Joint Rate Adaptation and User Scheduling in HARQ-Based Multi-User Systems with Heterogeneous Mobility

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Abstract—**In this paper, we study a joint rate adaptation and user scheduling problem in HARQ-based multi-user systems. We first investigate a tradeoff between the rate selection and user selection through two extreme scheduling criteria: retransmission oriented scheduling (ROS) and mixed scheduling (MS) criteria. Then, we propose a baseline procedure for the joint rate adaptation and user scheduling (JRAUS). Based on the baseline procedure, we introduce a conventional MS-based JRAUS policy, our proposed ROS-based JRAUS policy, and reference JRAUS policies. Finally, through system-level simulations, we evaluate the system performance of the proposed ROS-based JRAUS policy, compared with the conventional and reference JRAUS policies, in homogeneous and heterogeneous mobility scenarios. Through this study, we find that the rate adaptation is not only important in a single point-to-point link but also is very significant in HARQ-based multi-user systems with heterogeneous mobility. Moreover, the rate adaptation needs to be more carefully considered than the user scheduling in heterogeneous mobility scenarios.**

I. Introduction

Traditionally, compensation for uncertain wireless fading phenomena is one of main challenging issues in wireless/mobile communications. To mitigate these drawbacks and enhance resource efficiency, a hybrid transmission scheme between forward error correction (FEC) and automatic repeat request (ARQ) techniques in physical layer, called *hybrid ARQ (HARQ)*, has been proposed [1]–[3]. In medium access control (MAC) layer, *dynamic link adaptation* [4], [5] and *user scheduling* [6], [7] techniques have been developed in order to enhance the resource efficiency in a single point-to-point and multi-user environments, respectively. Both techniques significantly enhance the resource efficiency through dynamic channel adaptation using channel status information (CSI) at the transmitter.

Such far, there were many previous studies related to link adaptation considering the HARQ schemes in various fading channel models – slow fading channel [8]–[10], fast fading channel [11], [12], and time-correlated fading channel [13], [14]. As investigated in the literature, the resource efficiency can be significantly improved by considering a time correlation factor in the rate adaptation with the HARQ, compared to that in slow or fast fading channel assumptions [13].

In addition, several scheduling algorithms have been proposed in HARQ-based multi-user systems. Liu *et al.* [15] and Beh *et al.* [16] proposed scheduling algorithms where retransmission users consider an HARQ-CC combining gain obtained at the previous (re)transmissions by means of summation of signal-to-noise-ratios (SNRs). Jo *et al.* [17] proposed a modified proportional fair (PF) scheduler, which grants higher priority to retransmission packets by introducing a scaling factor, in order to reduce the average transmission delay without any degradation of system throughput in HSDPA system. Huang *et al.* [18] proposed a scheduling policy to minimize a cost function which depends on queue length and the number of transmissions for head-of-line (HoL) packets in a slow fading channel. For the previous work, they did not take into account the rate selection at an initial transmission and only focused on the multi-user diversity gain.

Zheng *et al.* [19] investigated both the rate selection and scheduling policies in an HARQ based downlink packet data system. They proposed a rate selection scheme at the initial transmission in order to maximize long-term average throughput and studied various effective rate mapping criteria for the scheduler. However, they did not jointly take into account both problems due to complicated relationship of the both problems and they assumed a slow fading channel which are static during HARQ retransmissions. Rui *et al.* [20] combined a cross-layer scheduling and HARQ design for multi-user systems with out-dated CSI at the transmitter. Although they attempted to jointly solve power allocation, rate allocation, and user selection problems, they investigated only asymptotic analysis of average system goodput at high SNR due to mathematical complexity.

