A Joint Power and Rate Assignment Algorithm for Multirate Soft Handoffs in Mixed-Size WCDMA Cellular Systems

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***Abstract*—This paper proposes a joint power and rate assignment (JPRA) algorithm to deal with multirate soft handoffs (SHOs) in mixed-size wideband code division multiple access cellular systems. This JPRA algorithm contains a link proportional power allocation scheme and an evolutionary computing rate assignment method to determine an appropriate allocation of transmission power and service rate for multirate SHOs. It can achieve power balancing among cells better than the conventional site-selection diversity transmission scheme with best effort rate allocation. Simulation results show that the JPRA algorithm can achieve better cell's service coverage and higher system capacity with and without the measurement errors during the active set selection.**

***Index Terms*—CDMA, optimization methods, resource management, soft handoff.**

I. INTRODUCTION

SOFT HANDOFF (SHO) is one of the most important features in multirate wideband code division multiple access (WCDMA) cellular systems. However, base transceiver stations (BTSs) often have to consume more power to serve SHO users than that to serve nonhandoff (NHO) users. The fact of that the total power resource in each BTS is confined and shared among SHO and NHO users raises an issue of tradeoffs between coverage and capacity. For example, if a BTS fails to serve multirate HO users near cell boundaries, its cell service coverage is shrunk, whereas there are more power applicable to NHO users for higher transmission rates. Thus, a strategy of joint power allocation (PA) and rate assignment (RA) for multirate SHOs plays an important role for downlink radio resource management in multirate WCDMA cellular systems.

Many literatures discussed the topic of joint PA and RA for all users in the cellular system in the sense of global optimization problem [1]–[7]. However, possible combinatorial numbers of solutions are too large to be tractable for downlink optimal resource allocation, and the complexity would be greatly increased when taking multirate SHOs into account. References [1]–[3] focused on reverse link and did not consider multirate SHOs. Kim [4] dealt with rate-regulated power control in reverse link without HO. Reference [5] discussed resource management in multiple-chip-rate direct sequence CDMA systems supporting multiclass services. It arranged HO in the same subsystem or execute interfrequency HO. References [6] and [7] proposed joint PA and RA algorithms in downlink WCDMA homogeneous cellular systems. The former proposed two suboptimal algorithms based on a fairness concept, and the latter adopted dynamic programming to optimize the throughput. However, both considered homogeneous cellular systems without SHO mechanisms.

Moreover, plenty of publications ever addressed the issue of downlink PA for HO in the CDMA cellular system [8]–[14]. A conventional site-selection diversity transmission (SSDT) scheme was proposed in [8], which is also included in the specification of 3GPP TR 25.922 [9]. It provided transmission diversity by dynamically selecting one BTS with best link quality in the active set. However, due to the constraint of maximum link power, SSDT sometimes could not afford enough power required for multirate HO users. Also, since SSDT is a single-site transmission mechanism, it may choose a wrong link during the active set selection, resulting in wasting more power for HOs. The advantage of the power-saving characteristic for SSDT would disappear in the mixed-size environment [10], [11]. Morimoto *et al.* [12] proposed an enhanced SSDT technique to allow more than one BTS to transmit signals to an HO user. Reference [13] presented a cost-function-based differentiated power control technique to determine different power levels of each radio link from two BTSs to an HO user. Reference [14] studied two proportional PA methods in terms of transmission power and target signal quality. None of these aforementioned downlink PA schemes for HO users considered a maximum constraint of link power and multiple data rates in a mixed-size cellular system.

This paper considers a multirate WCDMA cellular system with mixed-size cells due to nonuniform traffic load distribution, in which all cells utilize the same frequency. Generally, congested microcells, which are with stringent power budget for maximum total transmission power, may easily exhaust their

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power because of serving SHO users in downlink [10], [11], and then, there would have no enough power resource to serve other NHO users in the system. When taking into account multirate services, this power-exhausting problem will become more critical. References [15]–[17] considered capacity issues in mixed-size cellular systems. References [15] and [16] focused on the reverse link, and only voice service was considered. Kishore *et al.* [17] concluded that uplink and downlink directions were equivalent in mixed-size cellular systems. Also, it did not consider multirate services. Note that multirate services are often regarded as highly resource-exhausting traffics and often have more volumes of traffic in downlink than that in uplink.

In this paper, a novel joint power allocation and rate assignment (JPRA) algorithm is proposed for downlink multirate SHOs in mixed-size WCDMA cellular systems. We first formulate this joint PA and RA issue as a combinatorial optimization problem. Then, the JPRA algorithm is designed in a cooperative two-phased process, which is composed of the link proportional PA (LPPA) scheme in the first phase and the evolutionary computing RA (ECRA) method in the second phase. The LPPA scheme is for PA of SHOs. Unlike the SSDT scheme, LPPA is a multisite transmission mechanism, which distributes the required power in proportion to link qualities between a SHO user and all BTSs in its active set. The BTSs in the active set with better link quality will allocate more power than others with worse link qualities. This will result in power balancing among cells. Also, the ECRA method, which is based on PA of supportable transmission rates for multirate SHO users obtained by LPPA, formulates the joint PA and RA issue to be an integer and discrete optimization problem, where the sum of the allocated rate for multirate SHO users can be maximized, under a predefined total power constraint for SHOs in each cell. It is well known that conventional optimization methods can hardly cope with problems with integer and discrete variables, whereas evolutionary computing methods are very efficient for these problems to reduce the searching complexity [18].

In the meantime, a new multiquality balancing PA (MQBPA) algorithm for NHO users with multiple service rates is also developed. With the MQBPA algorithm, each BTS can allocate the power required for each NHO user based on the ratio of the user's received interference to the link quality. Previous works for quality balancing PA technique were studied only for a single service rate with unique required signal quality [19], [20]. On the other hand, a multirate removal (MRV) algorithm is proposed to pick out a user, who consumes system resource most, to reduce its service rate or even block it when the system resource is insufficient. Several removal algorithms had been proposed [21]–[23]. Among these, link-based and received signal-strength-based removal algorithms were only suitable for single service [21], [22]; the prioritized removal algorithm [23], which is based on predefined service priority, did not adjust the service rates for users in the reverse link of a multiservice cellular system.

Simulation results show that the JPRA algorithm can achieve less forced handoff termination probability by over 300% and higher system throughput by around 5.0% than the conventional SSDT scheme with best effort RA. Also, on the perspective of users, it can support excellent user satisfaction indexes (USIs) for voice and data users. Moreover, if the measurement error (ME) during the active set selection is happened, JPRA behaves less sensitive than SSDT; JPRA can further enhance the forced termination probability of SHOs by about 500% and the total throughput by 8.0% over SSDT.

