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Allocation Fairness for MIMO Precoded UTRA-LTE TDD System

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ABSTRACT

In future Time Division Duplex (TDD)-based broad-band wireless systems, it will be possible to exploit the channel reciprocity to implement Channel State Information (CSI)-based Multi User Multiple Input Multiple Output (MU-MIMO) techniques, which will ensure highly efficient spectrum usage. To increase the cell coverage while ensuring the Quality of Service (QoS) for all UEs across the cell area, fairness should be maximized as much as possible. This paper presents a novel way to help improving fairness performance in the physical layer, via fair power allocation together with resource allocation, in MU-MIMO precoding scenarios where the common approach of guaranteeing fairness at MAC layer is not feasible. The results presented in this paper show that the proposed algorithm is able to reduce the system outage event to a large extent, thus increases fairness.

I. INTRODUCTION

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. The deployment of this latter at mass market level is believed to take place around year 2015 and facilitate what has already been a buzzword for the last decade, namely "4G". IMT-A systems are expected to provide peak data rates in the order of 1 Gbit/s in local areas and 100 Mbit/s in wide areas [1], [2]. In order to cope with such requirements, the employment of Multiple Input Multiple Output (MIMO) antenna technology and very high spectrum allocations (in the range of 100 MHz) is foreseen. The existence of multiple antennas at Node B (NB) and/or User Equipment (UE)s enables the simultaneous transmission to all UEs with the whole bandwidth, by means of MIMO precoding. These kinds of systems are also referred to as MU-MIMO. These systems can achieve high spectral efficiency via CSI at the transmitter.

It is also being discussed that possibly a TDD mode will be employed in local area scenario, so that channel reci-procity can be exploited and CSI dependant MU-MIMO precoding can be used. This future local area TDD based systems will be a logical extension of TDD mode of Universal Terrestrial Radio Access with Long Term Evolution (UTRA-LTE) as specified in [3]. 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. This is possible when the channel reciprocity benefits are exploited in TDD based systems.

In a MU-MIMO precoding system, all the time-frequency resources can simultaneously be used by all or a set of users, especially if low number of users are present, thus, the system would look like a traditional Space Division Multiple Access (SDMA) system. In this case, resource allocation fairness alone is not enough to ensure fairness among users, because all Resource Blocks (RBs) are used by all the users at the same time, thus, different kind of fairness technique needs to be considered. We combine the fairness constraints, power allocation and resource allocation together in this paper. we have defined a general fairness algorithm for MU-MIMO based precoded systems, then adopted it to a well-known linear precoding scheme, namely Channel Inversion (CI). By multiplying the data-stream with a precoder C, CI can fully invert the effect of fading channel and achieve zero intra-cell interference, so that each UE receives only the data-stream dedicated to itself. To maintain the total power constraint, additional requirement on the precoder is needed, which can be satisfied by including an weighting matrix W for the columns of C, as will be described in detail later.

Since the channel condition can be different from UE to UE, they will receive different service quality even if the transmit power is equally allocated. In this case, only maintaining resource allocation fairness will ensure a partially fair allocation scheme. To maintain fairness, the transmit power should also be able to be redistributed across sub-channels and among all UEs. After considering this fairness criteria in the Link Adaptation (LA) process,
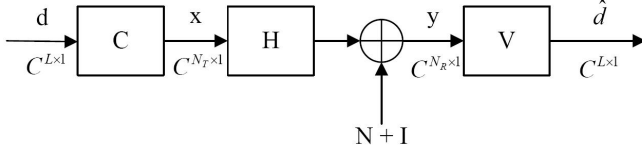
Fig. 1. System Model for Linear MIMO Precoding

we come up with a novel power and resource fairness algorithm that can efficiently improve the fairness and release the requirement for UE conditions, while satisfying the total power constraint and the Quality of Service (QoS) requirement of a certain Block Error Rate (BLER) level. The proposed algorithm, which is termed as Fair Adaptive Power, Modulation and Coding (FairAPMC), adopts an iterative procedure. It start with equal power allocation for all sub-channels[1], by comparing the resultant Signal to Noise Ratio (SNR) with a pre-generated SNR-BLER lookup table, the supportable modulation (M) & coding rate (C) can be found out. Meanwhile, the exact power (P) required can also be calculated. Since the transmission rates are discrete, and hence their required power, it is almost sure that some extra power will exist for each of the sub-channels. This power is then redistributed across to find the 'best' sub-channel that requires the minimum amount of power to convey the highest amount of (normalized) bit rate, allocate bit and power for that sub-channel, then go to the next iteration. The allocation algorithm will stop once the total power constraint has been met or all the sub-channels are transmitting at the highest M & C level.

