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Adaptive channel reservation for call admission control to support prioritized soft handoff calls in a cellular CDMA system

Kuo-Chung Chu · Lun-Ping Hung · Frank Yeong-Sung Lin

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Abstract This paper proposes a prioritized call admission control (CAC) model to support soft handoff calls with quality of service (QoS) assurances for both the uplink and downlink connections in a CDMA system. CAC is formulated as a combinatorial optimization problem in which the problem objective is to minimize the handoff forced termination rate. The model, which is based on the adaptive channel reservation (ACR) scheme for prioritized calls, adapts to changes in handoff traffic where the associated parameters (reserved channels, and new and handoff call arrival rates) can be varied. To solve the optimization model, iteration-based Lagrangean relaxation is applied by allocating a time budget. We express our achievements in terms of the problem formulation and performance improvement. Computational experiments demonstrate that the proposed ACR scheme outperforms other approaches when there are fewer rather than more channels, and it reduces the handoff call blocking rate more efficiently when the handoff traffic is heavily loaded. Moreover, the model can be adapted to any kind of reservation service.

K.-C. Chu (✉)
Department of Information Management,
National Taipei College of Nursing,
Taipei, Taiwan
e-mail: kcchu@ntcn.edu.tw

L.-P. Hung
Department of Information Management,
Technology and Science Institute of Northern Taiwan,
Taipei, Taiwan

F. Y.-S. Lin
Department of Information Management,
National Taiwan University,
Taipei, Taiwan

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1 Introduction

Demand for wireless communications and Internet applications continues to grow rapidly; hence, efficient call admission control is essential. The code division multiple access (CDMA) protocol, which provides a high-capacity mobile communications service, has the advantages of large-system capacity and soft handoff (SHO). Actually, handoff is an essential and complicated process in mobile cellular communication systems. Tripathi et al. [1] provide a comprehensive review of handoff approaches as well as the following related issues: (1) deployment scenarios, e.g., macro/micro cells; (2) resource management tasks, e.g., channel assignment and power control; (3) implementation protocols, e.g., network-controlled or mobile station (MS)-controlled protocols; and (4) evaluations, e.g., analytical and simulated approaches. In CDMA systems, SHO is so called to distinguish it from the conventional hard handoff (HHO) process. Wong and Lim [2] provide an overview of SHO, and consider the advantages and disadvantages of using SHO instead of HHO. They also discuss the tradeoff involved in selecting system parameters for the handoff process.

SHO is a characteristic of CDMA systems. By considering SHO when admitting a call request, an MS can maintain simultaneous connections with more than one base station (BS). MS is allocated a downlink channel at each BS, and the information transmitted on each channel is the same. Moreover, an MS combines diverse downlink paths, regardless of their origin. Therefore, SHO plays an important role in CDMA systems, as it enables MSs near the cell boundaries to use the same signals to transmit to, and receive from, more than one BS. By combining the signals from several BSs with macro-diversity, the signal to interference ratio (SIR) can be improved and thereby extend cell coverage. In this way, the communication quality, which is dependent on the SIR, can be enhanced, and the transition from one BS to another BS will be smoother than under conventional HHO. In [3], the proposed analytical model shows that SHO improves coverage by a factor of 2 to 2.5. To further investigate the characterization of SHO, some researchers have focused on how the SHO region affects system performance [4–6]. A simple result indicates that the larger the SHO region, the better MSs in the cellular network will function [5]. A much more extensive study in [6] examines the relation between the handoff call attempt rate and the channel holding time. The performance is evaluated as a function of the size of the SHO region and the overlap ratio of the region, as well as the mean cell residual time. Sectorized CDMA systems employ another kind of SHO called softer handoff, which is a handoff process between two sectors in the same cell under a non-ideal antenna radiation pattern. The overlapping of the sector antenna patterns causes additional interference, and the sectorization gain is smaller than the number of sectors [7, 8].

In a SHO zone, MS applies maximum ratio combining (MRC) of the contributions from involved BSs, such that the addition of energy-to-interference coming from those BSs must be larger than a target value at MS. The diversity gain for MSs must be considered. Two assumptions are possible to represent the handoff gain, they are the features of UMTS [9] and have been widely applied [4, 10–12]: (1) the transmission power signal from each involved BS is the same. If an MS is in a handoff zone in which two BSs (BS 1 and BS 2) are involved, under SHO, the first assumption implies that the transmitted power signal from BS 1 to the MS is same as the power signal from BS 2 to the MS. This is because the MS is equipped with a Rake receiver capable of performing MRC of the signals it receives from the transmitting BSs; (2) the energy-to-interference contributions from involved BSs are the same. They are used to simplify the modeling of the MRC mechanism and have been widely applied [4, 9, 13]. We denote Λ as the SHO factor (SHOF), which is the number of BSs involved in the SHO process for an MS. With perfect power control, the transmitted power from BS to MS should be proportional to the interference, and the power can be adjusted so that it has the same shape as the total interference. Specifically, the mechanism of power adjustment changes the power as the level of interference changes; therefore, the power will be high if there is a large amount of interference.

Handoff is an essential process, because of rejection of a SHO request results in forced termination of an ongoing service. A number of channel reservation approaches have been proposed to reduce the blocking of handoff calls [14–16]. However, they focus on general cellular mobile networks, not CDMA systems. In [14], for example, prioritized channel allocation methods are presented only for a single-cell system and one cluster of a multi-cell system. Baccelli et al. [17] propose admission control-based capacity analysis in terms of CDMA system load, the aim of the analysis is to maximize the system capacity that users are served at a given bit rate, or to offer users with maximal bit rate that the number of user is given. In [17], stochastic geometry was used to prove that the admission control algorithms provide scalability for large network. Stochastic geometry is also a powerful tool applied in [18]. However, the capacity analysis [17] is only focused on downlink. In general, jointly analyzing the downlink (DL) and the uplink (UL) with maximal power constraints will be more realistic.

The call admission control (CAC) problem in CDMA systems has been discussed from the perspective of UL analysis [19–24], while Elayoubi et al. [23] proposed measurement-based CAC approach to manage priorities between handoff and new calls. In [20, 24], for example, they consider channel reservation for handoff calls, and reserve a fixed number of channels at each BS. Generally, these methods give priority to handoff calls over new calls under the so-called cutoff priority scheme (CPS), and do not adapt to changes in the handoff traffic. Complete sharing scheme (CSS) [22] is the simplest way to give priority to handoff calls and reserve some channels for calls being handed off into the cell. The CSS allows each traffic class to access all channels; although it utilizes available channels efficiently, it cannot guarantee quality of service (QoS) for each class. To reduce the blocking of handoff calls, the CPS [20, 24], where some channels in each cell are reserved for handoff calls, is used to avoid unnecessary blocking of such calls. The remaining channels are shared by both handoff and new calls. This scheme, however, fails to guarantee new call the prescribed level of QoS, but it always keeps some of the available channels for the exclusive use of handoff calls. These channels are called *guard channels*. We assume there are C channels in a cell and g channels are reserved for handoff calls. Other C–g channels are assigned to both handoff and new calls, they are called *ordinary channels*. Actually, the channel utilization can be maximized if the number of guard channels is dynamically allocated under various handoff loads. However, the CAC schemes proposed in those articles above are not dynamic guard channel (DGC).

In contrast to [20, 24], Haung and Ho [16] proposed a distributed call admission algorithm that offers DGC for personal communication service (PCS) network, where the parameters (e.g., number of channels, new and handoff call arrival rates) of cells can be varied. The algorithm adapts the number of guard channels in each BS according to the estimate of the handoff call arrival rate, and is based on the moveable boundary scheme that dynamically adjusts the number of channels for different types of traffic. They considered traditional PCS networks, which are different from CDMA-based networks. Actually, the definitions on channel, QoS, interference model, and handoff for CDMA are different from traditional systems, such as 2G and 2.5G. In CDMA systems, multi-access interference is a function of the number of users and is a limiting factor in ensuring QoS. The CAC mechanism relies on the “soft capacity”, as determined by the level of multi-access interference, and is often characterized by the SIR. The interferences are comprised of inter- and intra-cellular interferences as well as background noises. The MSs served by neighboring cells generate inter-cellular interference, while active MSs in the coverage area generate intra-cellular interference. This situation requires that the interference caused by BS must be lower than pre-defined threshold to ensure communication QoS. Because the capacity of CDMA systems is bounded by interference, a key issue of capacity management relates to how an interference model is defined. An overview of SHO is given in [2]; SHO-based CAC is different from HHO-based CAC. Huang and Ho’s approach is not directly applicable to CDMA.

