An Energy-Efficient User Scheduling Scheme for Multiuser MIMO Systems with RF Chain Sleeping

Xu ZHANG, Sheng ZHOU, Zhisheng NIU, Xiaokang LIN
Tsinghua National Laboratory for Information Science and Technology,
Dept. of Electronic Engineering, Tsinghua Univ., Beijing, 100084, P.R. China
E-mail: zhang-xu10@mails.tsinghua.edu.cn, {sheng.zhou,niuzhs}@tsinghua.edu.cn

Abstract—With increased radio frequency (RF) chains, base station (BS) with multiple antennas consumes more circuit power. Turning off RF chains will help to save energy. However, in turn, it needs more sophisticated user scheduling. Therefore, an energy-efficient scheduling scheme is proposed with which users and RF chains are jointly selected at each frame. Here, Lyapunov drift-plus-penalty ratio is used to policy design. If the average data arrival rates locate in the capacity region, it is proved that the proposed policy achieves the maximum energy efficiency than any other stationary, randomized, queue-independent policies, while ensuring the stability of the system. At each frame, the selection of users and RF chains depends on the number of selected users, sum queue length of them and energy efficiency they achieve. A key observation is that the numbers of selected users and RF chains should be equal under zero-forcing beamforming. Simulation results have shown that it even achieves higher energy efficiency than the Maximum Weighted Queue scheduling scheme when average arrival rate vector is relative small.

I. INTRODUCTION

Due to the exponential traffic growth and limited energy resources, wireless networks require more energy-efficient designs. Meanwhile, multiuser multiple input multiple output (MIMO) technology has played an important role in the next generation cellular networks due to its high spectral efficiency performance. Moreover, massive MIMO with very large number of antennas is an emerging technology for future broadband networks. However, ever-increasing radio frequency (RF) chains at the base station (BS) consumes more circuit power. When traffic load is low or the channel states of some RF chains are not good enough to the transmission, those RF chains can be turned off to save energy.

By turning off RF chains, the dimension of signal spaces from the BS to each user is changed. The capacity of multiuser MIMO system [1] degrades. Packets have to wait longer time to be transmitted. Thus, in order to maintain stable queues for each user, the user scheduling is required to jointly designed with RF chain selection. Many joint user and antenna selection schemes have been proposed in literature for multiuser MIMO systems [2]-[4]. Most of them [2][3] focus on maximizing the system capacity, and some of them [4] further jointly consider fairness issue among the users. However, energy efficiency is defined as a fractional function rather than a convex one, and it is not summable. Those capacity-maximizing schemes can not be directly used.

For energy-efficient designs [5][6], authors of [5] minimize the energy consumption under transmitting power and ergodic capacity constraints. With the convex objective function, the optimal number of subcarriers and active RF chains are obtained. In [6], with a given set of RF chains, the fractional programming is used to solve the energy efficiency optimization problem, and the optimal set of RF chains is found by exhaustive search algorithm. However, both of those researches do not consider the random arrival of users and the policies of user scheduling.

In this paper, an energy-efficient scheduling scheme for downlink multiuser MIMO systems is proposed with which users and RF chains are jointly selected at each frame. Traditionally, with the average arrival rate constraints, optimal policy is achieved to minimizing total power consumption by using constrained Markov Decision Processes. However, the optimal policy is dependent on the value of average arrival rate and does not ensure the stability of the system. Here, Lyapunov drift-plus-penalty ratio is used to policy design. If the average arrival rate vector locates in the capacity region [7], it is proved that the proposed policy achieving the maximum value of energy efficiency which could be achieved by any other stationary, randomized, queue-independent policies, while stabilizing the whole system. In the scheme, an index value is introduced which depends on the number of selected users, sum queue length of them and energy efficiency they achieve. At each frame, the group of users and RF chains who has the minimum index value is selected. A key observation is that the numbers of selected users and RF chains should be equal. Simulation results show that the proposed scheduling scheme even achieves higher energy efficiency than the traditional Maximum Weighted Queue (MWQ) scheduling, when the average arrival rates are relative small.

The rest of this paper is organized as follows. The system model is proposed in section II. And the energy efficiency optimization problem is formulated. In section III, the energy-efficient scheduling policy is proposed and analyzed. In section IV, the joint user and RF chain selection scheme is proposed. Simulation results are also shown in this section. At last, section V concludes this paper.

