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On Admission Control and Scheduling of Multimedia Burst Data for CDMA Systems

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Abstract. In order to support transmissions of multimedia data (high data rate and burst) with performance guarantees in a wideband CDMA system, it is crucial to design a judicious algorithm for burst data admission control and scheduling. However, in the current literature there are only simple techniques (such as first-come-first-served and equal sharing) suggested for tackling the problem. Indeed, these existing schemes are not designed for optimizing the precious bandwidth resources while providing performance guarantees (e.g., a user admitted with a certain data rate can enjoy the assigned rate without interruption). In this paper, we first present our novel integer programming formulation of the burst data admission control and scheduling problem. The objective of the optimization can be maximizing the utilization of the bandwidth resources or minimizing the delays of the user transmissions. Taking into account all the important factors such as mobility, power control, and soft handoff, our formulation induces an algorithm for generating an optimal admission control solution which consists of: (1) the burst data rate (in terms of the number of channels); (2) the burst duration; and (3) the burst start time. For practical implementation, we also suggest a near-optimal version of the algorithm, which is evaluated via static and dynamic simulations, and comparisons with two existing schemes.

Keywords: CDMA, 3G, cdma2000, burst data, admission control, integer programming, optimal algorithm

1. Introduction

In third generation (3G) wireless communication systems, transmission of multimedia packet data is a key system requirement because it is widely envisioned that people will use the 3G devices to send and receive images, video clips, multimedia email messages, and so on, using the network. There are two major aspects to consider in the transmission of multimedia data over wireless cellular networks: data rate and traffic characteristics. First, the data rates of multimedia sources are high. For example, the data rate required to transmit a video clip in order to make an application (e.g., advertisements) meaningful can be at least 384 Kbps. Second, the transmission of such multimedia data, unlike the voice traffic, is usually very burst, meaning that there is no need to set up dedicated circuit-switched connections for such transmissions. Thus, from a resource management point of view, the functional requirements of a base-station is very different from those in the second generation. Specifically, the base-station has to judiciously allocate the bandwidth resources to the geographically distributed users who may generate traditional voice traffics as well as high data rate multimedia (mostly video) traffics. Such allocation and scheduling of resources must also work under one more constraint – to maintain the quality of service (QoS) of those committed transmissions (i.e., those connections that have been granted bandwidth resources for transmissions) [1,5,6,16]. Thus, the base-station has to perform careful admission control prior to distributing the bandwidth resources to those admitted in the system (i.e., allowed for transmissions). The objective of the base-station is to optimize the utilization of the bandwidth resources, while satisfying the user requests and the admission control (QoS) constraints.

It is now a world-wide consensus that 3G systems will be based on CDMA technologies, despite that two or more different versions (e.g., WCDMA and cdma2000) are being pursued [3,19,21]. In CDMA systems, the reverse links are interference limited while the forward links are power limited. Thus, for the reverse link, a data burst request could be admitted if the extra interference to the other users is below thresholds. For the forward link, a data burst request could be admitted if the extra load requirement at the base-station is below thresholds. Usually, the burst requests for the forward link and the reverse link directions are asymmetric and are treated independently. In general, the burst admission algorithm could be decomposed into two sub-layers: the *measurement sub-layer* and the *scheduling sub-layer*. The measurement sub-layer, for example, collects the load and interference measurement of the burst requests from the concerned mobile terminals and base-stations and evaluate their *admission feasibility*. The scheduling sub-layer, on the other hand, arbitrates and prioritizes multiple requests based on the current available resources (in the context of CDMA, system resource refers to the interference or cell load levels). For every admitted burst request, the output of the burst admission algorithm includes:

- the transmission rate,
- assigned burst duration, and
- the burst start time.

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Burst data admission control and scheduling is also relatively not explored [4,9]. Indeed, only a few burst admission control protocols have been proposed recently based on load and interference measurement [2,7,9,18,20]. Indeed, most existing burst admission control algorithms focus on the measurement sub-layer only. In other words, they are designed to handle single-burst assignment only. For example, in [7,9], only a single data user is considered for the burst admission algorithm. In the cdma2000 system [7,8], the burst requests are handled on a first-come-first-served manner. In [18], empirical scheduling such as equal sharing between multiple burst requests is considered.

In this paper, we focus on and illustrate the importance of the scheduling sub-layer of the burst admission algorithms for wideband CDMA systems. We first present a novel formulation of the burst admission scheduling as an integer programming problem (section 2). Our formulation induces an optimal algorithm (see section 3) for optimizing the system throughput and overall packet delay with respect to the data users. In our study, we focus on the multiple burst assignment on the *spatial dimension* only. By spatial dimension, we mean that the scheduling outcome depends only on the current set of geographically distributed (hence, spatial) users. Temporal dimension (i.e., unsuccessful user requests made earlier and new requests that might come up in the next frame) is ignored (but this is by itself an interesting research issue). Because efficiency of the admission control and scheduling algorithm is also of profound importance, we also suggest a heuristic based on the optimal algorithm for swiftly generating good (but not necessarily optimal) solutions. We also discuss (in section 3.3) the protocol design issues as well as the implementation issues such as the problem of *simultaneous transaction* between data requests in adjacent cells, which has been ignored by previous literature. Using realistic test cases, the performance of the proposed algorithm (sub-optimal version) is evaluated by static (for coverage and capacity) and dynamic (for outage) simulations [9], which take into account of the user mobility and soft handoff (see section 4). While our formulation, design, and testing are all based on the cdma2000 system, we believe that our approach can easily be adopted to other wideband CDMA systems with only minor modifications. We provide some concluding remarks in section 5.

