Delta Metric Scheduling for LTE-Advanced Uplink Multi-user MIMO Systems

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***Abstract*—Proportional fair (PF) scheduling algorithm has been extensively utilized in many different systems, since it can support both multi-user diversity and system fairness guarantee. Brute-force searching is the optimal scheduling, pairing and ordering algorithm. However, the optimal brute-force searching method is too computationally prohibitive, especially in case of the large number of users. This paper proposes a novel 2-dimensional grid based scheduling scheme for uplink MU-MIMO transmission using either the conventional proportional fairness metric or delta scheduling metric. Comparing to the scheduling approach using the conventional priority based pairing metric, the proposed scheduling algorithm based on delta scheduling metric could obtain approximate 7% gain for both cell and cell-edge throughput gain with neglectful computational complexity increase. With the aid of successive interference cancellation, MU-MIMO with MMSE-SIC receiver could also improve the cell-edge throughput compared to SU-MIMO. The advantage of the proposed scheme is that it can improve the throughput performance without the sacrifice of the user fairness guarantee.**

***Index Terms*—Virtual-MIMO, MMSE, MMSE-SIC, LTE, proportional fair, delta scheduler**

I. Introduction

In the 3GPP Long Term Evolution (LTE) systems, the single carrier frequency division multiple access (SC-FDMA) is adopted as the uplink multiple access scheme [1]. Compared to orthogonal frequency division multiplexing (OFDM), SC-FDMA can reduce peak-to-average peak ratio (PAPR) to facilitate the implementation of the mobile terminal with low complexity. Hybrid automatic repeat request (HARQ), link adaptation (LA) and dynamic packet scheduling are the entities in the medium access control (MAC) layer [2]. It has been proved that multi-user multiple-input and multiple-output (MU-MIMO) can significantly obtain the gain of the overall performance in terms of cell throughput and cell-edge user throughput over 1x2 single user (SU) baseline [3]. In the uplink LTE systems, the base station (BS) uses multiple receive antennas for simultaneous transmission scheduled on the same frequency resources to form virtual MIMO (V-MIMO) systems [4]. The bandwidth is divided into several separated chunks denoted as resource blocks (RBs). A RB is considered as the minimum scheduling resource unit in the time-frequency domain. In order to obtain the multi-user diversity gain and frequency diversity gain, the base station needs to know the information of all users and RBs, and assign RBs to users according to the selected scheduling scheme in each transmission time interval (TTI). Moreover, for LTE uplink, because the underlying waveform of SC-FDMA is essentially single-carrier [5], all the RBs allocated to a single user must be contiguous in frequency domain at each time slot. This resource contiguous constraint leads to high complexity for the scheduling design and user pairing. The number of users for simultaneous transmissions on each RB is limited by the number of transmit antennas, the number of receive antennas, and the richness of the channel. In order to obtain the optimal performance, user scheduling and user pairing have to be jointly considered. In the scheduling scheme design, either throughput or multi-user fairness should be considered. Proportional fair (PF) scheduling algorithm can support both multi-user diversity and system fairness guarantee [6], so it has been extensively utilized in many different systems. Brute-force searching is the optimal scheduling, pairing and ordering algorithm. However, the optimal brute-forcing searching method is too computationally prohibitive to be implemented, especially in case of the large number of users.

After calculating the pairing metric, which could be capacity, priority, etc, for every possible combination, the optimal user set, decoding order and pairing can be found. However, Brute-force searching is not practically feasible to implement due to its huge computational complexity, especially in case of the large number of users. In the LTE systems for MU-MIMO, we should consider the scheduling both in the spatial and frequency domain. This fact motivates on the need of low complexity scheduling schemes and user pairing methods to improve the performance and reduce the computational complexity. Based on channel correlation, a random pairing scheduling algorithm has been proposed in [7]. The first user equipment (UE) is selected according to Round-Robin, and the second user is chosen randomly. This scheduling algorithm is flexible and with high fairness and low complexity. The obvious disadvantage is that it can not support high system throughput. In [3], the channel-condition-dependent determinant pairing scheduling algorithm with maximizing the system throughput is proposed. However, it only considers the impact of small scale fading and ignores that of large scale fading.This paper proposes a novel 2-dimensional grid based scheduling algorithm and user pairing methods for uplink MU-MIMO transmission in LTE-A systems.

The remainder of the paper is organized as follows. After a description of system model in Section II, Section III discusses the user scheduling and user pairing algorithm in detail. Simulation results are presented and discussed in Section IV. Finally, our conclusions are given in Section V.