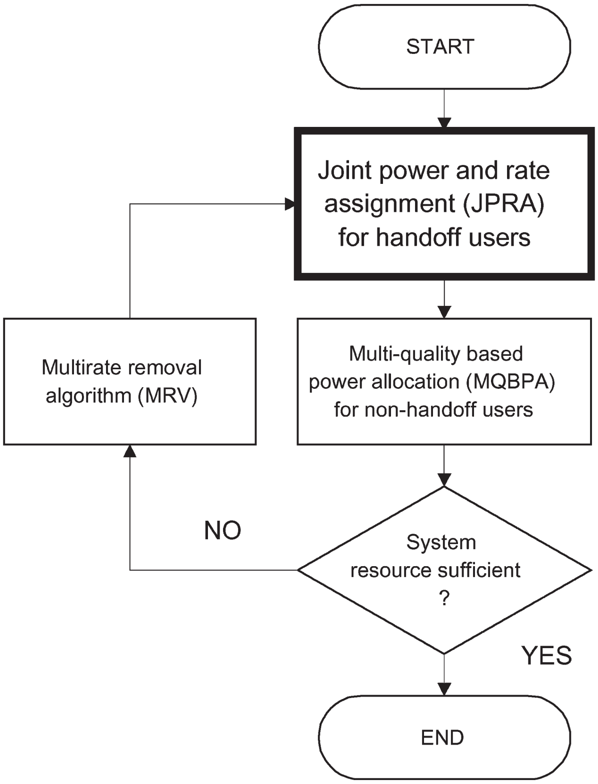

Fig. 1. System operation of downlink power and rate allocations.

The remaining parts of this paper are organized as follows. Section II details the flow of the system operation and provides the design of MQBPA and MRV algorithms. In Section III, the JPRA algorithm for multirate SHOs is presented, including LPPA and ECRA algorithms. Simulation results are provided and discussed in Section IV. Finally, Section V presents some conclusions.

II. SYSTEM OPERATION

The system operation of downlink power and rate allocations for mixed-size WCDMA cellular systems is shown in Fig. 1. A BTS allocates power to HO users first, based on the new JPRA algorithm, and then to NHO users, which is based on the MQBPA algorithm. If the system resource is insufficient to support all users with allocated rates in their required signal qualities, an MRV algorithm is activated to release system resources by reducing the users' service rates or even suspending the users' transmission, and the system operation is executed again.

A. System Model

In the multirate WCDMA mixed-size cellular system, the received interference of user j served by BTS i, which is denoted by $I_{i,j}$, is

$$I_{i,j} = (1-\alpha)P_i L_{i,j} + \sum_{k \neq i} P_k L_{k,j} + \eta_o \tag{1}$$

where α is the orthogonality factor, P_i is the downlink total transmission power of cell i, $L_{i,j}$ is the link quality from cell i to user j, which includes effects of both pathloss and shadowing, and η_o is the background noise. Note that the first and second terms in (1) denote intracell and intercell interferences, respectively, in which the first term is caused by imperfect orthogonality of spreading codes. Each user is with service rate r, where voice users are with single rate $r = r_v$ and data users are with one of M kinds of data service rates, $r = r_d \in \{r_d^1, \ldots, r_d^M\}$ and $r_d^1 < r_d^2 < \cdots < r_d^M$. The received bit-energy-to-noise ratio (E_b/N_o) of user j with service rate r in BTS i, which is denoted by $\gamma_{i,j}(r)$, must be larger than or equal to the required signal quality, which is denoted by $\gamma^*(r)$. With allocation power $q_{i,j}(r)$ from BTS i to user j, $\gamma_{i,j}(r)$ can be expressed as

$$\gamma_{i,j}(r) = \frac{q_{i,j}(r) \cdot L_{i,j} \cdot G(r)}{I_{i,j}} \geq \gamma^*(r) \tag{2}$$

where $G(r) = W/r$ is the processing gain and W is the frequency bandwidth.

Assume there are N_v voice HO users and N_d data HO users in the system. For each SHO user h with service rate r, its received E_b/N_o, $\gamma_h(r)$, can be obtained, if using the maximum ratio combining method to combine signals from all serving BTSs in active set D_h, by

$$\gamma_h(r) = \sum_{i \in D_h} \gamma_{i,h}(r) \tag{3}$$

where $r_h(r) \geq \gamma^*(r)$. The active set of each user h is determined according to an SHO algorithm which has SHO threshold η. If the strength difference between the received pilot signals of the original cell and a target cell is less than or equal to η, the target cell would be added as an active member in action set D_h.

B. MQBPA Algorithm

The MQBPA algorithm is to provide each NHO user the required signal quality of itself. Assume each service rate r has the required signal quality $\gamma^*(r)$; denote C_i (Q_i) as the total transmission power for NHO (SHO) in cell i such that $C_i + Q_i = P_i$; denote $\widehat{P}_i$ as the maximum total transmission power of cell i. The MQBPA algorithm assigns the NHO user j in cell i with service rate r an amount of power $q_{i,j}(r)$ by

$$q_{i,j}(r) = \frac{w_{i,j}}{\sum\limits_{j \in \mathbf{U}_i} w_{i,j}} \cdot C_i \tag{4}$$

where $\mathbf{U}_i$ is the set of NHO user in cell i, $\sum_{j \in \mathbf{U}_i} q_{i,j}(r) = C_i$; $w_{i,j}$ is the weight factor of the transmission power C_i for user j in cell i, which is defined as

$$w_{i,j} = \frac{I_{i,j}}{L_{i,j} \cdot G(r)} \cdot \gamma^*(r). \tag{5}$$

This $w_{i,j}$ is designed to combat the near–far effect for the WCDMA cellular system. In order to obtain the required balanced signal quality $\gamma^*(r)/G(r)$, which is based on (2), the required transmission power of each user j in BTS i with rate r, $q_{i,j}(r)$, must be proportional to the ratio of $I_{i,j}/L_{i,j}$. Thus, more (less) power would be allocated to the user with higher (lower) transmission rate r or larger (smaller) ratio of $I_{i,j}/L_{i,j}$. In the MQBPA algorithm, each user has to transmit the value of $w_{i,j}$, which can be obtained by measuring its received total interference and signal strength, to its serving BTS via the control channel. However, ME might be occurred in this stage, and it might degrade the system performance. We consider the case of that MS results in misarranging the users' active sets in Section IV.