2. Formulation of the burst admission control problem

In this section, we first present an overview of the cdma2000 MAC layer structure, which motivates an efficient algorithm for burst data admission control. We then discuss the measurement sub-layer followed by the scheduling sub-layer. Table 1 summarizes the key notation used throughout the paper.

2.1. cdma2000 MAC layer structure

As depicted in figure 1, the cdma2000 MAC layer is divided into four states for data service. A data user will initiate call request with packet data service option when it has backlog data packets to transmit. During the service request, it establishes link layer connection (RLP, Radio Link Protocol) and packet layer connection (PPP, Point-to-Point Protocol) with the base-station. It is assigned traffic channel and control

Table 1
Summary of notation.

Notation	Definition
FCH	fundamental channel
SCH	supplemental channel
m_j	burst request in terms of number of channels
$P_{j,k}$	load (power) required in base-station k to support the FCH of mobile terminal j
$\alpha_j^{(\mathrm{FL})}$	the adjustment factor taking into account of the difference in physical layer performance due to the reduced active set and the difference in the frame structure of FCH and SCH [7]
E_c	the received chip energy of pilot channel
G_FCH	the processing gain of the FCH
ξ_j	the transmit power ratio of FCH and pilot at the mobile terminal j
$X_{j,k}(\mathrm{FCH})$	the reverse link load of FCH of the jth mobile
γ_j	the additional margin to take into account of the attenuation fluctuations due to shadowing
$Y_{j,k}$	the projected interference to the neighbor cell (k') due to the burst transmission of mobile user (j) at host cell (k)
t_w	the request waiting time
D_s	the MAC setup delay penalty
$\vec{w}$	waiting time vector
$f(w_j, m_j)$	waiting time penalty function
Δ_j	the priority due to traffic type
λ	scaling factor
β	forgetting factor
Q_j	the burst packet size for the jth request
L_k	the total received power from the reverse link
$t_{j,k}^{(\mathrm{RL})}$	the reverse link pilot strength

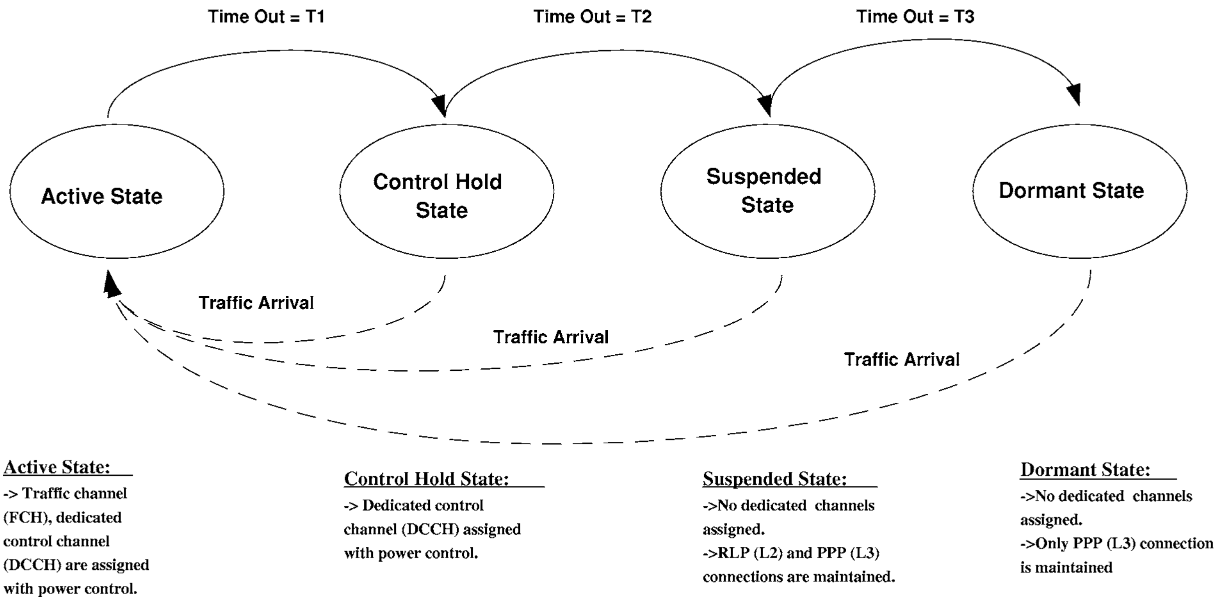


Figure 1. MAC states of cdma2000 to support high speed packet data.

channel and is at the *active state*. If the assigned traffic channel is idled for too long (timeout = T_1), it will be switched to the *control hold state*.