II. System Model

This paper considers an uplink V-MIMO cellular systems as illustrated in Fig. 1. The detailed assumptions can be found in section IV. We use 3GPP spatial channel model (SCM) for modelling the multi-path fading. Assuming that UEs are uniformly distributed in each cell, in which there are K active UEs. The BS is equipped with N_r antennas and each UE is equipped with N_t antennas. At each TTI, the scheduler in each BS chooses N_u UEs to transmit on the same RBs. So a $N_r \times N_t N_u$ SU V-MIMO system is emulated. The received signal in the frequency domain (i.e. the rth RB) can be written as

$$\mathbf{y} = \mathbf{H}_s \mathbf{x}_s + \sum_{i \neq s} \mathbf{H}_i \mathbf{x}_i + \mathbf{n}_s \tag{1}$$

where $\mathbf{x}_s$ is the desired transmitted signal vector, $\mathbf{x}_i$ is interference signal vector from the UEs in other cells, and $\mathbf{n}_s$ is the noise vector composed of additive complex Gaussian noise (AWGN) with the covariance matrix $E[\mathbf{n}_s \mathbf{n}_s^H] = \sigma^2 \mathbf{I}$ ($\mathbf{I}$ is identity matrix). $\mathbf{H}_s$ and $\mathbf{H}_i$ are channel matrices corresponding to the desired signal and co-channel interference. $(\cdot)^H$ denotes transpose conjugate operations. Assume a linear receiver is used to estimate the transmitted symbol by appropriately weighting the received signal with a complex-valued weight matrix $\mathbf{w}^H$. The processed receiver signal is given by

$$\hat{\mathbf{y}} = \mathbf{w}^H \mathbf{y} = \mathbf{w}^H \mathbf{H}_s \mathbf{x}_s + \underbrace{\sum_{i \neq s} \mathbf{w}^H \mathbf{H}_i \mathbf{x}_i}_{interference} + \underbrace{\mathbf{w}^H \mathbf{n}_s}_{noise} \tag{2}$$

For simplicity, $\mathbf{e} = \sum\limits_{i \neq s} \mathbf{H}_i \mathbf{x}_i$ is used to denote the sum of interference signals. If there is only one antenna at each UE, the post-Signal to Interference plus Noise ratio (post-SINR) can be written as

$$\mathrm{SINR} = \frac{\mathbf{w}^H \mathbf{H}_s \mathbf{H}_s^H \mathbf{w}}{\mathbf{w}^H (\mathbf{Q} + \sigma^2) \mathbf{w}} \tag{3}$$

where $\mathbf{Q} = E\{\mathbf{e}\mathbf{e}^H\}$ is the covariance matrix of the interference.

A. Receiver

For MU-MIMO user pairing, two types of the mechanism are categorized: user pairing with minimum mean-squared

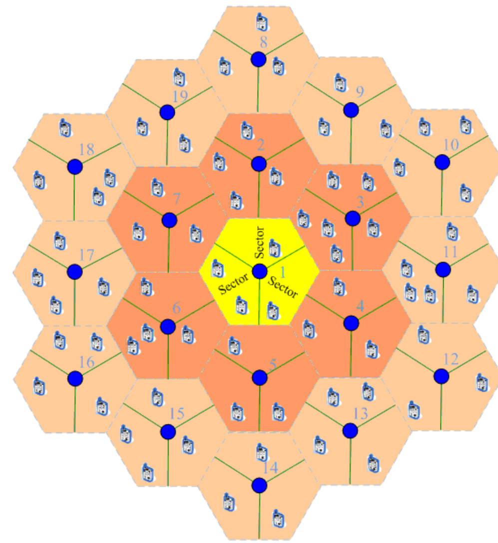

Fig. 1: illustration of uplink V-MIMO cellular systems

error (MMSE) and MMSE plus successive interference cancellation (MMSE-SIC) receivers. In this paper, both types of the receivers are adopted to analyze the performance of the schedulers.

1) MMSE receiver: Linear MMSE receiver is extensively adopted due to the low complexity and be easily implemented in the frequency domain. The weight matrix at the receiver can be written as

$$\mathbf{w} = (\mathbf{H}_s \mathbf{H}_s{}^H + \sigma^2 \mathbf{I})^{-1} \mathbf{H}_s \tag{4}$$

2) MMSE-SIC receiver: The successive interference cancellation (SIC) approach can be used to suppress the interference caused by the stronger UE efficiently before the detection of the weaker UE. So MMSE and SIC can be combined to further improve the MU-MIMO gain promisingly [8]. In this paper, the cancellation order is determined by the SINR of each UE in descending order.