This work was supported in part by the National Basic Research Program of China (973 Green: No. 2012CB316001), the Nature Science Foundation of China (No. 61021001, No.60925002).
where $P$ denotes the total transmitting power constraint and $P_k$ denotes the power allocated to the user $k$ and $\gamma_k = 1/[N_0W((\mathbf{H}(S)\mathbf{H}(S)^*)^{-1})_{k,k}]$. It worth to note that, no matter how good channel condition it is, the data rate for each user is always upper bounded by $r_{\text{max}}$ due to the limited capability of finite modulation and coding schemes in practice.

**B. Power Consumption Model**

As an approximation of the practical power consumption at the BS, we assume that the total power consumption is related to the transmitting power $P$, and the number of active RF chains $m$. Referred to [5][6], we consider an affine power consumption model, which is denoted as

$$P_{\text{total}} = \frac{P}{\eta} + mP_{RF},$$

where $\eta$ denotes the power amplifier efficiency, $P_{RF}$ denotes the power consumption of a single RF chain.

Note that there exit costs including delay and power consumption for frequently switching RF chains. Since these parts of cost is too small [12], it can be neglected.

**C. Queueing Model**

The system operates frame by frame which is assumed with duration $r$. If one of users could be out of data during transmission, the scheduler will not select it during current frame. The BS keeps queue with infinite buffer for each user, thus there are total $K$ queues at the BS. Data of each user arrives randomly according to independent random arrival processes with mean $\{\alpha_1, \alpha_2, \ldots, \alpha_K\}$ and bounded second moment. We assume the arrival process is independent of the past given the current arrivals $\{\alpha_1(t), \alpha_2(t), \ldots, \alpha_K(t)\}$, where $\alpha_k(t)$ denotes the newly arrived data of user $k$ during the $t$-th frame. Let $Q_k(t)$ represents the number of bits queued at the beginning of $t$-th frame for the user $k$. It is a non-negative value. For simplicity, we assume that the system is initially empty at frame $t = 0$, so that $Q_k(0) = 0$, $k \in \{1, 2, \ldots, K\}$.

At the beginning of each frame, some of users are selected to be served by BS. According to the multiuser MIMO system mentioned above, the data rate $r_k(t)$ for user $k$ is given by Eq.(2). Let $\mathbf{1}_k(t)$ represents the indicator variable for the user selection. If user $k$ is selected at frame $t$, $\mathbf{1}_k(t) = 1$, otherwise $\mathbf{1}_k(t) = 0$. Then the queue length evolves as shown in Eq.(4) for all users $k \in \{1, 2, \ldots, K\}$,

$$Q_k(t+1) = Q_k(t) - r_k(t) + \alpha_k(t),$$

where

$$r_k(t) = \begin{cases} \log[1 + \gamma_k P_k(t)], & \mathbf{1}_k(t) = 1 \\ 0, & \mathbf{1}_k(t) = 0 \end{cases}$$

The mean rate stability of the queue for each user is defined as following. For all $k \in \{1, \ldots, K\}$, if we have

$$\lim_{T \to \infty} \frac{\mathbf{E}[Q_k(T)]}{T} = 0,$$

with probability one, then we call all of queues are stable.
D. Problem Formulation

The decision process is formulated based on the system evolution at discrete time point \( t=1,2,...\). The action vector is given by \([S(t),M(t)]\), where \( S(t) \subset S \) and \( M(t) \subset M \). From the theorem of capacity region [7], there always exists a stationary, randomized, queue-independent policy could be in principle be designed to stabilize the system, if the arrival rate vector \([\lambda_1,\lambda_2,...,\lambda_k]\) is in the capacity region. The decision distribution of a given action vector \([S(t) = S,M(t) = M]\) is defined as \( \pi(S,M) \) which is not change over time.

The average sum data rate with given decision vector is given by \( \mathcal{R}[S(t),M(t)] = \mathbf{E}[R(t)]S(t),M(t)] \). Taking the expection with respect to the decision vector and averaging over the time, it comes to the time average expectation

\[
\mathcal{R} = \lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} \mathbf{E}[\mathcal{R}(S(t),M(t))].
\]

The average power consumption over time is defined similarly, \( \mathcal{P}_{total} \). The energy efficiency is defined as \( \mathcal{E}_{total} = \frac{\mathcal{R}}{\mathcal{P}_{total}} \).