Nasri and Altman [25] focused on the SHO that is dedicated in CDMA-based systems. They proposed a fuzzy logic controller for dynamically controlling SHO parameters; the controller translates human linguistic rules into simple mathematical equations. Using the Q-learning algorithm is to adapt the controller to any network situation. Even the controller continually learns the best parameterization in each network situation; readers cannot understand how the proposed mechanism outperforms existing approaches. In this paper, we consider the prioritized channel allocation problem in general multi-cell environments, which is to minimize the weighted average blocking rate of handoff calls while satisfying the pre-specified grade of service (GOS) for new calls and the co-channel interference constraints. Our paper focuses on optimal channel allocation under various network loads. We propose an adaptive channel reservation (ACR) scheme for prioritized SHO calls with QoS assurance (i.e., the SIR requirement). In addition to proposing ACR scheme, we make comprehensive comparisons to show that the proposed scheme outperforms existing channel allocation approaches. For simplicity, in our experiments, we focus on voice call requests to optimize the handoff call performance. To manage the system performance effectively, Lagrangean relaxation approach and the subgradient-based method are applied.

The remainder of this paper is organized as follows. In Section 2, we review the background of CDMA CAC, including the SIR models, performance metrics, and the problem formulation. The solution approach for the proposed model is described in Section 3. Section 4 contains the results of our computational experiments and a sensitivity analysis. Finally, in Section 5, we summarize our findings.

2 ACR-based CAC

2.1 SIR model

In a CDMA environment, all users communicate at the same time and on the same frequency, so each user’s transmission power is regarded as a part of the other users’ interference. Thus, CDMA is a kind of power-constrained or interference-limited system. With perfect power control and an interference-dominated system, we can ignore background noise. As shown in Fig. 1, we consider the SIR in terms of the UL interference and the DL interference caused by signals transmitted from MS to BS and from BS to MS respectively.

Let W^{UL} (W^{DL}) be the system bandwidth and d^{UL} (d^{UL}) be the traffic data rate for the UL (resp. DL); and let z_{jt}^{N} and $z_{jt}^{H}\left(z_{jt}=z_{jt}^{N}+z_{jt}^{H}\right)$ be the decision variables of new and handoff calls, respectively. Both variables are 1 if BS j admits MS t ($t \in T$, T is MS set), and 0 otherwise. We assume that the UL power is perfectly controlled, which ensures that the power received at BS j is the same (constant value) for all MSs in the same traffic class-c. Denote $P_{c(t)}^{\mathrm{UL}}$ as the UL power signal received at a BS from MS t in traffic class-$c(t)$; and denote D_{jt} as the distance from MS t to BS j. The received SIR, $\mathrm{SIR}_{j,c(t)}^{\mathrm{UL}}$ of the UL is given by Eq. 1, where θ^{UL} is the UL orthogonality factor and $\alpha_{c(t)}^{\mathrm{UL}}$ is the UL activity factor of traffic class-$c(t)$; the given attenuation factor τ=4. The UL processing gain is given by $G^{\mathrm{UL}}=W^{\mathrm{UL}}/d^{\mathrm{UL}}$. The first and second terms of the denominator in Eq. 1 represent the intra- and inter-cell interference, respectively. A very large artificial constant value V in the numerator is used to satisfy the SIR constraint. For MS t to be admitted by BS j (z_{jt}=1), the SIR value must be larger than a pre-defined threshold, i.e., bit energy-to-noise ratio (BENR). If MS t is rejected (z_{jt}=0), the constraint BENR≦SIR can be ignored, where $V>>P_{c(t)}^{\mathrm{UL}}$, $V>>P_{c(t)}^{\mathrm{DL}}$. For example, in the direction of the UL in Eq. 1, if MS t is to be admitted by BS j (z_{jt}=1), the SIR value $\mathrm{SIR}_{j,c(t)}^{\mathrm{UL}}$ is calculated to determine whether the SIR constraint is satisfied. In the scenario

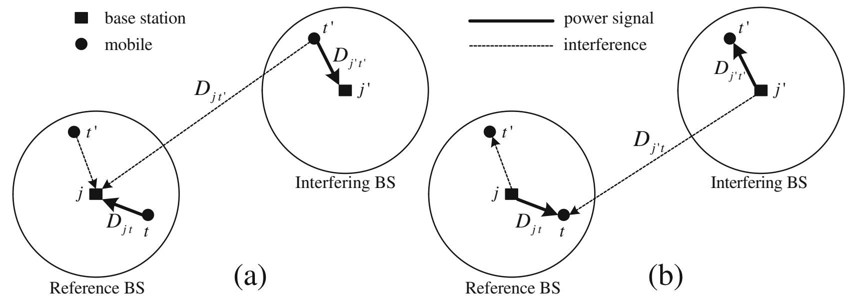


Fig. 1 An interference scenario: **a** UL interference; **b** DL interference

where MS t (z_{jt}=0) is ejected, the SIR value is always larger than BENR (BENR<<SIR) because the value V is a dominant; therefore, $\mathrm{SIR}^{\mathrm{UL}}_{j,c(t)}$ is calculated with a very large value. This implies that the constraint BENR≦SIR can be ignored because the constraint is always satisfied.

$$\mathrm{SIR}^{\mathrm{UL}}_{j,c(t)} = \frac{W^{\mathrm{UL}}}{d^{\mathrm{UL}}_{c(t)}} \frac{P^{\mathrm{UL}}_{c(t)} + \left(1 - z_{jt}\right)V}{\left(1-\theta^{\mathrm{UL}}\right)\left(\sum_{\substack{t'\in T\\ t'\neq t}} \alpha^{\mathrm{UL}}_{c(t')} P^{\mathrm{UL}}_{c(t')} z_{jt'}\right) + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{t'\in T\\ t'\neq t}} \alpha^{\mathrm{UL}}_{c(t')} P^{\mathrm{UL}}_{c(t')} \left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau} z_{j't'}} \tag{1}$$

In the DL case, the notations used are similar to those in the UL model. Applying the SHOF $\Lambda_t = \sum_{j\in B} \delta^{H}_{jt}$, where δ^{H}_{jt} is an indicator function if MS t is in the SHO zone of BS j and perfect DL power control is assumed, the received SIR, $\mathrm{SIR}^{\mathrm{DL}}_{j,c(t)}$, of the DL is given by (2).

$$SIR^{\mathrm{DL}}_{j,c(t)} = \frac{W^{\mathrm{DL}}}{d^{\mathrm{DL}}_{c(t)}} \frac{\Lambda_t P^{\mathrm{DL}}_{c(t)} + \left(1 - z_{jt}\right)V}{\left(1-\theta^{\mathrm{DL}}\right) \sum_{\substack{t'\in T\\ t'\neq t}} \alpha^{\mathrm{DL}}_{c(t')} P^{\mathrm{DL}}_{c(t')} \left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} z_{jt'} + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{t'\in T\\ t'\neq t}} \alpha^{\mathrm{DL}}_{c(t')} P^{\mathrm{DL}}_{c(t')} \left(\frac{D_{j't'}}{D_{j't}}\right)^{\tau} z_{j't'}} \tag{2}$$

2.2 CAC architecture and performance measure

Rejection of a SHO request results in forced termination of the current service. In [20, 24], the authors consider channel reservation approaches for handoff calls under the CPS. Generally, these approaches give priority to handoff calls over new calls, but they do not adapt to changes in the handoff traffic, i.e., adaptive channel reservation. Although Haung and Ho [16] propose a DGC approach that adapts the number of guard channels in each BS according to the estimate of the handoff call arrival rate, CDMA CAC is not considered. Because the MRC mechanism is applied in the SHO zone, in this section, we present a system architecture that supports prioritized CAC in CDMA systems.

