Mitigation of Sounding Pilot Contamination in Massive MIMO Systems

Taeseop Lee, Hyung-Sin Kim, Sangkyu Park, and Saewoong Bahk
Department of ECE, INMC, Seoul National University
Kwanak P. O. Box 34, Seoul 151-600, Korea
tlee, hskim, skpark}@netlab.snu.ac.kr, sbahk@snu.ac.kr

Abstract—In massive multiple-input multiple-out (M-MIMO) systems, conventional sounding schemes may suffer from pilot contamination of cell edge users or a lowered number of serviced users in a multi-cell scenario. In this paper, we propose a partial sounding resource reuse (PSRR) method which aims to seamlessly guarantee the quality of service (QoS) of mobile users by mitigating the pilot contamination as well as minimize the reduction in the number of serviced users. To this end, the PSRR divides each cell area into center and edge areas, and partially reuses sounding resources among users in neighboring edge areas. We use a Markov chain model to analyze the performance of the PSRR. Then we evaluate the accuracy of our analysis through simulations, and show that the PSRR considerably improves QoS performance over the conventional schemes.

I. INTRODUCTION

Recently, massive multiple-input multiple-output (M-MIMO) systems make base stations transmit downlink signals with the use of an unlimited number of antennas, thereby performing far better than the existing schemes [1]. In M-MIMO systems, uplink sounding techniques are commonly adopted for downlink channel information feedback, which use the channel reciprocity of time-division duplex (TDD) systems [2]. They show a critical impact on system performance since the number of sounding users is directly related with the number of serviced users in downlink, and the channel estimation error heavily affects the accuracy of a pre-coding matrix [3]. Despite of its importance, few researchers have focused on the design of sounding techniques to the best of our knowledge [4].

M-MIMO systems need to support very high mobility [2], incurring mobile users to pass through cell edge areas frequently (i.e. handover) in multi-cell environments. However, the performance of cell edge users is significantly degraded due to pilot contamination when each cell exploits the whole sounding resources for its own users in a non-cooperative manner [5]. To alleviate these problems, the sounding resource reuse method can be used among adjacent cells in a cooperative manner. It provides high signal to interference ratio (SIR) for each cell edge user at the cost of having a reduced number of serviced users. Thus, the development of a new sounding technique needs to consider the trade-off relation between pilot contamination and reduced number of serviced users.

In this paper, we propose a partial sounding resource reuse (PSRR) scheme to seamlessly guarantee the quality of service (QoS) of mobile users as many as possible. To this end, the PSRR first divides the cell area into two different subareas, i.e., center area where users can obtain high SIRs and edge area where users suffer from the pilot contamination problem. Accordingly it divides the whole sounding resources into two parts for the center and edge areas, respectively. Then it allocates the center area resource in a non-cooperative manner and the edge area resource in a cooperative manner. We mathematically analyze QoS provisioning performance of the PSRR according to two system parameters of ratios; they are the size ratio between center area and edge area, and the ratio between center area resource and edge area resource. Through simulations, we evaluate the effectiveness of our analysis, and show that the PSRR improves QoS provisioning performance.

The remainder of this paper is organized as follows. In Section II, we discuss the system model and presents the proposed PSRR. Section III mathematically analyzes the QoS provisioning performance of PSRR. In Section IV, we evaluate the performance of PSRR through simulations, and confirm the effectiveness of our mathematical model and its performance improvement over the competitive schemes. Finally, we summarize the contributions of this paper and conclude our work.

II. PROPOSED PSRR SCHEME

A. System Model

As depicted in Fig. 1, let’s consider a TDD-based M-MIMO system where a time slot comprises $T$ symbols. Here $T$ is determined by considering the coherence time during which the channel information does not change. Assume that the base station estimates the downlink channel condition for each terminal from the uplink sounding pilots received during the preceding $\tau_s$ symbols, and then transmits downlink data during the following $(T-\tau_s)$ symbols according to the estimated channel condition. Letting $N_{smooth}$ be the number of consecutive subcarriers in the frequency domain which have the same channel condition (i.e., coherence bandwidth), a block of $N_{smooth} \times \tau_s$ subcarriers has the same channel information. With the use of the subcarrier block, the M-MIMO system generates $N_{smooth} \times \tau_s$ orthogonal sounding sequences, each of which has the length of $N_{smooth} \times \tau_s$.

We assume that the base station obtains the perfect channel information if a user terminal transmits a sounding signal with the use of an unlimited number of antennas, thereby minimizing the estimation error heavily affects the accuracy of a pre-coding matrix [3]. Despite of its importance, few researchers have focused on the design of sounding techniques to the best of our knowledge [4].

