Effects of Heterogenous Mobility on Rate Adaptation and User Scheduling in Cellular Networks With HARQ

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***Abstract*—In this paper, we investigate the effects of heterogeneous mobility on rate adaptation and user scheduling in cellular networks with hybrid automatic repeat request (HARQ). To this end, we first show the performance tradeoff between two extreme scheduling criteria: retransmission-oriented scheduling (ROS) and mixed scheduling (MS) criteria over time-correlated Rayleigh fading channels. Then, we propose an ROS-based joint rate adaptation and user scheduling (JRAUS) policy for cellular networks and compare it with the conventional and reference JRAUS policies. We also evaluate the system-level performance of the proposed ROS-based JRAUS policy in various user distribution and mobility scenarios. In particular, in an asymmetric user distribution and heterogeneous mobility scenario, which is the most general one in practice, the proposed JRUAS policy yields a throughput gain of 49% and a fairness gain of 155% over the conventional JRAUS policies. In this paper, we find that the rate adaptation is significant not only in a single point-to-point link but in multiuser systems with heterogeneous mobility as well.**

***Index Terms*—Hybrid automatic repeat request (HARQ), mobility, multiuser environment, rate adaptation, user scheduling.**

I. Introduction

TRADITIONALLY, compensation for uncertain wireless fading phenomena is one of the main challenging issues in wireless/mobile communications. Thus far, various channel coding and retransmission schemes have been developed in physical and data link layers, respectively, to improve reliability. Although both schemes improve reliability over wireless fading channels, they cause a throughput loss due to additional resource use. To mitigate this drawback, a hybrid transmission scheme between forward error correction and automatic repeat request (ARQ) techniques, i.e., *hybrid ARQ (HARQ)*, has been proposed [1]–[5], and it has been widely and mandatorily employed in third-generation (3G) and beyond mobile communication systems, such as *High Speed Packet Access* [6], [7], *3G Partnership Project (3GPP) Long-Term Evolution (LTE)* [8], *Mobile Worldwide Interoperability For Microwave Access* [9], and their evolutions. On the other hand, *dynamic link adaptation* [10]–[13] and *user scheduling* [14], [15] techniques have been developed to enhance the resource efficiency in medium-access-control layer in a single point-to-point and multiuser environments, respectively. Both techniques can significantly enhance the resource efficiency through dynamic channel adaptation using channel state information (CSI) at the transmitter (CSIT). Although the HARQ schemes and channel adaptation techniques such as link adaptation and user scheduling are performed in different layers, both of them can contribute to the improvement of the resource efficiency in a cross-layer manner.

Thus far, there have been many studies related to link adaptation with HARQ schemes, including an optimal rate selection problem of packets at initial transmission over various fading channel models, such as slow-fading channels [16]–[19], fast-fading channels [20], [21], and time-correlated fading channels [22], [23]. As investigated in the previous work, the resource efficiency can be significantly improved by considering a time-correlation factor in the rate adaptation with the HARQ in more practical environments considering user mobility [22], compared with that in slow- or fast-fading channel assumptions.

In addition, several scheduling algorithms have been proposed in HARQ-based multiuser systems. Liu *et al.* [24] and Beh *et al.* [25] proposed scheduling algorithms in which we can utilize the combining gain of HARQ with Chase combining (HARQ-CC) obtained at the previous (re)transmissions by means of summation of SNRs. Jo *et al.* [26] proposed a modified proportional fair (PF) scheduler, which grants a higher priority to retransmission packets by introducing a scaling factor, to reduce the average transmission delay without any degradation of the system throughput in the high-speed

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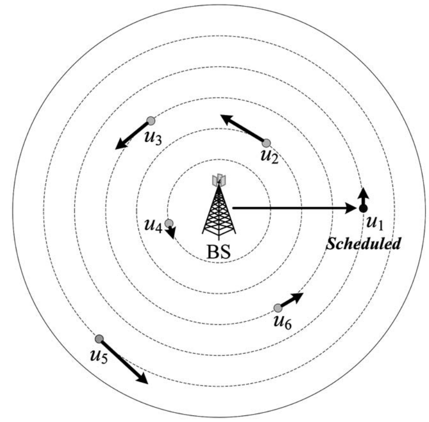
downlink packet access system. Huang *et al.* [27] proposed a scheduling policy to minimize a cost function that depends on queue length and the number of transmissions for head-of-line packets in a slow-fading channel. Lo *et al.* [28] extended this work to a relay-based system with the same scheduling policy. For the previous work, they did not take into account the rate selection at an initial transmission and just focused on the effect of multiuser diversity based on the user scheduling in mixed scheduling (MS) environments among new-transmission and retransmission users.

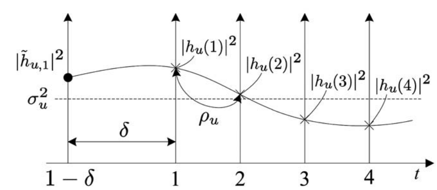
Zheng *et al.* [29] investigated both the rate selection and scheduling policies in an HARQ-based downlink packet data system. They proposed a rate selection scheme at the initial transmission to maximize long-term average throughput and studied various criteria for effective rate mapping (ERM) for the scheduler. However, they did not jointly take into account both problems due to the complicated relationship of both problems, and they assumed a slow-fading channel where channel coefficients are static during HARQ retransmissions, even if the time-correlation factor plays a very important role for link adaptation with the HARQ in mobile communication systems. Rui *et al.* [30] combined cross-layer scheduling and HARQ design for multiuser systems with outdated CSIT. Although they attempted to solve jointly power allocation, rate allocation, and user selection problems, they investigated the asymptotic analysis of average system goodput at high SNR under a slow-fading channel condition due to mathematical complexity.

In this paper, we first investigate a performance tradeoff between the rate selection and user selection in user scheduling considering a HARQ-CC protocol over time-correlated fading channels by introducing two extreme scheduling criteria: retransmission-oriented scheduling (ROS) and MS for new-transmission and retransmission users. Through this comparison, we investigate the effect of the number of users and the time-correlation factor on system throughput. Thereafter, we discuss difficulties in the joint rate adaptation and user scheduling (JRAUS) problem and suggest how to decouple both the rate adaptation and user scheduling. Then, we define a baseline procedure of the JRAUS and propose an ROS-based JRAUS policy over the 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) and a fairness metric, compared with various conventional and reference JRAUS policies in a variety of user distribution and 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 through numerical results. In Section IV, we define a baseline procedure of the JRAUS and present various JRAUS policies including our proposed ROS-based JRAUS policy. In Section V, through system-level simulations, we compare the performance of the proposed ROS-based JRAUS policy with that of the conventional and reference JRAUS policies, in various user distribution and mobility scenarios. Finally, we present conclusive remarks in Section VI.



(a)



(b)

Fig. 1. System and channel models. (a) Downlink multiuser scheduling environment. (b) Channel model for each user.

II. System and Channel Models

Fig. 1 shows system and channel models considered in this paper. We take into account a downlink scheduling system with HARQ-CC, 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 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 [22]. In this channel model, the channel coefficient for the ith packet of the uth user at the kth (re)transmission is rewritten as

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

where ρ_u denotes the time-correlation factor of the uth user, δ represents the channel feedback delay in a unit of time slots, and $\tilde{h}_{u,1,i}$ denotes the channel gain fed back from a receiver of the uth user at an initial transmission for the ith packet and implies the former channel gain by δ time slots from the channel gain at the first transmission $h_{u,i}(1)$, i.e., $\tilde{h}_{u,1,i} = h_{u,i}(1-\delta)$. Here, $\tilde{h}_{u,1,i}$ follows a complex Gaussian distribution with zero mean and variance σ_u^2, i.e., $\tilde{h}_{u,1,i} \sim \mathcal{CN}(0, \sigma_u^2)$. $w_{u,i}(k)$ denotes the independently varying fading term so that it is independent of $\tilde{h}_{u,1,i}$ and follows an identical and independent complex Gaussian distribution with zero mean and variance σ_u^2, i.e., $w_{u,i}(k) \sim \mathcal{CN}(0, \sigma_u^2)$. Note that $w_{u,i}(k)$ and $w_{u,i}(l)$ are independent of each other for all $k \neq l$. For mathematical simplicity, packet index i is eliminated in further analysis throughout this paper.

In general, the time-correlation factor ρ_u is given by a Bessel function, such as $J_0(2\pi f_c \tau v c^{-1})$, where $J_0(\cdot)$ denotes the zeroth-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 [15]. Hence, the time-correlation factor reflects the mobility effect in the channel model. For example, if the carrier frequency and subframe duration in the 3GPP LTE system [31] are set to $f_c = 2.6$ GHz and $\tau = 1$ ms, respectively, the ρ_u values have approximately 0.999, 0.95, 0.8, and 0.5 for 3, 30, 60, and 100 km/h, respectively, based on the Bessel function.