Substituting (4) and (5) into (2), the received signal quality of the NHO user j in cell i can be yielded as

$$\gamma_{i,j}(r) = \frac{C_i}{\sum\limits_{j \in \mathbf{U}_i} w_{i,j}} \gamma^*(r). \tag{6}$$

With the system requirement of that $\gamma_{i,j}(r) \geq \gamma^*(r)$, if $C_i / \sum_{j \in \mathbf{U}_i} w_{i,j}$ is less than one, the total allocation power C_i of BTS i should be adjusted by tuning factor ψ_i, which is given by

$$\psi_i = \frac{\gamma^*(r)}{\gamma_{i,j}(r)}. \tag{7}$$

In the following, the MQBPA algorithm is described

```
[The MQBPA Algorithm]
Step1: [Initialize]
    • Initialize $P_i$ to be $\widehat{P}_i$ for each cell $i$, and calculate $Q_i$ for SHO users in each cell $i$ after executing JPRA algorithm.
    • Initialize incremental tuning value $\Delta\psi_i$ and the last tuning value $\psi_i'$ of cell $i$ to be zero.
Step 2: [Calculate $w_{i,j}$]
    • Calculate $w_{i,j}$, based on (5), for user $j$ in cell $i$.
Step 3: [Calculate $q_{i,j}(r)$]
    • Calculate $C_i = P_i - Q_i$ for NHO users in each cell $i$.
    • Calculate $q_{i,j}(r)$ for each NHO user $j$ with service rate $r$ in cell $i$ based on (4), and $q_{i,j}(r) = \min(q_{i,j}(r), \widehat{q}_i)$.
Step 4: [Calculate $\psi_i$]
    • Calculate $\psi_i$ for each cell $i$, based on (6) and (7).
Step 5: [Calculate $\Delta\psi_i$ and save current tuning factor as $\psi_i'$]
    • Calculate $\Delta\psi_i = \psi_i - \psi_i'$ for each cell $i$.
    • Save $\psi_i'$ as $\psi_i$ for each cell $i$.
Step 6: [Check Stop Criterion for each cell $i$]
    • IF any $\psi_i \neq 1.0$ or any $\Delta\psi_i > 0.01$, denoting the convergence is not met, THEN
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—Adjust the total transmission power as

$$P_i = \min(\psi_i \times C_i + Q_i,\ \widehat{P}_i). \tag{8}$$

—Goto **Step 2**.
ELSE DONE.

The proposed MQBPA algorithm will converge to a desired solution of that an effective individual PA for each users exits and its required signal quality is satisfied. The convergence characteristic of (8) can be proved, similar to the proof in [20], where the power control algorithm for the single service is standard for it satisfies three properties: positivity, monotonicity and scalability. If the solution does not exist, the MRV algorithm will be activated.

C. MRV Algorithm

In order to squeeze resource from a user who consumes the largest power whenever lacking of resource enough for accommodating all users, a removal algorithm is launched to pick out a user based on a removal index. In this paper, the proposed MRV algorithm, for the mixed-size WCDMA cellular system with multirate services, defines a new removal index for user j with service rate r, which is denoted by $J_j(r)$, as $J_j(r) = \gamma^*(r)/\{\widetilde{P}_i \cdot L_{i,j} \cdot G(r)\}$, where $\widetilde{P}_i$ is the pilot power of BTS i, which is related to the cell size, and $\widetilde{P}_i \cdot L_{i,j}$ is equal to user j's received signal strength from BTS i. The removal index represents the degree of system resource required to serve user j with service rate r. A user with the largest value of the removal index will consume the most system resource currently, and this user should be first considered to be removed or reduced rate. The worse the received signal strength, the higher the service rate and required signal quality are, the larger the removal index value will be.

In order to provide higher priority for voice users, the proposed MRV algorithm removes system resource from data users first unless all the data users are reduced to basic service rate, which is the lowest transmission rate for data services. The flowchart of MRV algorithm is shown in Fig. 2. At first, the MRV scheme will check if all data users are with basic rate. If there exists at least one data user not with the basic rate, the MRV scheme will choose the data user with the maximum removal index. If the service rate of the selected user is with the basic rate, then the system will remove it directly, otherwise reduce its rate to the next lower service rate. If all data users are with basic rate, the system will remove the user which is with the maximum removal index.

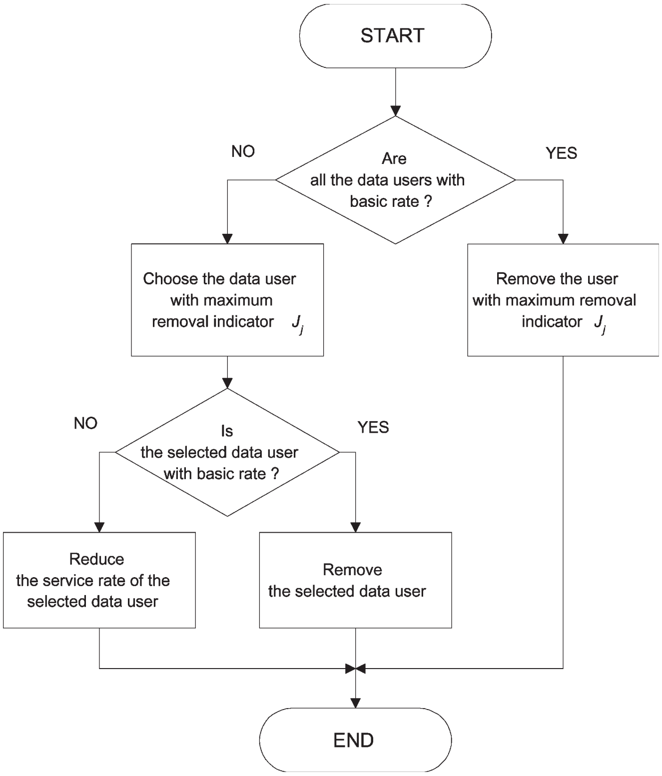

Fig. 2. Flowchart of the MRV algorithm.

III. JPRA ALGORITHM

The problem of the joint PA and RA for multirate SHOs is here defined as a constrained combinatorial optimization problem with an objective to maximize the total throughput of multirate SHOs, under the constraints of that the total power allocated to SHO users in each cell should be bounded by a maximum value, the power allocated to each SHO user from a cell of its active set is limited by an upper bound, and the received bit-energy-to-noise ratio of each SHO user must not be less than its requirement of signal quality. We define the total throughput of multirate SHO to be the sum of the allocated rate for the multirate SHO data users, excluding the service rate of SHO voice user which is constant. Also, for clarity, denote the allocation rate r for SHO data user h as $(r_d)_h$, $(r_d)_h \in \{r_d^1, \ldots, r_d^M\}$, and the rate vector for all multirate SHO data users by $\mathbf{R} = [(r_d)_1, \ldots, (r_d)_h, \ldots, (r_d)_{N_d}]$. Then, the optimization problem is mathematically formulated by

$$\mathbf{R}^* = \arg\max_{\mathbf{R}} \left\{ \sum_{h=1}^{N_d} (r_d)_h \right\} \tag{9}$$

subject to constraints for $r \in \{r_v,\ r_d^1, \ldots, r_d^M\}$

$$\sum_{h=1}^{N_v+N_d} q_{i,h}(r) \le \widehat{Q}_i, \qquad 1 \le i \le N_b \tag{10}$$

$$q_{i,h}(r) \le \widehat{q}_i, \qquad i \in D_h, \tag{11}$$

and

$$\gamma_h(r) \ge \gamma^*(r), \qquad \forall\, h, \tag{12}$$

where $\widehat{Q}_i$ is the maximum value of total allocation power of cell i for SHOs, $\widehat{q}_i$ is the upper bound of the PA to SHO user h from cell i, and N_b is the numbers of BTSs in the system. We propose a novel JPRA algorithm to efficiently solve the above optimization problem. The JPRA algorithm is mainly composed of the LPPA scheme, which determines all possible $q_{i,h}(r)$ under the constraints of (11) and (12), and the ECRA method, which searches for $\mathbf{R}^*$ of (9) under the constraint of (10). In this joint PA and RA for SHO users, power balancing can be accomplished among cells.

A. LPPA Scheme

The LPPA scheme is an iterative algorithm to determine the transmission power required for SHO user h, $q_h(r)$, and how much amount of $q_h(r)$ would be from cell i in its active set D_h, $q_{i,h}(r)$, under the constraint of the maximum link power, $\widehat{q}_i$, $i \in D_h$, as stated in (11). The resultant $q_{i,h}(r)$ is proportional to the link quality between the BTS $i \in D_h$ and the SHO user h [10]. That is, $q_{i,h}(r) = q_h(r) \times \varpi_{i,h}$, where $\varpi_{i,h}$ is the weighting factor of the required transmission power for the link between BTS i and user h. We set $\varpi_{i,h}$ by

$$\varpi_{i,h} = \frac{L_{i,h}}{\sum\limits_{i \in D_h} L_{i,h}}. \tag{13}$$

Basically, the link proportional strategy for PA is to let the active link with better link quality contribute more power than those with weaker link qualities. If the required transmission power of one link violates the constraint of the maximum link power, LPPA will compensate the required power through other links by using an iterative method to redistribute $q_h(r)$ to all serving BTSs to satisfy the required signal quality. The iteration is to try to accomplish the power balance among mixed-size cells. Also, the resultant signal quality of user h with service rate r should not be less than its required signal quality $\gamma_h^*(r)$, as stated in (12); otherwise, the $q_h(r)$ should be adjusted by a tuning factor ϕ_h, which is given by

$$\phi_h = \frac{\gamma_h^*(r)}{\gamma_h(r)}. \tag{14}$$

Besides, it is noteworthy that due to the constraint of the maximum link power, there exists a forced termination situation for SHO whenever SHO users cannot obtain the required signal quality even though all active links are allocated with maximum link power. If the SHO user is forced to be terminated, $q_{i,h}(r)$ of each link i in active set D_h is reset to zero. We have proven that the LPPA scheme is convergent in [10].

Here, the LPPA scheme will calculate all PA combinations of $q_{i,h}(r)$, $1 \le h \le N_v + N_d$, $1 \le i \le N_b$ and $r \in \{r_v, r_d^1, \ldots, r_d^M\}$, for the joint PA and RA problem described in (9)–(12). Here, only the determination of $q_{i,h}(r)$ for an arbitrary SHO user h with rate $r \in \{r_d^1, \ldots, r_d^M\}$ is stated. In the following, we brief the LPPA scheme, and the details can be found in [11].