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B. Proposed scheme

If error free channel information is available, the M-MIMO system can service multiple users with the same downlink resources without suffering inter cell interference [6]. However, conventional non-cooperative M-MIMO systems may suffer inter cell interference since non-cooperative sounding resource assignment schemes cannot provide accurate channel information due to the pilot contamination. To alleviate the pilot contamination problem, the cooperative reuse method that assigns each adjacent cell a different set of sounding sequences can be considered. However, it greatly reduces the number of users in service, resulting in the critical system capacity degradation. Thus, we propose the PSRR to guarantee the QoS provisioning for mobile users while minimizing the system capacity degradation.

The PSRR aims to mitigate the pilot contamination problem and support as many users as possible by applying a different sounding sequence assignment strategy according to the user’s location. The proposed PSRR divides each cell area into center area and edge area. Assuming that $F$ is the size ratio of edge area to cell area, it is given as

$$F = \frac{\text{Area}_E}{\text{Area}_{cell}}$$

for $\text{Area}_{cell} = \text{Area}_C + \text{Area}_E$ (1)

where $\text{Area}_C$ is the size of center area and $\text{Area}_E$ is the size of edge area.

Letting $S$ be the set of available orthogonal sounding sequences in an M-MIMO system, the PSRR divides $S$ into subsets $S_C$ and $S_E$. Then, it assigns $S_C$ to center area users in a non-cooperative manner (i.e. reuse factor 1), while assigning $S_E$ to edge area users in a cooperative manner. Considering the hexagonal cell configuration, the PSRR divides $S_E$ into three equal sized subsets $S_{Ei}$ for $i = 1, 2, 3$ (i.e., reuse factor 3) and allows each neighboring cell to use a different $S_{Ei}$ for users in each edge area. Defining $H$ as the ratio of the number of sounding sequences used for the edge area to the total number of sequences, we have

$$H = \frac{|S_E|}{|S|}$$

where $|S|$ is the cardinality of set $S$.

Assume that $F$ can be properly determined to provide the minimum required SIR $\text{SIR}_{th}$ even for cell edge users when sounding interference is mitigated. Then, it can be shown that the performance of PSRR depends on the value of $H$ when the value of $F$ is already determined by $\text{SIR}_{th}$. A large number of cell edge users may suffer from pilot contamination when $H$ is too small compared to $F$. On the contrary, the number of serviced users may significantly be reduced when it is too large compared to $F$. In Section III, we mathematically show the effect of parameter $H$ with given value of $F$ on the QoS provisioning performance of PSRR.

III. PERFORMANCE ANALYSIS OF PSRR

In this part, We analyze the relation between $H$ and the service failure probability with fixed value of $F$.

A. Relation between $H$ and the service failure probability

We define a service failure as a failure in assigning a sounding sequence to a mobile user. For the PSRR system, we consider two types of service failure for a mobile terminal depending on whether it is newly joining or in the middle of handover. Then we define service blocking and handover (HO) blocking as sounding sequence assignment failures for a new service user and a handover user, respectively. We define the service failure probability $P_{sf}$ as a probability that a user experiences service failure due to service blocking or handover blocking, and then mathematically analyze the relation between $P_{sf}$ and parameter $H$ by use of Markov chain.

1) Mobility model and queuing of handover requests:

As depicted in Fig. 2, let’s assume that cells are hexagonal and regular, and $R'$, $R$ and $r$ denote the radius of the circumscribed circle, the inscribed circle, and the center area circle, respectively. The mobility model in the PSRR system follows the following two assumptions.

(a) Users move at a constant velocity $V$.
(b) Each user crosses a cell along its maximum diameter.

When a mobile terminal crosses multiple cells, it experiences three kinds of handovers that are denoted by $\text{HO}_{EE}$, $\text{HO}_{EC}$ and $\text{HO}_{CE}$, (i.e. handover from edge to edge, edge to center, and center to edge). When it crosses
the boundary of two adjacent areas, it transmits a handover request to the base station to trigger the handover procedures. Then the PSRR system reassigns one of available sounding sequences in the target area. However, if all the sequences in that area are already in use, the handover request gets queued until a sounding sequence is available. If the user cannot be assigned a new sounding sequence until it gets out of the handover area, a handover blocking occurs. Defining a maximum handover queuing time as the time duration for which the user starts handover and gets out of the handover area, a handover blocking occurs. Defining the value of $t_{w}$ as the deterministic inter arrival times $dC$ and $dE$ represent the intervals elapsed from the arrival instant of a new user at center area and edge area, respectively, to the instant of its entering the handover area. According to the mobility assumptions, $t_{dC}$ and $t_{dE}$ are random variables uniformly distributed in $[0, 2r/V]$ and $[0, (R-r)/V]$, respectively. A new service user in center area (or edge area) generates a handover request whenever $t_{s} > t_{dC}$ (or $t_{dE}$). When the handover probabilities at center area and edge area are denoted by $P_{hC}$ and $P_{hE}$, respectively, they are given by