In this paper, we first investigate a tradeoff between the rate selection and user selection for HARQ-Chase Combining (CC) based systems by introducing two extreme scheduling criteria. Through this comparison, we investigate the effect of the number of users and time-correlation factor on system throughput. Then, we present a baseline procedure of the JRAUS and propose a retransmission oriented scheduling (ROS)-based JRAUS policy with an optimal rate adaptation scheme for time-correlated fading channels. Through system-level simulations, we evaluate the system performance of the proposed JRAUS policy in terms of system delay-limited throughput (DLT) with a maximum retry limit, compared to

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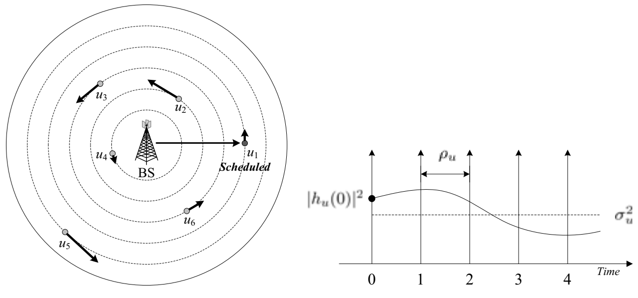

(a) (b)

Fig. 1. System and Channel Models (a) Downlink Multi-User Scheduling Environment (b) Channel Model for Each User

conventional and reference JRAUS policies in homogeneous and heterogeneous mobility scenarios.

The rest of this paper is organized as follows. In Section II, we introduce system and channel models. In Section III, we first introduce two extreme scheduling criteria and investigate a tradeoff between rate selection and user selection by comparing both criteria. In Section IV, we propose a baseline procedure of the JRAUS and present various JRAUS policies including our proposed JRAUS policy. In Section V, through system-level simulations, we compare the performance of the proposed JRAUS policy with that of the conventional and reference JRAUS policies in two mobility scenarios. Finally, we present conclusive remarks in Section VI.

II. System and Channel Models

Fig. 1 shows system and channel models considered in this paper. We take into account a downlink multi-user scheduling environment where each user suffers from time-correlated Rayleigh fading. A base station (BS) selects just one user within the system at a certain time slot. The scheduled user can only transmit his/her own data without any collision or interference at the time slot. In addition, we assume a full-queue scenario where each user has non-real time (NRT) traffic and is always active in a cell.

We consider a time-correlated channel model based on feedback channel gain for each user introduced in [13]. In this channel model, the channel coefficient of the u-th user for the i-th packet at the k-th (re)transmission is written as

$$h_{u,i}(k) = \rho_u^{k+\delta-1} h_{u,i}(0) + \sqrt{1-\rho_u^{2(k+\delta-1)}}\, w_{u,i}(k),$$
$$(k \geq 1, \delta > 0), \quad (1)$$

where ρ_u denotes the time correlation factor of the u-th user, $h_{u,i}(0)$ denotes the channel gain fed back from a receiver of the u-th user for the i-th packet and follows a complex Gaussian distribution with zero mean and variance σ_u^2, $h_{u,i}(0) \sim \mathcal{CN}(0, \sigma_u^2)$. δ represents the channel feedback delay in a unit of time slot, $w_{u,i}(k)$ denotes the independently varying fading term so that it is independent of $h_{u,i}(0)$ and follows an identical and independent complex Gaussian distribution with zero mean and variance σ_u^2, $w_{u,i}(k) \sim \mathcal{CN}(0, \sigma_u^2)$. Note that $w_{u,i}(k)$ and $w_{u,i}(l)$ are independent of each other for all $k \neq l$. In general, the time correlation factor ρ_u is given by a Bessel function such as $J_0\left(2\pi f_c \tau v c^{-1}\right)$ where $J_0(\cdot)$ denotes the zero-th order Bessel function of the first kind, f_c is the carrier frequency, τ is the time duration between two sampling instances, v is the mobile speed, and c is the speed of light [7]. Hence, the time correlation factor reflects mobility effects in the channel model. Throughout this paper, for mathematical simplicity, the packet index i is eliminated in further analysis.

III. A Tradeoff between Rate Selection and User Selection

In this section, we introduce two extreme scheduling criteria: retransmission oriented scheduling (ROS) and mixed scheduling (MS) criteria. The ROS criterion focuses on accurate rate selection, while the MS criterion focuses on multi-user diversity gain according to user selection. Therefore, we can investigate a tradeoff between the rate selection and user selection through these two extreme scheduling criteria. In order to investigate the tradeoff, for both of the scheduling criteria, we take into account the same optimal rate adaptation scheme (i.e., RA-Corr scheme[1]) for the time-correlated fading channels to maximize delay-limited throughput (DLT) [8], [10], [13] which represents the expected throughput under a maximum allowable number of transmissions.