The rest of this paper is organized as follows. Section II introduces the basics of CI that is used in this paper. Section III explains the proposed FairAPMC algorithm and how it is related with existing ones and formulates the problem when using FairAPMC in a precoded system with CI. Finally, Simulation results and conclusions are drawn in Sections IV and V respectively.

II. MIMO PRECODING: DESCRIPTION AND SYSTEM MODEL

In this section, we describe the MU-MIMO system based on CSI based precoding which we have used for further considerations in this paper. The system model for linear precoding is shown in Figure 1 and is described in the following as adopted from [4].

A 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 $N_R = \sum_{k=1}^{K} N_k$.

[1]In this paper, we use the terms *sub-channels* and *resource blocks* interchangeably which essentially mean a group of sub-carriers across several Orthogonal Frequency Division Multiplexing (OFDM) symbols.

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 $d = [d_1^T, \ldots, d_K^T]^T \in \mathbb{C}^{L \times 1}$, 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: $x = Cd$.

The received signal y is: $y = HCd + (N + I)$, 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 lead to different linear precoding techniques.

CI, as described in [5], 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 then becomes:

$$y = HCd + (N + I) = d + (N + I) \qquad (1)$$

Equation 1 shows that CI can totally remove the effect of channel on the transmitted signal and the Multiuser Interference (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 $\bar{C} = CW = [w_1 C_1, w_2 C_2, \ldots, w_L C_L]$. C is the pseudo-inversion of H, and W is decided in FairAPMC procedure.

III. IMPLEMENTATION OF PROPOSED ALGORITHM IN MULTI-CARRIER MULTI-USER PRECODED SYSTEMS

In order to limit the scope of our study, we do not consider scheduling in time domain. Hence the number of active UEs is considered to be very small and all the UEs are simultaneously served in a pure SDMA manner, the only resource that needs to be distributed fairly among UEs is the transmit power. This is a typical LA problem found in literature. To improve the system fairness, priorities should be given to UEs with poor channel conditions. Hence the transmission power should be able to be redistributed among the UEs across the whole bandwidth.

In literature, a number of algorithms are found which performs bit and power allocation in time/frequency domain for any multi-carrier system. We consider two representative algorithms here for analysis in comparison to our proposed algorithm, namely Adaptive Power, Modulation and Coding (APMC) and Adaptive Modulation

and Coding, Start With Fixed Power (AMCfixP). APMC aims at achieving the optimal cell throughput without considering the QoS for the individual UEs, thus, it is a very *unfair* algorithm in a sense that, UEs with good channel conditions are assigned more bits and power for transmission than those with bad channel conditions [6]. AMCfixP, however, divides the transmission power equally to all UEs without considering their requirements [7]. It achieves the ideal allocation fairness at the cost of lower throughput performance. The proposed algorithm, which is referred to as FairAPMC, is derived from our previous work in Simple Adaptive Modulation and Power Distribution Algorithm (SAMPDA) [8] and APMC [6], and extended to coded, multi-user systems with MU-MIMO precoding type of signalling environment in this work. It is expected to improve system fairness. FairAPMC is described with parameters shown in Table I.

P_T	Transmit power threshold
P_L	Loaded power
N	Number of sub-channels
F	The highest modulation & coding level
$\psi_{mod} = [0, 1, ..., F]$	Usable modulation & coding set
$P_{1 \times N}$	Vector of power for each sub-channel
$b_{1 \times N}$	Vector of loaded bits for each sub-channel
$c_{1 \times N}$	Vector of coding rate for each sub-channel
$R_{1 \times N}$	Vector of modulation & coding combinations for each sub-channel
n	Sequence number of the sub-channel
g_n	Channel gain at the nth sub-channel
$\frac{\Delta P}{\Delta b}_{1 \times N}$	Incremental power per incremental bit
γ_n	Signal to noise ratio in each sub-channel
σ_n^2	Noise power in each sub-channel
SNR^f	Required SNR to maintain the target BLER for the fth modulation & coding level
r^f	Number of raw bits supported by the fth modulation & coding level
NaN	Not a number, used to indicate the 'impossible' modulation & coding levels
n^*	Sequence number of the BEST sub-channel which has the minimum value of $\frac{\Delta P}{\Delta k}$.
α	A tunable parameter between 0 and 1, used for fairness adjustment
N_T, N_k	Number of antennas at NB and the k^{th}UE
N_R	Number of total receiving antennas
L_k, L	Number of data-streams from each UE and the total number of data-streams
d	Transmit data vector
C	Precoder for MU-MIMO precoding
V	Decoding matrix corresponds to precoder C
W	Weighting matrix for precoder C