As an MS in the SHO zone applies MRC contributions from the involved BSs, the BENR addition of those BSs must be larger than the target value of MS. The diversity gain of MSs in the SHO zone must also be taken into account. With perfect power control, on the UL, the power $P^{\mathrm{UL}}_{c(t)}$ received at BS j from MS t in traffic class-$c(t)$ can be adjusted to be a constant value. Specifically, the power adjustment factor changes the power transmitted from MS so that the power level will be high if there is a large amount of interference. The situation is similar on the DL, where the strength of the power signal received at MS from BS maintains a constant value. To better understand the prioritized CAC model, related notations are detailed in Table 1.

For each BS j, denote $\lambda_j = \lambda_j^N + \lambda_j^H$ as the total arrival rate in a Poisson distribution, where λ_j^N and λ_j^H are the arrival rates for new and handoff calls, respectively. In BS j, denote g_j^N as the traffic intensity of admitted new calls and g_j^H as the traffic intensity of handoff calls. To assess the effect of traffic intensity on the performance analysis, we denote ξ_j as the ratio of g_j^N to g_j^H in BS j. Figure 2 shows the prioritized CAC architecture for each BS, where the CAC is manipulated based on SIR evaluation and the ACR scheme. The proposed approach adaptively reserves channels for prioritized handoff calls. It not only reserves a different number of channels for each BS in terms of the traffic load on a BS, but also provides runtime channel

Table 1 The notations for the prioritized CAC model

Notation	Description
λ_j^N/λ_j^H	Mean arrival rate of new/handoff calls in a Poisson process
ξ_j	Ratio of g_j^N to g_j^H in BS j
β_j	Threshold of call blocking probability (CBP) for new MS call requests in BS j
Ω_j/Φ_j	Threshold of service rate for new/handoff calls in BS j
Λ_t	SHOF, which is the number of BSs involved in the SHO process for MS t.
μ	Mean call holding time (in seconds) of call requests
F	The set of ratios for guard channels
M_j^o/M_j^g	The number of ordinary/guard channels in BS j
M_j	The upper bound (UB) on the number of available channels in BS j
u_j^N/u_j^H	The indicator function, which is 1 if MS t is a new/handoff call and covered by BS j; and 0 otherwise
w_j	The weight of the traffic load in BS j

reservation. The call blocking probabilities (CBP) of new and handoff calls in BS j are given by $\mathrm{BN}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right)$ and $BH_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right)$ [14, 15], defined in Eqs. 3 and 4, respectively, where $g_j = g_j^N + g_j^H$. Both equations are derived from a continuous-time Markov chain with birth–death process. Admitted traffic intensity (g_j^N and g_j^H) is a function of admission decision variable (z_j^N and z_j^H); the new call intensity is expressed by $g_j^N = \left(\sum_{t\in T} z_{jt}^N/\lambda_j^N\right)\cdot\left(\lambda_j^N/\mu\right) = \sum_{t\in T} z_{jt}^N/\mu$, while the handoff call intensity is expressed by $g_j^H = \left(\sum_{t\in T} z_{jt}^H/\lambda_j^H\right)\cdot\left(\lambda_j^H/\mu\right) = \sum_{t\in T} z_{jt}^H/\mu$.

Providing reserved channels for existing/ongoing calls is more important than admitting new call requests. If we give priority to new calls, the forced termination of existing calls would degrade the service level. The ACR scheme is very useful since it gives priority to handoff requests. The adaptive reserved channels that dedicated for handoff calls, M_j^g $(=\lceil M_j \times f_j\rceil$, a ceiling function), among M_j channels available in BS j are referred to *guard channels*, where f_j is the reserved ratio of M_j that must be determined. The remaining $M_j^o\left(=M_j - M_j^g\right)$ channels, called *ordinary channels*, are shared by both new and handoff calls [15, 26]. When a new MS call attempt is generated by BS j, it is blocked if the number of free channels is less than or equal to M_j^g.

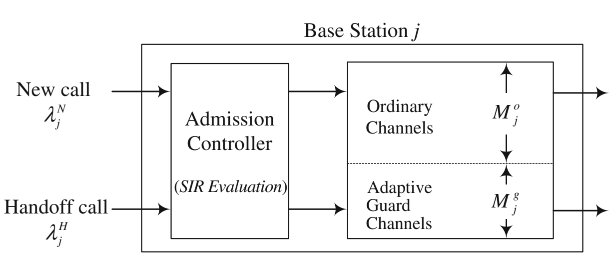


Fig. 2 A prioritized CAC architecture

$$\mathrm{BN}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) = \frac{(g_j)^{M_j^o}/M_j^o! + (g_j)^{M_j^o}\sum_{m=1}^{M_j^g}\left(g_j^H\right)^m/\left(M_j^o+m\right)}{\sum_{m=0}^{M_j^o}(g_j)^m/m! + (g_j)^{M_j^o}\sum_{m=1}^{M_j^g}\left(g_j^H\right)^m/\left(M_j^o+m\right)} \tag{3}$$

$$\mathrm{BH}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) = \frac{(g_j)^{M_j^o}\left(g_j^H\right)^{M_j^g}/\left(M_j^o+M_j^g\right)!}{\sum_{m=0}^{M_j^o}(g_j)^m/m! + (g_j)^{M_j^o}\sum_{m=1}^{M_j^g}\left(g_j^H\right)^m/\left(M_j^o+m\right)} \tag{4}$$

In this paper, we focus on voice traffic, which consists of new and handoff calls. It is assumed that the call holding time of both types of calls is exponentially distributed with mean μ. The locations of MSs are generated in a uniform distribution.

2.3 Adaptive channel reservation model

Capacity analysis by CAC has been conducted for the UL connection, as the non-orthogonality that leads to the limited capacity is in the UL [27]. However, asymmetric Internet traffic has increased, so power allocation on the DL is also an important issue. Theoretically, the capacity of the DL and the UL is not equal [28]; thus, analysis of both links is required under CAC.

In this section, we propose a prioritized CAC model, which adaptively reserves channels for SHO calls with QoS assurance of SIR requirements on both the UL and the DL. To differentiate a new call from a handoff call, we denote the calls as N and H, respectively. The two decision variables z_{jt}^N, z_{jt}^H are mutually exclusive, i.e., $z_{jt} = z_{jt}^N + z_{jt}^H$, where z_{jt}=0 or 1. Other decision variables are defined in Table 2. The objective function (P) is to minimize the weighted handoff call blocking rate (CBR). We denote CBR as Z_P, which is a product of weighted handoff CBP and admitted traffic intensity g^H. A weighted handoff CBP

Table 2 The decision variables of the ACR-based CAC model

Notation	Description
f_j	The ratio of reserved (or guard) channels to the total number of available channels
g_{jt}^N / g_{jt}^H	The aggregate (admitted) traffic intensity of new/handoff calls for BS j
z_{jt}^N	The value is 1 if MS t is a new call and admitted by BS j, and 0 otherwise
z_{jt}^H	The value is 1 if MS t is a handoff call and admitted by BS j, and 0 otherwise

(P_{WHB}) is defined in Eq. 5, where the weight is given by $w_j = g_j^H / \sum_{j\in B} g_j^H$.

$$P_{\text{WHB}} = \sum\nolimits_{j\in B} w_j \text{BH}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) \tag{5}$$