$$P_{hC}(\alpha) = Pr\{t_{s} > t_{dC}\} = \frac{1 - e^{-\alpha}}{\alpha} \quad \alpha = \frac{2r}{VT_{m}}. \quad (4a)$$

$$P_{hE}(\beta) = Pr\{t_{s} > t_{dE}\} = \frac{1 - e^{-\beta}}{\beta} \quad \beta = \frac{R-r}{VT_{m}}. \quad (4b)$$

On the other hand, an ongoing service user who has already experienced a handover with success travels a deterministic distance of equal to $2r$ and $R-r$ in center area and edge area, respectively, before starting a new handover process. Note that the residual service time of an ongoing service user after a successful handover, $t_{r}$, is exponentially distributed with the same mean $T_{m}$ due to the memoryless property. Then we define $t'_{dC}$ and $t'_{dE}$ as the deterministic inter arrival times for handover at center area and edge area after the initial arrival, and they have constant values of $2r/V$ and $(R-r)/V$, respectively. Let $P_{hC}'$ and $P_{hE}'$ be the probabilities that a user already having experienced a handover, begins a new handover process in center area and edge area, respectively. These probabilities are calculated as

$$P_{hC}'(\alpha) = Pr\{t_{s} > t'_{dC}\} = e^{-\alpha} \quad \alpha = \frac{2r}{VT_{m}}. \quad (5a)$$

$$P_{hE}'(\beta) = Pr\{t_{s} > t'_{dE}\} = e^{-\beta} \quad \beta = \frac{R-r}{VT_{m}}. \quad (5b)$$

From the above analysis, it can be known that a handover request arrival in each area also has the memoryless property, which means that the sounding resource assignment problem can be modeled by using a Markov chain.

3) Markov model for sounding sequence assignment: Now we solve the sounding resource assignment problem by using a Markov chain model. For analysis we use the following assumptions [7].

(a) New arrivals and handover arrivals are two independent Poisson processes with mean rates $\lambda_{s}$ and $\lambda_{h}$, respectively.

(b) The sequence holding times are approximated as exponentially distributed random variables with means $\frac{1}{\mu_{s}}$ and $\frac{1}{\mu_{E}}$ for center area and edge area, respectively.

(c) The maximum handover queuing time is approximated as a random variable exponentially distributed, with expected value $t_{w}^{max} \approx 0.134R^{2}$.

(d) The queue size is infinite.

Based on the above assumptions, the sounding resource assignment problem in PSRR is modeled as an $M/M/\infty$ system, queuing system for area $A$ where $A = C$ for center area or $E$ for edge area. In these queuing systems, the state is defined as the number of users who need a sounding sequence in each area. To calculate the service blocking probability and the handover blocking probability in each area, we need to seek the steady state probabilities in the Markov chain. To this end, for a given number of available sounding sequences for area $A$, $|S_{A}|$, we first obtain the average new arrival rate $\lambda_{A}$, the average handover arrival rate $\lambda_{hA}$, and the average sounding sequence holding time $1/\mu_{A}$ for given $F$ and $H$. Simply we have

$$|S_{C}| = (1-H)|S|,$$  

$$|S_{E}| = \frac{|S|}{3} = \frac{H|S|}{3} \quad \text{for} \quad i = 1, 2, 3. \quad (6b)$$

When the average new service arrival rate at a cell is given as $\lambda$, the average new service arrival rates $\lambda_{C}$ and $\lambda_{E}$ for center area and edge area, respectively, are expressed as

$$\lambda_{C} = (1-F)\lambda, \quad (7a)$$

$$\lambda_{E} = F\lambda. \quad (7b)$$

Then the average handover arrival rates $\lambda_{hA}$ for each area can be expressed as follows by using the statistical equilibrium state in PSRR system.