Without loss of generality, we first consider a *symmetric user distribution* that has independently and identical distributed (i.i.d.) channel gains for all users and a *homogeneous mobility* scenario (i.e., $\sigma_u^2 = \sigma^2$, $\rho_u = \rho \, \forall u \in \Pi$, where Π denotes the set of users in the cell) to investigate a tradeoff between the rate selection and user selection in Section III. Then, we extend this scenario to an *asymmetric user distribution* case where users have independent but nonidentically distributed channel gains and *heterogenous mobility* scenarios in Section V.

III. Tradeoff Between Rate Selection and User Selection

To select the best user, a BS basically should know each user's expected transmission rate based on its current channel condition before user scheduling. Thus, the BS first determines each user's transmission rate and selects one user with the highest value of the expected transmission rate in each scheduling instance. On the other hand, if we take into account HARQ retransmissions, then the initial transmission rate can be set more aggressively to achieve higher throughput because HARQ protocols yield much higher successful probabilities at retransmission rounds, compared with conventional ARQ protocols. From this property, if we know when the retransmissions will be carried out[1] after the initial transmission fails, the source rate can be optimized in advance. This is a main point of the optimal rate adaptation with consideration of HARQ. Even if we exactly know the time slot of the retransmission, we cannot know future channel gains at the initial transmission instance where the source rate should be determined and needs to be maintained throughout the retransmission phase in the HARQ-CC protocol. Therefore, in our previous work, a channel prediction-based rate selection scheme, i.e., *RA-Corr scheme,*[2] has been proposed in time-correlated Rayleigh fading channels. It is considered as a basic rate selection scheme in this paper.

Here, we introduce two extreme scheduling criteria: ROS and MS criteria. The ROS criterion focuses on accurate rate selection considering an HARQ retransmission process, whereas the MS criterion focuses on multiuser diversity gain through opportunistic user selection. From these different points of view, we can investigate a tradeoff between the rate selection and user selection with respect to user scheduling in a multiuser system with HARQ retransmissions, in terms of expected throughput. To simplify a JRAUS problem and to investigate the performance tradeoff, we assume the same rate adaptation scheme aforementioned (i.e., RA-Corr scheme) for both criteria to maximize DLT over the time-correlated fading channels modeled in (1). The DLT, which is a main objective function of this paper, is given by [16], [18], [19], [22]

$$S(R) = \sum_{k=1}^{N_{\max}} \frac{R}{k} \cdot P_s(R, k) \tag{2}$$

where R denotes the transmission source rate, $N_{\max}$ denotes the maximum allowable number of transmissions, and $P_s(R, k)$ represents the successful transmission probability at the kth (re)transmission when the transmission rate is R. After all, for given transmission rate R, the DLT implies the expected throughput under a given maximum allowable number of transmissions.

A. ROS Criterion

To fully achieve throughput improvement through rate adaptation considering the HARQ retransmission processes based on a channel prediction in time-correlated fading channels, the scheduled user should transmit his/her own data over predicted channel statistics. In the viewpoint of the rate selection, the optimal transmission scheme is to (re)transmit data, which is encoded as a source rate selected based on the channel prediction at the expected known time slots, until (re)transmission is successfully completed. In the RA-Corr scheme [22], we assumed that consecutive (re)transmissions since it has been originally invented for a single point-to-point link. For simplicity, we also assume consecutive (re)transmissions for an optimal rate selection at an initial transmission instance in this paper. Hence, the scheduled user is required to (re)transmit a packet consecutively until the packet transmission is complete (i.e., a success or a failure until maximum retry limit) to achieve the expected throughput through the channel prediction-based optimal rate adaptation scheme. Fig. 2(a) shows an operation example of the ROS criterion for a three-user case when the maximum transmission limit is set to three. At each scheduling instance, a BS first calculates each user's expected throughput within a given prediction window and determines its optimal transmission rate. Thereafter, it transmits the best user's packet with the highest expected throughput until the (re)transmissions are completed, and then, it performs the next scheduling. Thus, in the ROS criterion, each scheduling instance is not every transmission time interval but a time slot right after the previous transmission completion. Consequently, the retransmission user scheduled at the previous time slot always has a higher transmission priority than the new-transmission users.

The properties of the ROS criterion are summarized as follows:

- new scheduling after the end of (re)transmissions of the scheduled user;
- achieving accurate rate selection;

[1]This is referred to as *synchronous HARQ* operation in 3GPP LTE standards [31].

[2]The RA-Corr scheme was proposed by the authors as an optimal rate adaptation scheme in time-correlated Rayleigh fading channels to maximize the expected throughput in a single point-to-point link. The details are given in [22].

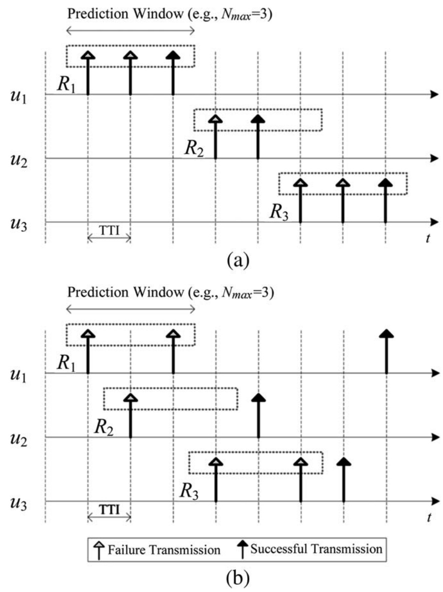


Fig. 2. Example with three users in two extreme scheduling criteria. (a) ROS criterion. (b) MS criterion.

- achieving full time diversity for the rate adaptation of the HARQ;
- shorter transmission latency for the scheduled user (i.e., bounded by the maximum allowable number of transmissions).

B. MS Criterion

Since users' channel conditions vary at each time slot, most of the studies related to wireless scheduling with HARQ have considered scheduling criteria at every time slot to fully obtain multiuser diversity [24], [26], [29]. In the MS criterion, we consider to select a user among all users with retransmissions or new transmissions at every time slot. Therefore, both the retransmission and new-transmission users basically have the same transmission priority in the MS criterion.

Fig. 2(b) shows an operation example of the MS criterion for a three-user case. Different from the ROS criterion, the scheduled user's retransmissions can be intercepted by another user with better expected throughput at each time slot. If there exist more than one interception during retransmissions, the user's expected throughput cannot be achieved since the source rate was optimally determined based on the given prediction window but the actual retransmissions cannot be completed over the expected time slots. Moreover, at each scheduling instance, i.e., every time slot, retransmission users need to maintain the transmission source rates, which were set at the initial transmission to utilize combining techniques, such as maximal ratio combining, in the HARQ-CC. Hence, this results in inaccurate rate adaptation. Even if the MS criterion fully utilizes the multiuser diversity by exploiting a full user pool at every time slot, it causes inaccurate rate adaptation due to rate mismatches caused by scheduling interceptions from other users when the prediction-based rate adaptation scheme (e.g., the RA-Corr scheme) is adopted. In the worst case, a specific user has a possibility of an infinite number of interceptions from other users for a single packet transmission.

The properties of the MS criterion are summarized as follows:

- MS of retransmission and new-transmission users at every time slot;
- achieving efficient user selection;
- achieving full multiuser diversity for the user selection;
- longer transmission latency for scheduled users (i.e., unbounded latency).

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

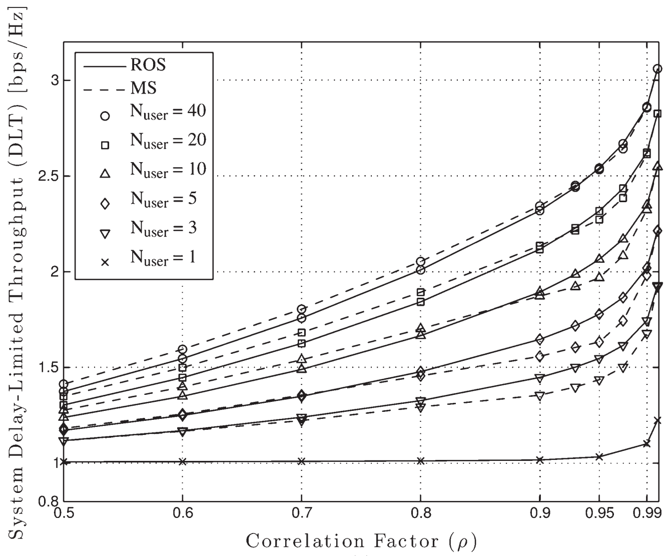
Here, we present numerical results for a tradeoff between the rate selection and user selection through comparison of the ROS and MS criteria. First of all, we consider a symmetric user distribution and homogeneous mobility scenario (i.e., $\sigma_u^2 = \sigma^2, \rho_u = \rho\ \forall u \in \Pi$). Under this environment, the maximum carrier-to-interference (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 $\sigma^2 = 1, \delta = 1, N_{\max} = 4$, and $\mathrm{SNR}_{\mathrm{tx}} = 3$ dB (transmit SNR). All the results are averaged over 100 000 packets.

