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ABSTRACT

In a pre-coded Multi User Multiple Input Multiple Output (MU-MIMO) system, the channelization can be done either by using any of the two basic access techniques, namely Orthogonal Frequency Division Multiple Access (OFDMA) and Space Division Multiple Access (SDMA), or by combining them. From resource allocation point of view, choice of any technique will require different fairness conditions among users. In this paper, we have studied these different fairness conditions when combined with basic or joint access schemes mentioned above, while applied in a MU-MIMO based UTRA-LTE system. We have evaluated the resource allocation fairness issue when two well-known linear MU-MIMO precoding is used on a UTRA-LTE system. User grouping issue is dealt with when SDMA component is considered in the system. The results in this work provides an indicative analysis of the usability of different channelization techniques for considered system.

I. INTRODUCTION

Next generation wireless networks will be required to achieve very high spectral efficiency to support increasing number of mobile broadband users. Multi-antenna techniques are one of the well-known solutions to increase overall system throughput without requiring extended bandwidths, thus increasing the spectral efficiency. Presence of multi-antennas at the both ends of the transmission facilitates multi-stream Multiple Input Multiple Output (MIMO) operation across multiple users, which is also termed as Multi User Multiple Input Multiple Output (MU-MIMO) precoding technique. When detailed or instantaneous Channel State Information (CSI) is available at Node B (NB), then MU-MIMO schemes can provide very high system throughput. So, it is desirable to have CSI at the transmitter, which can be difficult to obtain in Frequency Division Duplex (FDD) based systems. Thus, current broadband wireless standard, such as Universal Terrestrial Radio Access with Long Term Evolution (UTRA-LTE) system specifies code-book based MU-MIMO precoding [1], where feedback requirement is relaxed required for FDD based systems. UTRA-LTE standard also specifies a Time Division Duplex (TDD) mode which operates in similar bandwidth configurations as described in [2]. Here, a specific frame structure type 2 is devised for TDD based UTRA-LTE systems. In this case, CSI based MU-MIMO systems can be implemented without requiring huge amount of feedback.

In a CSI-based MU-MIMO precoding system, all the time-frequency resources are simultaneously used among users, especially if low number of users are present, thus, the system would look like a traditional SDMA system. In this case, resource allocation fairness alone is not enough to ensure fairness among users, thus, different kind of fairness technique needs to be considered. We combine the fairness constraints in terms power allocation and resource allocation together in this paper. we have evaluated a general fairness algorithm adapted to a well-known linear precoding scheme, namely Channel Inversion (CI) and Block Diagonalization (BD) for MU-MIMO based precoded systems.

OFDMA can be used in MU-MIMO system combined with SDMA fashioned channelization. In this case, users will not only be differentiated in time and frequency, but also in space via precoding technique. This will increase the scheduling freedom, while also increasing the system complexity. When OFDMA is combined with SDMA in MU-MIMO systems, then user grouping becomes an important issue, because suitable pairs of users need to be selected for precoding at any certain resource block. In this case, fairness in user group selection needs to be considered together with usual OFDMA fairness conditions, such as throughput fairness, allocation fairness etc. One more interesting point here is that, when SDMA
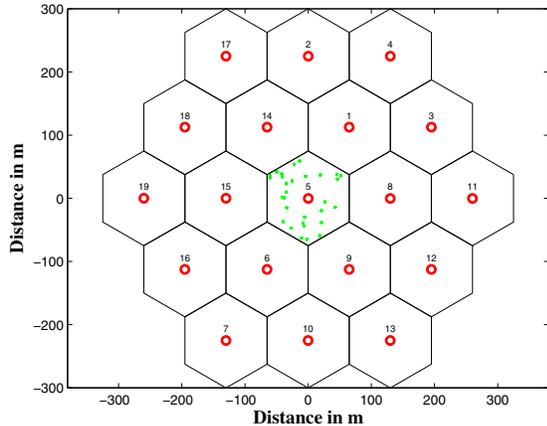
Fig. 1.   Layout of a Cellular System

component is used, the equal distribution of power across all precoded users in certain resource block will also result in an unfair system, as different users experience different levels of channel conditions. So, fairness across power allocation also need to be considered together with user group selection and resource block allocation.