Objective function:

$$Z_{\text{P}} = \min \sum\nolimits_{j\in B} w_j g_j^H BH_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) \tag{P}$$

subject to:

$$\left(\frac{E_b}{N_{\text{total}}}\right)_{c(t)}^{\text{UL}} \leq \text{SIR}_{j,c(t)}^{\text{UL}} \qquad \forall j \in B, t \in T \tag{6}$$

$$\left(\frac{E_b}{N_{\text{total}}}\right)_{c(t)}^{\text{DL}} \leq \text{SIR}_{j,c(t)}^{\text{DL}} \qquad \forall j \in B, t \in T \tag{7}$$

$$\frac{\sum_{t\in T} z_{jt}^N}{\mu} = g_j^N \qquad \forall j \in B \tag{8}$$

$$\frac{\sum_{t\in T} z_{jt}^H}{\mu} = g_j^H \qquad \forall j \in B \tag{9}$$

$$z_{jt}^N D_{jt} \leq u_{jt}^N R_j \qquad \forall j \in B, t \in T \tag{10}$$

$$z_{jt}^H D_{jt} \leq u_{jt}^H R_j \qquad \forall j \in B, t \in T \tag{11}$$

$$z_{jt}^N + z_{jt}^H \leq 1 \qquad \forall j \in B, t \in T \tag{12}$$

$$z_{jt}^N \leq \left(1 - u_{jt'}^H\right) + z_{jt'}^H \qquad \forall j \in B, t, t' \in T, t \neq t' \tag{13}$$

$$\text{BN}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) \leq \beta_j \qquad \forall j \in B \tag{14}$$

$$\Omega_j \leq \frac{\sum\limits_{t\in T} z_j^N}{\sum\limits_{t\in T} u_j^N} \qquad \forall j \in B \tag{15}$$

$$\Phi_j \leq \frac{\sum\limits_{t\in T} z_j^H}{\sum\limits_{t\in T} u_j^H} \qquad \forall j \in B \tag{16}$$

$$M_j^o + M_j^g \leq M_j \qquad \forall j \in B \tag{17}$$

$$f_j \in F \qquad \forall j \in B \tag{18}$$

$$z_{jt}^N = 0 \text{ or } 1 \qquad \forall j \in B, t \in T \tag{19}$$

$$z_{jt}^H = 0 \text{ or } 1 \qquad \forall j \in B, t \in T \tag{20}$$

In a CDMA system, a BS with the required QoS on both the UL and the DL connections serves each traffic demand. For a UL connection with perfect power control, the SIR value $\text{SIR}_{j,c(t)}^{\text{UL}}$ defined in Eq. 1 must be greater than the predefined threshold $(E_b/N_{\text{total}})_{c(t)}^{\text{UL}}$, as shown in Constraint 6. Perfect power control is also assumed on the DL. For each call request of MS t in BS j, the threshold of the required QoS is $(E_b/N_{\text{total}})_{c(t)}^{\text{DL}}$, as shown in Constraint 7, where $\text{SIR}_{j,c(t)}^{\text{DL}}$ is defined in Eq. 2. Constraints 8 and 9 check the aggregate traffic intensity of new calls and handoff calls in BS j, based on all granting MSs. Constraints 10 and 11 require that MS t must be in the coverage area of a BS j with the transmission power radius R_j. Each call request z_{jt}=1 admitted under Constraint 12 must be either a new call $\left(z_{jt}^N = 1\right)$ or a handoff call $\left(z_{jt}^H = 1\right)$. Constraint 13 guarantees the priority of handoff calls. For each BS j, a new call $\left(z_{jt}^N\right)$ can only be accepted if all handoff calls $\left(z_{jt'}^H\right)$ have been admitted and if the new call initiates $\left(u_{jt}^H = 1\right)$, which is the indicator function if MS t initiates a call request to BS j; otherwise, z_{jt}^N is admitted directly if there are no more handoff calls to be admitted (i.e., $u_{jt}^H = 0$). Constraint 14 requires that each BS services new call requests under a pre-defined CBP threshold β_j. Constraints 15 and 16 stipulate that the service rate for new and handoff calls in BS j must be fulfilled. For channel reservation, all available channels are bounded by the value of M_j in Eq. 17. The decision variable f_j, which belongs to the discrete set $F=\{0.1, 0.2... 1.0\}$ in Constraint 18 is then applied. Constraints 19 and 20 enforce the integer property of the decision variables z_{jt}^N and z_{jt}^H, respectively.

3 Solution approach

3.1 Lagrangean relaxation

Lagrangean relaxation (LR) is a solution approach that solves mathematical optimization problems by decomposing them to exploit their special structures [29]. LR has the following significant advantages: (a) it is a very flexible approach that decomposes models in several ways, and then applies Lagrangean multipliers to each decomposition; (b) when decomposing a problem, it solves core subproblems as stand-alone models; (c) it permits users to set bounds on the value of the optimal objective function and quickly generate good optimal solutions with associated performance guarantees; and (d) it can be used to develop effective heuristic methods for solving complex combinatorial optimization problems. The steps of the LR method are as follows: relax complicating constraints, multiply the relaxed constraints by the corresponding Lagrangean multipliers, and then add them to the primal objective function. As a result, the primal optimization problem is transformed into an LR problem, which can be decomposed into several independent subproblems and solved optimally. To obtain optimal solutions, we must iteratively adjust the Lagrangean multipliers to optimally solve the Lagrangean dual problem. In addition, by calculating the multipliers in all procedures, sensitivity analysis of the associated constraints can be conducted. We discuss this aspect in Section 4.2.

3.2 Solution procedure

Based on the LR, the primal optimization problem (P) can be transformed into an LR problem (LR) in which Constraints 6–9 and 13 are relaxed.

$$
\begin{aligned}
Z_D\left(v_{jt}^1, v_{jt}^2, v_j^3, v_j^4, v_{jtt'}^5\right) = \min \sum\nolimits_{j\in B} w_j g_j^H BH_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) + \qquad \text{(LR)}\\
+\sum\nolimits_{j\in B}\sum\nolimits_{t\in T} v_{jt}^1 \Bigg(\left(\frac{E_b}{N_{total}}\right)_{c(t)}^{UL}\frac{1}{G_{c(t)}^{UL}}\Bigg[\left(1-\theta^{\mathrm{UL}}\right)\sum\nolimits_{\substack{t'\in T\\ t'\neq t}} \alpha_{c(t')}^{\mathrm{UL}} P_{c(t')}^{\mathrm{UL}} z_{jt'}\\
+\sum\nolimits_{\substack{j'\in B\\ j'\neq j}}\sum\nolimits_{\substack{t'\in T\\ t'\neq t}} \alpha_{c(t')}^{\mathrm{UL}} P_{c(t')}^{\mathrm{UL}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau} z_{j't'}\Bigg] - \left(P_{c(t)}^{\mathrm{UL}} + \left(1-z_{jt}\right)V\right)\Bigg)\\
+\sum\nolimits_{j\in B}\sum\nolimits_{t\in T} v_{jt}^2 \Bigg(\left(\frac{E_b}{N_{total}}\right)_{c(t)}^{\mathrm{DL}}\frac{1}{G_{c(t)}^{\mathrm{DL}}}\Bigg[\left(1-\theta^{\mathrm{DL}}\right)\sum\nolimits_{\substack{t'\in T\\ t'\neq t}} \alpha_{c(t')}^{\mathrm{DL}} P_{c(t')}^{\mathrm{DL}} \left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} z_{jt'}\\
+\sum\nolimits_{\substack{j'\in B\\ j'\neq j}}\sum\nolimits_{\substack{t'\in T\\ t'\neq t}} \alpha_{c(t')}^{DL} P_{c(t')}^{DL} \left(\frac{D_{j't'}}{D_{j't}}\right)^{\tau} z_{j't'}\Bigg] - \left(\Lambda_t P_{c(t)}^{DL} + \left(1-z_{jt}\right)V\right)\Bigg)\\
+\sum\nolimits_{j\in B} v_j^3\left(\lambda^N/\mu\sum\nolimits_{t\in T} z_{jt}^N - g_j^N\right) + \sum\nolimits_{j\in B} v_j^4\left(\lambda^H/\mu\sum\nolimits_{t\in T} z_{jt}^H - g_j^H\right)\\
+\sum\nolimits_{j\in B}\sum\nolimits_{t\in T}\sum\nolimits_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\left(z_{jt}^N - \left(\left(1-u_{jt'}^H\right) + z_{jt'}^H\right)\right),
\end{aligned}
$$

subject to: Eqs. 10, 11, 12, and 14–20.