Fig. 3(a) shows a tradeoff between the ROS and MS criteria in terms of the system DLT for varying the number of users N_{user} and time-correlation factors ρ. 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., $\rho = 0.999$), regardless of the number of users. In particular, in the region with a high correlation factor (e.g., about $\rho > 0.93$), the ROS criterion is always efficient, 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 the time diversity of the channel increases as the correlation factor decreases, and the multiuser diversity increases as the number of users increases. Consequently, the MS criterion is useful in high-diversity regions in terms of the time and the user, whereas the ROS criterion is useful in medium-/high-correlation regions with small/moderate number of users.

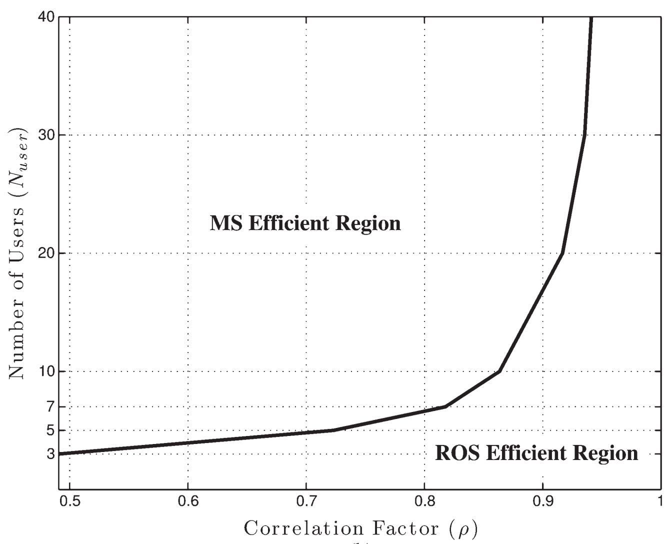
Fig. 3(b) shows the crossover points between the ROS and MS criteria for varying the number of users and time-correlation factors. As investigated in Fig. 3(a), the ROS criterion becomes more efficient as the number of users decreases and the time-correlation factor increases, whereas the MS criterion is efficient in the other regions. Although it is shown as if the MS criterion has a broader efficient region than the ROS criterion, the ROS criterion is more promising than the MS criterion in the practical operation region since the rate adaptation and scheduling is actually efficient in the medium-/high-correlation region due to channel feedback.

IV. Joint Rate Adaptation and User Scheduling Policy

Here, we first investigate difficulties in a JRAUS problem in a HARQ-based multiuser system and then discuss the decoupling approaches of the rate adaptation and user scheduling problems based on the ROS criterion. Then, we present a baseline



(a)



(b)

Fig. 3. Tradeoff between the ROS and MS criteria. (a) System DLT versus correlation factor ρ. (b) Crossover points between the ROS and MS criteria ($N_{\max} = 4$, $\mathrm{SNR}_{\mathrm{tx}} = 3$ dB, $\delta = 1$, and $\sigma^2 = 1$).

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 the reference JRAUS policies.

A. Difficulty of JRAUS for the HARQ-Based System Under the MS Criterion

Different from the rate adaptation in a single point-to-point link, other users in a multiuser environment based on the MS criterion can interrupt a scheduled user during retransmission. Therefore, the transmitter should take into account scheduling interception by the other users when it selects the source rate at the initial transmission. Fig. 4 shows a generalized diagram for successful transmission cases by considering a scheduling interception of the other users with retransmission or new-transmission packets during retransmissions. At each transmission attempt, the scheduled user is scheduled again from the BS or interrupted by the other users who acquire scheduling

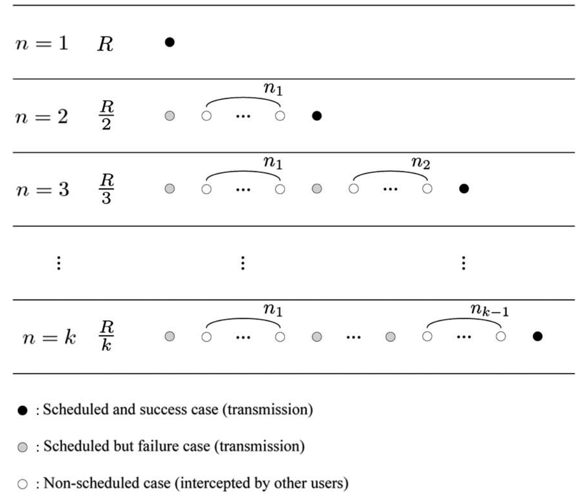


Fig. 4. Generalized diagram for successful transmission cases.

from the BS. If the scheduled user acquires scheduling again, the BS transmits the user's data, and the transmission results in a success or a failure at the receiver. Otherwise, the user who newly acquires scheduling has an opportunity to receive his/her own data from the BS. The number of scheduling interceptions by the other users may be infinite (i.e., $n_{k-1} \to \infty\ \forall k > 2$) if any packet drop constraint does not exist. The achievable rate per channel use is divided by the number of transmission attempts for every transmission success or failure case when the user is scheduled. Therefore, the successful transmission probability at each transmission instance is used to determine the achievable rate, and it plays an important role to determine the optimal source rate for throughput maximization at the initial transmission in the HARQ-based system.

If the index of the tagged user is set to t, at the kth transmission attempt, the successful transmission probability of the tagged user for given channel information is expressed as (3), shown at the bottom of the next page, where R_u denotes the source rate of the tagged user, and $|\vec{\tilde{h}}_1|^2 = [|\tilde{h}_{1,1}|^2, \ldots, |\tilde{h}_{|\Pi|,1}|^2]$, $\vec{\rho} = [\rho_1, \ldots, \rho_{|\Pi|}]$, and $\vec{\sigma}^2 = [\sigma_1^2, \ldots, \sigma_{|\Pi|}^2]$, in which Π denotes the set of users and $|\Pi|$ denotes the cardinality of the set of users. For mathematical simplicity, we assume that the summation or product operation is invalid if an upper limit of the summation or product is less than its lower limit. In this case, the summation and the product are regarded as 0 and 1, respectively, i.e., $\sum_{k=i}^{j} f(k) = 0$ and $\prod_{k=i}^{j} g(k) = 1$ for $i > j$. $P_{\mathrm{sch}}(j)$ represents the probability that the tagged user is scheduled at the jth time slot, $P_{\mathrm{sd}}(R_t, k|\cdot,\cdot)$ denotes the successful decoding probability of the tagged user with source rate R_t at the kth transmission for given channel information and transmitted time slot information, and $\vec{I}_k$ denotes the vector of the transmitted time slot indexes and is expressed as $[1, (n_1+2), \ldots, (\sum_{l=1}^{k-1} n_l + k)]$.

By considering the given channel information in (3), the DLT of the tagged user is rewritten as

$$S\left(R_t \left| \left\{ \left|\vec{\tilde{h}}_1\right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) = \sum_{k=1}^{N_{\max}} \frac{R_t}{k} P_s\left(R_t, k \left| \left\{ \left|\vec{\tilde{h}}_1\right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) \quad (4)$$

where $N_{\max}$ denotes the maximum allowable number of transmissions. Then, the optimal source rate of the tagged user t to maximize the DLT is normally determined by

$$R_t^* = \underset{R_t > 0}{\operatorname{argmax}} \; S\left(R_t \left| \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right). \tag{5}$$

In (3), the probability that the tagged user is scheduled at the jth time slot is written as

$$\begin{aligned} P_{\rm sch}(j) &= P_{\rm sch}\left(j \left| \vec{R}^*, \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) \\ &= \Pr \Bigg\{ \text{scheduled at the } j\text{th time slot} \\ &\qquad \text{for given } \vec{R}^* \text{ and } \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \Bigg\} \\ &= \Pr \Bigg\{ S\left(R_t^*, j-1 \left| \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) \\ &\qquad \geq \max_{u \in \Pi \setminus \{t\}} S\left(R_u^*, j-1 \left| \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) \Bigg\} \end{aligned} \tag{6}$$

where $\vec{R}^* = [R_1^*, \ldots, R_{|\Pi|}^*]$, and $S(R_u^*, j-1|\cdot)$ denotes the optimized DLT of the uth user calculated at the $(j-1)$th time slot for the given channel information. The third equality in (6) is derived from an assumption that the best user is selected based on the maximum DLT.