B. Power Control

For the LTE uplink, power control has become an important means to mitigate the interference and increase the cell-edge and thus, system throughput [9]. Hence, the fractional power control is mostly used as a simple open-loop scheme

$$P\,(i) = \min\{P_{\mathrm{MAX}}, 10\log_{10} M\,(i) + P_0\,(i) + \alpha\,(i)\, PL\,(i)\} \tag{5}$$

where P_{MAX} is the maximum UE transmit power, P_{O} is a parameter composed of the sum of a cell-specific nominal component and a UE-specific component provided by higher layers, M is the assigned bandwidth expressed in number of RBs, α is a constant path loss compensation factor, and PL is the path loss derived based on the reference signal received power (RSRP) measurements. In this paper, we adopt an open-loop fractional power control using the path loss difference between the serving cell and strongest neighbor cell.

C. IoT

According to ITU evaluation guidelines, Interference over Thermal noise (IoT) measure is used to reflecting the 'effective' interference received by BS. The IoT can be defined as the ratio between the total effective noise and interference power to the effective thermal noise power [2]

$$\mathrm{IoT} = \frac{\mathbf{W}^H(\mathbf{Q}+\sigma^2)\mathbf{W}}{\sigma^2\mathbf{W}^H\mathbf{W}} \tag{6}$$

III. Scheduling Algorithm Design

In this section, the basic ideas of user scheduling and user pairing algorithms are presented. According to the characteristics of uplink V-MIMO systems, we should consider both the spatial domain and the frequency domain. This leads to the problem how to determine the scheduling order. There are three options for consideration:

- Frequency domain first, then spatial domain,
- Spatial domain first, then frequency domain,
- Dynamic switch across frequency and spatial domain.

Separating the scheduling in spatial and frequency domain will restrict the scheduling flexibility, so we prefer to adopt the cross frequency and spatial scheduling. The feature of contiguous resource allocation constrains raise higher complexity for scheduling scheme and user pairing metric design. In order to reduce the decoding complexity and decoding delay, we adopt equal resource allocation scheme by means of priority metric.

In uplink MU-MIMO implementation, the user pairing scheme is one of the most important elements due to a significant effect on system performance. In order to guarantee the fairness, the scheduling metrics in spatial and frequency domain are both based on PF utility. The PF scheduling algorithm allocates the resource to the user that can transmit at the highest rate, relative to its average achieved throughput during some window of past transmissions. In order to decide the selection of users, each user with data to transmit is assigned a priority metric C_u, defined by:

$$C_u(t) = \arg\max_{j=1,\ldots,n} \frac{r_j(t)}{T_j(t)} \tag{7}$$

where $r_j(t)$ is the transmission rate of user j at tone t if scheduled. $r_j(t)$ can be derived from Shannon's capacity formula or according to the selection of modulation and coding scheme (MCS). The average throughput $T_j(t)$ is typically evaluated through an exponentially smoothed average:

$$\begin{aligned} T_j(t) = &\left(1-\tfrac{1}{t_c}\right)T_j(t-1) + \\ &\tfrac{1}{t_c}\times r_j(t-1)\,|_{\{i(t-1)=j\}} \end{aligned} \tag{8}$$

The time constant t_c captures the time-scale of the PF scheduler. In this paper, a novel user pairing metric in the spatial domain called delta scheduler is proposed. It is assumed that user u_a has been scheduled at the first layer, then the scheduling metric pairing with user u_b is evaluated. Denote the PF priority scheduling metric of user u_a as $C(u_a)$. Denote the PF priority scheduling metric for user u_a with considering the multi-user interference (MUI) from user u_b as $C(u_a|u_b)$, and similarly $C(u_b|u_a)$ is defined. The delta scheduling metric is calculated as follow:

$$P_{delta} = C(u_a|u_b) + C(u_b|u_a) - C(u_a) \tag{9}$$

In order to describe the proposed idea clearly, we give a step by step description of the 2-dimensional grid based scheduling process in detail as follows.

Algorithm 1 Proposed scheduling algorithm

step 1) Get valid UE list and valid RB list.

step 2) Calculate each UE's PF priority metric on each RB, and find out the UE with maximum metric on each RB to finish the frequency domain scheduling. Then, put the selected users with the maximum PF priority metric on the lowest layer in the 2-dimension grid. The dimension size of the Grid is (X, Y), where X is equal to the number of users within sector, and y is equal to the maximum number of paired users on spatial domain. One example of the grid with $Y = 4$ is shown in Fig. 2.