A. Retransmission Oriented Scheduling (ROS) Criterion

To fully achieve throughput improvement through rate adaptation based on channel prediction in time-correlated fading channels, the scheduled user should transmit his/her own data over predicted channel statistics. That is, in the viewpoint of the rate selection, the optimal transmission scheme is to consecutively transmit data until (re)transmission is completed because we assume (re)transmissions over consecutive channel realizations according to the time correlation factor in the RA-Corr scheme [13], [14], when the distribution of the effective channel power gain after HARQ-CC combining is analyzed for a given channel condition. From this reason, in the ROS criterion, a new scheduling process is performed in a unit of packet transmission of the scheduled user in order to accomplish the objective of accurate rate adaptation. Consequently, the re-transmission user, who was scheduled at the previous time slot, always has a higher transmission priority than the new-transmission users.

The properties of the ROS are summarized as follows:

- New scheduling after the end of (re)transmissions of the scheduled user
- Achieving accurate rate selection
- Fully achieved time diversity for the rate adaptation of the HARQ
- Shorter transmission latency for the scheduled user (i.e., bounded by the maximum number of transmissions)

B. Mixed Scheduling (MS) Criterion

Since users' channel conditions vary at each time slot, most of literature related to wireless scheduling with HARQ have

[1]The RA-Corr scheme was proposed as an optimal rate adaptation scheme for the time-correlated Rayleigh fading channels to maximize the expected throughput in a single point-to-point link. The details are given in [13].

considered scheduling criteria performing at every time slot in order to fully obtain multi-user diversity [15], [17], [19]. In the MS criterion, we consider to select a user among all users with re- or new-transmissions at every time slot. Therefore, both the re- and new-transmission users basically have the same transmission priority in the MS criterion. At each scheduling instance, retransmission users maintain the source rates which were determined at the initial transmission in order to use the combining technique such as MRC in the HARQ-CC. Even if the MS criterion fully utilizes the multi-user diversity, it causes inaccurate rate adaptation due to rate mismatch by scheduling interception of the other users during the scheduled user's retransmissions when the prediction-based optimal rate adaptation scheme (e.g., the RA-Corr scheme) is adopted. In the worst case, a specific user has a possibility of interception by an infinite number of other users.

The properties of the MS are summarized as follows:

- Mixed scheduling of re- and new-transmission users at every time slot
- Achieving efficient user selection
- Fully achieved multi-user diversity for the user selection
- Longer transmission latency for scheduled users (i.e., unbounded latency)

C. Numerical Results for the Tradeoff Between Rate Selection and User Selection

We present a numerical result for a tradeoff between the rate and user selections through comparison of the ROS and MS criteria in an HARQ-CC-based system. First of all, we consider a symmetric user distribution and homogeneous mobility scenario (i.e., $\sigma_u^2 = \sigma^2, \rho_u = \rho, \forall u$). Under this environment, the Max C/I algorithm is employed as a scheduler since there is no user fairness issue in the symmetric user distribution scenario. As a basic set of parameters, we assume that $\sigma^2 = 1$, $\delta = 1$, $N_{max} = 4$ (maximum number of transmissions), $SNR_{tx} = 3$ dB (transmit SNR). All the results are averaged over 100000 packets.

Fig. 2 shows a tradeoff between the ROS and MS criteria in terms of the system DLT for varying the number of users and time correlation factors. In general, the ROS criterion outperforms the MS criterion in regions with high-correlation factors. These regions become much broader as the number of users decreases. However, both criteria achieve nearly the same DLT performance in an extremely high-correlation factor (e.g., ρ=0.999), regardless of the number of users. On the contrary, the MS criterion outperforms the ROS criterion with decreasing the correlation factors and increasing the number of users because inherent time diversity of the channel increases as the correlation factor decreases and multi-user diversity increases as the number of users increases. Consequently, the MS criterion is useful in high-diversity regions in terms of the time and user, while the ROS criterion is useful in medium/high-correlation regions with small/moderate number of users. In the high-correlation region (e.g., about $\rho > 0.93$), the ROS criterion is always efficient regardless of the number of users. Since the rate adaptation and user scheduling is actually efficient in the medium/high-correlation region due to a feasibility of the channel feedback, we can say that the ROS criterion is more promising than the MS criterion in the practically operating region.