The optimal source rate R_u^* in $S(R_u^*, j-1|\cdot)$ of (6) is determined by (5), and (5) is determined by (4) by substituting (3) for (4). After all, the optimal source rate R_u^* in (6) is determined by (3), and the probability of scheduling $P_{\rm sch}(\cdot)$ in (3) is determined by (6) again. Therefore, (3) and (6) are tightly coupled. This implies that both the rate adaptation expressed as (5) and the user scheduling determined by (6) are also tightly coupled under the MS criterion. In addition, $P_{\rm sch}(j)$ of (6) requires the predetermined $\vec{R}^*$ and $\{|\vec{\tilde{h}}_1|^2, \vec{\rho}, \vec{\sigma}^2\}$ information, and it needs to be computed recursively due to $P_{\rm sch}(\cdot)$ terms in (3). Therefore, it is so complicated to jointly solve both problems under the MS criterion, which was primarily considered as a basic scheduling criterion in most of the previous work.

In [29], which is regarded as a conventional policy in this paper, for the sake of simplicity, it was assumed that both the rate adaptation and user scheduling are performed independently, even if they should be jointly performed under the MS scheduling criterion to optimize the system performance. Different from the MS criterion, since the scheduled user does not have any interception from other users during his/her retransmissions in the ROS criterion, the rate adaptation and user scheduling problems are naturally decoupled. Therefore, in this paper, we have an approach of an ROS-based JRAUS policy to consider separately both the rate adaptation and the user scheduling, although the ROS criterion dose not provide full multiuser diversity.

B. Baseline Procedure for JRAUS

The JRAUS consists of four main components: *rate adaptation*, *scheduling criterion*, *scheduler*, and *ERM*. 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 optimal source rate $R_u^*(t)$ for each user at initial transmission instance of the HARQ-based system. As described in [22], the *RA-Slow*, *RA-Fast*, and *RA-Corr* schemes were proposed in our previous work, and the RA-Corr scheme is known as the optimal rate adaptation scheme for a single point-to-point link 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 earlier, there are two extreme scheduling criteria: *ROS* and *MS* criteria. In the ROS criterion, if the transmission fails, the scheduled user retransmits his/her own packet until successful transmission or maximum transmission limit, whereas in the MS criterion, the best user is rescheduled after the transmission of the scheduled user, regardless of transmission success or failure. Therefore, the scheduling instance of the ROS criterion is the time slot right after the end of the scheduled user's transmission, whereas that of the MS criterion is every time slot, regardless of the previously scheduled user's transmission.

$$P_s\left(R_t, k \left| \left\{ \left| \vec{\tilde{h}}_1 \right|^2, \vec{\rho}, \vec{\sigma}^2 \right\} \right.\right) = \begin{cases} P_{\rm sd}\left(R_t, k \left| \left\{ \left| \tilde{h}_{t,1} \right|^2, \rho_t, \sigma_t^2 \right\} \right.\right), & \text{if} \quad k = 1 \\ \displaystyle\sum_{n_1=0}^{\infty} \cdots \sum_{n_{k-1}=0}^{\infty} \left(\prod_{j_1=2}^{n_1+1} \left[1 - P_{\rm sch}(j_1)\right] P_{\rm sch}(n_1+2) \right) \cdots \\ \displaystyle\left(\prod_{j_{k-1}=\sum_{l=1}^{k-2} n_l + k}^{\sum_{l=1}^{k-1} n_l + k - 1} \left[1 - P_{\rm sch}(j_{k-1})\right] P_{\rm sch}\left(\sum_{l=1}^{k-1} n_l + k \right) \right) \\ \cdot P_{\rm sd}\left(R_t, k \left| \left\{ \left| \tilde{h}_{t,1} \right|^2, \rho_t, \sigma_t^2 \right\}, \vec{I}_k \right.\right), & \text{if} \quad k \geq 2 \end{cases} \tag{3}$$

3) Scheduler: The scheduler determines which user is the best at every scheduling instance. There are three representative scheduling algorithms: *round robin*, *Max C/I*, and *PF*. In the following, we basically consider the Max C/I scheduler expressed as $u^* = \underset{u\in\Pi}{\text{argmax}}\, R_u(t)$, where $R_u(t)$ denotes the instantaneous rate of the uth user at time slot t for symmetric user distribution scenarios, and the PF scheduler expressed as $u^* = \underset{u\in\Pi}{\text{argmax}}(R_u(t)/T_u(t))$, where $T_u(t)$ denotes the average rate of the uth user at time slot t for asymmetric user distribution scenarios to consider user fairness.

4) ERM: The ERM determines effective rate $R_{\text{eff},\,u}(t)$ for each user based on the optimal source rate $R_u^*(t)$ and the current channel information $\{|\tilde{h}_{u,\,1}|^2,\, \rho_u,\, \sigma_u^2\}$, and then, the instantaneous rate $R_u(t)$ in the scheduler is replaced by the effective rate $R_{\text{eff},\,u}(t)$. This is because a transmission source rate can be different from an achievable rate when HARQ retransmissions are taken into account. For example, in the Max C/I scheduler, the best user is determined based on the instantaneous transmission rate as $u^* = \underset{u\in\Pi}{\text{argmax}}\, R_u(t)$. However, in a throughput perspective, it is reasonable that a user with the highest expected throughput is chosen as the best user. Thus, the effective rate that can represent the expected throughput is needed in the scheduler. After all, the scheduler selects a user with the highest value among utility values substituted for the effective rates through the ERM methods. Since the ERM plays a primary role to determine the order for scheduling, it is also called the *ranking*. Various ERM methods for the MS criterion were taken into account in [29].

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

(1) [**Rate Adaptation**]: Determine $R_u^*(t)$
(2) [**ERM**]: Determine $R_{\text{eff},\,u}(R_u^*(t))$
(3) [**Scheduler**]: Determine $u^* = \underset{u\in\Pi}{\text{argmax}}\, R_{\text{eff},\,u}(R_u^*(t))$ (assuming the Max C/I scheduler)
(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 his/her own packet once at the scheduled time slot.
    $-$Go to (1) for new-transmission users and go to (2) for retransmission users.

C. Various JRAUS Policies

Here, we introduce various JRAUS policies: the genie-aided policy, the conventional MS-based JRAUS policy, the proposed ROS-based JRAUS policy, 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, ERM$\}$ (e.g., $\mathcal{P}\{\text{MS}, \text{RA-Slow}, R^*_{\text{inst}}\}$). Additionally, for mathematical simplicity, we eliminate the current time slot index t from the equations.

1) Genie-Aided Policy ($\mathcal{P}\{\cdot$, RA-Opt, $R^*_{\text{inst}}\}$): The genie-aided policy has perfectly known 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. Although this policy is rather unrealistic, it provides an upper bound of the system performance.

According to the RA-Opt scheme, the source rate of the uth user is expressed as

$$R_u^* = \log_2\left(1 + |h_u(1)|^2\, \text{SNR}_{\text{tx}}\right) \tag{7}$$

where $|h_u(1)|^2$ denotes the exact channel power gain of the uth user at the initial transmission.

Next, since the genie-aided policy does not cause outage, the *instantaneous rate* ERM method R^*_{inst} is employed as follows:

$$R_{\text{eff},\,u} = R_u^*. \tag{8}$$

2) Conventional MS-Based JRAUS Policy ($\mathcal{P}\{$MS, RA-Slow, $S_{\text{Slow}}(R_u^*, L)\}$): The conventional MS-based JRAUS policy was proposed in [29]. In this policy, an MS criterion is basically considered. Moreover, since a quasi-static channel condition is assumed, the RA-Slow scheme[3] is employed as the rate adaptation scheme. As the ERM method, DLT with slow-fading assumption for the user with the Lth transmission, which is expressed as $S_{\text{Slow}}(R_u^*, L)$,[4] was considered.

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

$$R_u^* = \underset{R_u > 0}{\text{argmax}} \sum_{k=1}^{N_{\max}} \frac{R_u}{k} \left[P_{\text{out}}(R_u, (k-1)\gamma_{u,\,1}) - P_{\text{out}}(R_u, k\gamma_{u,\,1})\right] \tag{9}$$

where $P_{\text{out}}(R_u, \gamma_{u,\,1}) = \Pr\{\log_2(1+\gamma_{u,\,1}) < R_u\}$, and $\gamma_{u,\,1}$ denotes the instantaneous SNR of the uth user at the initial transmission based on feedback channel power gain $\gamma_{u,\,1} = |\tilde{h}_{u,\,1}|^2 \text{SNR}_{\text{tx}} = |h_u(1-\delta)|^2 \text{SNR}_{\text{tx}}$ in which δ denotes the feedback delay whose unit is expressed in terms of the number of time slots. Here, the term $[P_{\text{out}}(R_u, (k-1)\gamma_{u,\,1}) - P_{\text{out}}(R_u, k\gamma_{u,\,1})]$ implies the successful probability for given R_u and $\gamma_{u,\,1}$ at the kth transmission, i.e., $P_s(R_u, k\gamma_{u,\,1})$.