Suppose there exist an optimal stationary randomized policy which achieves the maximum energy efficiency and satisfies the necessary stability condition (the average serve rate for each queue is larger than the average arrival rate). We denote the optimal decision distribution as \( \pi_*(S,M) \) and optimal energy efficiency as \( \mathcal{E}_{opt} \).

III. Energy-Efficient Scheduling Policy

In this section, we aim to use Lyapunov optimization theory to design optimal scheduling policy.

A. Scheduling Policy

In order to incorporate the maximization of energy efficiency, we choose decision vector \([S(t),M(t)]\) by minimizing an upper bound on the following drift-plus-penalty ratio. Given the queue length vector \( Q(t) \), the drift-plus-penalty ratio is given by

\[
\frac{\mathbf{E}[\Delta(t) + V \mathcal{P}_{total}(t)\mathcal{R}(t)]}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)]},
\]

where \( V \) is a non-negative parameter that weights the terms of power consumption. And the Lyapunov Drift is defined as \( \Delta(t) = \frac{1}{2} \sum_{k=1}^{K} Q_k(t + 1)^2 - \frac{1}{2} \sum_{k=1}^{K} Q_k(t)^2 \).

The drift-plus-penalty ratio is upper bounded as follows.

**Lemma 1:** For all frames \( t \in \{1,2,...,T\} \), all possible \( Q(t) \), and under any decisions, we have

\[
\frac{\mathbf{E}[\Delta(t) + V \mathcal{P}_{total}(t)\mathcal{R}(t)]}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)]} \leq \frac{B}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)\mathcal{R}(t)]} + \frac{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)\mathcal{R}(t)]}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)]} \sum_{k=1}^{K} \mathbf{E}[Q_k(t)]=\mathcal{R}_k(t)}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)]},
\]

where \( B \) is a constant that satisfies the following for all possible \( Q(t) \) and all policy, \( B \geq \frac{1}{2} \sum_{k=1}^{K} \mathbf{E}[\alpha_k(t)^2 + \mathcal{R}_k(t)\mathcal{R}(t)^2]\mathcal{R}(t)]. \)

Such a constant \( B \) exists by the assumptions of the second moment boundedness of arrival processes and bounded data rate for each user.

The proof of Lemma 1 is obtained through the boundness of Lyapunov drift which is proposed in [7].

From the right-hand-side of inequality (9), the control parts for each frame are given as

\[
\frac{\mathbf{E}[\mathcal{P}_{total}(t)\mathcal{R}(t)] - \sum_{k=1}^{K} \mathcal{R}_k(t)\mathcal{R}(t)]^2\mathcal{R}(t)]}{\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)]} \leq \frac{1}{E_{opt}} \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \frac{1}{E_{opt}} \mathbf{E}[\mathcal{P}_{total}(t)] \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \frac{1}{E_{opt}} \mathbf{E}[\mathcal{P}_{total}(t)].
\]

For each frame the policy takes actions to minimize the Eq.(10).

B. Performance Analysis

**Proposition 1:** Suppose \( \mathcal{R}_k(0) = 0 \), for all \( k \in \{1,2,...,K\} \).

Then, with the proposed scheduling policy, the

a) we have

\[
\mathbf{E}[\mathcal{P}_{total}(t)\mathcal{R}(t)] \leq \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \frac{1}{E_{opt}} \mathbf{E}[\mathcal{P}_{total}(t)].
\]

where \( \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \) is the energy under the proposed scheduling policy, \( B \) is defined in Lemma 1, \( \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \) is the lower bound of \( \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \).

b) Further, for the queue length, we have

\[
\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \leq \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \frac{1}{E_{opt}} \mathbf{E}[\mathcal{P}_{total}(t)].
\]

where \( \beta \geq \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \mathbf{E}[\mathcal{P}_{total}(t)] \) and such a constant \( \beta \) exits because both of the random processes are bounded.

It is worth to note that if data arrival rates locate at the stability region, the proposed policy approaches the optimal performance with an enough large value of \( V \). On the other hand, with a finite value of \( V \) the average queue length for each user is always finite.