```
[The LPPA Scheme]
Step 0: [Initialize service rate $r$ for SHO user $h$]
  • IF SHO user $h$ is with voice service, THEN set $r = r_v$.
    ELSE Set $r = r_d^m$ and $m = 1$ for SHO user $h$ is with data service.
Step 1: [Exam the SHO feasibility]
  • Set $\phi_h = 1.0$.
  • Allocate maximum link power $\widehat{q}_i$ for each active links $i$.
  • Calculate received signal quality $\gamma_h(r)$ based on (2), (3).
  • IF $\gamma_h(r) > \gamma^*(r)$, THEN goto Step 2.
    ELSE IF $\gamma_h(r) = \gamma^*(r)$,
        THEN set $q_{i,h}(r) = \widehat{q}_i$, $i \in D_h$, and goto Step 6.
    ELSE
        IF $r = r_v$ or $r = r_d^1$,
        THEN SHO user $h$ is forced to terminate such that
                $q_{i,h}(r) = 0$, $i \in D_h$, DONE.
        ELSE goto Step 6.
Step 2: [Initialize power settings]
  • Initialize required transmission power $q_h(r)$ for SHO
    user $h$ by $q_h(r) = \sum_{i \in D_h} \widehat{q}_i$.
Step 3: [Calculate weighting factor $\varpi_{i,h}$]
  • Obtain weighting factor $\varpi_{i,h}$ for the transmission power
    from BTS $i$ in $D_h$ to SHO user $h$, based on $L_{i,h}$ by (13).
Step 4: [Calculate allocation power $q_{i,h}(r)$]
  • Determine the power that BTS $i$ in $D_h$ allocates to SHO
    user $h$, $q_{i,h}(r)$, by

    $q_{i,h}(r) = \min\{q_h(r) \times \varpi_{i,h},\ \widehat{q}_i\}, \quad \forall\, i \in D_h.$   (15)

Step 5: [Compute received $E_b/N_o$ and tuning factor $\phi_h$]
  • Compute the corresponding $\gamma_h(r)$ based on (2) and (3),
    and set tuning factor $\phi_h$ based on (14).
Step 6: [Check Stop Criterion]
  • IF $\phi_h \ne 1.0$,
        THEN let $q_h(r) = \phi_h \times q_h(r)$ and goto Step 2.
    ELSE
        IF $r \in r_d$ and $r \ne r_d^M$,
        THEN $m = m + 1$, $r = r_d^m$ and goto Step 1.
        ELSE DONE.
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B. ECRA Method

The ECRA method performs optimal RA for multirate SHO users based on the formulation in (9)–(12). It is found that even after we have reduced the complexity of the global optimization problem by taking care of joint PA and RA only for multirate SHO users, the computation time would still be a major concern for practical applications, particularly when there is a larger number of multirate SHO users being managed. Recall that there are N_d (N_v) SHO data (voice) users and M kinds of data service rate in the system. The LPPA scheme has determined the $q_{i,h}(r)$, $i \in D_h$ for $r = \{r_d^1, \ldots, r_d^M\}$ if HO data user and for $r = r_v$ if HO voice user, $1 \le h \le N_d + N_v$. The searching complexity is larger than $(M+1)^{N_d}$ by using exhaustive method, in which 1 means a zero service rate for suspending transmission. If N_d is 10 and M is 4, there are nearly 10^7 searching complexity. This is far beyond a reasonable computation time for feasible application. In this paper, an evolutionary computing algorithm [18], which is a promising intelligent technique to effectively search a global optimal solution, is adopted.