Since the ERM method of the conventional MS-based JRAUS policy takes into account the MS criterion, the effective rate for the uth user with the Lth transmission is expressed as

$$\begin{aligned} R_{\text{eff},\,u} &= S_{\text{Slow}}\left(R_u^*, L \middle| \left|\tilde{h}_{u,\,L}\right|^2, \hat{\gamma}_{u,\,L}\right) \\ &= \sum_{k=1}^{N_{\max}-(L-1)} \frac{R_u^*}{k} \left[P_{\text{out}}\left(R_u^*, (k-1)\,\gamma_{u,\,L} + \hat{\gamma}_{u,\,L}\right) - P_{\text{out}}\left(R_u^*, k\gamma_{u,\,L} + \hat{\gamma}_{u,\,L}\right)\right] \end{aligned} \tag{10}$$

where $\gamma_{u,\,L}$ denotes the instantaneous SNR of the uth user at the Lth transmission based on feedback channel power

[3]The RA-Slow scheme assumed a static channel condition (i.e., $\rho = 1$) during retransmissions. The details are introduced in [22].

[4]This ERM method corresponds to *Ranking* $E\,[R_{\text{AA},u}(t)]$ in [29].

gain $\gamma_{u,L} = |\tilde{h}_{u,L}|^2 \mathrm{SNR}_{\mathrm{tx}} = |h_u(L-\delta)|^2 \mathrm{SNR}_{\mathrm{tx}}$, in which $|\tilde{h}_{u,L}|^2$ denotes the feedback channel power gain of the uth user at the Lth transmission and δ denotes the feedback delay, and $\hat{\gamma}_{u,L}$ represents the previously accumulated SNR gain of the uth user at the Lth transmission; thus, it is expressed as the sum of SNR gains during the previous $(L-1)$ transmissions $\hat{\gamma}_{u,L} = \sum_{k=1}^{L-1} \gamma_{u,k}$. In this policy, for $L \geq 2$ (i.e., retransmissions), the Lth transmission user has updated SNR feedback $\gamma_{u,L}$ at the Lth transmission instance, which is different from one at the initial transmission $\gamma_{u,1}$. However, it is assumed that the current feedback channel gain is kept during the remaining future retransmissions from the Lth transmission instance when determining the effective rate used in the scheduler.

3) Proposed ROS-Based JRAUS Policy ($\mathcal{P}\{ROS, RA\text{-}Corr, S_{\mathrm{Corr}}(R_u^*, 1)\}$)*:* 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 ERM is only performed at the initial transmission in the ROS criterion, we employ DLT considering a time-correlation factor at the initial transmission as the ERM method, which is expressed as $S_{\mathrm{Corr}}(R_u^*, 1)$.

According to the RA-Corr scheme,[5] the source rate of the uth user is expressed as

$$R_u^* \approx \underset{R_u \geq 0}{\mathrm{argmax}} \sum_{k=1}^{N_{\max}} \frac{R_u}{2k} \left[\mathrm{erf}\left(\frac{\frac{2^{R_u}-1}{\mathrm{SNR}_{\mathrm{tx}}} - \mu_{u,X(k-1)}}{\sqrt{2}\sigma_{u,X(k-1)}} \right) - \mathrm{erf}\left(\frac{\frac{2^{R_u}-1}{\mathrm{SNR}_{\mathrm{tx}}} - \mu_{u,X(k)}}{\sqrt{2}\sigma_{u,X(k)}} \right) \right] \quad (11)$$

where

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

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

Here, $|\tilde{h}_{u,1}|^2 = |h_u(1-\delta)|^2$ denotes the feedback channel power gain of the uth user at initial transmission.

Next, the effective rate by the employed ERM method is expressed as

$$\begin{aligned} R_{\mathrm{eff},u} &= S_{\mathrm{Corr}}\left(R_u^*, 1 \middle| \left\{|\tilde{h}_{u,1}|^2, \rho_u, \sigma_u^2\right\}\right) \\ &= \sum_{k=1}^{N_{\max}} \frac{R_u^*}{2k} \left[\mathrm{erf}\left(\frac{\frac{2^{R_u^*}-1}{\mathrm{SNR}_{\mathrm{tx}}} - \mu_{u,X(k-1)}}{\sqrt{2}\sigma_{u,X(k-1)}} \right) - \mathrm{erf}\left(\frac{\frac{2^{R_u^*}-1}{SNR_{\mathrm{tx}}} - \mu_{u,X(k)}}{\sqrt{2}\sigma_{u,X(k)}} \right) \right]. \end{aligned} \quad (12)$$

[5]Here, the RA-Corr-GA scheme in [22] is actually employed to reduce computational complexity.

As explained earlier, the given effective rate substitutes for the instantaneous rate in a scheduler, which may vary according to user distribution scenarios.

4) Reference JRAUS Policy 1 ($\mathcal{P}\{MS, RA\text{-}Corr, S_{\mathrm{Corr}}(R_u^*, 1)\}$)*:* 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 ($\mathcal{P}\{MS, RA\text{-}Corr, S_{\mathrm{Corr}}(R_u^*, L)\}$)*:* This policy modifies the ERM method of the reference JRAUS policy 1 to a version with the previous combining gain and an updated feedback channel power gain at the Lth transmission similar to the ERM method of the conventional ROS-based JRAUS policy. While the reference JRAUS policy 1 maintains the effective rate of retransmission users, which is determined at the initial transmission, the reference policy 2 replaces it by 1, the reference policy 2 replaces it by the rate, which is recalculated by considering the remaining number of retransmissions, based on the updated channel power gain $|\tilde{h}_{u,L}|^2 = |h_u(L-\delta)|^2$ and the previous combining gain $\hat{\gamma}_{u,L}$ at the Lth transmission. Therefore, the effective rate by the reference JRAUS policy 2 implies the expected throughput from the Lth transmission to the $N_{\max}$th transmission, based on an updated feedback channel power gain $|\tilde{h}_{u,L}|^2$ at the Lth transmission. As a result, the effective rate of reference JRAUS policy 2 is expressed as

$$\begin{aligned} R_{\mathrm{eff},u} &= S_{\mathrm{Corr}}\left(R_u^*, L \middle| \left\{|\tilde{h}_{u,L}|^2, \rho_u, \sigma_u^2\right\}\right) \\ &= \sum_{k=1}^{N_{\max}-(L-1)} \frac{R_u^*}{2k} \left[\mathrm{erf}\left(\frac{\frac{2^{R_u^*}-1}{\mathrm{SNR}_{\mathrm{tx}}} - \mu_{u,X(k-1)} - \frac{\hat{\gamma}_{u,L}}{\mathrm{SNR}_{\mathrm{tx}}}}{\sqrt{2}\sigma_{u,X(k-1)}} \right) - \mathrm{erf}\left(\frac{\frac{2^{R_u^*}-1}{\mathrm{SNR}_{\mathrm{tx}}} - \mu_{u,X(k)} - \frac{\hat{\gamma}_{u,L}}{\mathrm{SNR}_{\mathrm{tx}}}}{\sqrt{2}\sigma_{u,X(k)}} \right) \right] \end{aligned} \quad (13)$$

where $|\tilde{h}_{u,L}|^2 = |h_u(L-\delta)|^2$ and $\hat{\gamma}_{u,L} = \sum_{k=1}^{L-1} \gamma_{u,k}$

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

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

V. Performance Evaluation and Discussion

Here, we evaluate the performance of the conventional, proposed, and reference JRAUS policies in various user distribution and mobility scenarios through system-level simulations. Fig. 5 shows four different types of user distribution and mobility scenarios considered here. We take into account two types of scenarios according to user distribution: *symmetric* (i.e., $\sigma_i^2 = \sigma_j^2 \forall i \neq j$) and *asymmetric* (i.e., $\sigma_i^2 \neq \sigma_j^2 \ \forall i \neq j$) user distributions. In the symmetric user distribution, all users have i.i.d. user distribution with respect to average channel statistics; thus, they have the same value as 1, i.e., $\sigma^2 = 1$, whereas they