In the *control hold state*, only a dedicated control channel (DCCH) is maintained between the user and the base-station. The idle traffic channel is released to reduce the load and interference to the network. The DCCH is maintained to carry signalling information for burst data requests with virtually no latency. Power control is also maintained so that high speed burst operation could begin with no delay due to stabilization of power control loops. If the DCCH is idled for more than T_2 (note that T_2 and T_3 are the MAC layer time-out parameters), the user will be switched to the *suspended state*. In the *suspended state*, the idle DCCH is released as well to reduce the extra load and the interference to the network. However, the links for RLP and PPP are maintained between the user and the network. Furthermore, there is also a *virtual active set* to keep track of the best base-station to service packet data request. Since there is no dedicated channel to carry signalling information, data request occurred in the suspended state will suffer from an access delay. If the user remains in the *suspended state* for more than T_3, it will be switched to the *dormant state*. In this state, only the PPP link between the user and the network is maintained. Other physical or logical connections are released. Thus, data request occurred in the dormant state will suffer from the access delay as well as the setup delay for the logical connections such as RLP.

This MAC structure for cdma2000 is an improvement over IS95B MAC structure where only two states: the *active state* and the *dormant state* exist. The two states MAC works properly for fairly low speed data services with relatively low occupancy for any given user in IS95B. However, the MAC is not adequate to meet the requirement of the third generation systems because of the long setup time and high system overhead to transition from the dormant state to the active state. With the new MAC structure for cdma2000, the setup delay, D_s, for the data burst request depends on the current MAC state.

$$D_s = \begin{cases} 0 & \text{state} = \text{active state or control hold state,} \\ D_1 & \text{state} = \text{suspended state,} \\ D_2 & \text{state} = \text{dormant state.} \end{cases} \tag{1}$$

This setup delay penalty poses a constraint in the burst request scheduling problem as illustrated in the next subsection. Intuitively, we must try to service all burst requests before timeout values because otherwise, we have various level of setup delay penalties.

2.2. Measurement sub-layer

Unlike orthogonal TDMA or FDMA systems, the forward link and the reverse link of CDMA systems are power limited and interference limited respectively. For simplicity, we assume that the fundamental channel and/or the dedicated control channel is established for the high speed data user before the burst request. In general, the burst request for high speed data user will be granted only if the associated transmission will not affect the QoS of the existing active users in the system. Thus, all burst requests will be accomplished with the necessary load and interference level measurements to facilitate the decision. Furthermore, since the data requirement for the forward and the reverse link could be asymmetric, the burst admission is handled independently for the both links.

2.2.1. Forward link measurement

Consider we have N_d high speed data users in a cell. The mobile terminals are labeled by the index $j \in [1, N_d]$ and the cell is labeled by the index k. Assume the maximum load of a cell is $P_{\max}$ and the load of the base-station k to support the

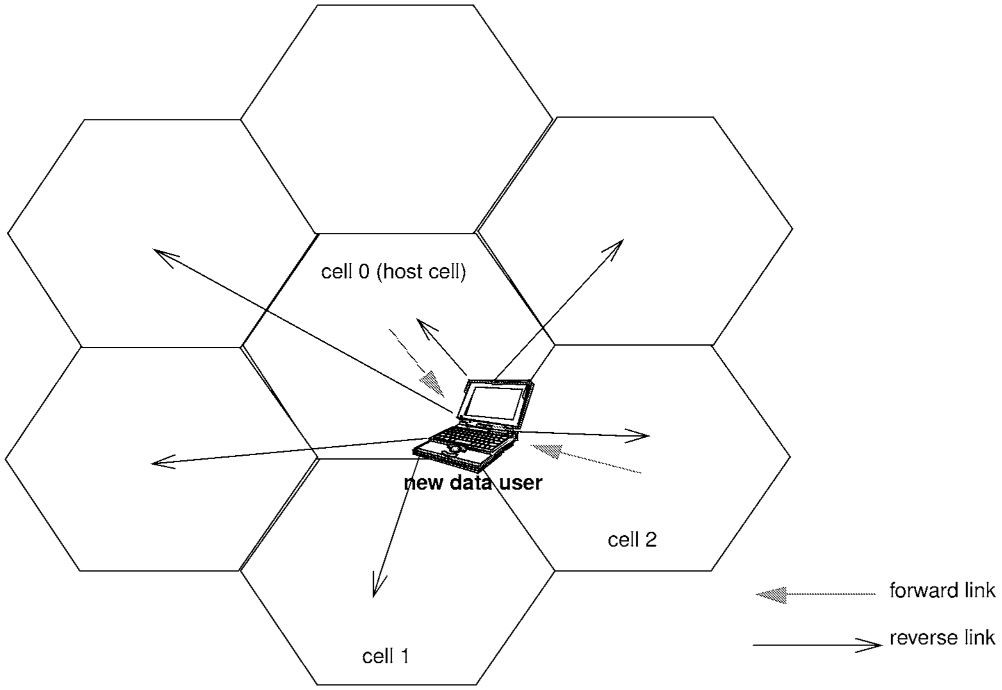


Figure 2. The scenario in which the reduced active set of a new data user consists of cells 0 and 2.