step 3) Select the best user in both the frequency and spatial domain according to the scheduling metric. In order to avoid the condition of RB overlap between different users, the user will be put in either the frequency domain or spatial domain at step 2. That means the best user in the spatial domain and the best user in the frequency domain will be compared, the one with larger scheduling metric will be selected to be scheduled. The scheduling metric in the frequency domain is the conventional PF priority metric as described above. The conventional approach to calculate the scheduling metric is to straightforwardly use $C(u_b|u_a)$ based on linear MMSE receiver as the scheduling metric when comparing the best users in the spatial and frequency domain. In our proposal, we choose the delta scheduling metric $C(u_a|u_b) + C(u_b|u_a) - C(u_a)$ to improve performance at the similar cost of computational complexity. This approach can be easily further extended to the case that the number of the scheduled users is more than 2. One example of the filling processing is shown in Fig. 3.

step 4) Move the scheduled user in step 3 to the highest layer, and remove the scheduled user from the set of valid user set and on the other RBs.

step 5) Loop back to step 2 until no unscheduled user is remained or resource unit is used up.

step 6) Extend the residual RBs to the UEs scheduled on the nearby RBs if the utility of UE is increased.

step 7) Assign TB size and modulation schemes for all the scheduled users.

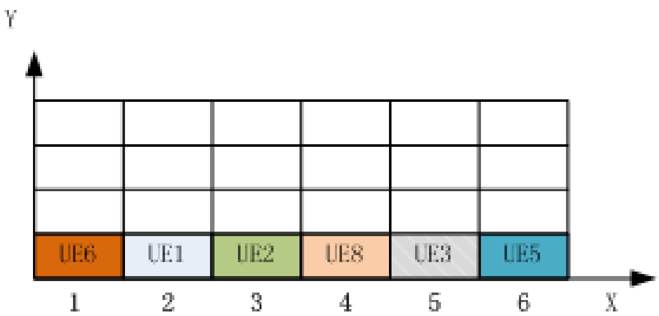

Fig. 2: The example of 2-dimension grid filled by the selected users

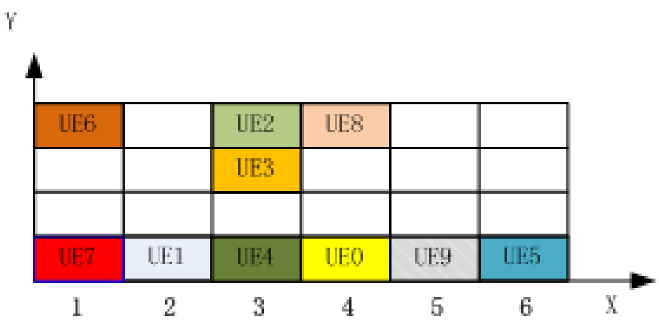

Fig. 3: The example of filling process

IV. Simulation Methodology & Results

In this section, system-level simulations are performed through performing the proposed user scheduling and user pairing algorithm for a 3GPP LTE release 10 cellular layout, corresponding to the standard hexagonal grid consisting of 19 cell sites with 3 sectors per site. There are 10 UEs in each sector with single antennas in our simulation. The maximum number of paired users on the same RB is 2. Wrap around technique is used to maintain the uniform distribution of BSs and mitigate the effect of the layout border in order to guarantee the fair amount of interference for all UEs. Exponential effective SINR mapping (EESM) is adopted accurately to predict the link layer performance for the link to system interface mapping [10]. The cell-edge user spectral efficiency is defined as 5% point of the cumulative distribution function (CDF) of the normalized user throughput. The simulation assumptions can be found in Table I.

Figs. 4 and 5 show the CDF of UE post-SINR and cell-edge throughput between SU-MIMO and the two pairing metric schemes with MMSE and MMSE-SIC receivers, respectively. It is observed that the proposed pairing scheme has better performance than conventional priority pairing scheme in terms of UE post-SNR and cell-edge throughput with both MMSE and MMSE-SIC receivers. Table 2 shows cell spectral efficiency, cell-edge UE spectral efficiency and IoT values of SU-MIMO and the two user pairing schemes with MMSE

TABLE II: Cell and cell-edge user spectral efficiency with MMSE receiver

MMSE Receiver	Cell Spectral Efficiency (bps/Hz)	Cell-edge User Spectral Efficiency (bps/Hz)	IoT (dB)
SU-MIMO	1.54	0.0673	4.8054
Priority Pairing metric	1.6335	0.0617	6.1317
Delta pairing metric	1.7327	0.0661	6.0299
Gain Of different metrics	6.07%	7.13%	