In addition to our previous research on Link Adaptation (LA) [3], [4], which focuses on single cell scenarios with single User Equipment (UE), and the performance is mainly limited by thermal noise, we extend our research to a more generalized scenario in this work. The scenario we take is a multi-cell multi-user network, with possible MIMO antenna configurations. The purpose is to study the impact of these fairness conditions for different channelization techniques. We emphasize the usability of such analysis in TDD type of systems, as detailed CSI at transmitter is unrealistic to assume in FDD systems. So, we primarily state that our analysis stands for TDD mode of UTRA-LTE system, although needless to note that this study can be equally used for any other Orthogonal Frequency Division Multiplexing (OFDM) based broadband systems.

In this paper, we focus on OFDMA, SDMA and their combination, evaluate their performance in TDD mode of UTRA-LTE wireless broadband systems. The rest of this paper is organized as follows. Section II describes the system setup considered for this study. Section IV shows the result for SDMA with different precoding techniques in order to mitigate Multiuser Interference (MUI). The performance for combined OFDMA and SDMA is shown in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM SCENARIO

The layout of a cellular system is shown in Figure 1, where red circle means NB and green dot means UE. Since our interest lies only within one cell, i.e. cell 5 in the figure, UEs in the other cells are not shown.

Most of the simulation parameters are taken from UTRA-LTE downlink transmission [1], some of them are summarized in Table I.

TABLE I
SIMULATION PARAMETERS FOR UTRA-LTE LIKE SYSTEMS

Parameter	Assumption
Cellular layout	Hexagonal grid, 19 cells, 1 sector per cell
Antenna pattern (horizontal)	omni-directional
Carrier frequency	CF=2GHz
UE speed	between 20kmph and 40kmph, mean 30kmph
Total BS TX power	35dBm
Antenna gain plus cable loss at NB	6dBi
Minimum distance between UE and NB	10m
Delay spread	$0.5\mu s$
Coding Rate	$\frac{1}{3}, \frac{1}{2}, \frac{2}{3}$
Modulation	4QAM, 16QAM, 64QAM
Sub-channel size	16 sub-carriers per sub-channel
Number of sub-channels	18 sub-channels, corresponds to 288 of the total 512 sub-carriers
Block size	16 sub-carriers in frequency domain, 6 OFDM symbols in time domain
Active UE numbers	K=2
File buffer size	250KBytes
Throughput average window	$N_{av} = 100$ frames
FFT size	512
Target Block Error Rate (BLER)	0.1
Distance-dependent path loss	$P_L[dB] = \begin{cases} 39 + 20log_{10}(d[m]) & \text{when } d \leq 45 \\ -39 + 67log_{10}(d[m]) & \text{when } d > 45 \end{cases}$
Correlation distance of shadowing	25m
Fast fading model	Interpolated SUI-6 channel [5]

III. FAIRNESS CONSIDERATIONS WITH DIFFERENT CHANNELIZATION TECHNIQUES

When all users are scheduled across all resource blocks, the system becomes an OFDM-SDMA system where SDMA component is realized using ceratin CSI based precoding. From this point onwards, we denote such a system as an SDMA system.

For pure SDMA systems, UEs that are spatially separated are multiplexed onto the same time-frequency resource unit, thus fairness cannot be improved by Resource Allocation (RA). In this work, we have used a novel LA technique bearing in mind the fairness criterion. Later when considering the case of combined OFDMA and SDMA, fairness is handled in User Grouping (UG) procedure. Details of the fairness improving mechanism in RA, LA and UG can be found in [6]. They are summarized in the following:

- Fairness in RA: To improve fairness in RA, a common way is to use Proportional Fair (PF) algorithm. It
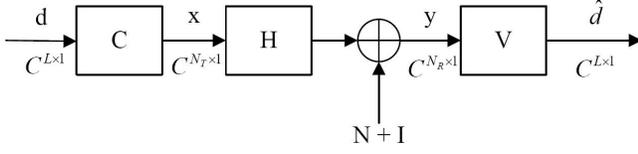
Fig. 2. System Model for Linear MIMO Precoding

allocates the UE with maximized normalized (with average throughput) achievable throughput. In formula,

$$k_{selected} = argmax_k \frac{TP(k,n)}{TP_{av}(k)}$$

where k is the UE index, $TP(k,n)$ is the achievable throughput for k^{th} UE at the nth block, $TP_{av}(k)$ is the average throughput for k^{th} UE.