TABLE I

SYMBOLS USED TO DESCRIBE THE ALGORITHM

Due to the fact that CI sends one data stream per receiving antenna, if UEs are equipped with multiple antennas, the high correlation among them will lead to poor performance [5]. In this situation, other precoding techniques e.g. Block Diagonalization (BD) can be employed

to optimize the transmission to a group of antennas rather than a single antenna [9]. To avoid the poor performance for CI, only single antenna per UE is assumed. This leads to a distributed MIMO scheme.

The block diagram for FairAPMC is shown in Figure 2 and it works as follows:

- **Step 1, Initialization:** In order to combine precoding with the proposed joint Resource Allocation (RA)-LA algorithm, a mapping between transmit power and received Signal to Interference plus Noise Ratio (SINR) is required. For a Single Input Single Output (SISO) system this is very simple, as equal power per sub-channel for each UE is assigned,

$$P_{k,n} = P_T/(N * K)$$

, where N is the number of sub-channels, K is the number of UEs.

- **Step 2, Initialize M & C & P:**
  1) From the feedback CSI, calculate the post-SNR:

  $$\gamma_{k,n} = \frac{P_{k,n}g_{k,n}}{\sigma^2}$$

  2) Compare with a pre-defined SNR lookup table to find out the supportable **M & C** level.

  $$R_{k,n} = f_{k,n} \text{ where } SNR^{f_{k,n}} \leq \gamma_{k,n} < SNR^{f_{k,n}+1}$$

  where each **R** corresponds to one **M & C** combination.

  3) Bring down the transmission power $P_{k,n}$ for each UE in each sub-channel so that no power is wasted.

  $$P_{k,n} = \frac{SNR^{R_{k,n}}\sigma^2}{g_{k,n}}; \qquad P_L = \sum_{k=1}^{K}\sum_{n=1}^{N}P_{k,n}$$

However, with precoded MIMO, the following steps are used in stead of Step-1 and 2 as described above which fits for SISO systems.

1) For the nth sub-channel,
   a) Calculate C_n based on H_n: $C_n = H_n^\dagger$, where C_n and H_n is the precoder and channel matrix for the nth sub-channel.
   b) Normalize each column of C_n so that transmit power is equally distributed to all UEs, and the total power constraint should be met. $P_n = [P_{1,n}, P_{2,n}, \ldots, P_{L,n}]$ is used to denote the power for each data stream (to each UE) and PT is the total power constraint. $\bar{C}_n = C_nW_n$, where $W_n = diag(W_{1,n}, W_{2,n}, \ldots, W_{L,n})$ is the weighting matrix for each sub-channel. $W_{l,n} = \sqrt{\frac{PT}{L*N}\frac{1}{\sum_{t=1}^{N_T}|C_{t,l,n}|^2}}$. Where $C_{t,l,n}$ is the precoder for the tth transmit antenna to transmit the lth data-stream in the nth sub-channel.

c) Calculate the received signal strength for each data stream: $S_n = H_n C_n W_n = W_n$

d) Calculate the received SINR for each data stream $\gamma_n = [\gamma_{1,n}, \gamma_{2,n}, \ldots, \gamma_{L,n}]$ based on the desired signal strength, the interference and noise level.

2) Repeat Step 1 for each sub-channel.

3) Take $\gamma = [\gamma_1^T, \gamma_2^T, \ldots, \gamma_N^T] \in \mathbb{C}^{L \times N}$ as the input for LA.