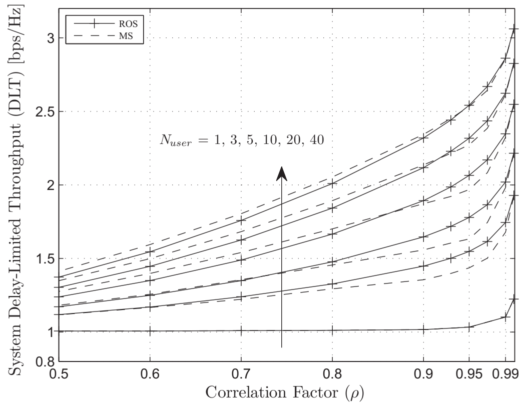

Fig. 2. Tradeoff between ROS and MS Criteria ($\sigma^2 = 1$, $SNR_{tx} = 3$ dB, $N_{max} = 4$, $\delta = 1$)

IV. Joint Rate Adaptation and User Scheduling (JRAUS) Policy

In this section, we present a baseline procedure for the JRAUS. Based on the baseline procedure, we introduce various JRAUS policies including our proposed ROS-based JRAUS policy, a conventional MS-based JRAUS policy, and reference JRAUS policies.

A. A Baseline Procedure for Joint Rate Adaptation and User Scheduling (JRAUS)

The JRAUS consists of four main components: *rate adaptation*, *scheduling criterion*, *scheduler*, and *ranking*. A baseline procedure of the JRAUS is configured by organic connections of these four components. The roles of components and the representative schemes are described as follows:

1) Rate Adaptation: The rate adaptation plays a role to determine an optimal source rate $R_u^*(t)$ for each user at initial transmission instance of the HARQ-based system. As described in [13], the *RA-Slow*, *RA-Fast*, and *RA-Corr* schemes were proposed in the previous work and the RA-Corr scheme is known as the optimal rate adaptation scheme in time-correlated Rayleigh fading channels considered in this paper.

2) Scheduling Criterion: The scheduling criterion determines when a scheduler selects the best user and how to retransmit a packet after a transmission failure of the scheduled user. As investigated in the previous section, there are two extreme scheduling criteria: *ROS* and *MS* criteria. The scheduling instance of the ROS criterion is the time slot right after the end of the scheduled user's transmission, while that of the MS criterion is every time slot regardless of the previously scheduled user's transmission.

3) Scheduler: The scheduler determines which user is the best at every scheduling instance. There are three representative scheduling algorithms: *Round Robin (RR)*, *Max C/I*, and *Proportional Fair (PF)*. In the next section, we basically consider the Max C/I scheduler assuming symmetric user distribution scenarios without a user fairness issue.

4) Ranking – Effective Rate Mapping: The ranking determines an effective rate $R_{\text{eff},u}(t)$ for each user based on the optimal source rate $R_u^*(t)$ and the current channel information $\{|h_u(0)|^2, \rho_u, \sigma_u^2\}$ and then the instantaneous rate $R_u(t)$ in the scheduler is replaced by the effective rate $R_{\text{eff},u}(t)$. Thus, this ranking is also so called the *effective rate mapping*. After all, the scheduler selects a user with the highest value among utility values substituted for the effective rates through the ranking. Various ranking methods for the MS criterion were taken into account in [19].

A baseline procedure of the JRAUS, which consists of the above four components, is consecutively processed as follows:

(1) [**Rate Adaptation**]: Determine $R_u^*(t)$
(2) [**Ranking**]: Determine $R_{\text{eff},u}(R_u^*(t))$
(3) [**Scheduler**]: Determine $u^* = \underset{u\in\Pi}{\text{argmax}}\ R_{\text{eff},u}(R_u^*(t))$
(4) [**Scheduling Criterion**]
  (a) [**ROS Criterion**]:
    – u^* transmits until successful transmission or maximum transmission limit.
    – Go to (1) for all users after the end of the (re)transmissions of the scheduled user u^*.
  (b) [**MS Criterion**]:
    – u^* transmits its own packet once at the scheduled time slot.
    – Go to (1) for new-transmission users and go to (2) for re-transmission users.

