antenna number respectively, and $M_R > M_T$.

Based on the CSI at the transmitter, the general MIMO channel matrix between the Node B and all UEs can be constructed as following:

$$\mathbf{H} = \left[\mathbf{H}^1, ..., \mathbf{H}^k, ..., \mathbf{H}^K \right] \quad (2)$$

To achieve the highest capacity, M_R transmit antenna presented as A_n can be selected to maximize the capacity, the selected sub-channel matrix is presented as $\bar{\mathbf{H}}$. Then the post-detection SNR for the signal from transmitter antenna $A_n(j)$ can be expressed as:

$$SNR_{A_n(j)} = \frac{P_T}{M_T} \frac{1}{\sigma^2 \|\mathbf{w}_j\|^2} \tag{3}$$

Where M_T is the selected antenna number, P_T is the total transmitter power on the subcarrier, σ^2 is the noise power experienced by the signal transmitted from antenna $A_n(j)$, $\mathbf{w}_j$ is the detection weight for the signal transmitted from antenna $A_n(j)$ by ZF detection.

$$\mathbf{w}_j = \left(pinv\left(\bar{\mathbf{H}}\right)\right)_j \tag{4}$$

Where $pinv$ means the pseudo-inversion, and $(\ )_j$ means the row j of the matrix.

The system capacity on a subcarrier can be expressed as:

$$C = \sum_{j=1}^{M_T} B\log_2\left(1+SNR_{A_n(j)}\right) = \sum_{j=1}^{M_T} B\log_2\left(1+\frac{P_T}{M_T}\frac{1}{\sigma^2\|\mathbf{w}_j\|^2}\right) \tag{5}$$

B is the subcarrier spacing. The total system capacity is the sum of the capacity on all subcarriers.

2. MU-SVD

When CSI is available at both the receiver and the transmitter, Singular Value Decomposition (SVD) can approach the MIMO capacity bound with water-filling power allocation.

$$\mathbf{H}_i = \mathbf{USV}^H \tag{6}$$

$\mathbf{U}$ and $\mathbf{V}$ are the left and right singular matrices, $\mathbf{S} = diag(\lambda_1, \lambda_2, ..., \lambda_M, 0...)$ is the singular value matrix with singular value on the diagonal element in descendent order. λ_k is the k singular value, $\lambda_1 > \lambda_2 > ....$, and $M = rank(H^i)$.

If we perform beamforming at the transmitter with $\mathbf{V}$, and reception beamforming at the receiver with $\mathbf{U}^H$, then the MIMO channel can be decomposed into several independent spatial SISO sub-channels in parallel with channel gain λ_k respectively.

$$\mathbf{r} = \mathbf{U}^H\mathbf{H}_i\mathbf{V} = \mathbf{U}^H\left(\mathbf{USV}^H\right)\mathbf{V} = \mathbf{S} \tag{7}$$

If the power allocated on the sub-channel is presented as p_k, $P_T = \sum_{k=1}^{M} p_k$, then the capacity of subcarrier n is:

$$C_n = \sum_{k=1}^{M} B\log_2\left(1+SNR_k\right) = \sum_{k=1}^{M} B\log_2\left(1+p_k\lambda_k^2/\sigma^2\right) \tag{8}$$

Usually, for single user SVD, besides λ_1, the other Eigen values are quite small. In [5]], the MU-SVD based SDMA is also proposed to utilize the principal eigen modes of several UEs to transmit independent data streams from different UEs to Node B simultaneously and adopt ZF detection at the Node B to cancel the inter-user interference jointly.

Assume the selected user set is $U_n = \{1,2,...,k,...M\}$ on subcarrier n. For every selected user, its principal Eigen mode is selected to transmit, and then the MU-SVD can be expressed as:

$$\mathbf{U} = [\mathbf{u}_1, ..., \mathbf{u}_k, ..., \mathbf{u}_M], \mathbf{V} = [\mathbf{v}_1, ..., \mathbf{v}_k, ..., \mathbf{v}_M] \tag{9}$$

$$\mathbf{S} = diag(s_1, ..., s_k, ..., s_M), \mathbf{d} = [d_1, ..., d_k, ..., d_M]^T \tag{10}$$

$\mathbf{u}_k$, $\mathbf{v}_k$, s_k and d_k are respectively the left and right singular vector, singular value corresponding to the principal Eigen mode and the transmitted data symbol on the principal Eigen mode of user k in U_n. The total received signal of all the scheduled users at the Node B is expressed as:

$$\mathbf{r} = \sum_{i=1}^{M} \mathbf{H}_i\mathbf{V}_i\sqrt{p_i}d_i + \mathbf{n} = \mathbf{US}\sqrt{\mathbf{p}}\mathbf{d} + \mathbf{n} \tag{11}$$