**Proof:** (Proposition 1 part (a)) Given \( \mathcal{R}(t) \) for frame \( t \), the control decision is given by minimizing the Eq.(10). We have

\[
\mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \mathbf{E}[\mathcal{P}_{total}(t)] \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \mathbf{E}[\mathcal{P}_{total}(t)].
\]

where \( \mathbf{E}[\mathcal{P}_{total}(t)], \mathbf{E}[\mathcal{R}(t)] \) and \( \mathbf{E}[\mathcal{R}(t)] \) denote the power consumption and data rate based on the current system states under the proposed scheduling policy. Recall the existence of optimal policy \( \pi_+ \). Since the optimal policy is independent with queue length, we have

\[
\mathbf{E}[\mathcal{P}_{total}(t)] \leq \mathbf{E}[\mathcal{R}(t)\mathcal{R}(t)] - \frac{1}{E_{opt}} \mathbf{E}[\mathcal{P}_{total}(t)].
\]
Then, the inequality (13) is rewritten as
\[
\mathbb{E}[\Delta(t) + VP_{\text{total}}(t)\tau|Q(t)] - B \leq \frac{1}{EE_{\text{opt}}} \mathbb{E}[\sum_{k=1}^{K} E_{kk}(t)\Delta_k(t) - \tau_k|Q(t)] + \frac{V}{EE_{\text{opt}}},
\]
(16)
Since the optimal policy has larger expected data rate than the average arrival rate, then the original inequality (16) is rewritten as
\[
\mathbb{E}[\Delta(t) + VP_{\text{total}}(t)\tau|Q(t)] = \frac{B}{EE_{\text{opt}}} + \frac{V}{EE_{\text{opt}}} - \mathbb{E}[\sum_{k=1}^{K} E_{kk}(t)\Delta_k(t) - \tau_k|Q(t)].
\]
(17)
Rearranging terms, it gives
\[
\mathbb{E}[\Delta(t) + VP_{\text{total}}(t)\tau - \frac{VR'\tau|Q(t)}{EE_{\text{opt}}}] \leq B.
\]
(18)
Denote the random process \(X(t) = \Delta(t) + VP_{\text{total}}(t)\tau - VR'\tau\) and \(\Delta Y(t) = X(t) - \hat{X}(Q(t))\), where \(\hat{X}(Q(t)) = \mathbb{E}[\Delta(t) + VP_{\text{total}}(t)\tau - \frac{VR'\tau|Q(t)}{EE_{\text{opt}}} | Q(t)]\). Let \(Y(t) = \sum_{i=1}^{t} \Delta Y(i)\), then we have
\[
\mathbb{E}[Y(t+1)|Y(1), Y(2), ..., Y(t)] = \mathbb{E}[Y(t) + \Delta Y(t+1)|Y(1), Y(2), ..., Y(t)] = Y(t).
\]
(19)
Therefore, \(Y(t)\) is a martingale. With the bounded sum data rate, power consumption, and \(\sum_{i=0}^{\infty} \mathbb{E}[\Delta Y(t)|Q(t)] \leq \infty\) [11], then we have \(\sum_{i=0}^{\infty} \mathbb{E}[\Delta Y(t)|Q(t)] \leq \infty\). By the law of large number of martingale [9], we have
\[
\limsup_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} [X(t) - \hat{X}(Q(t))] = 0, \text{ a.s.}
\]
(20)
With the inequality (18), we have
\[
\limsup_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} X(t) \leq B.
\]
(21)
By the definition of \(X(t)\), inequality (21) is rewritten as
\[
\frac{1}{T} \sum_{t=0}^{T-1} X(t) = \frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E}[\Delta(t) + VP_{\text{total}}(t)\tau - \frac{VR'\tau|Q(t)}{EE_{\text{opt}}}] \geq V \frac{1}{T} \sum_{t=0}^{T-1} P_{\text{total}}(t)\tau - \frac{V}{EE_{\text{opt}}} \sum_{t=0}^{T-1} R'(t)\tau,
\]
(22)
where the last inequality is because \(L(T) \geq 0\) and \(L(0) = 0\). Take the inequality (22) into (21), we have
\[
\limsup_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} P_{\text{total}}(t)\tau \frac{EE_{\text{opt}}}{EE_{\text{opt}}} - \frac{B}{V} \leq \frac{1}{EE_{\text{opt}}} \sum_{t=0}^{T-1} R'(t)\tau.
\]
(23)
Since \(P_{\text{total}}(t)\) is lower bounded, the part (a) is proved.