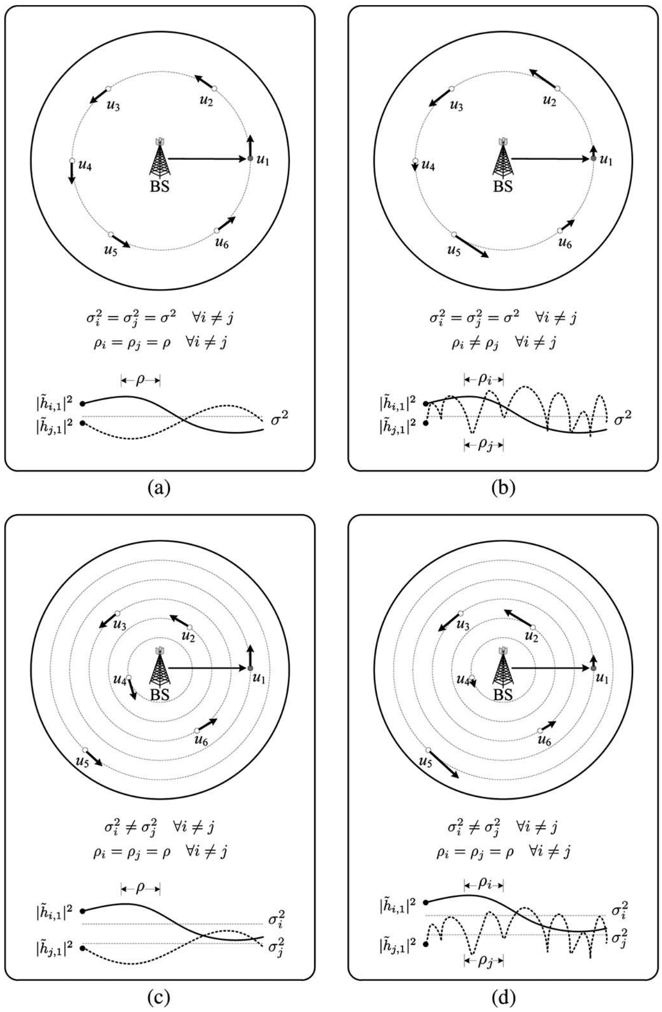


Fig. 5. (a) *Scenario 1*: Symmetric user and homogeneous mobility. (b) *Scenario 2:* Symmetric user and heterogeneous mobility. (c) *Scenario 3*: Asymmetric user and homogeneous mobility. (d) *Scenario 4*: Asymmetric user and heterogeneous mobility.

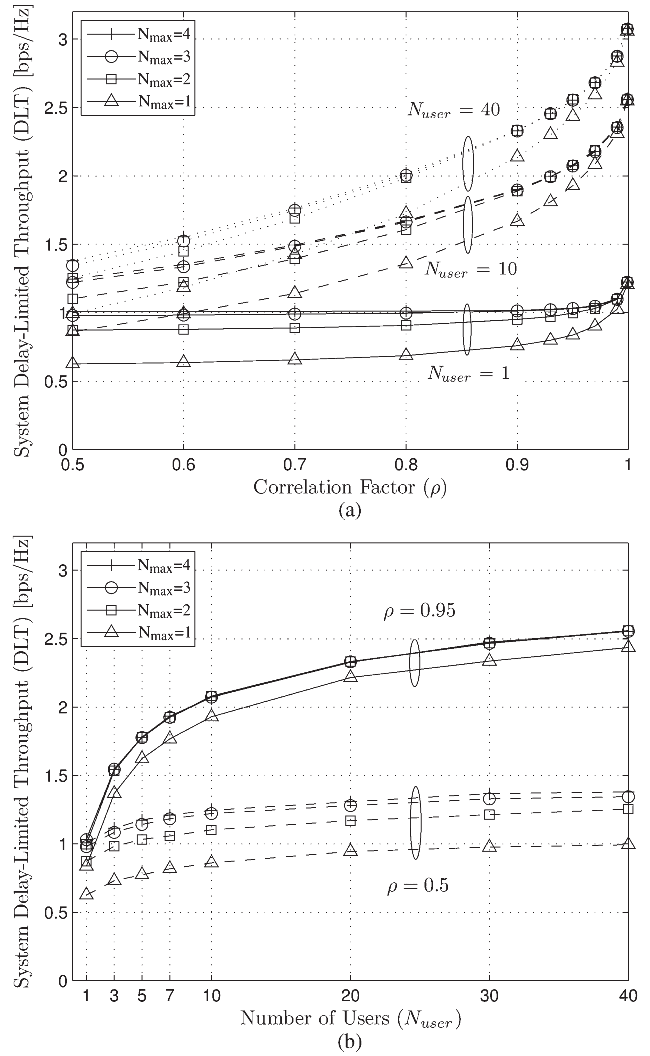


Fig. 6. *Scenario 1*. Performance of the proposed JRAUS policy. (a) System DLT versus correlation factor ρ. (b) System DLT versus the number of users N_{user} ($\sigma^2 = 1$, $\text{SNR}_{\text{tx}} = 3$ dB, and $\delta = 1$).

have different values in the asymmetric user distribution. We consider a profile vector [0.25, 0.5, 1, 2, 4] for the average channel statistics. Each element in the vector implies a value of the average channel power gain, and it is equally set with a multiple of 5 according to the number of users. For instance, when the number of users is 20, each value in the vector is allocated to four users, respectively. For the symmetric user distribution, a Max C/I scheduler is employed to maximize throughput performance, whereas a PF scheduler is applied for the asymmetric user distribution due to a user fairness issue. Moreover, we also consider two types of scenarios according to user mobility: *homogeneous mobility* (i.e., $\rho_i = \rho_j \forall i \neq j$) and *heterogeneous mobility* (i.e., $\rho_i \neq \rho_j \forall i \neq j$). In the homogeneous mobility, all users have the same time-correlation factor where the value is determined according to different scenarios. On the contrary, in the heterogeneous mobility, two kinds of mobility scenarios are considered according to a range of values: a *whole region* and a *high-correlation region*. In the whole-region scenario, each user's correlation factor is randomly chosen from 0.5 to 0.999, i.e., $\rho_u = \text{Uniform}[0.5, 0.999]$, whereas in the high-correlation-region scenario, it is randomly chosen from 0.8 to 0.999, i.e., $\rho_u = \text{Uniform}[0.8, 0.999]$. Although the *asymmetric user distribution* and *heterogeneous mobility scenario* is the most generalized scenario, the others also provide insights on the impact of average channel statistics and time-correlation factors in various JRAUS policies. The basic simulation parameters are set to the same values as described in Section III-C (i.e., $\sigma^2 = 1$, $\delta = 1$, $N_{\max} = 4$, and $\text{SNR}_{\text{tx}} = 3$ dB). All the results are also averaged over 100 000 packets.

A. Scenario 1: Symmetric User Distribution and Homogeneous Mobility

First, to understand the basic trend of the performance in terms of system DLT, we investigate numerical results of the proposed JRAUS policy for varying the number of users, the time-correlation factors, and the maximum number of transmissions. Fig. 6 shows the system DLT performance of the proposed JRAUS policy to vary the time-correlation factors and the number of users. In Fig. 6(a), the system DLT of the proposed JRAUS policy increases with an increase in the time-correlation factor, the number of users, and the maximum number of transmissions. Compared with the single-user case (i.e., $N_{\text{user}} = 1$), the system DLT more significantly increases

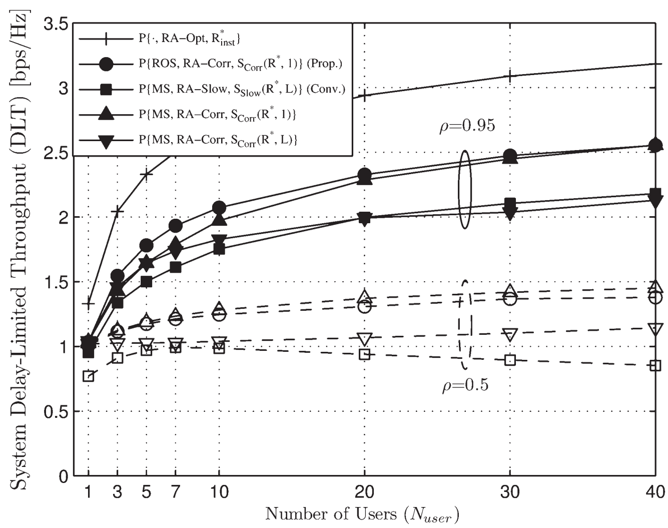


Fig. 7. *Scenario 1.* System DLT of various JRAUS policies for varying the number of users ($\sigma^2 = 1$, $\mathrm{SNR_{tx}} = 3$ dB, $N_{\max} = 4$, and $\delta = 1$).