- Fairness in LA: The LA algorithm used in this work is derived from [3], but extended to Multi-user systems with FEC coding. It follows an iterative processing, within each iteration, some bits for transmission can be allocated to the sub-channel with the lowest $\frac{\Delta P}{\Delta b}$, where ΔP is the required power for increasing the transmission rate to the next level and Δb is the increased rate. By normalizing Δb with the UE average throughput, fairness is improved.

- Fairness in UG: When the number of UEs is larger than the number of users that the NB can simultaneously serve, UG and group selection is required. Usually the group that achieves the highest throughput is selected. In order to improve fairness, this achievable group throughput should be normalized by its averaged value.

IV. MULTI-CARRIER MU-MIMO SYSTEM WITH CI/BD BASED PRECODING

MIMO precoding techniques are used in SDMA to mitigate MUI. They are generally classified into two categories: Linear precoding and Non-linear precoding. Linear precoding techniques, e.g. CI and BD are usually simpler than non-linear techniques, e.g. Dirty Paper Coding (DPC) and Tomlinson-Harashima Precoding (THP), at the cost of a worse performance [7]. This paper focuses on linear precoding techniques, because of their simplicity.

The system model for linear precoding technique is shown in Figure 2 and is described in the following [8].

A single NB equipped with N_T antennas serves K decentralized UEs. UE k is equipped with N_k antennas. The number of total receiving antennas is $N_R = \sum_{k=1}^{K} N_k$. UE k receives L_k data streams from NB and the total data streams sent out from NB is: $L = \sum_{k=1}^{K} L_k$.

The transmit data vector is

$$d = [d_1^T, \ldots, d_K^T]^T$$

where d_k is the data symbols for the kth UE.

$C = [C_1, C_2, \ldots, C_L] \in \mathbb{C}^{N_T \times L}$ is the precoder which maps d to the transmit signal:

$$x = Cd \in \mathbb{C}^{N_T \times 1}$$

The received signal y is:

$$y = HCd + (N + I) \qquad (2)$$

where $H = [H_1^T, H_2^T, \ldots, H_{N_R}^T]^T \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix between all transmitting and receiving antennas, H_n is the channel matrix between the nth receiving antenna and all transmitting antennas. N is the thermal noise generated at receiver and I is the interference from other cells. At the receiver, the linear operator $V \in \mathbb{C}^{L \times N_R}$ is applied to estimate the information:

$$\hat{d} = Vy = VHCd + V(N + I) \in \mathbb{C}^L$$

Different C and V leads to different linear precoding techniques.

A. Precoding using Channel Inversion Technique

As described in [7], CI uses Zero Forcing (ZF) to fully invert the effect of the wireless channel on the transmission, i.e. $C = H^\dagger = H^H(HH^H)^{-1}$. Each receiving antenna receives one separate data stream so that $L_k = N_k$ and $L = N_R$. The received signal y in Equation 2 becomes:

$$\begin{aligned} y &= HCd + (N + I) \\ &= HH^H(HH^H)^{-1}d + (N + I) \\ &= d + (N + I) \qquad (3) \end{aligned}$$

Equation 3 shows that CI can totally remove the effect of channel on the transmitted signal and the MUI, i.e. zero MUI. Moreover, the columns of precoding matrix C can be weighted to yield different receive signal power for each data stream. Let $W = diag(w_1, w_2, \ldots, w_L) \in \mathbb{C}^{L \times L}$ is the weighting matrix. The weighted precoder C_w can be written as $\bar{C} = CW = [w_1 C_1, w_2 C_2, \ldots, w_L C_L]$. W is decided in LA procedure.