The evolutionary computing technique is a more advanced genetic algorithm; it uses stochastic searches to solve difficult optimization problems in real world through simulating natural genetic processes of living organisms, including selection, mutation, and crossover, to come up with better populations with better chromosomes generation by generation. It represents the service rate of each HO user as a chromosome, and a collection of chromosomes forms a population. Each population is regarded as the possible solution for the optimal RA of all HO data users. For M kinds of data service rates, each rate r_d is encoded into $\lfloor \log_2(M+1) \rfloor$ binary digits, denoted by chromosome x, and the decoder function for x is denoted by $s(x)$. Thus, for SHO data user h with service rate r_d, its corresponding allocation power is $q_h(s(x_h))$, in which the allocation power from active link i by the LPPA scheme is $q_{i,h}(s(x_h))$. Recall that r_v is the service rate for SHO voice users and $q_{i,h}(r_v)$ is the corresponding allocation power from active link i to SHO user h.

The ECRA method is to find an optimal RA vector (decision vector) for N_d multirate SHO users, $\mathbf{x}^* = [x_1^*, x_2^*, \ldots, x_{N_d}^*]$, by maximizing the objective function $O(\mathbf{x})$, which is defined to be the total throughput of SHO data users. We restate the optimization problem defined in (9) and (10) as

$$\mathbf{x}^* = \arg\max_{\mathbf{x}} \left\{ O(\mathbf{x}) \equiv \sum_{h=1}^{N_d} s(x_h) \right\} \tag{16}$$

subject to constraints

$$\sum_{h=1}^{N_v} q_{i,h}(r_v) + \sum_{h=1}^{N_d} q_{i,h}\left(s(x_h)\right) \leq \widehat{Q}_i, \qquad 1 \leq i \leq N_b. \tag{17}$$

Note that each $\mathbf{x}$ reveals different degree of the power balance among cells, and $\mathbf{x}^*$ in (16) is corresponding to $\mathbf{R}^* = [s(x_1^*), \ldots, s(x_{N_d}^*)]$ in (9). Because of the constraint, some decision vectors may be out of the feasible domain. A violation function is used to rank the violation degree of the decision vector [18]. The value of the violation function indicates how far the solution deviates from the feasible region. This constrained violation function is defined as

$$\Psi(\mathbf{x}) = \frac{\sum_{i=1}^{N_b} M_i \left[\sum_{h=1}^{N_v} q_{i,h}(r_v) + \sum_{h=1}^{N_d} q_{i,h}\left(s(x_h)\right)\right]^2}{2N_b} + \frac{\sum_{h=1}^{N_d} H_h \left[\gamma_h\left(s(x_h)\right)\right]^2}{2N_d} \tag{18}$$

where M_i and H_h are the Heaveside operators [18], in which $M_i[\cdot] = 1$ $\{H_h[\cdot] = 1\}$ whenever the constraint in (17) is violated, and $M_i[\cdot] = 0$ $\{H_h[\cdot] = 0\}$ otherwise. In the following, the ECRA method is described. Noticeably, the allocation powers for SHOs are corresponding to the ones obtained by the LPPA scheme.

```
[The ECRA method]
Step 1: [Initialize]
    • Set crossover rate $p_c$, mutation rate $p_u$, and maximum number of generations $T$.
    • Initialize generation $t = 1$, optimal objective value $O^* = 0$, and optimal decision vector $\mathbf{x}^* = \mathbf{0}$ (zero pattern).
    • Generate $K$ populations that are randomly selected decision vectors $\mathbf{x}_k = [x_1^k, \ldots, x_{N_d}^k]$, $1 \leq k \leq K$.
Step 2: [Execute constraint tournament selection to form $\mathbf{x}'_k$]
    • Choose $K$ tournament pairs randomly among $\mathbf{x}_k$, and calculate $\Psi(\mathbf{x}_k)$ (18) for each competitive pair.
    • Replace $\mathbf{x}_k$ with winner $\mathbf{x}'_k$ which has minimum $\Psi(\mathbf{x}_k)$.
Step 3: [Execute variable point crossover to form $\mathbf{x}''_k$]
    • Choose $K/2$ crossover pairs from adjacent population $\mathbf{x}'_k$ and $\mathbf{x}'_{k+1}$, where $k$ is odd.
    • Generate a random number $c$ in [0, 1] for each chromosome in each crossover pair.
    • For the chromosome with $c < p_c$, generate the crossover point randomly in $[1, \lfloor \log_2(M+1) \rfloor]$ and make the crossover operation within it.
Step 4: [Execute uniform mutation to form $\mathbf{x}'''_k$]
    • Generate a random number $u$ in [0, 1] for every bit in each population $\mathbf{x}'''_k$.
    • Mutate any bit with $u < p_u$.
Step 5: [Update $O^*$ and $\mathbf{x}^*$]
    • Find feasible populations $\{\mathbf{x}'''_k\}$ with $\Psi(\mathbf{x}'''_k) = 0$
    • Set $O^* = \max\{O(\mathbf{x}'''_k)\}$ and $\mathbf{x}^* = \arg_{\mathbf{x}'''_k} \max\{O(\mathbf{x}'''_k)\}$.
Step 6: [Check the stop criterion]
    • IF $t < T$, THEN Set $t = t + 1$, and Goto Step 2.
      ELSE DONE.
```

IV. SIMULATION RESULTS AND DISCUSSION

A. *Simulation Model*

Consider an example of mixed-size WCDMA cellular system with 12 wrapped around squared cells, including four microcells in the central congested region and eight macrocells in the neighboring cells [11]. The radii of macrocell and microcell are $R_M = 1$ km and $R_\mu = 1/2$ km, respectively; thus, the cell radius ratio between microcell and macrocell is $\rho = R_\mu / R_M = 1/2$. The antenna height of BTS in macrocell (microcell) are 20 (10) m, and the antenna height of mobile station is 1.5 m. For the propagation channel model, both pathloss and long-term shadowing are taken into account, in which two slope pathloss exponents are 2 and 4 dB, and the standard deviations of two slope shadowing are 4 and 8 dB [24]. Note that we also consider the cases of $\rho = 1$ and $\rho = 1/3$ in Fig. 8 to show the performance results versus different cell size ratios in mixed-size cell architecture. Furthermore, assume the bandwidth W is 4.096 MHz, and each cell utilizes the same frequency, in which the orthogonality factor is 0.5.