To simplify the expression of the problem, we define the terms $A_{c(t)}^{\mathrm{dir}}$, B^{dir}, and $C_{c(t)}^{\mathrm{dir}}$ in 21, 22, and 23, respectively, where dir means the UL and the DL connections. That is, the (LR) problem is reduced to a (LR′) problem as follows:

$$A_{c(t)}^{\mathrm{dir}} = \left(\frac{E_b}{N_{total}}\right)_{c(t)}^{\mathrm{dir}}\frac{1}{G_{c(t)}^{\mathrm{dir}}} \tag{21}$$

$$B^{\mathrm{dir}} = \left(1-\theta^{\mathrm{dir}}\right) \tag{22}$$

$$C_{c(t)}^{\text{dir}} = \alpha_{c(t)}^{\text{dir}} P_{c(t)}^{\text{dir}} \tag{23}$$

$$\begin{aligned}
Z_D\left(v_{jt}^1, v_{jt}^2, v_j^3, v_j^4, v_{jtt'}^5\right) = \min \textstyle\sum_{j\in B} w_j g_j^H BH_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) + \sum_{j\in B}\sum_{t\in T} v_{jt}^1 \Bigg(A_{c(t)}^{\text{UL}} \Bigg[B^{UL} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{UL}} (z_{jt'}^N + z_{jt'}^H) \\
+ \textstyle\sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{UL}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^\tau \left(z_{j't'}^N + z_{j't'}^H\right)\Bigg] - \left(P_{c(t)}^{\text{UL}} + \left(1 - \left(z_{jt}^N + z_{jt}^H\right)\right)V\right)\Bigg) \\
+ \textstyle\sum_{j\in B}\sum_{t\in T} v_{jt}^2 \Bigg(A_{c(t)}^{\text{DL}} \Bigg[B^{DL} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{DL}} \left(\frac{D_{jt'}}{D_{jt}}\right)^\tau \left(z_{jt'}^N + z_{jt'}^H\right) \\
+ \textstyle\sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{DL}} \left(\frac{D_{j't'}}{D_{j't}}\right)^\tau \left(z_{j't'}^N + z_{j't'}^H\right)\Bigg] - \left(\Lambda_t P_{c(t)}^{\text{DL}} + \left(1 - \left(z_{jt}^N + z_{jt}^H\right)\right)V\right)\Bigg) \\
+ \textstyle\sum_{j\in B} v_j^3 \left(\lambda^N/\mu \sum_{t\in T} z_{jt}^N - g_j^N\right) + \sum_{j\in B} v_j^4 \left(\lambda^H/\mu \sum_{t\in T} z_{jt}^H - g_j^H\right) \\
+ \textstyle\sum_{j\in B}\sum_{t\in T}\sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5 \left(z_{jt}^N - \left(\left(1 - u_{jt'}^H\right) + z_{jt'}^H\right)\right),
\end{aligned} \tag{LR$'$}$$

subject to: Eqs. 10, 11, 12, and 14–20.

Furthermore, the (LR′) problem can be rewritten in terms of (LR′-1), (LR′-2), and (LR′-3), where (LR′-1) and (LR′-2) are associated with decision variables $\left(z_{jt}^N, z_{jt}^H\right)$ and $\left(g_{jt}^N, g_{jt}^H\right)$, respectively. As the term (LR′-3) is not related to the decision variables, it can be calculated first. It is not part of the procedure for optimally solving the problem (LR′), so we drop it and add it back after solving the other subproblems. The (LR′) problem is therefore decomposed into two independent subproblems (SUB 1) and (SUB 2) related to the above decision variables, both of which can be optimally solved by the respective algorithms.

$$\begin{aligned}
Z_D\left(v_{jt}^1, v_{jt}^2, v_j^3, v_j^4, v_{jtt'}^5\right) = \min \sum_{j\in B} w_j g_j^H \text{BH}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) \\
+ \sum_{j\in B}\sum_{t\in T} z_{jt}^N \Bigg[v_{jt}^1 A_{c(t)}^{\text{UL}} B^{\text{UL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{UL}} \left(1 + \sum_{\substack{j'\in B\\ j'\neq j}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^\tau\right) \\
+ v_{jt}^2 A_{c(t)}^{\text{DL}} B^{\text{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^\tau + \sum_{\substack{j'\in B\\ j'\neq j}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^\tau\right) + V\left(v_{jt}^1 + v_{jt}^2\right) + v_j^3 \lambda^N/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\Bigg] \\
+ \sum_{j\in B}\sum_{t\in T} z_{jt}^H \Bigg[v_{jt}^1 A_{c(t)}^{\text{UL}} B^{\text{UL}} \sum_{\substack{t\in T\\ t\neq t'}} C_{c(t')}^{\text{UL}} \left(1 + \sum_{\substack{j\in B\\ j\neq j'}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^\tau\right) \\
+ v_{jt}^2 A_{c(t)}^{\text{DL}} B^{\text{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\text{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^\tau + \sum_{\substack{j'\in B\\ j'\neq j}} \left(\frac{D_{j't'}}{D_{jt'}}\right)^\tau\right) + V\left(v_{jt}^1 + v_{jt}^2\right) + v_j^4 \lambda^H/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\Bigg]
\end{aligned} \tag{LR$'-1$}$$

$$-\sum_{j\in B}\left(v_j^3 g_j^N + v_j^4 g_j^H\right) \tag{LR$'-2$}$$

$$-\sum_{j\in B}\sum_{t\in T}\left[v_{jt}^1\left(P_{c(t)}^{\text{UL}} + V\right) + v_{jt}^2\left(\Lambda_t P_{c(t)}^{\text{DL}} + V\right)\right] + \sum_{j\in B}\sum_{t\in T}\sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\left(u_{jt'}^H - 1\right), \tag{LR$'-3$}$$

subject to: Eqs. 10, 11, 12, and 14–20.

Subproblem (SUB 1) related to decision variables z_{jt}^N, z_{jt}^H:

$$\begin{aligned}Z_{\mathrm{SUB1}} = \min \sum_{j\in B}\sum_{t\in T} z_{jt}^N \Bigg[v_{jt}^1 A_{c(t)}^{\mathrm{UL}} B^{\mathrm{UL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{UL}} \left(1+\sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) \\ + v_{jt}^2 A_{c(t)}^{\mathrm{DL}} B^{\mathrm{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} + \sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) + V\left(v_{jt}^1+v_{jt}^2\right) + v_j^3\lambda^N/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5 \Bigg] \\ + \sum_{j\in B}\sum_{t\in T} z_{jt}^H \Bigg[v_{jt}^1 A_{c(t)}^{\mathrm{UL}} B^{\mathrm{UL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{UL}} \left(1+\sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) \\ + v_{jt}^2 A_{c(t)}^{\mathrm{DL}} B^{\mathrm{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} + \sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) + V\left(v_{jt}^1+v_{jt}^2\right) + v_j^4\lambda^H/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5 \Bigg],\end{aligned} \quad \text{(SUB1)}$$

subject to: Eqs. 10, 11, 12, 19, and 20.

To differentiate a new call from a handoff call and solve this subproblem, let Coef_{jt}^N and Coef_{jt}^H be the coefficients of the decision variables z_{jt}^N and z_{jt}^H defined in Eqs. 24 and 25, respectively.

$$\begin{aligned}\mathrm{Coef}_{jt}^N = v_{jt}^1 A_{c(t)}^{\mathrm{UL}} B^{\mathrm{UL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{UL}} \left(1+\sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) + v_{jt}^2 A_{c(t)}^{\mathrm{DL}} B^{\mathrm{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} + \sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) \\ + V\left(v_{jt}^1+v_{jt}^2\right) + v_j^3\lambda^N/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\end{aligned} \quad (24)$$

$$\begin{aligned}\mathrm{Coef}_{jt}^H = v_{jt}^1 A_{c(t)}^{\mathrm{UL}} B^{\mathrm{UL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{UL}} \left(1+\sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) + v_{jt}^2 A_{c(t)}^{\mathrm{DL}} B^{\mathrm{DL}} \sum_{\substack{t'\in T\\ t'\neq t}} C_{c(t')}^{\mathrm{DL}} \left(\left(\frac{D_{jt'}}{D_{jt}}\right)^{\tau} + \sum_{\substack{j'\in B\\ j'\neq j}}\left(\frac{D_{j't'}}{D_{jt'}}\right)^{\tau}\right) \\ + V\left(v_{jt}^1+v_{jt}^2\right) + v_j^4\lambda^H/\mu + \sum_{\substack{t'\in T\\ t'\neq t}} v_{jtt'}^5\end{aligned} \quad (25)$$

To optimally solve (SUB 1), we decompose it into $|B|\times|T|$ subproblems, each of which solves decision variables z_{jt}^N and z_{jt}^H by checking Coef_{jt}^N and Coef_{jt}^H respectively. For each subproblem related to MS t in BS j, z_{jt}^N and z_{jt}^H are mutually exclusive because $z_{jt}^N + z_{jt}^H \leq 1$ is constrained by Eq. 12. If both Coef_{jt}^N and Coef_{jt}^H are less than or equal to zero, one of the decision variables will be assigned the value 1, depending on the indicator function u_{jt}. If, however, Coef_{jt}^N and Coef_{jt}^H are both greater than zero, both will be assigned the value 0. The four cases are summarized in Table 3.