FCH (fundamental channel) of the mobile terminal j is $P_{j,k}$. Here, because the constraint in forward link is the available transmitted power, forward link load refers to the transmission power required at the base-station. Note that $P_{j,k} = 0$ if cell k is not in the reduced active set of the mobile terminal j. One point worth mentioning is that although soft handoff is beneficial to the reverse link, it requires extra forward link transmission power in the associated base-stations and is detrimental to the forward link capacity. Since high transmission power is involved in high speed transmission, reduced active set is adopted for the SCH (supplemental channel) in cdma2000. The reduced active set is assumed to be the set of the two base-stations with the strongest pilot E_c/I_{or} and is a subset of the active set of FCH (note that E_c is the received chip energy of pilot channel). Let P_k be the existing load in the cell k and $m_j \in [0, M]$ be the ratio of spreading gain of FCH to SCH. Here, it should be noted that in cdma2000, high speed transmission is supported by reduced spreading gain on the supplemental channel (SCH). In the first phase of cdma2000 implementation, only single SCH is supported per data request. Thus, we assume single SCH assignment with variable spreading gain in this paper to support high speed data transmission. Thus, a burst should be admitted if there is available power in all the base-stations (involved in soft handoff to accommodate the extra forward link load of the burst requesting mobile terminal. Suppose there are N_d concurrent burst requests in a cell and $m_j \in [0, M]$ where $m_j = 0$ denotes that the burst request is rejected. The additional forward link power required at the kth base-station to accommodate the jth data user is given by

$$\Delta P = m_j P_{j,k} \alpha_j^{(FL)}, \tag{2}$$

where $\alpha_j^{(FL)}$ is the adjustment factor taking into account of the different in physical layer performance due to the reduced active set and the difference in the frame structure of FCH and SCH [7]. Thus, for N_d concurrent data users, the *admissible region* is given by

$$P_k + \sum_{j=1}^{N_d} m_j P_{j,k} \alpha_j^{(FL)} \leqslant P_{\max}$$

or

$$\mathcal{A}\vec{m} \leqslant \vec{P}, \tag{3}$$

where $\vec{m} = [m_1, m_2, \ldots, m_{N_d}]'$, $\vec{P} = [(P_{\max} - P_1), (P_{\max} - P_2), \ldots]'$ and $\mathcal{A}$ is a $K \times N_d$ matrix with elements a_{jk} given by

$$a_{jk} = P_{jk} \alpha_j^{(FL)}. \tag{4}$$

Thus, the measurements accomplished with the forward burst request includes:

- the current cell load P_k, and
- the current forward link load associated with the mobile terminal j, $P_{j,k}$, which could be obtained directly from the base-stations in the reduced active set.

For example, in the scenario depicted in figure 2, the base cell of the user (i.e., cell 0) has to obtain its current load P_0 and the current forward link load of cell 2 (a member of the reduced active set; note that the full active set may include cell 1 also).

2.2.2. *Reverse link measurement*

In contrast to the forward link measurement, the reverse link is interference constrained and the associated measurements are based on the interference caused to the same cell users and the neighbor cell users. Thus, reverse link burst assignment is more complicated. In general, a reverse link burst should be admitted if

- the extra reverse link interference caused by the data burst transmission in the host cell is within threshold, and
- the extra reverse link interference for the neighbor cells is within thresholds as well.

Thus, we deal with reverse link burst assignment in the following two cases.

Cells in soft handoff. For the base-station k in soft handoff with a mobile terminal (j), it measures:

- the total received power from the reverse link L_k, and
- the reverse link pilot strength $t_{j,k}^{(\mathrm{RL})} = E_\mathrm{c}/I_\mathrm{or}$ from the mobile terminal j.

Let $X_{j,k}(\mathrm{FCH})$ be the received power at base-station k from mobile terminal j, supporting the fundamental channel (FCH). The received bit energy to interference ratio of the reverse FCH, $(E_\mathrm{b}/I_0)_{j,k}[\mathrm{FCH}]$ is given by

$$\left(\frac{E_\mathrm{b}}{I_0}\right)_{j,k}[\mathrm{FCH}] = G_\mathrm{FCH}\frac{X_{j,k}(\mathrm{FCH})}{L_k}, \tag{5}$$

where G_FCH is the processing gain of the FCH. Thus, the reverse link received power at base-station k due to the FCH of the jth mobile terminal, $X_{j,k}(\mathrm{FCH})$, is given by

$$X_{j,k}(\mathrm{FCH}) = \frac{L_k}{G_\mathrm{FCH}}\left(\frac{E_\mathrm{b}}{I_0}\right)_{j,k}[\mathrm{FCH}].$$

However, we do not have $(E_\mathrm{b}/I_0)_{j,k}[\mathrm{FCH}]$ measurement directly. Instead, we have the reverse link pilot strength measurement, $t_{j,k}^{(\mathrm{RL})} = E_\mathrm{c}/I_0$. Since we have

$$\left(\frac{E_\mathrm{b}}{I_0}\right)_{j,k}[\mathrm{FCH}] = G_\mathrm{FCH}\xi_j t_{j,k}^{(\mathrm{RL})},$$

where ξ_j is the transmit power ratio of FCH and pilot at the mobile terminal j, the reverse link load of FCH of the jth mobile terminal could be expressed as follows:

$$X_{j,k}(\mathrm{FCH}) = L_k t_{j,k}^{(\mathrm{RL})}\xi_j. \tag{6}$$

Thus, the extra reverse link interference caused to the cell k by the addition of data user j, $Y_{j,k}$, is given by

$$Y_{j,k} = m_j X_{j,k}(\mathrm{FCH})\alpha_j^{(\mathrm{RL})}, \tag{7}$$

where $\alpha_j^{(\mathrm{RL})}$ is the power adjustment factor to account for the difference in physical layer performance due to the reduced active set and the difference in the frame structure of the SCH and the FCH. Substituting from (6), we have

$$Y_{j,k} = m_j\alpha_j^{(\mathrm{RL})}\xi_j t_{j,k}^{(\mathrm{RL})}L_k, \tag{8}$$

where $m_j \in [0, M]$ is the ratio of the spreading gain of FCH to SCH. Note that $m_j = 0$ denotes that the burst request is rejected.