With the input ready, the supportable **M & C** and the required P for each data-stream within each sub-channel can be calculated following the iterative LA processing (Step 3 until end). The power adjustment factor $a_n = [a_{1,n}, a_{2,n}, \ldots, a_{L,n}]^T \in \mathbb{C}^{L \times 1}$ and $a = [a_1, a_2, \ldots, a_N] \in \mathbb{C}^{L \times N}$ can then be calculated as the square root of the ratio between the required and maximum transmit power. For each sub-channel n, weight the precoder by $diag(a_n)$. $C'_n = \bar{C}_n diag(a_n) = C_n W_n diag(a_n)$ is the precoder used for the transmission, where $n \in [1, 2, \ldots, N]$.

- **Step 3, Check the Termination Condition:** If $P_L = P_T$ or $min(R_{k,n}) = F$, go to step 7, else continue;

- **Step 4, Iteration Starts:**

  a) Calculate $\frac{\Delta P}{\Delta b}$, the indicator for 'good' or 'bad' sub-channels.
  $$\frac{\Delta P}{\Delta b}\bigg|_{k,n} = \frac{(SNR^{R_{k,n}+1} - SNR^{R_{k,n}})\sigma^2}{(r^{R_{k,n}+1} - r^{R_{k,n}})g_{k,n}} \quad if \ R_{k,n} \neq F$$
  $$\frac{\Delta P}{\Delta b}\bigg|_{k,n} = NaN \quad if \ R_{k,n} == F$$

  b) Normalize the incremental bits Δb for UE k by its average throughput, so that:
  $$\frac{\Delta P}{\Delta b'} = \frac{\Delta P}{\Delta b / TP_k^\alpha} = \frac{TP_k^\alpha \Delta P}{\Delta b}$$
  where TP_k is the average throughput for the kth UE;

  c) Find the BEST UE and the BEST sub-channel that minimizes $\frac{TP_k^\alpha \Delta P}{\Delta b}$:
  $$k^*, n^* = argmin_{k,n} \frac{TP_k^\alpha \Delta P}{\Delta b}$$

  d) Increase the supportable **M & C** level:
  $$R_{k^*,n^*} = R_{k^*,n^*} + 1$$

  e) Recalculate **P** required for the selected sub-channel:
  $$P_{k^*,n^*} = \frac{SNR^{R_{k^*,n^*}}\sigma^2}{g_{k^*,n^*}}$$

- **Step 5, Check Whether the Distributed Power Overflows:** if $\sum_{k=1}^{K} \sum_{n=1}^{N} P_{k,n} \geq P_T$, exclude the infeasible **M & C** combinations:
  $$\frac{\Delta P}{\Delta b}\bigg|_{k^*,n^*} = NaN; \quad R_{k^*,n^*} = R_{k^*,n^*} - 1$$

$$P_{k^*,n^*} = \frac{SNR^{R_{k^*,n^*}}\sigma^2}{g_{k^*,n^*}}$$

go to step 3; else go to step 6.

- **Step 6, Update the Parameters:**
  $$P_L = \sum_{k=1}^{K} \sum_{n=1}^{N} P_{k,n}$$
  $$\frac{\Delta P}{\Delta b}\bigg|_{k^*,n^*} = \frac{(SNR^{R_{k^*,n^*}+1} - SNR^{R_{k^*,n^*}})\sigma^2}{(r^{R_{k^*,n^*}+1} - r^{R_{k^*,n^*}})g_{k^*,n^*}} \quad if \ R_{k^*,n^*} \neq F$$
  $$\frac{\Delta P}{\Delta k}\bigg|_{k^*,n^*} = NaN \quad if \ R_{k^*,n^*} == F$$

  Map from **R** to corresponding **M & C** level. go to step 3;