Where $\sqrt{\mathbf{p}} = diag(p_1, p_2, ..., p_M)$ is the power allocation vector. After the reception beamforming, the signal can be expressed as:

$$\mathbf{y} = \mathbf{U}^H\mathbf{r} = \mathbf{U}^H\mathbf{US}\sqrt{\mathbf{p}}\mathbf{d} + \mathbf{U}^H\mathbf{n} = \Re\mathbf{S}\sqrt{\mathbf{p}}\mathbf{d} + \mathbf{U}^H\mathbf{n} \tag{12}$$

$\Re = \mathbf{U}^H\mathbf{U}$ is the correlation matrix of the principal singular vector of the selected users, and its element $\rho_{i,j} = \mathbf{u}_i^H\mathbf{u}_j$.

To eliminate the interference among the users, ZF multiuser detection can be done to $\mathbf{y}$:

$$\hat{\mathbf{d}} = \Re^{-1}\mathbf{y} = \mathbf{S}\sqrt{\mathbf{p}}\mathbf{d} + \Re^{-1}\mathbf{U}^H\mathbf{n} \tag{13}$$

Although the interference among the users is forced to be zero, the noise covariance is enhanced to be $\boldsymbol{\eta} = \sigma^2\Re^{-1}$. The SINR of the user k in U_n can be expressed as:

$$SINR_k = \frac{p_k\lambda_k^2}{(\boldsymbol{\eta}_n)_{k,k}} \tag{14}$$

Where $(\ )_{k,k}$ means the k diagonal element of the matrix. Then the total system capacity on subcarrier n is:

$$C_n = \sum_{k=1}^{M} B\log_2(1+SINR_{n,U_n(k)}) = B\sum_{k=1}^{M}\log_2(1+\frac{p_k\lambda_k^2}{(\boldsymbol{\eta}_n)_{k,k}}) \tag{15}$$

III. PROPORTIONAL FAIRNESS SCHEDULING

To achieve the maximum multiuser diversity gain, the greedy scheduling is optimal and the radio resource is allocated to the UE who can achieve highest capacity on it. However, in a practical cellular system, the user fairness should be guaranteed to improve the user experience. In this work, a novel Joint Spatial Frequency PF scheduler (JSFPF) is proposed to achieve the tradeoff between the user fairness and the system throughput improvement of None-Real Time

(NRT) service contributed from the multiuser diversity gain in spatial and frequency domain.

Assume the set of M antennas selected from all the UEs is presented as A_n, and the set of the users selected on subcarrier n is presented as U_n, and then the selected optimal antenna set and user set of MU-PARC can be obtained optimally as following:

$$\left(A_n^{'},U_n^{'}\right)=\underset{C_n\in[1,M_T]}{\arg}\ \underset{U_n\in[1,K]}{\arg}\ \max\sum_{U_n}C\left(A_n,U_n\right) \tag{16}$$

Where $C\left(A_n,U_n\right)$ is the total capacity of the selected users and antennas, calculated as equation (5).

To find the optimal solution, all the possible sets are compared. So the greedy algorithm is too complicated to be implemented.

We propose JSFPF scheduling on every subcarrier as following:

$$\Pr_n^k(t)=\frac{\bar{R}_n^k(t)}{T_k(t)} \tag{17}$$

Where $\bar{R}_n^k$ is the estimated data rate on subcarrier n of user k, and T_k is the average transmission data rate of user k, and updated as equation (19).

$$\bar{R}_n^k=B\log_2\left(\det\left(\mathbf{I}+\rho\left(\mathbf{H}_n^k\right)^H\mathbf{H}_n^k\right)\right) \tag{18}$$

Where B is the subcarrier spacing. Here we assume that only one antenna at most can be assigned to one user on a subcarrier to guarantee the user fairness. Then on subcarrier n, M users' group A_n is selected as following:

$$\underset{C_n\in[1,K]}{\arg}\ \max\sum_{k\in C_n}\Pr_n^k(t)=\underset{C_n\in[1,K]}{\arg}\ \max\sum_{k\in C_n}\frac{\bar{R}_n^k(t)}{T_k(t)} \tag{19}$$

M users with highest priority are selected to transmit in next timeslot.

For MU-PARC, every user is assigned a transmitter antenna to maximize the total system capacity. For MU-SVD, the principle Eigen modes of selected user is scheduled to transmit.