The receiver complexity for CI is reduced because V is not needed. However, the drawback of CI is that the requirement of zero MUI is too stringent. When two or more antennas are highly correlated, the required power for achieving zero interference among these antennas will be extremely high [7]. An alternative approach to perform CI without suffering from the high transmit power requirement is to use Minimum Mean Square Error (MMSE) instead of ZF equalizer. However, power control for MMSE is not so straightforward as for ZF. Thus we consider LA with MMSE-CI as future work.
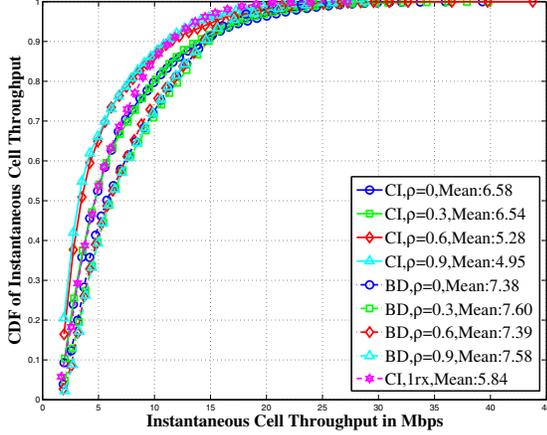
Fig. 3. CDF of Throughput for SDMA with Different Precoding Techniques

B. Precoding Using Block Diagonalization

When more than one antennas exist at each UE, it is still possible but not an efficient solution to use CI, since the antennas belonging to the same UE are usually highly correlated [7]. BD or block CI is used to optimize the transmission to a group of antennas rather than a single antenna [9].

Assume $H_k \in \mathbb{C}^{L_k \times N_T}$ and $C_k \in \mathbb{C}^{N_T \times L_k}$ the channel matrix and precoder for the kth UE. BD works by forcing

$$H_l C_k = 0 \ for \ \forall l \neq k \tag{4}$$

thus cancels the MUI and gives

$$y_k = H_k C_k x_k \tag{5}$$

Equation 4 can be achieved with the Singular Value Decomposition (SVD) of H. Define

$$\tilde{H}_k = [H_1^T, \ldots, H_{k-1}^T, H_{k+1}^T, \ldots, H_K^T]^T$$

and its SVD as:

$$\tilde{H}_k = \tilde{U}_k \tilde{D}_k [\tilde{V}_k^{(1)} \ \tilde{V}_k^{(0)}]^H$$

where $\tilde{U}_k$ and $\tilde{D}_k$ are the left singular vector matrix and the matrix of singular values of $\tilde{H}_k$. $\tilde{V}_k^{(1)}$ and $\tilde{V}_k^{(0)}$ denote the right singular matrices corresponding to non-zero singular values and zero singular values. Any precoder C_k that is a linear combination of the columns of $\tilde{V}_k^{(0)}$ can guaranty that C_k lies in the null space of $\tilde{H}_k$, and satisfies Equation 4 [9], [10]. The precoder C can also be adjusted to offer $\bar{y}_k = H_k C_k W_k x_k$, where W_k is the weighting matrix for each UE.

Figure 3 shows the Cumulative Distribution Function (CDF) of cell throughput for CI and BD. Note that BD is only applicable with multiple receiving antennas. While the antennas at NB are assumed to be uncorrelated, antennas belonging to the same UE are assumed to be correlated with correlation coefficients of 0, 0.3, 0.6 or 0.9. It can be seen that:

1) BD has a better performance than CI, even if the MIMO links are totally uncorrelated. The reason is that CI requires some power to achieve orthogonal transmission for each antenna. With BD, multiple receiving antennas can cooperate with each other to offer diversity gain and array gain.
2) The performance for CI decreases as antenna correlation increases. However, BD is hardly affected.
3) Using CI with multiple receiving antennas can only benefit when the correlation is low. In fact, when the correlation is high, the performance is even worse than with single receiving antenna.