Proof: (Proposition 1 part (b)) From (18), and taking expectation with respect to the queue length vector, we have
\[
\mathbb{E}[\Delta(t)] \leq B + V\beta.
\]
(24)
Fixing any positive \(T\) and summing over \(t \in [0, ..., T - 1]\), by the definition of \(\Delta(t)\) and noting that \(L(0) = 0\), we have
\[
\sum_{k=1}^{K} \mathbb{E}[Q_k^2(T)] \leq 2(B + V\beta)T.
\]
(25)
Therefore, similar as [10] for any \(k \in \{1, 2, ..., K\}\), we have
\[
\lim_{T \to \infty} \mathbb{E}[Q_k(T)] = \lim_{T \to \infty} \frac{\mathbb{E}[||Q(T)||]}{T} \leq \lim_{T \to \infty} \frac{\sqrt{2(B + V\beta)T}}{T} = 0,
\]
where \(||Q(t)|| \leq \sqrt{\sum_{k=1}^{K} Q_k^2(t)}\). Then it proves the stability of the queues for each user.

IV. USER AND RF CHAIN SELECTION SCHEME

In this section, a deterministic scheduling approximation to achieve this policy is used to design the user and RF chain selection scheme for practical implementation.

A. Selection Scheme

At the beginning of the frame \(t\), the BS observes the queue length \(Q(t)\) and obtains full channel information \(h_k(t)\) for all \(k \in \{1, 2, ..., K\}\). The user and RF chain selection problem is formulated as following.

\[
\min \ : \ U[S(t), M(t)] = \frac{VP_{\text{total}}(t) - \sum_{k=1}^{K} Q_k(t)P_k(t)}{R(t)}.
\]
(27)
\[
s.t. \sum_{k \in S(t)} P_k(t) = P
\]
\[
S(t) \subset S, M(t) \subset M, |M(t)| \geq |S(t)|
\]

The optimization is difficult since it have to search over all of user set and RF chain set. Firstly we will given the selected users to investigate the selection of RF chains. Note that the objective function is the combination of convex and concave functions. Since the numerator is convex function and the denominator is always positive, the problem is a quasiconvex optimizing problem [13].

By introducing the parameter \(\nu\), \(U[S(t), M(t)] \leq \nu\), the quasiconvex problem is changed as a convex feasibility problem (27) as following:

\[
\text{Find} \ : \ \nu
\]
\[
s.t. \sum_{k \in S(t)} [Q_k(t) + \nu r_k(t)] \geq VP_{\text{total}}(t)
\]
(28)
\[
\sum_{k \in S(t)} P_k(t) = P
\]
\[
S(t) \subset S, M(t) \subset M, |M(t)| \geq |S(t)|
\]

The optimal decision vector can be obtained \([S'(t), M'(t)]\) which achieves the minimum value of \(\nu\). Therefore we define the value of \(\nu\) as the index of decision vector. The optimal decision vector has the minimum index value.

In order to calculate the index value, given the set of selected users and RF chains, we define that
\[
Z[S(t), M(t), \nu] = \max_{\nu : \sum_{k \in S(t)} P_k(t) = P} \sum_{k=1}^{K} [Q_k(t) + \nu r_k(t)].
\]
(29)
which can be solved by water-filling algorithm to optimize
the allocation of transmitting power among the selected users.
Substituting the optimal value of $P_i$ into Eq.(29), we have

$$Z[S(t), M(t), v] = \sum_{k \in S(t)} a_k \left( \sum_{k \in S(t)} q_k \log(q_k \gamma_k) + \log(P + \sum_{k \in S(t)} \frac{1}{\gamma_k}) \right),$$

(30)

where $a_k = P_{k} = Q_{k}(t) + v$, $q_k = \frac{a_k}{\sum_{k \in S(t)} a_k}$. The index value $v$ is obtained by solving the equation which is given by

$$Z[S(t), M(t), v] = VP_{total}(t).$$

(31)

Furthermore, since the trace of a matrix is the sum of
eigenvalues, $\sum_{k \in S(t)} \frac{1}{\gamma_k} = \sum_{k \in S(t)} \frac{1}{\mu_k}$ where $\{\mu_k, \forall k \in S(t)\}$ are eigenvalues of $[N_0 \omega H(S(t))H(S(t))^\dagger]$, and rearranging the
terms of Eq. (31), we have

$$\frac{VP_{total}(t)}{\sum_{k \in S(t)} \mu_k} - \sum_{k \in S(t)} q_k \log(q_k) - \sum_{k \in S(t)} q_k \log(\gamma_k) = \log(P + \sum_{k \in S(t)} \frac{1}{\mu_k}).$$