For the power budget design, $\widehat{P}_i$ for macrocell (microcell) i is 20 (10) watts, and $\widehat{q}_i$ of the macrocell (microcell) is 1 (0.5) watts. Here, η is 2 dB, and the maximum active set size is 3. In simulations, two cases of which there are without and with MEs during the active set selection are concerned. For the case with MEs, the received signal strength of each user is added an error signal that is Gaussian distributed random variable with zero mean and 1.5 dB standard deviation.

TABLE I
SERVICE CLASSES

Service (r_v and r_d)	r (kbps)	$\gamma^*(r)$(dB)	encoded x
Voice	12.2	5	N/A
Data	16	4	(0,0)
Data	32	3	(0,1)
Data	64	2	(1,1)
Data	144	1.5	(1,0)

Users are assumed to be uniformly distributed in each cell, and each user moves in a constant speed of 36 km/h. The probability of moving direction change for users is 0.2, and the range of each direction angle change is among ±45° [25]. By mobility, the correlated shadowing effect is based on Gudmundson model [26], in which the decorrelation length is equal to 20 m in a vehicular environment. Assume the shadowing factor will not be varied when the moving distance is less than 4 m and there are five averaging windows in each snapshot. For 36 km/h mobility speed, the correlated shadowing duration is 400 ms. Also, assume the allowable number of iteration for system operation is 40, and each iteration takes 1 frame time (10 ms). Performance measurements are averaged from 2000 independent instances of user location and shadowing, and each snapshot has five correlated instances. For parameters of the ECRA method in the JPRA algorithm, the supportable service classes and the corresponding codes for the ECRA method are listed in Table I. The population size K is 100, the crossover rate p_c is 0.5, the mutation rate p_m is 0.05, and the stop generation T is 20.

In simulations, each cell has the same numbers of voice and data users; thus, the central four microcells form a highly traffic congested region. Assume the number of voice users N_v is 30 and that of data users N_d ranges from 3 to 12 in each cell.

B. Results and Discussion

There are two essential performance measures investigated. One is the HO forced termination probability, which indicates the service continuity and the effectiveness of the cell's service coverage. It is evaluated by counting the proportion of SHO users that are terminated by the system due to insufficient power resource for SHOs temporarily. The other is the total throughput of the system, which is obtained by summing all allocated transmission rates of users, which represents the system capacity. Because of limited downlink power resources of one BTS, under various nonuniform traffic load situations, there exist tradeoffs between the cell's service coverage and the system capacity using different joint PA and RA schemes.

The proposed JPRA algorithm is compared with SSDT [8] and LPPA schemes with the best effort RA. The best effort RA is to assign HO users maximum allowable transmission rate which exists feasible PA solutions to satisfy the users' required quality of services. In order to achieve fair comparison for all schemes, the total power constraint of SHOs is confined to 0.3 times maximum transmission power of each BTS [27]. In simulations, we take the best effort rate allocation as the benchmark for comparisons, and denote SSDT and LPPA with the best effort RA by SSDT and LPPA, respectively.

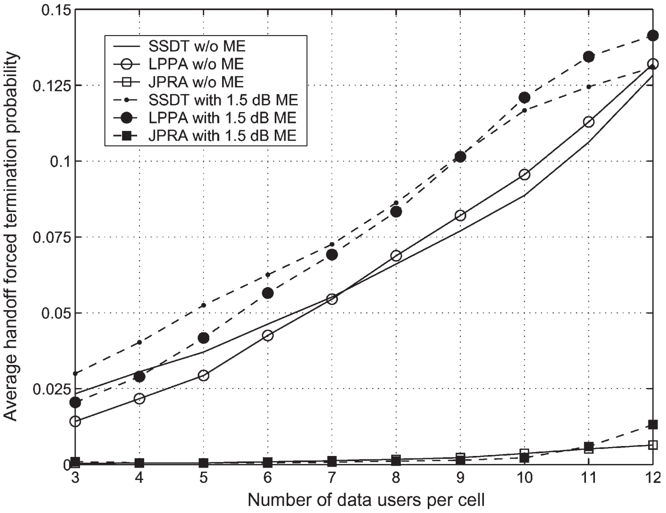


Fig. 3. Averaged forced termination probability of SHO without ME and with 1.5 dB ME.

Fig. 3 shows the average forced termination probability of SHO under different traffic loads. It can be seen that the HO forced termination probability of JPRA is much less than those of SSDT and LPPA schemes by over 300% and around 200%, respectively. It can be inferred that the significant gain of JPRA over LPPA comes from the RA for SHO by the ECRA method, and the gain of LPPA over SSDT comes from the PA strategy for SHO [10], [11]. The reasons are that the allowable transmission rates are highly correlated to the feasible PA solutions; RA for each SHO user directly affects the management of power resource in at least two BTSs; thus, an optimal RA for SHO users obtained by the ECRA method will further enhance the effect of power balance among cells.

Also, it can be seen that, when the traffic load is light, LPPA achieves less average forced termination probability of SHO than SSDT. When the traffic load is heavy, LPPA performs worse than SSDT. The reason is that higher interferences are induced by the multisite transmission mechanism than by the single-site transmission mechanism for HOs. The finite total power resource of the BTS may be insufficient to support more HO users at heavy load situations. Moreover, consider the case with ME during the active set selection. It is observed that MEs incur higher HO forced termination probabilities for all schemes because BTSs in active set waste more power on multirate HO users. Also, the superiority of JPRA over SSDT is increased up to around 500%. This is because the outstanding power balance characteristic of JPRA can release the effect of MEs. If the HO forced termination probability is regraded as the performance index of the cell's service coverage, in which smaller HO forced termination probability means better cell coverage, JPRA achieves better cell's service coverage than SSDT and LPPA. JPRA indeed provides the superb power balance characteristic and optimal RA for multirate SHOs; thus, it cannot only provide better service continuity performance but also possess the capability of the resistance to MEs.