B. Various Joint Rate Adaptation and User Scheduling (JRAUS) Policies

In this section, we introduce various JRAUS policies: genie-aided, the conventional MS-based JRAUS, the proposed ROS-based JRAUS, and their variants which are considered as reference JRAUS policies. From now on, we basically express a specific JRAUS policy as $\mathcal{P}\{$Scheduling Criterion, Rate Adaptation, Ranking$\}$ (e.g., $\mathcal{P}\{$MS, RA-Slow, $R_{\text{inst}}^*\}$).

1) Genie-Aided Policy ($\mathcal{P}\{\cdot$, RA-Opt, $R_{inst}^*\}$): The genie-aided policy has perfectly known channel status information at the transmitter (CSIT) without any feedback delay. In this case, the transmitter can accurately adapt to instantaneous channel conditions and the varying capacity for the instantaneous channel gain is achieved without any retransmission and outage. Even though this policy is rather unrealistic, it offers an upper bound of the system performance. According to the RA-Opt scheme, the source rate of the u-th user is expressed as $R_u^* = \log_2\left(1 + |h_u(1)|^2 SNR_{tx}\right)$ where $|h_u(1)|^2$ denotes the exact channel power gain of the u-th user at initial transmission. Next, since the genie-aided policy does not cause outage, the *Instantaneous Rate* ranking method is employed as $R_{\text{eff},u} = R_u^*$.

2) Conventional MS-Based JRAUS Policy ($\mathcal{P}\{$MS, RA-Slow, $S_{Slow}(R_u^*, L)\}$): The conventional MS-based JRAUS policy was proposed in [19]. In this policy, an MS criterion is basically considered. Moreover, since a quasi-static channel condition is assumed, the RA-Slow scheme[2] is employed as a rate adaptation scheme. As the ranking method, DLT with slow fading assumption for a user with the L-th transmission, which is expressed as $S_{Slow}(R_u^*, L)$[3], was considered.

According to the RA-Slow scheme, the source rate of the u-th user is expressed as

$$R_u^* = \underset{R_u>0}{\text{argmax}} \sum_{k=1}^{N_{max}} \frac{R_u}{k} \big[P_{out}(R_u, (k-1)\eta_{u,1}) - P_{out}(R_u, k\eta_{u,1})\big], \quad (2)$$

where $P_{out}(R_u, \eta_{u,1}) = \Pr\{\log_2(1+\eta_{u,1}) < R_u\}$, $\eta_{u,1}$ denotes the instantaneous SNR of the u-th user at initial transmission based on feedback channel power gain, $\eta_{u,1} = |h(1-\delta)|^2 SNR_{tx}$ in which δ denotes the feedback delay whose unit is expressed in terms of the number of time slots.

Since the ranking method of the conventional MS-based JRAUS policy takes into account the MS criterion, the effective rate for the u-th user with the L-th transmission is expressed as

$$\begin{aligned} R_{\text{eff},u} &= S_{Slow}\left(R_u^*, L \big| \left|h_u(L-\delta)\right|^2, \hat{\eta}_{u,L}\right) \\ &= \sum_{k=1}^{N_{max}-(L-1)} \frac{R_u^*}{k} \big[P_{out}(R_u^*, (k-1)\eta_{u,L} + \hat{\eta}_{u,L}) \\ &\qquad - P_{out}(R_u^*, k\eta_{u,L} + \hat{\eta}_{u,L})\big], \end{aligned} \quad (3)$$

where $\eta_{u,L}$ denotes the instantaneous SNR of the u-th user at the L-th transmission based on feedback channel power gain, $\eta_{u,L} = |h_u(L-\delta)|^2 SNR_{tx}$ in which $|h_u(L-\delta)|^2$ denotes the feedback channel power gain of the u-th user at the L-th transmission. $\hat{\eta}_{u,L}$ represents the previously accumulated SNR gain of the u-th user at the L-th transmission and, thus, it is expressed as the sum of SNR gains during the previous $L-1$ transmissions, $\hat{\eta}_{u,L} = \sum_{k=1}^{L-1} \eta_{u,k}$.