Neighbor cells not in soft handoff. For a neighbor cell k' not in soft handoff, the base-station does not have the reverse link pilot measurement from the mobile terminal j $(t_{j,k'})$. For example, as depicted in figure 2, all the cells except cells 0 and 2 (i.e., those cells outside the reduced active set) do not have the reverse link pilot measurements from the user and, as such, these cells have to use the forward link pilot strengths as estimates using the *pilot strength measurement message* (PSMM), as detailed below.

Note that the base-station only have the current reverse link interference level measurement, L'_k. The admission of the reverse burst (j) in the host cell k should not cause extra interference to existing users in the neighbor cells k'. To estimate the projected neighbor cell interference, we have to estimate the relative path loss between the neighbor cell and the host cell. Since path loss depends on the distance of the mobile terminal and the base-station, path loss is symmetrical for the forward and the reverse link and could be estimated as follows (strictly speaking, in FDD systems, the forward and reverse links use different frequencies and thus, slightly different path loss characteristics may be observed; however, we make the symmetry assumption in our study). When there is a reverse burst request, the mobile terminal will send a supplemental channel request message (SCRM) to the base-station. The SCRM message contains the forward link pilot strength measurements,

$$t_{j,k'}^{(\mathrm{FL})} = \left(\frac{E_\mathrm{c}}{I_0}\right)_{jk}, \tag{9}$$

for a number of neighbor cells. In cdma2000, the SCRM message contains at most 8 pilot strength measurements. These pilot strength measurements are used to estimate the relative path loss. Let $\rho_{k'}$ be the path loss of the cell k' (here, it should be noted that path loss is defined between the base-station of a cell and a mobile terminal; we drop the subscript for indicating the particular mobile terminal for brevity):

$$\rho_{k'} \propto t_{j,k'}^{(\mathrm{FL})}. \tag{10}$$

Thus, the relative path loss of the neighbor cell k' and the host cell k, $\delta\rho_{k,k'}$, is given by

$$\delta\rho_{k,k'} = \frac{t_{j,k'}^{(\mathrm{FL})}}{t_{j,k}^{(\mathrm{FL})}}. \tag{11}$$

Thus, the projected interference to the neighbor cell k' due to the burst transmission of mobile terminal j at host cell k, $Y_{j,k'}$, is given by

$$\begin{aligned} Y_{j,k'} &= \left(m_j\alpha_j^{(\mathrm{RL})}\xi_j t_{j,k}^{(\mathrm{RL})}\right)\gamma_j\delta\rho_{k,k'}L_k \\ &= m_j\alpha_j^{(\mathrm{RL})}\xi_j\gamma_j t_{j,k}^{(\mathrm{RL})}\frac{t_{j,k'}^{(\mathrm{FL})}}{t_{j,k}^{(\mathrm{FL})}}L_k, \end{aligned} \tag{12}$$

where γ_j is the additional margin to take into account of the attenuation fluctuations due to shadowing.

Thus, for N_d concurrent data users in the host cell, we have:

$$L_k + \sum_{j=1}^{N_\mathrm{d}} Y_{j,k} \leqslant L_{\max} \quad \forall k \in [1, K],$$

where $Y_{j,k}$ is given by (8) if k is in soft handoff with mobile terminal j or is given by (12) if k is not in soft handoff, and $L_{\max}$ is the maximum tolerable reverse link total interference level. Rearranging the terms, the *admissible region* for the N_d concurrent data users is given by

$$\sum_{j=1}^{N_\mathrm{d}} b_{jk} m_j \leqslant \frac{L_{\max}}{L_k} - 1 \tag{13}$$

or

$$\mathcal{B}\vec{m} \leqslant \vec{L}, \tag{14}$$

where $\vec{m} = [m_1, m_2, \ldots, m_{N_\mathrm{d}}]'$, $\vec{L} = [L_{\max}/L_1 - 1, \ldots]'$ and $\mathcal{B}$ is a $K \times N_\mathrm{d}$ matrix with elements b_{jk} given by

$$b_{jk} = \begin{cases} \alpha_j^{(\mathrm{RL})} \xi_j t_{j,k}^{(\mathrm{RL})}, & \text{cell } k \text{ in soft handoff,} \\ \alpha_j^{(\mathrm{RL})} \xi_j \gamma_j t_{j,k}^{(\mathrm{RL})} \dfrac{t_{j,k'}^{(\mathrm{FL})}}{t_{j,k}^{(\mathrm{FL})}}, & \text{cell } k \text{ not in soft handoff.} \end{cases} \tag{15}$$

Thus, the measurements accomplished with the reverse burst request includes:

- the reverse interference, L_k, from the cells,
- the reverse pilot strength measurements, $t_{j,k}^{(\mathrm{RL})}$, from the soft handoff cells, and
- the forward link pilot strength measurement reported from the mobile terminal, $t_{j,k}^{(\mathrm{FL})}$.