TABLE III: Cell and cell-edge user spectral efficiency with MMSE-SIC receiver

MMSE-SIC Receiver	Cell Spectral Efficiency (bps/Hz)	Cell-edge user Spectral Efficiency (bps/Hz)	IoT (dB)
SU-MIMO	1.54	0.0673	4.8054
Priority Pairing metric	1.7026	0.0655	6.2347
Delta pairing metric	1.8188	0.07	6.3259
Gain Of different metrics	6.82%	6.87%	

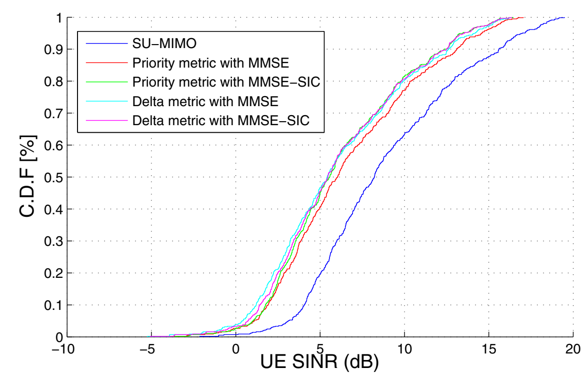

Fig. 4: The UE SINR curves between SU-MIMO and the two pairing scheme with MMSE and MMSE-SIC receivers

and MMSE-SIC receivers. The proposed scheduling metric scheme can increase both the cell and cell-edge user spectral efficiency comparing to conventional priority pairing scheme with neglectful computational complexity increase. According to the simulation results, the gain for both cell and cell-edge is approximately 7%. Compared to the SU-MIMO, both the pairing metric schemes can obtain some gain for cell average throughput and with MMSE-SIC receiver the cell-edge throughput can be also improved.

V. Conclusions

This paper proposes a 2-dimensional grid based scheduling scheme for uplink LTE systems using either the conventional proportional fairness metric or delta scheduling metric. Compared to the traditional priority based pairing metric, the pro-

TABLE I: Simulation assumptions

Parameter		**Assumption**
Cellular Layout		Hexagonal grid, 19 cell sites, 3 sectors per site with wrap-around
Duplex method		FDD
Handover margin		1dB
Distance-dependent path loss		L=128.1 + 37.6$\log_{10}$(.R), R in kilometers
Lognormal Shadowing with shadowing standard deviation		8 dB
Inter site distance		500m
Correlation distance of Shadowing		50 m (See D,4 in UMTS 30.03)
Shadowing correlation	Between cells	0.5
	Between sectors	1.0
Penetration Loss		20 dB
Antenna pattern (horizontal) (For 3-sector cell sites with fixed antenna patterns)		$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ θ_{3dB} = 70degrees, A_m = 20 dB
Channel model		SCM
UE TX power		24 dBm
Minimum distance between UE and cell		35 meters
Power control		Open loop fractional power control using the path loss difference between the serving cell and strongest neighbour cell. α = 0.6, P_0 = -60.
HARQ		Synchronous IR with N=6 stop-and-wait HARQ. The maximum of 4 retransmissions
SC-OFDM symbols (Data symbols) per subframe		14 symbols
Scheduler		As described in PART II
Antenna configuration		1Tx, 4Rx
maximum number of paired users		2
Link Mapping		EESM
UE Transmitter / eNB Receiver		1x4 (antennas with space is 10 wavelength)
Precoding scheme		Uplink CodeBook in R10, Rank adaptation
Reference Signal and control channel overhead		8 PRB reserved for PUCCH, 2symbol per TTI reserved for Demodulation RS
Channel estimation and Demodulation RS		Ideal
UE traffic		Full buffer
Number of UE per sector		10

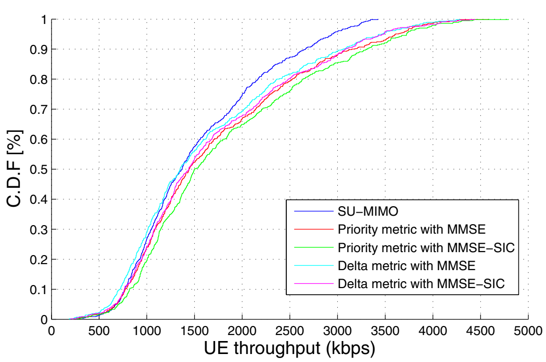

Fig. 5: The average UE throughput performance curves between between SU-MIMO and the two pairing scheme with MMSE and MMSE-SIC receivers

posed algorithm based on delta scheduling metric could obtain approximately 7% gain for both cell and cell-edge throughput with little computational complexity increasing. Furthermore, MU-MIMO with MMSE-SIC receiver could bring more than 10% gain in cell average throughput over SU-MIMO. The advantage of our scheme is that it can guarantee the user fairness while improving the throughput performance.

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