Table 3 Four decision cases for new and handoff calls

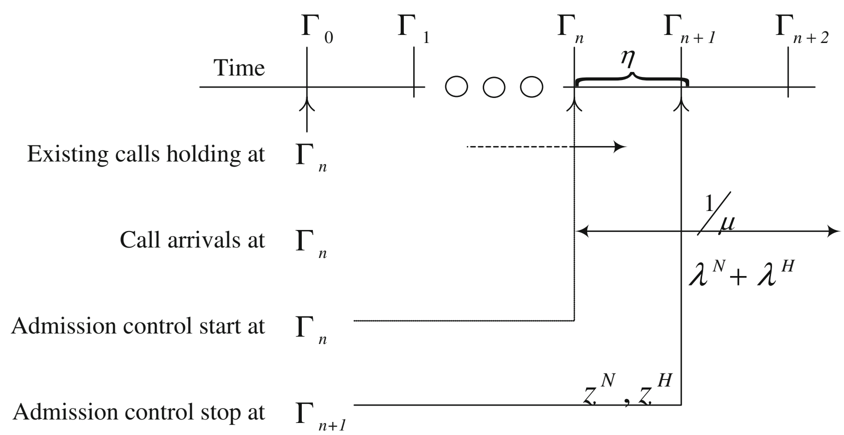
Case	If				Then	
	$Coef_{jt}^N$	$Coef_{jt}^H$	u_{jt}^N	u_{jt}^H	z_{jt}^N	z_{jt}^H
1	≤0	≤0	0	1	0	1
			1	0	1	0
2	≤0	>0	0	1	0	0
			1	0	1	0
3	>0	≤0	0	1	0	1
			1	0	0	0
4	>0	>0	0	1	0	0
			1	0	0	0

Subproblem (SUB 2) related to decision variables g_j^N, g_j^H, and f_j

Table 4 Adjustment rules for prioritized handoff call decisions

MS	t'		t	
BS	u_{jt}^N	z_{jt}^N	u_{jt}^H	z_{jt}^H
j	0/1	0/1	0	0
	0/1	0	1	0
	0/1	0/1	1	1

Fig. 3 The timing diagram of prioritized CAC



$$Z_{\mathrm{SUB2}} = \min \sum_{j\in B}\left(w_j g_j^H \mathrm{BH}_j\left(g_j^N, g_j^H, M_j^o, M_j^g\right) - \left(v_j^3 g_j^N + v_j^4 g_j^H\right)\right), \tag{SUB2}$$

subject to: Eqs. 14, 15, 16, 17, 18, and

$$\underline{g_j^N} \le g_j^N \le \overline{g_j^N} \qquad \forall j \in B,\ g_j^N \in \mathrm{GS}_j^N \tag{26}$$

$$\underline{g_j^H} \le g_j^H \le \overline{g_j^H} \qquad \forall j \in B,\ g_j^H \in \mathrm{GS}_j^H \tag{27}$$

The goal of (SUB 2) is to reserve channels for prioritized handoff calls such that the weighted CBR of the calls can be minimized. The decision variable f_j is the ratio of reserved channels to the total number of channels (M_j); and the decision variables g_j^N and g_j^H are the admitted traffic intensity in BS j for new and handoff calls, respectively.

They are limited by the discrete set $\mathrm{GS}_j^N = \left\{\underline{g_j^N},\ g_j^N + 1/\mu,\ g_j^N + 2/\mu,\ \ldots.\ \overline{g_j^N} - 1/\mu,\ \overline{g_j^N}\right\}$, $\mathrm{GS}_j^H = \left\{\underline{g_j^H},\ g_j^H + 1/\mu,\ g_j^H + 2/\mu,\ \ldots.\ \overline{g_j^H} - 1/\mu,\ \overline{g_j^H}\right\}$. Thus, Constraints 26 and 27 are introduced to solve this subproblem effectively. (SUB 2) is further decomposed into $|B|$ subproblems, one for each BS j. We then exhaustively search combinations of the sets GS_j^N, GS_j^H, and F to calculate the minimal value of Z_{SUB2}.

In summary, we transform the problem (P) into a dual problem (D) by multiplying the relaxed constraints by the corresponding Lagrangean multipliers $v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5$, and adding the modified constraints to the primal objective function. According to the weak Lagrangean duality theorem, for any $v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5 \ge 0$, the objective value of $Z_D\left(v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5\right)$ is a lower bound (LB) of the weighted handoff CBR (Z_{P}). Thus, the following dual problem (D) is constructed to calculate the tightest LB by adjusting the multipliers.

$$Z_D = \max Z_D\left(v_{jt}^1, v_{jt}^2, v_j^3, v_j^4, v_{jtt'}^5\right), \tag{D}$$

subject to: $v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5 \ge 0$.

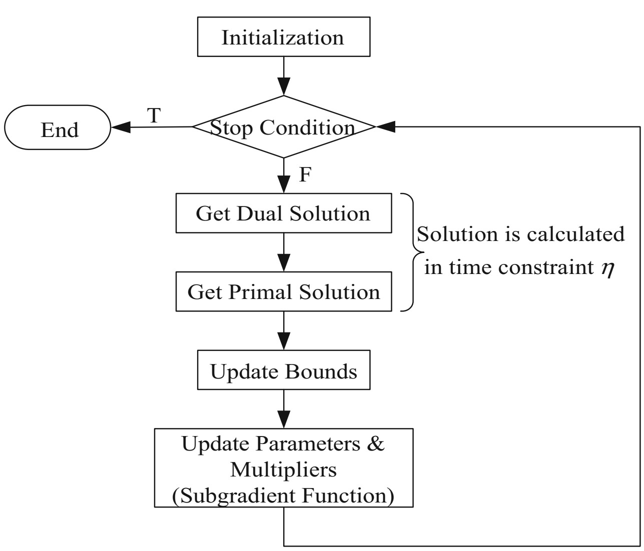


Fig. 4 Procedure of Lagrangean relaxation-based CAC

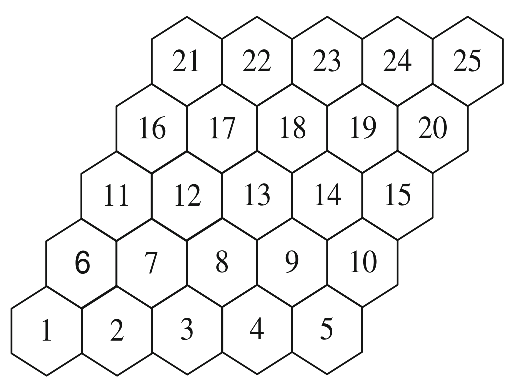
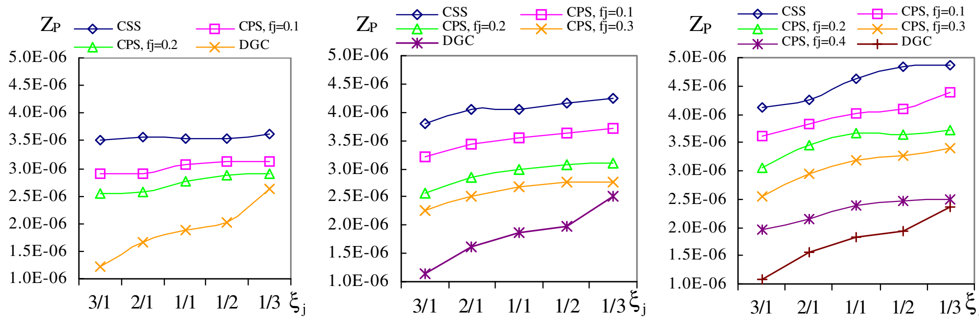


Fig. 5 The structure of a cellular system

Fig. 6 Effect of traffic loads on Z_P



(a) β_j=0.01 (b) β_j=0.03 (c) β_j=0.05

Then, the subgradient method is applied to solve the dual problem. Let the vector S be a subgradient of $Z_D\left(v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5\right)$ at $v_{jt}^1,\ v_{jt}^2,\ v_j^3,\ v_j^4,\ v_{jtt'}^5 \geq 0$. In iteration k of the subgradient optimization procedure, the multiplier vector π is updated by $\pi^{k+1} = \pi^k + \zeta^k S^k$. The step size ζ^k is determined by $\varepsilon\left(Z_P^* - Z_D(\pi^k)\right)/\left\|S^k\right\|^2$, where Z_P^* is an upper bound (UB) on the primal objective function value after iteration k, and ε is a constant, where $0 \le \varepsilon \le 2$. Solutions calculated for the dual problems need to be checked to ensure that they satisfy all constraints relaxed in the problem (LR). We also develop a heuristic for getting primal feasible solutions.