(32)

Under a very large value of $V$, the left-hand-side of Eq.(32)
is dominated by its first term. Therefore, we have

$$v \approx \frac{VP_{total}(t)}{\|S(t)\| \log(P + \sum_{k \in S(t)} \frac{1}{\mu_k})} - \frac{\sum_{k \in S(t)} Q_k(t)}{\|S(t)\|}.$$  

(33)

**Lemma 2:** Given the selected users, the value of $U(|M|) = \sum_{k \in S(t)} \frac{1}{\mu_k}$ is an increasing function as the number of selected RF chains decreases, $|M|$. 

**Proof:** Given the selected users $S$, the channel matrix of the selected subset $M$ of RF chains is $H(M)$. If a random RF chain is added to the selected subset denoted as $\tilde{M}$, the corresponding channel matrix is denoted as $\tilde{H}(M)$. Note that the relationship between $H(M)H(M)^\dagger$ with eigenvalues $\mu_1 \leq \mu_2 \leq \ldots \leq \mu_{|S|}$ and $\tilde{H}(M)\tilde{H}(M)^\dagger$ with eigenvalues $\theta_1 \leq \theta_2 \leq \ldots \leq \theta_{|S|}$ is given by

$$H(M)H(M)^\dagger + \Omega = \tilde{H}(M)\tilde{H}(M)^\dagger,$$

where $\Omega \in C^{(|S|)|S|}$ with eigenvalues $0 \leq \omega_1 \leq \omega_2 \leq \ldots \leq \omega_{|S|}$. Under the monotonicity theorems [14], it always has $\theta_k \geq \mu_k + \omega_1$, $k = 1, 2, ..., |S|$. Therefore, $\sum_{k=1}^{|S|} \frac{1}{\theta_k} \leq \sum_{k=1}^{|S|} \frac{1}{\mu_k}$. 

**Proposition 2:** Suppose that the minimum value of $v$ is achieved, the number of selected user and the number of selected RF chains is equal, $|S| = |M|$. 

Under the condition of $|S| = |M|$, this proposition is obtained by using Lemma 2.

From Eq.(33), the RF chain selection only affects the first term. If the selected subset of users is given, the number of selected RF chains is determined according to Proposition 2. The subset of RF chains are determined by $M(t) = \arg\max \log(P + \sum_{k \in S(t)} \frac{1}{\mu_k})$. It means that the optimal subset of RF chains achieves the maximum sum eigenvalues of $[N_0 \omega H(S(t))H(S(t))^\dagger]$. There are lots of antenna selection algorithms being able to achieve this goal.

On the other hand, with the optimal subset of RF chains, the selection of subset users affects both parts of Eq.(33). Given the number of selected users, the subset users is selected as achieving not only the maximum sum data rate but also the sum of queue length. Using the exhaustive search algorithm the optimal subset of users is found.

Therefore, the joint selection of user and RF chain algorithm is shown as following:

**Stage 1:** Initiate the number of selected users the number of RF chains, $n = |M|$.

**Stage 2:**

(1) Given a subset of users $S(n) \in \mathcal{S}(n)$, find the subset of RF chains $M^*(n) \in \mathcal{M}(n)$, achieving $\max_{M^*(n)} \log(P + \sum_{k \in S(n)} \frac{1}{\mu_k})$, where $\mathcal{S}(n)$ and $\mathcal{M}(n)$ denote the collection of subsets with $n$ users and RF chains.

(2) Find the subset of users $S^*(n) \in \mathcal{S}(n)$ with $M^*(n)$, achieving $\min_{S^*(n)} \nu(S(n)) = \frac{VP_{total}(n)}{\|S(n)\|} - \frac{\sum_{k \in S(n)} \nu_0}{n}$.

**Stage 3:** Find the optimal number of users $n^*$ by repeating the Stage 2 which achieves $\min_{n^*} \nu(S^*(n))$. Therefore, the optimal decision vector $[S^*(n^*), M^*(n^*)]$ is obtained accordingly.