3) Proposed ROS-Based JRAUS Policy ($\mathcal{P}\{$ROS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$): The objective of the proposed ROS-based JRAUS policy is to keep the accurate rate adaptation gain of the RA-Corr scheme. Hence, the ROS criterion is basically considered and the scheduling is performed in a unit of packet transmission of a single user. Since the ranking is only performed at the initial transmission, we employ DLT considering a time-correlation factor at initial transmission as the ranking method, which is expressed as $S_{Corr}(R_u^*, 1)$.

According to the RA-Corr scheme[4], the source rate of the u-th user for given channel information is expressed as

$$R_u^* \approx \underset{R_u\geq 0}{\text{argmax}} \sum_{k=1}^{N_{max}} \frac{R_u}{2k}\left[\text{erf}\left(\frac{\frac{2^{R_u}-1}{SNR_{tx}} - \mu_{u,X(k-1)}}{\sqrt{2}\sigma_{u,X(k-1)}}\right) - \text{erf}\left(\frac{\frac{2^{R_u}-1}{SNR_{tx}} - \mu_{u,X(k)}}{\sqrt{2}\sigma_{u,X(k)}}\right)\right], \quad (4)$$

where

$$\mu_{u,X(k)} = \begin{cases} k\left|h_u(0)\right|^2 & \text{if } \rho_u = 1, \\ k\sigma_u^2 + \left(\left|h_u(0)\right|^2 - \sigma_u^2\right)\frac{\rho_u^{2\delta}\left(1-\rho_u^{2k}\right)}{1-\rho_u^2} & \text{if } \rho_u \neq 1, \end{cases}$$

[2]The RA-Slow scheme assumed a static channel condition (i.e., assumed $\rho = 1$) during retransmissions. The details are introduced in [13]

[3]This ranking method corresponds to *Ranking E* $[R_{AA,u}(\text{t})]$ in [19].

[4]Here, the RA-Corr-GA scheme in [13] is actually employed for reducing computational complexity.

and

$$\sigma_{u,X(k)}^2 = \begin{cases} 0 & \text{if } \rho_u = 1, \\ k\sigma_u^4 + \left(\sigma_u^4 - 2\sigma_u^2 |h_u(0)|^2\right) \frac{\rho_u^{4\delta}(1-\rho_u^{4k})}{1-\rho_u^4} & \\ + \left(2\sigma_u^2 |h_u(0)|^2 - 2\sigma_u^4\right) \frac{\rho_u^{2\delta}(1-\rho_u^{2k})}{1-\rho_u^2} & \text{if } \rho_u \neq 1. \end{cases}$$

Next, the effective rate by the employed ranking method is expressed as:

$$\begin{aligned} R_{\text{eff},u} &= S_{Corr}\left(R_u^*, 1 \middle| \{|h(0)|^2, \rho_u, \sigma_u^2\}\right) \\ &= \sum_{k=1}^{N_{max}} \frac{R_u^*}{2k} \left[\text{erf}\left(\frac{(2^{R_u^*} - 1)/SNR_{tx} - \mu_{u,X(k-1)}}{\sqrt{2}\sigma_{u,X(k-1)}} \right) \right. \\ &\quad \left. - \text{erf}\left(\frac{(2^{R_u^*} - 1)/SNR_{tx} - \mu_{u,X(k)}}{\sqrt{2}\sigma_{u,X(k)}} \right) \right]. \end{aligned} \quad (5)$$

As explained in the previous section, the above effective rate substitutes for the instantaneous rate in a scheduler.

4) Reference JRAUS Policy 1 ($\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$): This policy just changes the scheduling criterion of the proposed ROS-based JRAUS policy to the MS criterion. It was used to investigate the tradeoff between the ROS and MS criteria in the previous section.