$$\lambda_{hA} = \lambda_{hA}(1-P_{hbaA})P_{hA} + \lambda_{A}(1-P_{shA})P_{hA} \quad (8)$$

where $P_{hbaA}$, $P_{shA}$ denote handover and service blocking probabilities in each area, and $P_{hA}$, $P_{hA}'$ are handover probabilities derived from eqs. (4) and (5). Then we can calculate
the handover arrival rate \( \lambda_{hA} \) for each area \( A \), when the
service blocking probabilities, \( P_{sbA} \) and the handover blocking
probabilities, \( P_{hbA} \) are given. To obtain \( P_{sbA} \) and \( P_{hbA} \) from
the Markov chain model, we need the handover arrival rates
\( \lambda_{hA} \) again. Thus, we apply a recursive approach to compute
these values.

Let the sounding sequence holding times for a new service
user in each area \( A \) be \( t_{HA} \). Then these can be expressed as
\[
    t_{HA} = \min[t_s, t_{dA}].
\]
Denoting the sounding sequence holding time of an ongoing
service user in area \( A \) which has already experienced a first
handover as \( t'_{HA} \), we have
\[
    t_{HA'} = \min[t'_s, t'_{dA}].
\]
Let’s denote the average sounding sequence holding times as
\( 1/\mu_A \) for each area \( A \). Then we obtain \( 1/\mu_A \) as
\[
    \frac{1}{\mu_A} = \frac{\lambda_{A}}{\lambda_{A} + \lambda_{hA}}E[t_{HA}] + \frac{\lambda_{hA}}{\lambda_{A} + \lambda_{hA}}E[t'_{HA}]
    = \frac{\lambda_{A}}{\lambda_{A} + \lambda_{hA}}T_m(1 - P_{hA}) + \frac{\lambda_{hA}}{\lambda_{A} + \lambda_{hA}}T_m(1 - P'_{hA}).
\]
(11)

As mentioned earlier, the state in the queuing model equals
the sum of the number of users in service and the number of
queued handover requests. When the state is below the number of
available sounding sequences in area \( A (A = C \) or \( E \), the
PSRR system can accept all the users and the total arrival rate
is equal to \( \lambda_{A} + \lambda_{hA} \). If the state is higher than \( |S_A| \) ( \( |S_{Ei}| \)
in the case of edge area), the total arrival rate becomes \( \lambda_{hA} \).

When the queuing system state is \( |S_A| + j \) for \( j = 1, 2, \ldots \),
we need to consider the case in which a handover blocking
occurs because the queuing delay exceeds the maximum
handover queuing time approximated as an exponentially
distributed random variable with expected value \( t_{max} \). Thus
we represent the death rate due to handover blocking
as \( \mu_{w} \) which is equal to \( j/t_{max} \). Therefore, the steady state
probabilities in area \( A \), denoted as \( P_{nA} \), can be expressed as
\[
P_{nA} = \frac{n^{n\mu_{W}}P_{0A}}{(n\mu_{W})!\prod_{j=1}^{n}|S_A|^{j\mu_{W}}(|S_A|+j\mu_{W})^{-1}} P_{0A} \quad |S_A|+1 \leq n,
\]
where the system idle probability \( P_{0A} \) is
\[
P_{0A} = \sum_{n=1}^{|S_A|} \left( \frac{\lambda_{A} + \lambda_{hA}}{n\mu_{W}} \right)^n + \sum_{n=|S_A|+1}^{\infty} \left( \frac{\lambda_{A} + \lambda_{hA}}{|S_A|^{n\mu_{W}}\prod_{j=1}^{n}|S_A|^{j\mu_{W}}} \right)^{-1}
\]
(13)

In this queuing system, a service blocking occurs when there
is no available sounding sequence. Then the service blocking
probability in area \( A \), \( P_{sbA} \), can be given as
\[
P_{sbA} = \sum_{n=|S_A|}^{\infty} P_{nA}
\]
(14)

In the case of handover request queuing, the handover blocking
occurs when the queuing time exceeds the maximum handover
queuing time approximated as an exponentially distributed
random variable, with expected value \( t_{w}^{\text{max}} \). Defining
the conditional handover blocking probability at state \( n \) as \( P_{hbA|n} \),
we obtain
\[
P_{hbA|n} = 1 - \prod_{j=0}^{\infty} \left[ 1 - \frac{\mu_{w}}{(|S_A|\mu_{A} + \mu_{w})^{2j}} \right].
\]
(15)

Then the handover blocking probability \( P_{hbA} \) in area \( A \) can be given by
\[
P_{hbA} = \sum_{n=0}^{\infty} P_{hbA|n} P_{nA}.
\]
(16)