3.3 An algorithm for getting primal feasible solutions

Infeasible solutions would probably violate the UL QoS requirement in Constraint 6, the DL QoS requirement in Constraint 7, and prioritized admission in Constraint 13. The solution to Constraints 6 and 7 is simply to reject call requests until the received SIR achieves a pre-defined threshold. Assuming a new call request to BS j from MS t' and a handoff call request to BS j from MS t are issued at the same time, if $z_{jt'}^N = 1$ and $z_{jt}^H = 0$ are solved in the subproblem (SUB 1), Constraint 13 would be violated. The adjustment rules that satisfy Constraint 13 are listed in Table 4.

Applying the rules, we develop the following primal feasible solution algorithm.

[Primal Algorithm]

Step 1. For each BS j, adjust z_{jt}^N and z_{jt}^H by the rules listed in Table 4.

Step 2. Check Constraints 6 and 7,

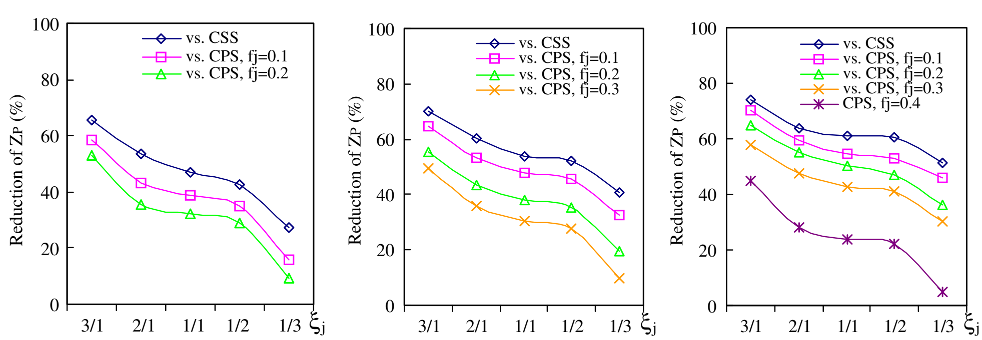
Step 2.1 If both constraints are still violated, increase f_j once by 0.1 until Constraint 14 is violated; otherwise go to Step 3.

Step 2.2 If Constraints 6 and 7 are still violated, block the users (reset $z_{jt}^N = 0$ and $z_{jt}^H = 0$) in descending order of their distance from a BS until Constraints 15 and 16 are violated; otherwise go to Step 3.

Step 3. No feasible solutions found and end algorithm.

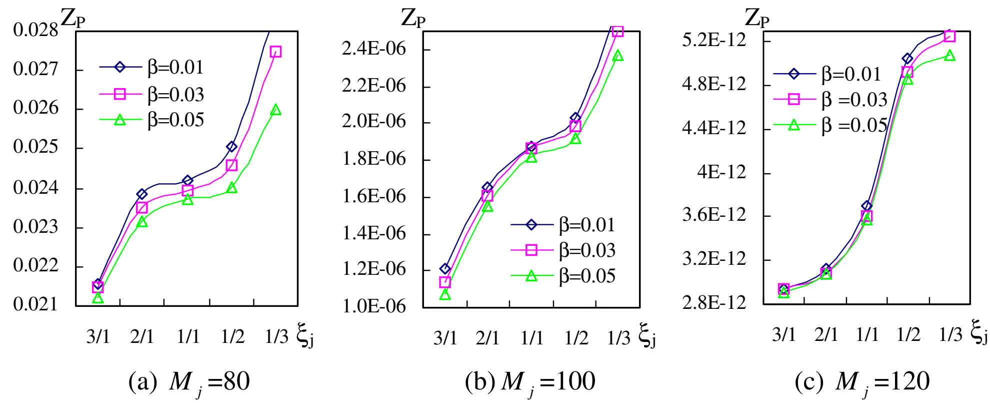
Based on the LR approach, a pre-defined time budget η= 5 s is given to solve the Lagrangean dual problem and to get primal feasible solutions iteratively. The time budget is a period of time slot for admission control. The value of time slot is adopted from analysis result of our project research report [30]. The project investigates a long-term revenue analysis to optimize revenue, in which the tradeoff of service rate and solution quality is considered. Using the value to calculate the parameters, then they are applied to do CAC for prioritized SHO calls, as shown in Fig. 3. We assume existing/ongoing MS calls are still held after time Γ_n, and both calls $\left(\lambda_j^N + \lambda_j^H\right)$ will arrive in next time slot.

Fig. 7 Reduction in the weighted handoff CBR (Z_P) by the proposed ACR scheme vs. various schemes **a** M_j=80, **b** M_j= 100, **c** M_j=120



(a) β_j=0.01 (b) β_j=0.03 (c) β_j=0.05

Fig. 8 The impact of the total number of available channels on the weighted handoff CBR (Z_P)



After time budget η is exhausted, CAC is also completed, i.e., z_{jt}^N and z_{jt}^H are decided. Updating ε in an iteration process is carefully controlled by the error gap in the iteration. The tighter the calculated gap, the smaller the value of ε that will be assigned. Figure 4 shows the overall procedure of the LR-based CAC scheme in which the time requirement of our proposed ACR scheme is within the time budget η.

4 Computational experiments

4.1 Results

For simplicity, we consider a cellular network comprised of 25 BSs arranged as a 5×5 two-dimensional array with hexagonal cells, as shown in Fig. 5, and analyze the voice call requests. Given λ_j=12 and μ=90, the analysis examines the effect of traffic load ξ_j on the weighted handoff CBR (Z_P) in terms of several channel reservation schemes.

The system bandwidth allocated to both the UL (W^{UL}) and the DL (W^{DL}) is 1.5 MHz, while the voice activity factor (AF; α^{UL}, α^{DL}) and orthogonality (θ^{UL}, θ^{DL}) for both links are (0.3, 0.3) and (0.7, 1), respectively. It is assumed that ($P_{c(t)}^{UL}$, $P_{c(t)}^{DL}$) = (7 dB, 10 dB), the available channels M_j=100, and R_j=5 km. The required BENR, i.e., E_b/N_{total}, for both links is 5 dB, and the bit rate of both links is 9.6 KHz. The service requirement rates Φ_j and Ω_j are both set at 0.3. For comparison purposes, we implement the CSS [22] and the CPS [20] schemes with a fixed number of guard channels f_j.

Figure 6 illustrates the effect of the traffic load on the weighted handoff CBR (Z_P). The number of reserved channels significantly affects the performance with respect to the pre-defined threshold β_j. Theoretically, the more channels reserved, the less the weighted handoff CBR (Z_P) will be calculated. However, the minimization of the weighted handoff CBR (Z_P) is constrained by β_j. If we apply CPS with a fixed number of reserved channels, the fraction (f_j) of reserved channels is 0.2, 0.3, and 0.4 in the cases of β_j=0.01, 0.03, and 0.05, respectively. Thus, the proposed ACR approach outperforms the compared schemes.

For the analysis of performance improvement, Fig. 7 shows the reductions in the weighted handoff CBR (Z_P) achieved by our ACR scheme compared to those of various approaches. It is given that β_j=0.01, 0.03, and 0.05, as shown in Fig. 7a, b, and c, respectively. In each instance, the ACR scheme reduces the weighted handoff CBR (Z_P) in the case of ξ_j=3/1 by as much as 65%, 72%, and 75% respectively; thus, it outperforms CSS.