**B. Simulation Results**

In this section, we evaluate the energy efficiency of multiuser MIMO system with the proposed user and RF chain scheduling scheme. The total number of users is set to 8. The parameters of channel are set according to [6]. The path loss of user $k$ is $128.1 + 37.6 \log_{10} d_k$ dB ($d_k$ in kilometers). Without further statement, $d_k$ is equal to 0.5km for any user $k$. Noise density is -174dBm. The bandwidth is 5MHz. Identical independent distributed Rayleigh fading is assumed in each frame. The parameters related to power consumption is set to $P = 46dbm$, $P_{RF} = 83W$, and $\eta = 0.38$ [6]. The average data arrival rate for each user is 0.5 bits/frame/Hz. The frame duration is set to 50 ms. The traditional MWQ scheduling and a stationary, randomized, queue-independent policy (SRQ) are selected to compare. With the MWQ policy, the group of users and RF chains is selected based on the products of data rate and queue length. In the SRQ policy, the decision probability is uniformly distributed. The simulation operates over total 1000 frames. $V$ is set to 100000.

The energy efficiency of different scheduling schemes over different total number of RF chains are shown in Figure 2. The proposed Energy Efficient scheduling achieves the best performance than any other scheduling schemes. When the total number of RF chains is relative small, MWQ scheduling has almost the same performance with the Energy Efficient one. This is because that the transmission capability is limited due to the small total number of antennas. It implies that the average traffic arrival rate locates outside the capacity region. All of antennas have to open all the time. As the total number of antennas increased, the energy efficiency of MWQ scheduling decreased. There are more than 40% performance gain achieved by the proposed scheduling scheme when the total number of RF chains equals to 7. This is because more opportunities to sleeping RF chains are obtained. Moreover, SRQ scheduling even have better performance than MWQ scheduling at the case of large number of RF chains. The energy efficient scheduling scheme has much better performance than the SRQ scheduling scheme. As mentioned in previous
section, the proposed Energy Efficient scheduling achieves the maximum performance than any other SRQ scheduling schemes with which the average serve rate is larger than the average traffic arrival rate.

The average delay (s) for each user with different scheduling schemes is given in Table I. The average delay of all schemes decreases over the increasing of total number of RF chains, since the increased transmission capability. The SRQ scheduling have the largest average delay, since this policy can not ensure the stability of the system. In Table I, it also shows that the proposed Energy Efficient scheduling has relative large delay than MWQ scheduling, since it trades delay for more energy saving.

The number selected users and RF chains over time is shown in Figure 3. In Figure 3, the total number of antennas is set to 5. For the MWQ scheduling, relative larger number of RF chains is preferred to choose, since it always want to maximize the transmission capability. On the other hand, in Energy Efficient scheduling, the selected number users and RF chains are always the same. The number of active RF chains is relative smaller.

V. CONCLUSIONS

In this paper, an energy-efficient user scheduling scheme with RF chain sleeping in downlink multiuser MIMO system is proposed. If the average arrival rate locates within the capacity region, it is proved that the proposed scheduling policy achieves the optimal energy efficiency than any other stationary, randomized, queue-independent policies, while ensuring the stability of system. In the proposed scheme, the numbers of selected users and RF chains for each transmission are the same under the zero-forcing beamforming. Simulation results show that the proposed scheme always achieve higher energy efficiency than Maximum Weighted Queue scheduling. The performance gain is higher in low traffic load region. It shows that more than 40% performance gain is achieve when there are 7 RF chains and 8 users under 0.5 bits/frame/Hz traffic load. Simulation results also show that ignorable delay increasing the proposed scheme has compared with MWQ scheduling.

![Fig. 2. Energy efficiency performances over the number of RF chains under different scheduling schemes. (MWQ: Maximum Weighted Queue policy, SRQ: Stationary Randomized Queue-independent policy)](image)

![Fig. 3. Number of active antennas and Number of selected users over time slots. (Dash-line: number of active RF chains, Dash-dot-line: number of selected users)](image)

<table>
<thead>
<tr>
<th>No. of RF chains</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficient (s)</td>
<td>6.95</td>
<td>1.74</td>
<td>0.19</td>
<td>0.12</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>MWQ (s)</td>
<td>7.18</td>
<td>1.93</td>
<td>0.11</td>
<td>0.07</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>SRQ (s)</td>
<td>14.39</td>
<td>12.64</td>
<td>10.51</td>
<td>9.33</td>
<td>8.26</td>
<td>7.11</td>
</tr>
</tbody>
</table>

REFERENCES