The power allocated to different data streams is expressed as p_n^k, and $P_T=\sum_{n=1}^{N}\sum_{k\in U_n}p_n^k$. If the user k is not scheduled to share the subcarrier n, $p_n^k=0$. The reception Signal to Interference and Noise Ratio (SINR) of the user $C_n(k)$ on subcarrier n can be calculated as equation (3) and (14) for MU-PARC and MU-SVD respectively, and the data rate of every data stream R_n^k is decided by the selected Modulation and Coding Scheme (MCS) according to the SINR on the data stream of every subcarriers. By configuring proper SINR threshold for the switching among the MCSs, the highest system throughput can be achieved with adaptive Modulation and coding (AMC).

The total data rate of user k in the next scheduling period is:

$$R_k=\sum_{n=1}^{N}R_n^k \tag{20}$$

Where N is the subcarrier number. Then T_k can be updated with R_k after the scheduling:

$$T_k=\begin{cases}(1-\alpha)T_k+\alpha R_k, \textit{if user k is served}.\\(1-\alpha)T_k, \qquad\qquad\qquad else\end{cases} \tag{21}$$

Where $0<\alpha<1$ is the forgetting factor.

IV. Simulation Parameters

In this paper, the frame structure from [6] is adopted in our simulation as Figure 1.

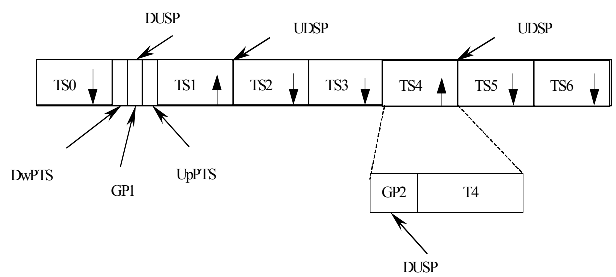

Figure 1 Frame structure of TD-SCDMA LTE

For TDD system is assumed, the Channel Status Information (CSI) of the UE is assumed to be available at the transmitter. AMC is implemented by combing QPSK and 16QAM with convolution coding. The full buffer NRT service is assumed, where the user is assumed to have enough packets to transmit any time.

TABLE 1 The MCS and the SNR threshold

MCS	Mod	Code Ratio	data bits	SNR threshold
1	QPSK	1/3	2/3	0.5dB
2	QPSK	1/2	1	3.7dB
3	QPSK	3/4	3/2	6.3dB
4	16QAM	1/2	2	10dB
5	16QAM	3/4	3	15.2dB

To observe the multiuser diversity gain in spatial domain obviously, the path loss and the shadowing are not considered in our simulation. In fact, the path loss and the shadowing may lead to more multiuser diversity gain observed since the multiuser diversity gain is contributed from the variation of the channel gain of different users, and more serious variation in fading leads to more multiuser diversity gain. The total power is equally allocated to different data streams on different subcarriers, and on every receiver antenna of a subcarrier, the SNR of the received signal is 10dB or 20dB in this paper.

The other simulation parameters are given in Table 1.

TABLE 1. System parameters

Parameter	Assumption
Carrier Frequency	2GHz
Band width	10MHz

Sample Frequency	1.92 MHz
Sub-carrier spacing	15 kHz
CP length(μs/samples)	7.29/14
FFT Size	1024
Occupied Subcarriers number	600
Subcarrier Group number	75
SNR at the receiver antenna	10dB
Channel PDP	GSM Typical Urban
MIMO channel Model	Uncorrelated Rayleigh fading

V. Simulation Results

The system throughputs of MU-PARC and MU-SVD in single cell scenario are presented as Figure 2 when the SNR at receiver antenna of Node B is set as 10dB without shadowing and path loss. The average data rate CDF of MU-PARC and MU-SVD in single cell scenario are given as Figure 3 when the SNR at receiver antenna of Node B is set as 10dB.

In Figure 2, the spectrum efficiency of MU-PARC and MU-SVD is compared. For 4×2 MIMO scenario, the throughput of MU-SVD is 32.5% higher than that of MU-PARC. For 8×4 MIMO scenario, the throughput of SVD-ZF is 31.4% higher than that of MU-PARC. It can be explained that the full diversity gain of MIMO can be achieved by SVD, and the principal Eigen modes of the scheduled users are multiplexed to obtain the spatial and frequency multiuser diversity gain and spatial multiplexing gain. The only cost paid for the gain is the enhanced noise. As observed from the simulation, at most time, the enhancement to the noise is not so obvious. So MU-SVD has much higher spectrum efficiency than MU-PARC.