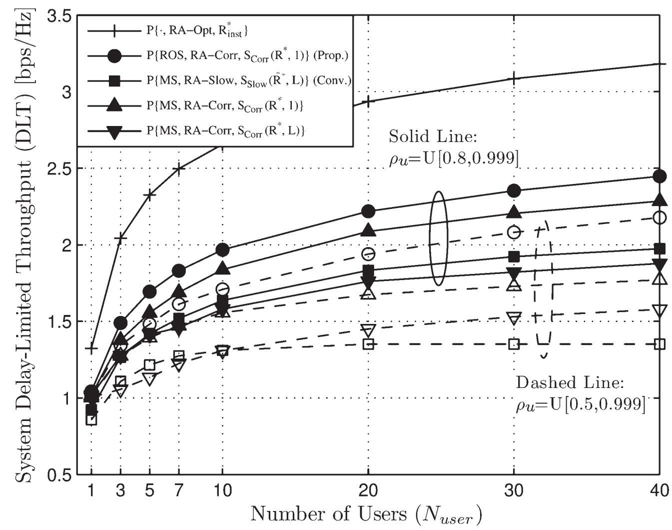


Fig. 8. *Scenario 2.* System DLT of various JRAUS policies for varying the number of users ($\sigma^2 = 1$, $\mathrm{SNR_{tx}} = 3$ dB, $N_{\max} = 4$, and $\delta = 1$).

as the time-correlation factor increases in multiuser cases (i.e., $N_{\mathrm{user}} = 10$ and $N_{\mathrm{user}} = 40$). This implies that the proposed JRAUS policy can obtain much larger multiuser diversity in the high-correlation region as the number of users increases. Additionally, the system DLT of the proposed JRAUS policy is less sensitive for the maximum number of transmissions as the number of users increases. Thus, for a large number of users, more than two transmissions (i.e., $N_{\max} > 2$) are enough to fully achieve the system DLT.

In Fig. 6(b), the system DLT of the proposed JRAUS policy for a high-correlation factor (i.e., $\rho = 0.95$) is much larger than that for a low-correlation factor (i.e., $\rho = 0.5$). It implies that lower mobility users (i.e., users with higher correlation factors) achieve larger system DLT for the symmetric user distribution scenario in a multiuser environment. Moreover, since the system DLT of users with high-correlation factors is more slowly saturated than for users with low-correlation factors as the number of users increases, low-mobility users can achieve a larger gain with increasing the number of users, compared with high-mobility users. Finally, since the system DLT of users with a high-correlation factor is less sensitive than for users with a low-correlation factor, low-mobility users require a smaller maximum number of transmissions, compared with high-mobility users.

Fig. 7 shows the system DLT of various JRAUS policies for varying the number of users. First of all, the genie-aided 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 the average channel statistics. As shown in Fig. 6, all the JRAUS policies also achieve higher system DLT for high-correlation factors. Basically, the proposed JRAUS policy (i.e., $\mathcal{P}\{\mathrm{ROS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$) outperforms the other policies, except for $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ at a low-correlation factor ($\rho = 0.5$). As investigated earlier, $\mathcal{P}\{\mathrm{ROS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ and $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ policies have a performance tradeoff according to the time-correlation factor and the number of users in this scenario. Hence, the $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ policy achieves slightly larger system DLT in the MS-efficient region (i.e., a large number of users and a low-correlation region).

On the other hand, the proposed JRAUS policy significantly outperforms the conventional JRAUS policy for both correlation factors. In particular, 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 a comparison between $\mathcal{P}\{\mathrm{MS}, \text{RA-Slow}, S_{\mathrm{Slow}}(\bar{R}_u^*, L)\}$ and $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ policies, it is noted that the rate adaptation is more important than the user scheduling in even multiuser 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 ERM methods determined by the rate adaptation. Additionally, the $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, L)\}$ policy provides a higher priority to retransmission users based on the MS criterion. However, since the optimal source rate in the RA-Corr scheme is determined by considering the HARQ retransmission process, it has been already reflected in the selected source rate. Thus, the $\{S_{\mathrm{Corr}}(R_u^*, L)\}$ ERM method causes rather performance degradation, compared with the $\{S_{\mathrm{Corr}}(R_u^*, 1)\}$ ERM method of $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ policy.

B. Scenario 2: Symmetric User Distribution and Heterogeneous Mobility

Fig. 8 shows the system DLT performance of various JRAUS policies for varying the number of users. Interestingly, in the heterogeneous mobility scenario, the proposed JRAUS policy always significantly outperforms the $\mathcal{P}\{\mathrm{MS}, \text{RA-Corr}, S_{\mathrm{Corr}}(R_u^*, 1)\}$ policy, whereas in the homogeneous mobility scenario, both policies exhibit a performance tradeoff according to the time-correlation factor and the number of users. This is because a scheduled user based on the MS criterion suffers from a smaller correlation factor effectively than that based on the ROS criterion due to scheduling interceptions from other users during retransmissions in an average sense. As shown in Fig. 3(a), if a user has the same feedback channel gain at an initial transmission, the higher correlation factors generally provide the higher throughput, regardless of the scheduling criteria. In addition, the transmission source rate is no longer optimal since the scheduled user by the MS criterion suffers from the reduced effective correlation factor, whereas the source rate is selected by assuming the initial correlation factor and feedback channel gain at the initial transmission. Therefore, this rate mismatch causes additional performance degradation in the viewpoint of the expected throughput. In the heterogenous mobility scenario, the scheduling interceptions of the MS criterion occur more frequently since the time-correlation factor and the feedback channel gain also affect them, whereas the feedback channel gain only affects them in the homogeneous mobility scenario. As a result, since the performance degradation caused by the reduced effective correlation factor and the rate mismatch is larger than the performance enhancement achieved by the scheduling intercepting user with a higher feedback channel gain or time-correlation factor, the performance tradeoff disappears in the heterogenous mobility scenario. Eventually, the ROS criterion with accurate rate adaptation is better than the MS criterion, which was primarily considered in the most previous work, in the heterogeneous mobility environments, although the ROS criterion cannot fully obtain the multiuser diversity gain, compared with the MS criterion.

The performance gain of the proposed JRAUS policy over the conventional JRAUS and $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policies is 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 $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policies select a user with a low-correlation factor is reduced in the high-correlation-region scenario, whereas 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. 6. Therefore, the differences in user selection are reduced in the high-correlation-region scenario, and this reduces the performance gap in that scenario. Consequently, the proposed JRAUS policy is more useful in some environments where users have more heterogeneity of mobility.

C. Scenario 3: Asymmetric User Distribution and Homogeneous Mobility

In *Scenario 3* with *asymmetric user distribution* and *homogeneous mobility*, since users have different average channel statistics, a user fairness issue occurs. If the Max C/I scheduler is employed in this scenario, the system can still obtain high throughput performance, but cell-edge users with low average channel statistics suffer from starvation in the viewpoint of user throughput. Therefore, in general, a scheduler considering user fairness is used in the asymmetric user distribution scenario. For example, the PF and max–min fairness schedulers are mainly considered in communication systems and networks. As mentioned previously, we consider the PF scheduler for the asymmetric user distribution scenarios in this paper.

To evaluate the system performance in the asymmetric user distribution scenarios, we additionally consider a *fairness metric* [29], [32], [33] that reflects system throughput and user fairness. The *fairness metric* is defined as follows:

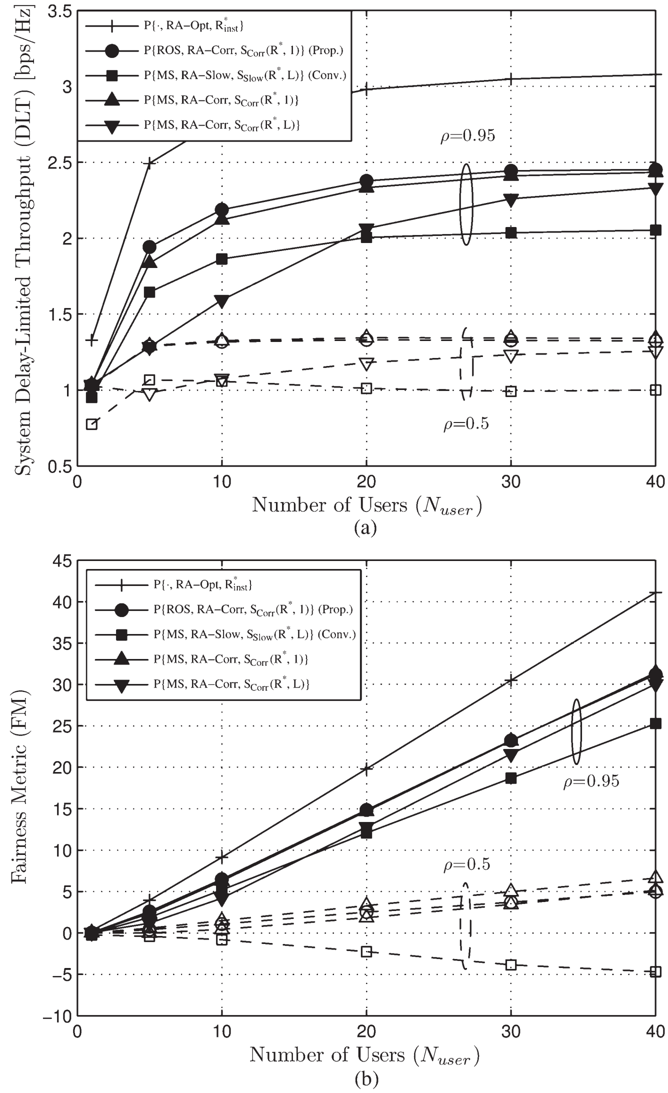


Fig. 9. *Scenario 3*. Performance of various JRAUS policies. (a) System DLT versus the number of users N_{user}. (b) Fairness metric versus the number of users N_{user} ($\sigma_u^2 \in [0.25, 0.5, 1, 2, 4]$, $\text{SNR}_{\text{tx}} = 3$ dB, $N_{\max} = 4$, and $\delta = 1$).

$$\mathcal{FM}(T_1, \ldots, T_K) = \sum_{u=1}^{K} \log(T_u) \tag{14}$$

where T_u denotes the throughput of the uth user, and K denotes the number of users in the system. Under the PF scheduling algorithm with averaging time scale $t_c = \infty$, the *fairness metric* is maximized almost surely among the class of all schedulers [33]. Thus, this metric is used as a system performance measure for the asymmetric user distribution scenarios here and in Section V-D. Throughout this paper, the averaging time scale t_c is set to 100 for the numerical results.