Fig. 4 shows the total HO throughput versus different number of data users. It is found that both LPPA and JPRA have higher throughput than SSDT because of the multisite transmission

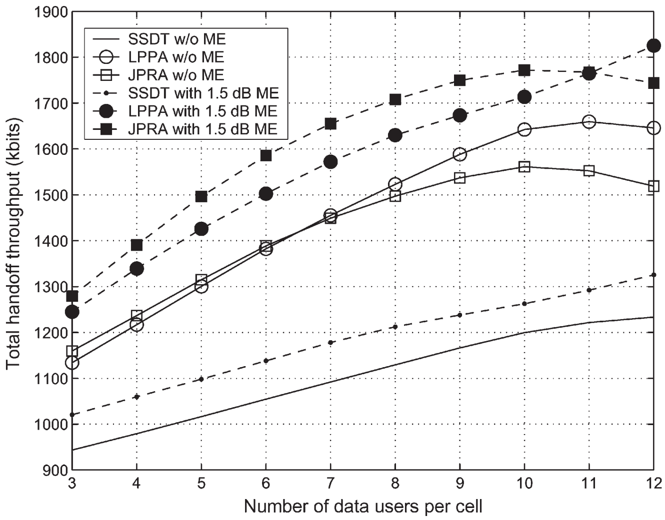


Fig. 4. Total handoff throughput versus the number of data users per cell without ME and with 1.5 dB ME.

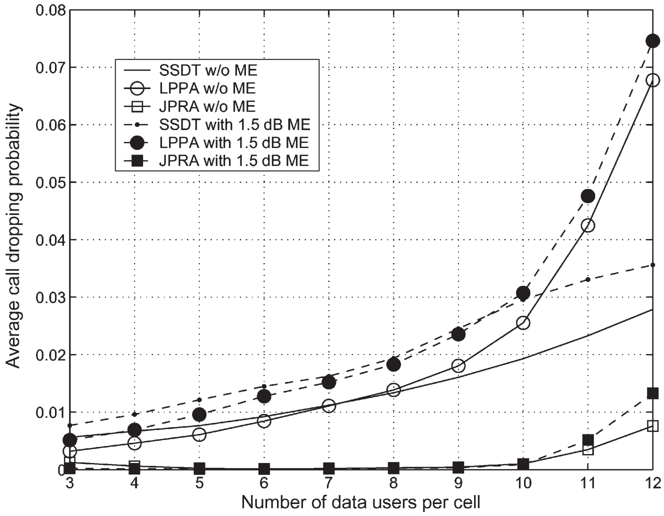


Fig. 5. Average call dropping probability versus the number of data users per cell without ME and with 1.5 dB ME.

mechanism, and JPRA achieves capacity gain over LPPA as in the aspect of the HO force termination probability shown in Fig. 3. The reason is that there exists a tradeoff between coverage and capacity for JPRA and LPPA schemes due to the total power constraint of SHOs. The ECRA method in the JPRA reduces the average transmission rate of multirate SHOs so as to accomplish better cell coverage while LPPA leads to more terminated HO users and, thus, higher HO throughput than JPRA. The similar results could be observed in the case of MEs. But, since higher HO forced termination probability in this case results in more power left for survived HO users to transmit with higher average transmission rates, the total HO throughput in the case of MEs is higher than those in the case of error free. In addition, we can see that the ECRA method in JPRA plays an important role to reduce performance degradation by MEs. This is because the ECRA method allocates optimal transmission rates for multirate SHOs to further balance power loads among cells. Therefore, JPRA successfully enhances cell's service coverage and HO throughput.

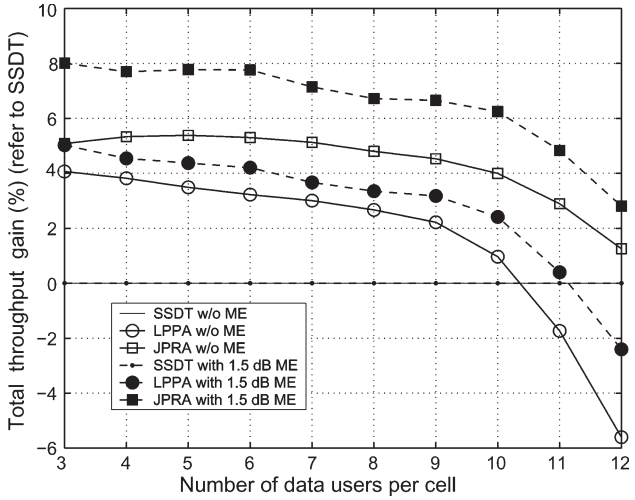


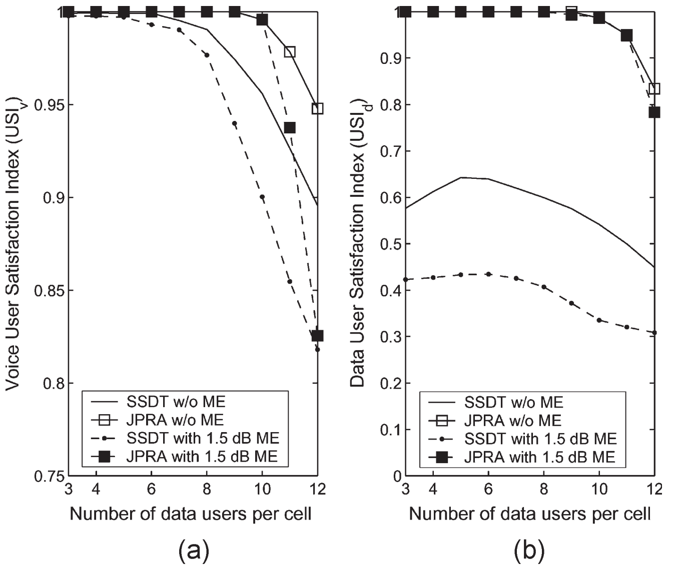
Fig. 6. Total system throughput gain versus the number of data users per cell without ME and with 1.5 dB ME.

Fig. 5 shows the average call dropping probability versus the number of data users. The call will be dropped when there is no feasible PA solution to support the user with its required service qualities for a period of time. When the required average call dropping probability is 0.01, JPRA (LPPA) can improve the average call dropping probability of all users by 71% (0%) and 200% (25%) without and with MEs, compared to SSDT. It is mainly because JPRA owns a better power balance characteristic via multirate SHO resulting from LPPA and ECRA. This optimal radio resource management can achieve an appropriate assignment among BTSs in the active set, preventing one BTS from using too much power resources to serve multirate SHOs. Thus, there would be more power resource preserved to serve NHO users.

Fig. 6 shows the total system throughput gain, referred to SSDT. We can see that JPRA (LPPA) can achieve a higher total system throughput than SSDT by 5% (3%) and 8% (4%) in the case of ME free and 1.5 dB MEs, respectively. The reasons are that the power balance characteristic of JPRA and LPPA schemes can aid the system to balance the power load more among cells, and the multisite transmission can support higher transmission rates for SHO users. JPRA indeed makes great improvements in cell's service coverage and system capacity because it can optimally allocate resource for multirate SHOs. However, it is found that when the number of data users gets larger, the gain gets worse. This is because the multisite transmission induces larger interference that results in the degradation of the system throughput.