- **Step 7, STOP.**

After these steps, loaded bits, coding rate and power for each UE at each sub-channel are stored in the three matrices $b_{K \times N}$, $c_{K \times N}$ and $P_{K \times N}$, which will be used for the transmission.
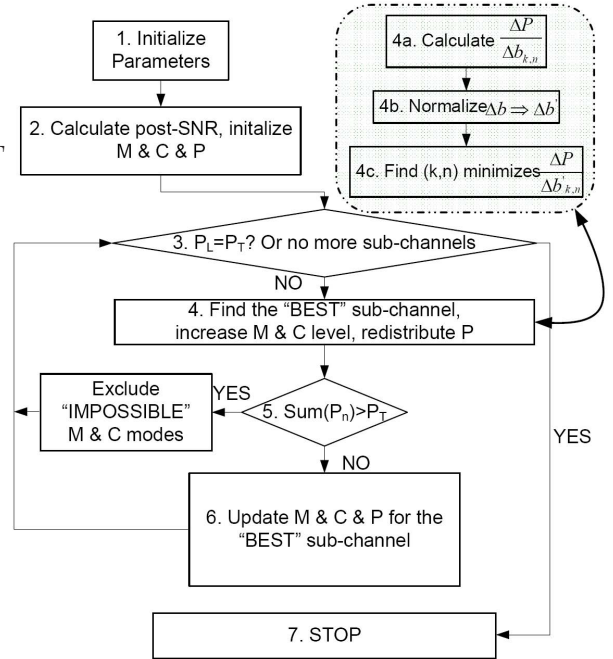

Fig. 2. Block Diagram for FairAPMC

Note that the CSI estimation must be fast and accurate enough, so that the precoding matrix will be able to match the actual channel gain. How to operate with limited and long term CSI is taken as future work.

a) The relations between FaiAPMC *and other related algorithms:* The proposed FairAPMC is closely related to some of the existing LA algorithms, which are summarized in the follows:

- When the tunable parameter α is set to 0, FairAPMC becomes identical to APMC and achieves the maximum cell throughput.
- When α is set to 1, it tries to maximize the fairness after the first iteration of power distribution process. However, equal power is allocated across all sub-channels after the iterations of power distribution. The reason for not considering fairness in Step 1 is to maintain a reasonable good throughput performance. As can be understood straightforwardly, the more number of UEs and sub-channels with poor channel gain are served, the worse the performance would be.
- Start with 0 bit and 0 power at the beginning, FairAPMC becomes similar as Adaptive Power Distribution (APD), which is introduced in [6], but with fairness improving mechanism. By doing this, fairness is expected to be maximized, at the cost of low cell throughput and high complexity.
- By using only the first two steps in FairAPMC, it is simplified to AMCfixP.

According to different fairness and/or throughput requirement, the proper α value can be chosen. The power level in Step 1 can also be adjusted between 0 and $P_T/(N*K)$. Both methods offer a compromise between cell throughput and fairness. In this paper, we focus on a simple case when equal power is assigned in Step 1 to guarantee throughput and $\alpha = 1$ to maximize the fairness afterwards. How to find the proper α and initial power for different QoS criteria is considered as future work.

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
Minimum throughput requirement	$TP_{min} = 0.5$Mbps
Target 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 [10]

TABLE II

SIMULATION PARAMETERS

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, the proposed FairAPMC algorithm is evaluated and compared with APMC [6] and AMCfixP [7]. Since NB serves only limited number of UEs, if these UEs are in poor channel conditions, transmission is blocked. The QoS criteria of minimum throughput is introduced to prevent NB from serving those 'bad' UEs. If the averaged (across a minimum of N_{av} frames duration) throughput for one UE is lower than TP_{min}, it is dropped from the system. A new UE can then be served. A finite buffer is assigned to each UE, after finishing the transmission of this amount of data, the UE is disconnected from the system, and it is marked as 'Served UE'. The more number of UEs been served, the higher the cell throughput.

Most of the system parameters are taken from UTRA-LTE downlink transmission, some of which are summarized in Table II.

Figure 3 shows the Cumulative Distribution Function (CDF) distribution of SINR with different LA algorithms. Clearly it can be seen that, on average AMCfixP has a higher SINR than APMC, which in turn is higher than FairAPMC. The reason is: AMCfixP can not use the transmit power efficiently to improve throughput or

fairness, thus drops UEs with poor channel conditions much easier than APMC and FairAPMC. The dropping of 'bad' UEs means AMCfixP will serve UEs only in good channel conditions, next is APMC. FairAPMC tries to serve UEs even if their channel conditions are poor, this leads to the low averaged SINR. Since SINR is related with distance, the low SINR with FairAPMC means it can support a larger coverage than APMC and AMCfixP.