4) Service failure probability in PSRR system: We compute
the service failure probability \( P_{sf} \), using the above results.
Let’s denote the forced service termination probabilities due
to the handover blocking as \( P_{dropC} \) and \( P_{dropE} \), respectively,
according to the user’s service starting location. Then the
service failure probability \( P_{sf} \) is
\[
P_{sf} = (1 - F) \{ P_{sbC} + (1 - P_{sbC})P_{dropC} \}
+ F \{ P_{sbE} + (1 - P_{sbE})P_{dropE} \}
\]
(17)

Here the first term indicates the forced service termination
probability due to the service blocking or handover blocking
for a center area service starting user and the second term
represents the same for an edge area service starting user.

To compute \( P_{dropC} \) and \( P_{dropE} \), we denote the probabilities
that a service attempt is served and it has \( i (= 1, 2, 3, \ldots \) \)
successful handovers starting at center area and edge area as
\( H_{IC} \) and \( H_{IE} \), respectively. Then we obtain these as
\[
H_{IC} = \begin{cases} 
    P_{hC}(P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 1 \\
    P_{hC}^iP_{hE}^2(P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 2 \quad (18a) \\
    P_{hC}^iP_{hE}^2(P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 0, \quad (18b)
\end{cases}
\]

\[
H_{IE} = \begin{cases} 
    P_{hE}(P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 1 \\
    P_{hC}P_{hE}^2(P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 2 \quad (18a) \\
    P_{hC}^iP_{hE}^2P_{hC}^2P_{hE}^2)^{(i-1)/3} & \text{for } i \%3 = 0, \quad (18b)
\end{cases}
\]

where \( \% \) represents a modulo operation, and \( \lfloor x \rfloor \) chooses
a largest integer that is smaller than or equal to \( x \). In the case of
a user starting to receive a service in the center area, the
user moves according to the mobility model and experiences
multiple handovers. The probability that the user experiences
a first handover is given as \( P_{hC} \) (see eq. (4a)), and the
probability that the user experiences a second handover is
given as \( P_{hC}P_{hE}^2 \) by using the memoryless property of the
service time. Then we compute the \( i \)-th handover probability
of the user starting to receive a service in a center area through
the same procedures.

Let’s define the probabilities that a user in service is dropped
at the \( i \)-th handover \( (i = 1, 2, 3, \ldots) \) and has started to receive
its service at center area and edge area, as \( B_{IC} \) and \( B_{IE} \).
respectively. Then we obtain these probabilities as (19). From eqs. (18) and (19), we have

\[
B_{iC} = \begin{cases} 
(1 - P_{hbE})^2(1 - P_{hbc})^{\left(i-1\right)/3} & \text{for } i\%3 = 1, \\
(1 - P_{hbE})P_{hbE}P_{hbc}^{\left(i-1\right)/3} & \text{for } i\%3 = 2, \\
(1 - P_{hbE})^2P_{hbc} & \text{for } i\%3 = 0,
\end{cases}
\]

\[
B_{iE} = \begin{cases} 
(1 - P_{hbE})^2(1 - P_{hbc})^{\left(i-1\right)/3} & \text{for } i\%3 = 1, \\
(1 - P_{hbE})P_{hbE}P_{hbc}^{\left(i-1\right)/3} & \text{for } i\%3 = 2, \\
(1 - P_{hbE})(1 - P_{hbc})P_{hbE}^{\left(i-1\right)/3} & \text{for } i\%3 = 0.
\end{cases}
\]  

Finally, we obtain the service failure probability from (17).

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of PSRR through simulations, and show the effectiveness of our mathematical model and its performance improvement over the competitive schemes.

A. Scenario for simulations

We consider a TDD M-MIMO system based on the LTE standard where the system bandwidth is 20MHz, \(\tau_s = 12\) symbols, and \(N_{\text{smooth}} = 14\) subcarriers [2]. We consider the user mobility of up to 100 km/h (i.e., coherence time of 1.6ms), which can provide large \(T\) enough to support 12 sounding symbols (e.g., \(T \leq 24\) symbols when the symbol time is 66.7\(\mu\)s as in LTE systems) [8]. Assume that the path loss exponent is 3.8 and the standard deviation of shadow-fading is 8dB [2].

For cell configuration in simulation, we assume that each cell has the radius of 300m and evaluate the performance considering the area of 19 cells. Assume that the number of service requests from users in each cell follows a Poisson process with the average of 6 (requests/s) and the service time is an exponentially distributed random variable with the average of 15 s. For user mobility, we use the random waypoint model where a user chooses its destination randomly [9].