5) Reference JRAUS Policy 2 ($\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, L)\}$): This policy modifies the ranking method of $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ to a version of user with the previous combining gain at the L-th transmission like the ranking method of the conventional ROS-based JRAUS policy. The effective rate by $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, L)\}$ is expressed as:

$$\begin{aligned} R_{\text{eff},u} &= S_{Corr}\left(R_u^*, L \middle| \{|h_u(L-\delta)|^2, \rho_u, \sigma_u^2\}\right) \\ &= \sum_{k=1}^{N_{max}-(L-1)} \frac{R_u^*}{2k} \left[\text{erf}\left(\frac{\frac{2^{R_u^*}-1}{SNR_{tx}} - \mu_{u,X(k-1)} - \frac{\hat{\eta}_{u,L}}{SNR_{tx}}}{\sqrt{2}\sigma_{u,X(k-1)}} \right) \right. \\ &\quad \left. - \text{erf}\left(\frac{\frac{2^{R_u^*}-1}{SNR_{tx}} - \mu_{u,X(k)} - \frac{\hat{\eta}_{u,L}}{SNR_{tx}}}{\sqrt{2}\sigma_{u,X(k)}} \right) \right], \end{aligned} \quad (6)$$

where $\hat{\eta}_{u,L} = \sum_{k=1}^{L-1} \eta_{u,k}$.

V. Performance Evaluation and Discussion

In this section, we evaluate the performance of the conventional, proposed, and reference JRAUS policies through system-level simulations. We first take into account a symmetric user distribution scenario (i.e., $\sigma_i^2 = \sigma_j^2 \; \forall i \neq j$). Moreover, we consider two different types of scenarios according to user mobility: *homogeneous* (i.e., $\rho_i = \rho_j \; \forall i \neq j$) and *heterogeneous* (i.e., $\rho_i \neq \rho_j \; \forall i \neq j$) mobilities. The basic simulation environment is same as that in Section III-C.

A. Scenario 1: Homogeneous Mobility

In *Scenario 1* with *homogeneous mobility*, all the users have identically and independently distributed (i.i.d.) user distribution and mobility. Therefore, all the users have the same average channel statistics (σ^2) and time-correlation factor (ρ).

Fig. 3 shows the system DLT of various JRAUS policies for varying the number of users. First of all, the genie-aided

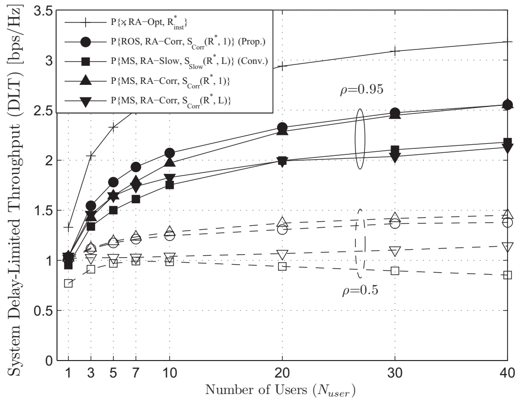

Fig. 3. System DLT of Various JRAUS Policies for Varying The Number of Users in *Scenario 1* ($\sigma^2 = 1$, $SNR_{tx} = 3$ dB, $N_{max} = 4$, $\delta = 1$)

JRAUS policy provides a single upper bound of the system DLT regardless of the time-correlation factor because the time-correlation factor does not give any effect on average channel statistics. All the JRAUS policies achieve higher system DLT for high-correlation factor. Basically, the proposed JRAUS policy (i.e., $\mathcal{P}\{$ROS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$) outperforms the other policies except for $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ at low-correlation factor ($\rho = 0.5$). As investigated in the previous section, $\mathcal{P}\{$ROS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ and $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ policies have the performance tradeoff according to the time-correlation factor and the number of users in this scenario. Hence, $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ policy achieves slightly larger system DLT in the MS efficient region (i.e., large number of users and low-correlation region).