Figure 4 shows the cell throughput for all three algorithms considered in this work. Whereas the performance are shown to be similar among them, except that APMC has a higher averaged throughput than AMCfixP and FairAPMC. However, at low SINR values, FairAPMC and APMC offer a better performance than AMCfixP. Because AMCfixP cannot redistribute the power to needed sub-channels.

Figure 5 shows the number of served and dropped UEs per second for different LA algorithms. It can be seen that despite the high SINR that AMCfixP has, it achieves a much worse performance than the other two algorithms. APMC serves the highest number of UEs,
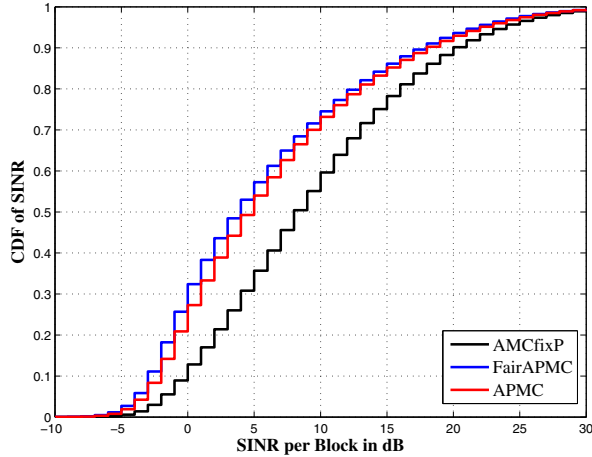
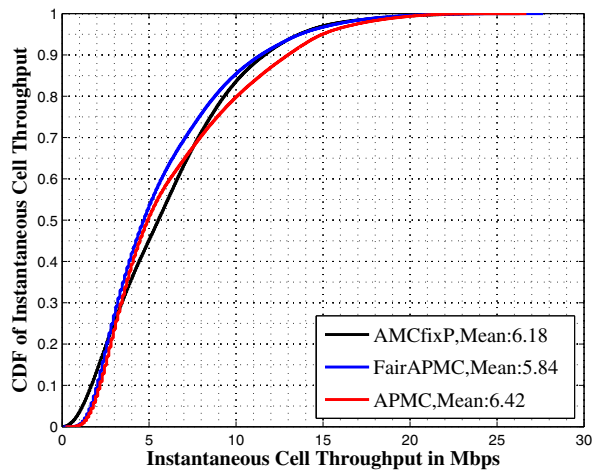Fig. 3. CDF of Per Block UE SINR
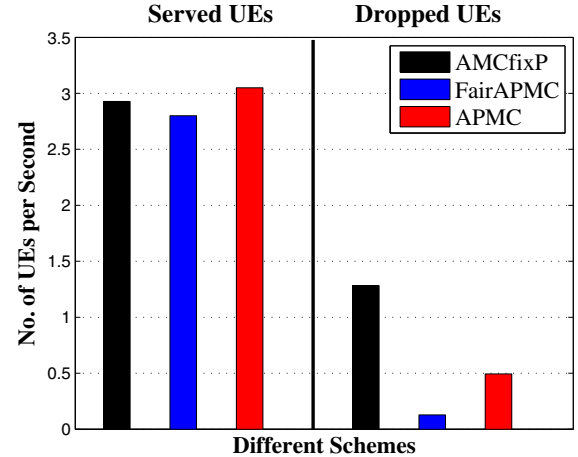

Fig. 4. CDF of Cell Throughput

Fig. 5. Number of Served and Dropped UEs per Second

improved, it reduces the service quality variation among the UEs, which makes it attractive for real-time services like voice call. The drawback is slightly lower throughput than the two referenced algorithms.

with outage event lower than AMCfixP, but much higher than FairAPMC. FairAPMC offers the lowest capacity, but benefit in terms of outage event.

So, we can summarize the results as follows. APMC offers a higher throughput performance than AMCfixP and FairAPMC. FairAPMC can reduce the outage event at the cost of reduced cell throughput. AMCfixP offers a lower throughput than APMC with reduced complexity. If the target is to cover a wide area, FairAPMC should be used. If the target is to offer high throughput for best effort services, e.g. web browsing, APMC is more preferable than the other two.

V. CONCLUSION

In this paper, we have introduced a novel fair LA algorithm for CSI-based MU-MIMO systems which can be used to improve the system fairness. It is able to improve the cell coverage, reduce outage event and release the requirements on UE channel conditions. With fairness

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