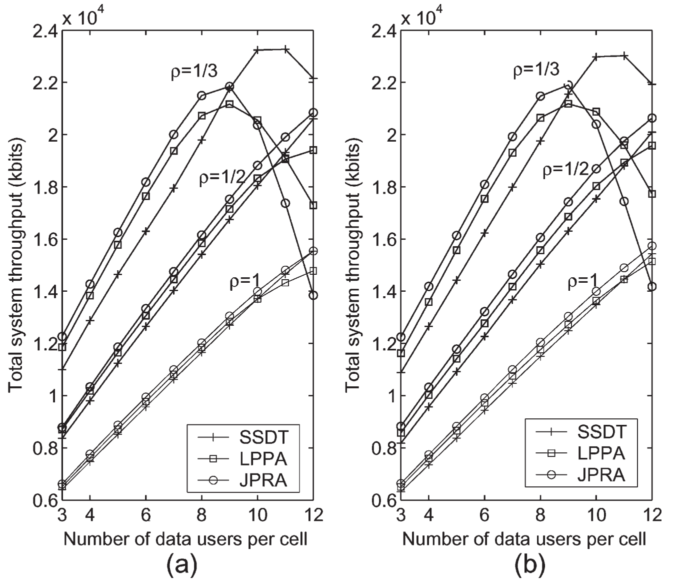
In the meantime, on the perspective of the user satisfaction, voice and data users should have different service requirements. Denote the call dropping probabilities of voice (data) users as $\mathbf{P}_v$ ($\mathbf{P}_d$). Also, the summation of allocated (requested) transmission rates of data users is represented by $\mathbf{R}_d$ ($\mathbf{R}_d^*$). Two USIs for voice and data services, denoted by USI_v and USI_d, respectively, are defined as

$$\begin{cases} \mathrm{USI}_v = \left(\mathbf{P}_v^* - \mathbf{P}_v\right)/\mathbf{P}_v^* \\ \mathrm{USI}_d = \kappa_d \times \mathbf{R}_d/\mathbf{R}_d^* + (1-\kappa_d) \times \left(\mathbf{P}_d^* - \mathbf{P}_d\right)/\mathbf{P}_d^* \end{cases} \tag{19}$$



(a) (b)

Fig. 7. USI versus the number of data users per cell for (a) USI of voice users (USI_v) and (b) USI of data users (USI_d), respectively.



(a) (b)

Fig. 8. Total system throughput for the SSDT, LPPA, and JPRA schemes under different cellular architecture in cell radius ratio $\rho = 1$, 1/2, and 1/3, with and without ME.

where κ_d is the weighting factor for the total throughput and call dropping probability of data users, and P_v^* (P_d^*) is the system requirement for voice (data) call dropping probability. Fig. 7(a) and (b) shows USI_v and USI_d versus the number of data users, respectively, where both $\mathbf{P}_v^*$ and $\mathbf{P}_d^*$ are set as 0.05, and assume κ_d is 0.7 because data users usually are satisfied with higher transmission rates and can tolerate longer transmission delay. It is shown that the proposed JPRA scheme can provide better USI_d, whereas it still could maintain good USI_v even when there exist MEs.

Fig. 8(a) and (b) shows the total system throughput for the SSDT, LPPA, and JPRA schemes under cell radius ratio $\rho = 1$, 1/2, and 1/3 with and without MEs, respectively. It is found that when the number of data users is smaller than nine, JPRA always achieves the highest total throughput for any cell radius ratio. In particular, for the mixed-size cellular system with smaller cell radio ratio, JPRA can achieve the capacity gain larger than the others because of its outstanding power balance characteristic. In the case of MEs, we can see that, compared to without ME case, JPRA has much higher gain of the system throughput than SSDT and LPPA. When the cell radius ratio is 1/3 and the number of data users is getting larger, the total system throughput of the multisite transmission schemes, LPPA and JPRA, is degraded severely. This is because multisite transmission schemes for HO users may cause large interference in the highly congested mixed-size WCDMA cellular system. Also, when the system is overloaded and exceeds predetermined power budget, in order to release some power load and preserve users' required signal quality as much as possible, JPRA adjusts the transmission rates of the SHO data users aggressively. But, LPPA cannot respond to the variation of the interference promptly due to the lack of rate adaptation function. The LPPA has decrement rate of system throughput less than JPRA. On the other hand, SSDT is very suitable for applying to the highly congested environment with small cell radius ratio, 1/3 in this case, because the single-site transmission scheme induces less interference than other multisite transmission ones. However, based on the previous results from Figs. 3–7, SSDT gets the worst performance of USI_d for cell radius ratio of 1/2, in which USI_d is related to not only throughput but also call dropping probability for data users. In the case of cell radius of 1/3, although JPRA could not achieve better system throughput when the traffic load is highly congested, compared to SSDT, it can still achieve better USI_d because of smaller call dropping probability.

As for the searching complexity issue, it is defined as the number of operations for all searching patterns needed to come up with an optimal rate allocation for all multirate SHO users. In the case of the exhaustive search, the searching complexity is $(M+1)^{N_d}$. In the case of the ECRA method, the searching complexity is given as $\lfloor \log_2(M+1) \rfloor \times K \times T \times N_d$, upper bounded by the multiplication of the length of populations, number of SHO data users N_d, population size K, and number of generation T. Note that M is the number of supportable service rates in the system. It can be found that when the number of multirate data users is larger than seven, the searching complexity of the exhaustive search grows exponentially. The ECRA method can efficiently reduce the searching complexity, compared to the exhaustive search.

V. CONCLUSION

In this paper, a JPRA algorithm is proposed to deal with multirate SHOs in WCDMA mixed-size cellular systems. It contains the LPPA scheme and the ECRA method. Compared to SSDT and LPPA schemes with best effort based RAs, simulation results show that JPRA accomplishes superior power balance among cells so that the JPRA algorithm can achieve better cell's service coverage and higher system capacity. Also, JPRA can offer greater user satisfaction for voice and data users. Furthermore, JPRA is less sensitive to MEs in the active set selection than SSDT with best effort rate allocation.

It is noteworthy that the aforementioned advantages of JPRA are more conspicuous in WCDMA mixed-size cellular systems with smaller cell radius ratio between microcell and macrocells. Also, the evolutionary computing algorithm is applied for the first time to solve the downlink resource optimization problem for SHO in this paper; the JPRA algorithm can efficiently reduce the complexity problem of downlink resource management and make real system implementation feasible.

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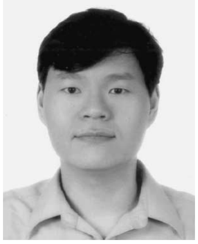

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