From Figure 3, the distribution of the user data rate is very tight, so the user fairness is guaranteed very well in the sense of the user data rate.

VI. Conclusion

In this paper, the MU-PARC and MU-SVD based SDM is proposed to enhance the multiuser uplink performance of MIMO OFDM TDD system. Since the Channel reciprocity of TDD system can be utilized to obtain the channel Status Information (CSI) at the transmitter conveniently, the joint spatial-frequency subcarrier and antenna scheduling with AMC is very feasible to be implemented at the Node B to achieve multiuser diversity gain in frequency and spatial domain. To guarantee the user fairness required in a practical cellular system, a joint spatial frequency proportional Fairness (PF) scheduler is proposed to achieve the tradeoff between the user fairness and the throughput contributed from the multiuser diversity gain in spatial and frequency domain. Since MU-SVD achieves full MIMO diversity gain and multiuser diversity gain, and MU-PARC only achieves reception diversity and multiuser diversity gain. From the simulation results, the throughput of MU-SVD is 32% higher than that of MU-PARC for 4×2 MIMO scenario, and it is 31% higher than that of MU-PARC for 8×4 MIMO scenario when the SNR at the receiver antenna is set as 10dB without path loss and shadowing.

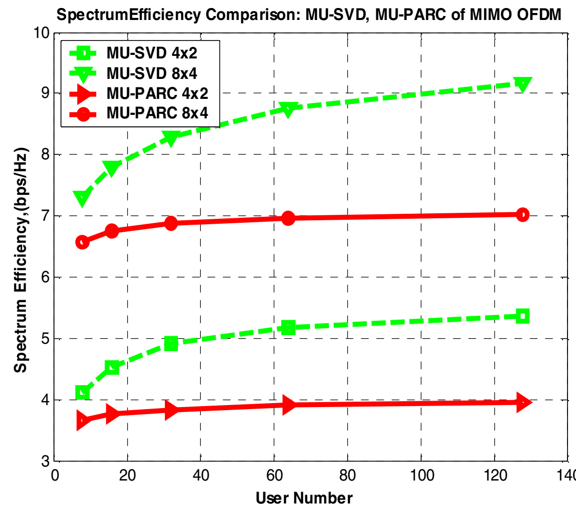

Figure 2 Spectrum efficiency Vs. UE number per cell (SNR=10dB)

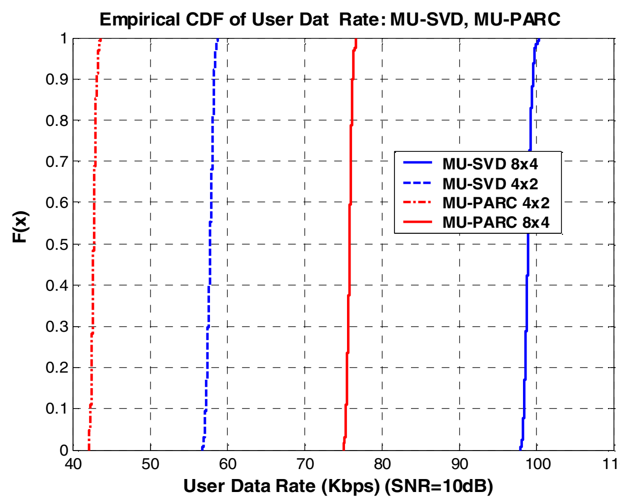

Figure 3 CDF of User Spectrum Efficiency (128 users)

References

[1] G. Foschini, M. Gans, "On limits of wireless communications in a fading environment when using multiple antennas", IEEE Wireless Personal Communications, March 1998, 6(3): 311-335.

[2] M. Costa, "Writing on dirty paper", IEEE Trans. Information Theory, Vol. 29, May 1983.

[3] R.D. Wesel and J. M. Cioffi, "Achievable rates for Tomlinson-Harashima precoding", IEEE Trans. Information Theory, vol. 44, no. 2, Mar 1998.

[4] Grant, S. J., Molnar, K. J, Krasny L., "system level performance gains of Per-antenna-rate-control (S-PARC)", IEEE VTC2005 Spring.

[5] J. Kim and J. Coiffi, "Spatial multiuser access with antenna diversity using singular value decomposition", IEEE ICC'00, vol. 3, 2000.

[6] 3GPP TSG RAN WG1#42, R1-050800, "Numerology and Frame Structure of EUTRA TDD based on OFDMA and text proposal for TR 25.814", CATT, RITT, ZTE, Huawei.

1-4244-0517-3/06/$20.00 ©2006 IEEE