B. Analysis and simulation results according to parameters \(H\)

Fig. 3 shows the service failure probability \(P_{sf}\) with respect to \(H\) with \(F=0.2\) and 0.4. It can be observed that the analysis and simulation results show almost the same pattern, but the analysis provides slightly lower \(P_{sf}\) than the simulation. It can be inferred that the difference between analysis and simulation results comes from the mobility assumption since users change their moving directions more frequently in the simulation than in the analytic model.

Since the minimization of \(P_{sf}\) indicates the maximum of the number of serviced users and system capacity, \(H\) can be considered the optimum value when it minimizes \(P_{sf}\). It can be seen that the optimum values of \(H\) obtained from analysis and simulation are very close, notwithstanding some gap in \(P_{sf}\).

C. Performance of PSRR

1) Number of QoS users: For evaluation, we define a QoS user as a user who has maintained a SIR value greater than \(SIR_{th}\) for 95% or more of his service duration. Fig. 4 shows the number of QoS users in the system with respect to \(SIR_{th}\) for the non-cooperative scheme, the reuse factor-3 scheme, and our proposed PSRR scheme. We consider the user velocity of 100km/h. In the case, the proposed PSRR system outperforms the two compared schemes and the performance gap increases with the increase of \(SIR_{th}\) in the practical range of lower than 17.6dB.

Fig. 3. Service failure probability vs. \(H\).

Fig. 4. Number of QoS users vs. \(SIR_{th}\) for the velocity 100km/h.
On the other hand, the performance gap starts to decrease when $SIR_{th}$ is higher than 17.6dB because the PSRR cannot guarantee the SIR in that range. The PSRR cannot always guarantee $SIR_{th}$ since it only mitigates the pilot contamination problem. In M-MIMO systems, the PSRR is not able to meet $SIR_{th}$ for cell boundary users eventually due to the path loss. Note that overcoming the path loss problem is beyond the scope of this paper.

As the $SIR_{th}$ range of higher than 17.6dB is not practical, we can say that the PSRR outperforms the other two schemes, which is shown on the left side of the dotted line in Fig.4. The PSRR shows the performance gain of up to 80.6% and 23.4% compared to the non-cooperative and reuse factor-3 schemes, respectively.

2) System capacity and Jain’s fairness: Figs. 5 and 6 illustrate the system capacity and Jain’s fairness index for the considered schemes according to the $SIR_{th}$ when the user velocity is 100km/h. In the non-cooperative and reuse factor-3 schemes, the system capacity and fairness performance remain the same regardless of the $SIR_{th}$ because they do not change their operations according to $SIR_{th}$. The PSRR operates like the non-cooperative scheme for low $SIR_{th}$ and gradually like the reuse factor-3 scheme with the increase of $SIR_{th}$.

Fig. 5 shows that the system capacity of the PSRR gradually decreases with the increase of $SIR_{th}$. For the practical range of $SIR_{th}$, the PSRR scheme shows the system capacity close to that of the non-cooperative scheme, and the performance gain of 37% over the reuse factor-3 scheme. We can confirm that the PSRR can accommodate a largest number of QoS users, while minimizing the degradation in system capacity owing to partial reuse of the sounding resources.

Fig. 6 plots Jain’s fairness index according to $SIR_{th}$ for the three schemes. The fairness performance of the PSRR gradually approaches that of the reuse factor-3 scheme as $SIR_{th}$ approaches 17.6dB and the PSRR always performs better than the non-cooperative system, and similarly to the reuse factor-3 scheme.

Interestingly, the PSRR’s fairness index is slightly higher than that of the reuse factor-3 scheme for the $SIR_{th}$ range of greater than 17.6dB. This is because the partial reuse of sounding sequences works for cell edge areas and mitigates the throughput difference between center users and edge users.

V. CONCLUSION

In this paper, the partial sounding resource reuse (PSRR) method has been proposed to guarantee seamless QoS provisioning for mobile users in M-MIMO systems. The QoS provisioning is considered in two aspects for each user, achievable SIR and seamless sounding sequence assignment. We mathematically analyze the QoS provisioning performance of the PSRR according to the system ratio parameter $H$. Then, the effectiveness of our analysis model on performance is evaluated through simulations. The results confirm that the PSRR system performs best among the competitive schemes in terms of the number of QoS users and fairness, while minimizing the degradation in system capacity.

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