V. TIME-FREQUENCY USER GROUPING WITH MU-MIMO PRECODING

In the previous section, CI and BD is evaluated with SDMA, where the active UE number is restricted to be the same as the number of transmit antenna. In this section, a more generic situation when there are more UEs than the number of antennas at NB is studied. We call such a system a combination of OFDMA-SDMA. NB is assumed to have 2 antennas and can serve maximum 2 UEs with the same transmission resource. The total number of UEs that are connected to NB is 10. UEs are divided into different groups and the transmit resources will be assigned to the selected group.

Three UG methods are tested, namely Optimal UG, Sub-optimal UG and Simple UG. Optimal UE tests all possible group combinations to find the best one; Sub-optimal UE selects the first UE according to the channel gain, then selects from the rest UEs the one offers highest group throughput; Simple UE selects the two UEs with the maximized achievable throughput [10], hence is very simple. To improve fairness in group selection, the above mentioned throughput should be normalized with its averaged value. Once the selection is done, a normal LA technique can be used to maximize the spectral efficiency.

When combined with two receiving antennas, if CI is used as the precoding technique, then NB will have $2 * K$ choices to select from, where K is the number of UEs. While BD offers only K choices for NB to select, because the two receiving antennas for each UE must be selected simultaneously. Specially for CI, if the antennas belonging to the same UE are both selected, their high correlation is expected to give poor throughput performance. In order to maintain a good performance, we should enforce maximum one receiving antenna been selected for each UE. For multiple receiving antenna cases, only Simple UG is tested, because of its computational simplicity. The two antennas in the same UE are assumed to be correlated with a correlation coefficient of 0.6.
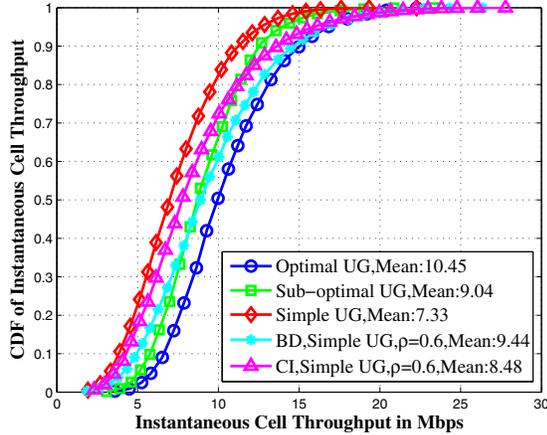
Fig. 4. CDF of Throughput for Combined OFDMA and SDMA with Single and Multiple-antenna UEs

Figure 4 shows the CDF of cell throughput. It can be seen that:

1) Optimal UG on average has the highest UE throughput, next is Sub-optimal UG. Simple UG offers the lowest averaged UE throughput.
2) When combined with multiple receiving antennas, the performance can be improved. Specifically for Simple UG, the performance can be improved by 16% using CI and 29% using BD.
3) The gap between CI and BD is reduced, as compared to pure SDMA cases. This is because CI offers more degrees of freedom for antenna selection.

VI. CONCLUSION

In this paper, we have evaluated the performance for OFDMA and SDMA systems, as well as the combination of the two in MU-MIMO scenario. The result shows PF in OFDMA can efficiently improve the fairness while maintaining a reasonably good performance. If NB is equipped with more than one transmitting antenna, by means of MIMO precoding, the performance can be improved. Combined OFDMA together with SDMA can further improve the performance at the cost of high complexity.

If each UE has more than one receiving antenna, OFDMA sees a performance improvement by using Maximal Ratio Combining (MRC); SDMA can benefit from using BD as the precoding technique.

Future Outlook: The International Telecommunications Union (ITU) is currently specifying the requirements for the next generation of mobile communication systems, the so-called International Mobile Telecommunications-Advanced (IMT-A) systems. It is being discussed that possibly a TDD mode will be employed in local area scenario as part of the IMT-A system [11], [12], so that channel reciprocity can be exploited and CSI dependant

MU-MIMO precoding can be used. For this kind of scenario, the studies that we have performed in this work can be easily used to provide an indicative results of suitability of different channelization technique for MU-MIMO precoding systems.

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