2.3. Scheduling sub-layer

In some previous research efforts [7,9], single data burst request is considered. Thus, the burst admission algorithms were based on the measurement sub-layer only. The measurement sub-layer simply evaluates the admissibility of the current burst request. In other words, multiple burst requests are handled on a first-come-first-served basis. In [18], some discussions on other empirical scheduling methods, such as equal sharing between multiple requests, were mentioned but no detail investigations were reported.

In fact, the scheduling sub-layer should be designed with respect to an objective function. In general, an objective function should be a compromise of

- system resource utilization, and
- overall system delay.

In this paper, we consider the following two objective functions:

$$\mathcal{J}_1(\vec{m}) = \sum_{j=1}^{N_\mathrm{d}} m_j \tag{16}$$

and

$$\mathcal{J}_2(\vec{m}, \vec{w}) = \sum_{j=1}^{N_\mathrm{d}} \bigl[m_j(1 + \Delta_j) - f(w_j, m_j)\bigr], \tag{17}$$

where $\vec{w}$, $f(w_j, m_j)$ and Δ_j are the waiting time vector for N_d data users, the waiting time penalty function, as well as the priority due to traffic type, respectively (note that w_j is the time spent by request j in waiting for the resource). For example, voice traffic is given a higher priority over data traffic. The first objective function focuses on the overall system transmission rate (or system throughput) only. Intuitively, those requests occupying smaller resource should be given priority over the others in order to maximize $\mathcal{J}_1$. On the other hand, the second objective function considers the tradeoff between system utilization and overall system delay among users. For instance, we have to minimize the delay penalty $f(w_j, m_j)$ despite the fact that those requests may be at poor locations. Note that $\mathcal{J}_1(\vec{m})$ is a special case of $\mathcal{J}_2(\vec{m}, \vec{w})$.

A simple delay penalty function can be defined as

$$f(w_j, m_j) = D_0 - \lambda (w_j)^\beta m_j, \tag{18}$$

where λ and β are the scaling factor and the delay forgetting factor. The delay penalty increases with the overall request delay w_j and decreases with m_j. To take into account the set up delay penalty due to MAC states time out, the overall request delay is given by

$$w_j = t_\mathrm{w} + D_\mathrm{s}, \tag{19}$$

where t_w is the request waiting time and D_s is the MAC setup delay penalty (see (1)).

We have one additional constraint on m_j. Since burst admission involves a large signalling overhead, it would not be justified if the assigned burst duration is too short. Thus, we have a lower bound (T_l) on the assigned burst duration. That is:

$$m_j \geqslant \min\left\{M, \frac{Q_j}{T_\mathrm{l}}\right\}, \tag{20}$$

where Q_j is the burst packet size for the jth request. Thus, the objective functions ($\mathcal{J}_1$, $\mathcal{J}_2$) together with the admissible region constraint (14) and (3), and the burst duration constraint (20), form an integer programming problem. The optimal solution is derived in the next section.

In general, the scheduling space includes both the *spatial dimension* (i.e., choosing between different requests m_j) as well as the *temporal dimension* (i.e., adjusting the starting time of burst requests with different burst duration). However, for simplicity, we focus on the spatial dimension only. Thus, the starting time of the assigned burst will be at the earliest possible frame boundary. The assigned burst duration is given by Q_j/m_j.

3. The proposed algorithms

3.1. Optimal algorithm

In this section, we derive the optimal solution to the burst admission problem based on the principle of *divide-and-conquer*. Without loss of generality, we consider the objective function $\mathcal{J}_2$ and the forward burst assignment.

Define $\vec{m}$ and $\vec{\mu}$ (column vectors) to be the *allocation vector* and the *system resource vector*. The optimization problem to solve is given by

$$\begin{aligned}\mathcal{F}(\vec{\mu}) &= \max_{\vec{m}}\left\{\mathcal{J}_2(\vec{m}, \vec{w})\right\}\\ &= \max_{\vec{m}} \sum_{j=1}^{N_\mathrm{d}} \left(1 + \Delta_j + \lambda(w_j)^\beta\right) m_j \end{aligned} \tag{21}$$

with the constraint given by the *admissible region*:

$$\sum_{j=1}^{N_\mathrm{d}} a_{kj} m_j \leqslant \mu_k \quad \forall k \in [1, K]. \tag{22}$$

This is the general form of constraints, compared with the FL (3) and the RL constraints (14).

Theorem 1. The optimization problem (21) could be expressed into the following recursive form:

$$\mathcal{F}(\vec{\mu}) = \max\left\{0, \max_{j:\vec{\mu} \geqslant \vec{a}_j}\left[\left(1 + \Delta_j + \lambda(w_j)^\beta\right) + \mathcal{F}(\vec{\mu} - \vec{a}_j)\right]\right\} \tag{23}$$

where $\vec{\mu} \geqslant \vec{a}_j$ denotes $\mu_k \geqslant a_{kj}$ $\forall k \in [1, K]$.