We also investigate the effect of the total number of available channels on the weighted handoff CBR (Z_P). As shown in Fig. 8c, it is smoother among ξ_j when more channels are available than when fewer channels are available (shown in Fig. 8a). The greater the handoff traffic load, the more the weighted handoff CBR that is calculated. Under the proposed ACR scheme, the weighted handoff CBR (Z_P) is less affected by variations in the traffic load ξ_j when there are fewer available channels. For example, in Fig. 8a with β_j=0.03, the values of the weighted handoff CBR (Z_P) are (0.0235, 0.0239, 0.0244) when ξ_j is (2/1, 1/1, 1/2). However, the weighted handoff CBR (Z_P) becomes 0.0215 and 0.0275 when ξ_j is 3/1 and 1/3, respectively. The smaller the total number of available channels, the better will be the performance of the ACR scheme. In other words, the proposed ACR scheme outperforms other approaches when there are fewer available channels (M_j).

Table 5 Statistics of the error gaps with different traffic loads where β_j=0.01

Scheme	ξ_j				
	3/1	2/1	1/1	1/2	1/3
CSS	7.81%	8.50%	8.05%	7.70%	7.76%
CPS, f_j=0.1	8.73%	9.48%	7.78%	7.67%	9.12%
CPS, f_j=0.2	9.54%	9.97%	8.32%	9.27%	6.70%
CPS, f_j=0.3	8.59%	7.94%	7.98%	8.85%	7.05%
CPS, f_j=0.4	8.79%	9.47%	9.42%	6.99%	8.26%
ACR	8.82%	9.65%	8.19%	8.14%	8.86%

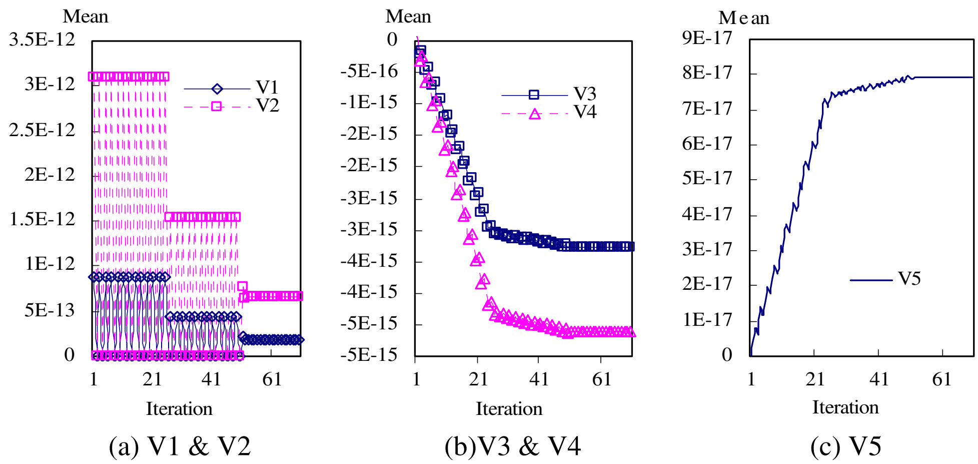


Fig. 9 Sensitivity analysis of the Lagrangean multipliers in the prioritized CAC scheme

The solution quality of the LR approach is demonstrated by the statistics of the error gaps detailed in Table 5. All the gaps are less than 10%. Our experiment results show that the proposed CAC model with the ACR scheme is worthy of further investigation.

4.2 Sensitivity analysis

In the prioritized CAC model, we relax five constraints. The first two are related to the SIR requirements on the UL and the DL. The corresponding multipliers are V1 related to Constraint 6 and V2 related to Constraint 7. The next two multipliers, V3 and V4, are related to Constraints 8 and 9, respectively, for aggregate (admitted) traffic flow in new and handoff call requests. The last multiplier, V5, relates to the prioritized CAC in Constraint 13. Figure 9 summarizes the analysis results. In Fig. 9a, both the multipliers V1 and V2 vibrate in less than 50 iterations, and then converge to constant values, i.e., 1.88E−13 for the V1 and 6.58E−13 for the V2. As shown in Fig. 9b, the values of V3 and V4 are negative, since the corresponding constraints are equal to, not less than or larger than the right-hand side. Figure 9c verifies the importance of V5 as a key constraint in fulfilling the priority requirements of handoff call requests. V5 is an increasing function of the number of iterations, and converges to 7.9E −17. The sensitivity analysis proves that the proposed model provides a higher priority for handoff calls than for new calls.

We also investigate how the BENR threshold in the SIR constraints affects the weighted handoff CBR (Z_P). The threshold value varies between −10% and +10%. The variations in Z_P with respect to different traffic loads (ξ_j) are shown in Fig. 10a for the UL and Fig. 10b for the DL. In general, the BENR threshold affects the weighted handoff CBR (Z_P) more significantly for the UL than for the DL. Given that ξ_j=1/3, the variations are in range 12.5% to −15% for the UL, and 10% to −7% for the DL. In terms of heavily loaded handoff traffic, irrespective of the link connection discussed, the proposed model reduces Z_P more effectively than the compared approaches.

5 Concluding remarks

5.1 Research contribution

The proposed prioritized CAC model for a DS-CDMA system considers the UL/DL and new/handoff calls jointly. Based on the ACR scheme for prioritized calls, the model adapts to

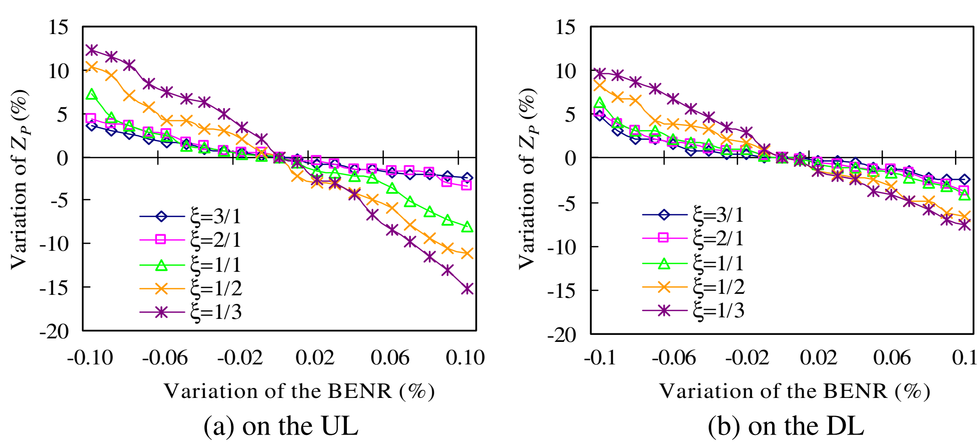


Fig. 10 Sensitivity analysis of BENR in handoff CBR

changes in handoff traffic by varying the associated parameters (guard channels, and new and handoff call arrival rates). We focus on handoff calls with a higher admission priority than ordinary new call requests, as guaranteeing services for ongoing calls is more important than granting requests for newly initiated calls. We express our achievements in terms of the problem formulation and performance improvement, and evaluate the performance of the CAC algorithm in terms of solution quality. The model minimizes the blocking rate of handoff calls subject to a pre-defined threshold for the blocking probability for new calls. Our computational results demonstrate that the proposed algorithm achieves a better solution quality than existing approaches. The adaptive model also outperforms other approaches in terms of reducing the blocking rate. By using our methodology, Lagrangean relaxation approach, OFDMA-based issues can also be solved so long as they are formulated as combinatorial optimization models.

5.2 Engineering guideline

SHO plays an important role in CDMA systems because it enables MSs near cell boundaries to use the same signals to transmit to, and receive from, more than one BS. Rejection of a SHO request results in forced termination of the current service. To maintain the service, we model the prioritized CAC problem as an adaptive channel reservation model for handoff calls in which a closed-form blocking model is expressed. The proposed ACR approach outperforms other methods when there are less rather than more channels, and reduces the handoff CBR more efficiently when the handoff traffic is heavily loaded. The model can be used in any kind of reservation service. In our future work, we will investigate using joint analysis of voice/data traffic and sectorization to fit real-world scenarios.

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