Fig. 9 shows the system DLT performance and *fairness metric* for various JRAUS policies in *Scenario 3*. Basically, for a high-correlation factor of 0.95, all the policies also achieve higher system DLT than those for a low-correlation factor do. The proposed JRAUS policy outperforms all the policies in terms of system DLT, except that it obtains nearly the same system DLT with the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy at a low-correlation factor of 0.5. Compared with the tradeoff between both policies in *Scenario 1*, the tradeoff between both policies has been weakened in terms of DLT in the asymmetric user distribution scenario. This comes from an inherent property of the PF scheduler, which is not a throughput optimal to keep the user fairness. In the PF scheduler, the best user is selected based on the ratio of the instantaneous expected throughput and the average throughput, although it does not have a maximum value in terms of the expected throughput. This causes a decrease in the multiuser diversity on which the MS criterion focuses, in the throughput perspective. As a result, the reduced multiuser diversity due to the PF scheduler diminishes the throughput of the MS criterion and weakens the performance tradeoff, although it is recovered as the number of users increases.

However, in the viewpoint of *fairness metric*, the tradeoff is still maintained, as shown in Fig. 9(b). In accordance with the *fairness metric*, the proposed JRAUS policy has nearly the same value as that of the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy for a high-correlation factor of 0.95, whereas it rather has a lower value than that of the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy for a low-correlation factor of 0.5. The reason is that the *fairness metric* reflects the degree of user fairness and the throughput. The conventional JRAUS policy has the worst *fairness metric* values for the low-correlation factor, and it is also almost the worst for the high-correlation factor, whereas the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, L)\}$ policy has a performance tradeoff with the conventional JRAUS policy in both *Scenarios 1* and *2*.

D. Scenario 4: Asymmetric User Distribution and Heterogeneous Mobility

Fig. 10 shows the system DLT and *fairness metric* performance for various JRAUS policies in *Scenario* 4, which is the most generalized case. The solid lines with filled markers indicate the *whole region* mobility scenario, and the dashed lines with empty markers represent the *high-correlation region* mobility scenario. The proposed JRAUS policy always outperforms all the policies in both mobility scenarios. In more detail, the proposed JRAUS policy yields approximately 49% and 29% throughput gains when N_{user} is set to 40 for the *whole region* and the *high-correlation region*, respectively, compared with those of the conventional JRAUS policy. In a *fairness metric* perspective, it also yields approximately 155% and 41% system performance gains when the number of users is set to 40 for the *whole region* and the *high-correlation region*, respectively, compared with those of the conventional JRAUS policy.

On the other hand, in the homogeneous mobility scenarios (i.e., *Scenarios 2* and *3*), the proposed JRAUS policy has a tradeoff with the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy according to the correlation factor and the number of users. However, in the heterogeneous mobility scenarios (i.e., *Scenarios 2* and *4*), it always outperforms the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy, regardless of the correlation factor and the number of users. In particular, in *Scenario 4*, which is the most generalized scenario, the proposed JRAUS policy yields 21% and 20% throughput gains when

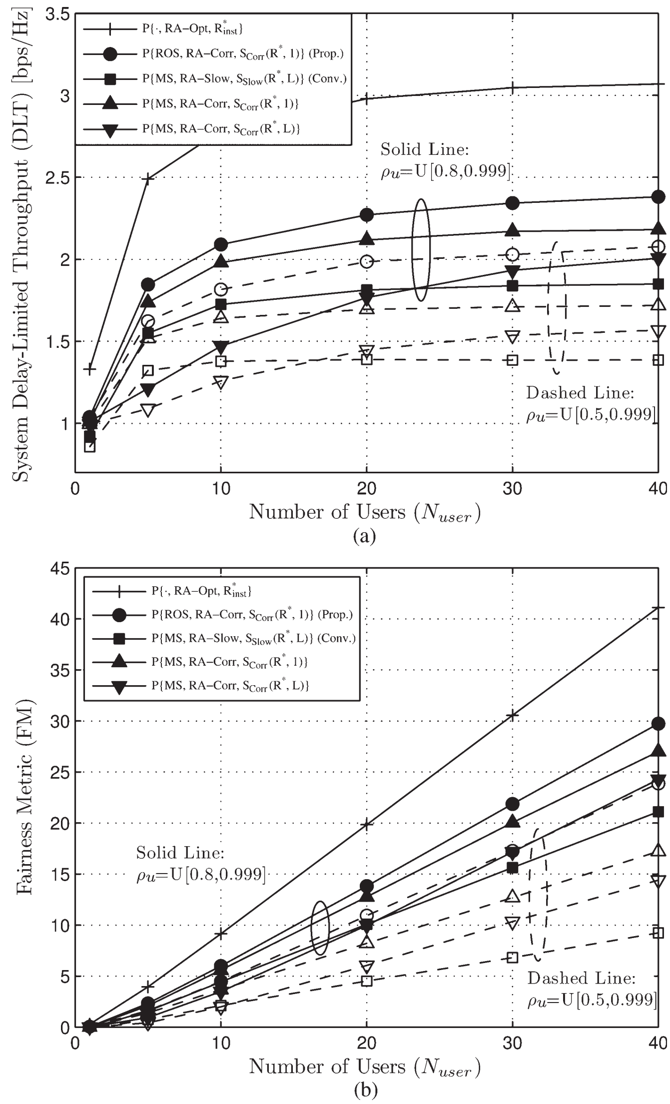


Fig. 10. *Scenario 4*. Performance of various JRAUS policies. (a) System DLT versus the number of users N_{user}. (b) Fairness metric versus the number of users N_{user} ($\sigma_u^2 \in [0.25, 0.5, 1, 2, 4]$, $\text{SNR}_{\text{tx}} = 3$ dB, $N_{\max} = 4$, and $\delta = 1$).

the number of users is set to 40 for the *whole region* and the *high-correlation region*, respectively, compared with those of the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)\}$ policy. Furthermore, it also yields 39% and 10% system performance gains in terms of the *fairness metric* for the *whole region* and the *high-correlation region*, respectively, compared with those of the $\mathcal{P}\{\text{MS}, \text{RA-Corr}, S_{\text{Corr}}(R_u^*, 1)$ policy. Consequently, the proposed ROS-based JRAUS policy that focuses on the accurate rate adaptation achieves better system performance in terms of system throughput and *fairness metric*, compared with those of the conventional and reference MS-based JRAUS policies, which focus on the multiuser diversity. It implies that the accurate rate adaptation is more important than the multiuser diversity gain obtained through user scheduling in practical HARQ-based multiuser systems.

VI. Conclusion

In this paper, we investigated the effect of heterogeneous mobility on both the rate adaptation and user scheduling in the downlink cellular networks with the HARQ-CC, where each user suffers from time-correlated Rayleigh fading. First, we investigated a performance tradeoff between the rate selection and user selection by introducing two extreme scheduling criteria when the same rate adaptation scheme over the time-correlated Rayleigh fading channels is adopted. The numerical results showed that the ROS criterion is more efficient than the MS criterion in the practical operation region with high correlation factors. Next, we proposed an ROS-based JRAUS policy. The performance of the proposed JRAUS policy was evaluated in terms of system throughput and fairness metric in four user distribution and mobility scenarios. Even if the proposed JRUAS policy has a tradeoff with the MS-based reference policy in the homogeneous mobility scenarios, it always outperforms the reference and conventional JRAUS policies in the heterogeneous mobility scenarios. Through this study, it is noted that accurate rate adaptation is not only important in a single point-to-point link but is very significant in the HARQ-based multiuser system with heterogeneous mobility as well. Furthermore, rate adaptation also needs to be more carefully considered than the user scheduling in heterogeneous mobility scenarios.

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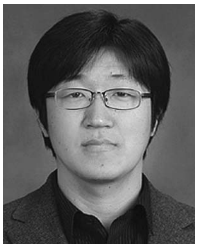

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