Proof. Starting from the resource vector $\vec{\mu}$ and allocation vector $\vec{m}$, suppose we assign a unit of resource to user j_0 ($j_0 \in [1, N_\mathrm{d}]$). Thus, $m_{j_0} = m'_{j_0} + 1$ where $m'_{j_0} \geqslant 0$. The optimization problem could be expressed as

$$\begin{aligned}\mathcal{F}(\vec{\mu}) &= \max_{\substack{\vec{m}:\sum_{j=1}^{N_\mathrm{d}} m_j a_{kj} \leqslant \mu_k \\ \forall k \in [1,K]}} \left\{0, \sum_{j=1}^{N_\mathrm{d}} \left(1 + \Delta_j + \lambda(w_j)^\beta\right) m_j\right\}\\ &= \max_{j_0:\mu_k \geqslant a_{kj} \forall k \in [1,K]} \Big\{0, \left(1 + \Delta_{j_0} + \lambda(w_{j_0})^\beta\right)\\ &\quad + \max_{\substack{\vec{m}':\sum_{j=1}^{N_\mathrm{d}} a_{kj} m'_j \leqslant \mu_k - a_{k,j_0} \\ \forall k \in [1,K]}} \left(1 + \Delta_j + \lambda(w_j)^\beta\right) m'_j\Big\}\\ &= \max_{j_0:\mu_k \geqslant a_{kj} \forall k \in [1,K]} \Big\{0, \left(1 + \Delta_{j_0} + \lambda(w_{j_0})^\beta\right)\\ &\qquad + \mathcal{F}(\vec{\mu} - \vec{a}_{j_0})\Big\}. \end{aligned} \tag{24}$$

Thus, theorem 1 follows. ☐

Intuitively, at every step, a unit of resource is allocated to the request contributing the most to the objective function. Since $\vec{\mu}$ is a real vector, the key step in solving the optimization problem (23) is to *partition* the resource space properly so that $\mathcal{F}(\vec{\mu})$ is constant within each partition. The optimal solution is outlined as follows.

Step I. Resource space partitioning. Define the resource interval $\mathcal{R}_k = [0, (P_{\max} - P_k)]$. The *resource space* $\mathcal{R}_+^K$ is given by

$$\mathcal{R}_+^K = \mathcal{R}_1 \times \mathcal{R}_2 \times \cdots \times \mathcal{R}_K. \tag{25}$$

Theorem 2. Define the set $\mathcal{A}_j = \{(\mu_1, \dots, \mu_K)\colon \mu_k \geqslant a_{kj}$ $\forall k \in [1, K]\} \bigcap \mathcal{R}_+^K$. The resource space $\mathcal{R}_+^K$ could be *completely partitioned* by the set of non-overlapping subspaces, $\mathcal{P}$, given by

$$\begin{aligned}\mathcal{P} = \big\{&\mathcal{S}(0), \mathcal{S}(1, [j_1]), \mathcal{S}(2, [j_1, j_2]), \dots,\\ &\mathcal{S}(N_\mathrm{d}, [j_1, \dots, j_{N_\mathrm{d}}])\colon j_n \in [1, N_\mathrm{d}],\\ &j_1 \neq j_2 \neq \cdots \neq j_{N_\mathrm{d}}\big\},\end{aligned} \tag{26}$$

where $\mathcal{S}(0) = \mathcal{R}_+^K - \bigcup_{j=1}^{N_\mathrm{d}} \mathcal{A}_j$ and $\mathcal{S}(n, [j_1, \dots, j_n])$ is given by

$$\mathcal{S}(n, [j_1, \dots, j_n]) = \bigcap_{i=1}^{n} \mathcal{A}_{j_i} - \bigcup_{j \neq [j_1, \dots, j_n]} \mathcal{A}_j. \tag{27}$$

Note that *complete partition* implies the following:

$$\bigcup_{n \in [0, N_\mathrm{d}], [j_1, \dots, j_n] \in \mathcal{C}_n^{N_\mathrm{d}}([1, \dots, N_\mathrm{d}])} \mathcal{S}(n, [j_1, \dots, j_n]) = \mathcal{R}_+^K, \tag{28}$$

where $\mathcal{C}^{N_\mathrm{d}}([1, \dots, N_\mathrm{d}])$ is the set of n-dimensional vectors selected from the combination of the range $[1, \dots, N_\mathrm{d}]$.

$$\begin{aligned}&\mathcal{S}(n_1, [j_1, \dots, j_{n_1}]) \bigcap \mathcal{S}(n_2, [j'_1, \dots, j'_{n_2}]) = \emptyset\\ &\quad \text{for } \mathcal{S}(n_1, [\,]) \neq \mathcal{S}(n_2, [\,]).\end{aligned} \tag{29}$$

Proof. Refer to the appendix. ☐

Note that $\mathcal{S}(n, [j_1, \dots, j_n])$ is called the level-n partition.

Step II. Quantization. Since $\vec{\mu}$ is a real vector, we quantize the non-empty partitions of the resource space in order to facilitate the evaluation of $\mathcal{F}(\vec{\mu})$ in these sub-spaces. However, observe that

$$\mathcal{F}(\vec{\mu} \in \mathcal{S}(0)) = 0. \tag{30}$$

Thus, we quantize the level-1 to level-N_d *non-empty* partitions of the resource space, $\mathcal{S}(n, [j_1, \dots, j_n]) \neq \emptyset$, only. Define the *quantized partition*, $\mathcal{Q}(n, [j_1, \dots, j_n]) \subset \mathcal{S}(n, [j_1, \dots, j_n])$, as

$$\begin{aligned}&\mathcal{Q}(n, [j_1, \dots, j_n])\\ &\quad = \Big\{(\mu_1, \dots, \mu_K) \in \mathcal{S}(n, [j_1, \dots, j_n]) \text{ and:}\\ &\qquad \mu_k = 0 \text{ if } a_{kj} = 0\ \forall j \in [j_1, \dots, j_n],\\ &\qquad \mu_k = \max_{j \in [j_1, \dots, j_n]} [a_{kj}] + i\delta q_n\\ &\qquad\quad \text{for some } i \in [0, 1, \dots] \text{ if } a_{kj} \neq 0\Big\},\end{aligned} \tag{31}$$

where δq_n is the quantization interval for level-n partition.