On the other hand, the proposed JRAUS policy significantly outperforms the conventional JRAUS policy for both correlation factors. Especially, the system DLT of the conventional JRAUS policy rather decreases for the low-correlation factor as the number of users increases, due to rate mismatch of the RA-Slow scheme in the low-correlation region. Through comparison between $\mathcal{P}\{$MS, RA-Slow, $S_{Slow}(R_u^*, L)\}$ and $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$ policies, it is noted that the rate adaptation is more important than the user scheduling in even multi-user environments. In other words, inaccurate rate adaptation causes significant performance degradation and it cannot be compensated by the user scheduling since the user scheduling is also based on the ranking methods determined by the rate adaptation.

B. Scenario 2: Heterogeneous Mobility

In *Scenario 2* with *heterogeneous mobility*, we assume that each user has a uniformly selected time-correlation factor which is independently varying for every scheduling instance. In addition, we consider two kinds of mobility scenarios: *whole region* ($\rho_u =$ Uniform$[0.5, 0.999]$) and *high-correlation region* ($\rho_u =$ Uniform$[0.8, 0.999]$).

Fig. 4 shows the system DLT of various JRAUS policies for varying the number of users. Surprisingly, in the heterogeneous mobility scenario, the proposed JRAUS policy always significantly outperforms $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}(R_u^*, 1)\}$

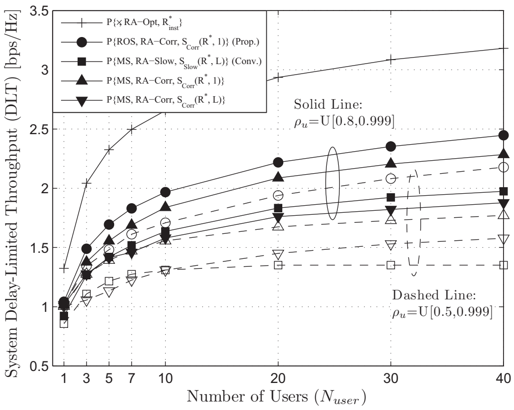

Fig. 4. System DLT of Various JRAUS Policies for Varying Number of Users in *Scenario 2* ($\sigma^2 = 1$, $SNR_{tx} = 3$ dB, $N_{max} = 4$, $\delta = 1$)

policy, while in the homogeneous mobility scenario, both policies exhibit a performance tradeoff according to the time-correlation factor and the number of users. It implies that the ROS criterion with accurate rate adaptation is better than the MS criterion, which is primarily considered in the most previous work, in the heterogeneous mobility environment, even though the ROS criterion cannot fully obtain the multi-user diversity gain, compared to the MS criterion.

The performance gains of the proposed JRAUS policy over the conventional JRAUS and $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}\,(R_u^*, 1)\}$ policies are much larger in the whole region scenario than that in the high-correlation region scenario. This is because the possibility that the conventional JRAUS and $\mathcal{P}\{$MS, RA-Corr, $S_{Corr}\,(R_u^*, 1)\}$ policies select a user with low-correlation factor is reduced in the high-correlation region scenario, while a user with the highest correlation factor becomes the best user in the proposed JRAUS policy when users have the identical average channel statistics, as shown in Fig. 2. Therefore, the differences in user selection are reduced in the high-correlation region scenario and this reduces performance gaps in that scenario. Consequently, the proposed JRAUS policy is more useful in some environments where users have more heterogeneity of mobility.

VI. Conclusion

In this paper, we investigated both rate adaptation and user scheduling problems in the HARQ-based multi-user system. First, we investigated a tradeoff between the rate selection and user selection by introducing two extreme scheduling criteria. The numerical results showed that the ROS criterion is more efficient than the MS criterion in the practically operating high correlation region. Next, we proposed an ROS-based JRUAS policy and its performance was evaluated in terms of system throughput in homogeneous and heterogeneous mobility scenarios. Even if the proposed JRUAS policy has a tradeoff with the MS-based reference policy 1 in the homogeneous mobility scenario, it always outperforms the reference and the conventional JRAUS policies in the heterogeneous mobility scenario. Through this study, it is noted that the accurate rate adaptation is not only important in a single point-to-point link but also is very significant in the HARQ-based multi-user system with heterogeneous mobility. Furthermore, the rate adaptation also needs to be more carefully considered than the user scheduling in the heterogeneous mobility scenario.

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