Step III. Partial resource allocation. We solve the iterative equation (23) for $\vec{\mu}$ in each element of the quantized partition set $\mathcal{P}$. The sequence of evaluation of $\mathcal{F}(\vec{\mu})$ starts from the zero level partition $\vec{\mu} \in \mathcal{S}(0)$ and then the first level quantized partition $\vec{\mu} \in \mathcal{Q}(1, [j_1])$, the second level quantized partition $\vec{\mu} \in \mathcal{Q}(2, [j_1, j_2])$ and so on because $\mathcal{F}$ could be expressed in terms of already found $\mathcal{F}$ at lower level partitions. For any $\vec{\mu} \in \mathcal{Q}(n, [j_1, \ldots, j_n])$, we have:

$$\mathcal{F}(\vec{\mu}) = \max_{j \in [j_1, \ldots, j_n]} \left\{ \left(1 + \Delta_j + \lambda (w_j)^{\beta}\right) + \mathcal{F}\left[\mathcal{G}_n(\vec{\mu} - \vec{a}_j)\right] \right\}. \tag{32}$$

Note that $\hat{\vec{x}} = \mathcal{G}_n[\vec{x}]$ is the quantized vector such that

$$\begin{aligned} &\left|\vec{x} - \hat{\vec{x}}\right| \leqslant |\vec{x} - \vec{y}| \\ &\forall \vec{y} \in \mathcal{S}(0) \bigcup_{r=1}^{n} \quad \bigcup_{(p_1, \ldots, p_r) \in \mathcal{Q}_r^n([j_1, \ldots, j_n])} \quad \mathcal{Q}\left(r, [p_1, \ldots, p_r]\right), \end{aligned} \tag{33}$$

where $\mathcal{C}_r^n([j_1, \ldots, j_n])$ is the *combinatorial set* given by

$$\begin{aligned} &\mathcal{C}_r^n\left([j_1, \ldots, j_n]\right) \\ &\quad = \left\{(p_1, \ldots, p_r)\colon\ p_i \in [j_1, \ldots, j_n],\ p_{i_1} \neq p_{i_2}\right\}. \end{aligned} \tag{34}$$

Denote the *allocation index* j^* as $j^* = f(\vec{\mu})$ where j^* is the result of the max operation in (32). The *allocation vector*, $g(\vec{\mu})$, is defined as $(m_1, m_2, \ldots, m_{N_\mathrm{d}})$ such that $m_{j^*} = 1$ and $m_{j'} = 0\ \forall j' \neq j^*$.

Step IV. Termination. Define the initial resource vector, $\vec{\mu}_1$, as $\mathcal{G}_{N_\mathrm{d}}[(P_{\max} - P_1), (P_{\max} - P_2), \ldots, (P_{\max} - P_K)]$. From step III, $\mathcal{F}(\vec{\mu}_1)$ has been found with the first allocation index $j_1^* = f(\vec{\mu}_1)$. The next resource vector, $\vec{\mu}_2 = \vec{\mu}_1 - \vec{a}_{j_1^*}$. Thus, the second allocation index, $j_2^* = f(\vec{\mu}_2)$. In general, we have the pth resource vector and the pth allocation index given by

$$\vec{\mu}_p = \vec{\mu}_{p-1} - \vec{a}_{j_{p-1}^*} \tag{35}$$

and

$$j_p^* = f(\vec{\mu}_p), \tag{36}$$

where the iteration stops when $\vec{\mu}_{p_0} \in \mathcal{S}(0)$ for some p_0. The resulting optimal allocation is given by $\sum_{p=1}^{p_0} g(\vec{\mu}_p)$.

Note that in the worst case, the total number of partitions in the partition set $\mathcal{P}$ is 2^{N_d}. Thus, the computational complexity of the above algorithm is exponential in N_d in the worst case. This motivates the following heuristic approach.

3.2. An efficient heuristic

Define the *resource index* at the pth iteration, $\zeta_j^{(p)}$, as

$$\zeta_j^{(p)} = \min_{k: a_{kj} > 0} \left[M_0, \frac{P_{\max} - P_k - \sum_{j'=1}^{N_\mathrm{d}} a_{kj'} m_{j'}^{(p-1)}}{a_{kj}} \right], \tag{37}$$

where $M_0 = \min[M, \lfloor Q_{j_*}/T_1 \rfloor]$ and $\vec{m}^{(p-1)} = [m_1^{(p-1)}, \ldots, m_{N_\mathrm{d}}^{(p-1)}]$ is the allocation vector at the $(p-1)$th iteration. Let $\gamma_j^{(p)}$ be the priority function at the pth iteration, which is given by

$$\gamma_j^{(p)} = \left(1 + \Delta_j + \lambda (w_j)^{\beta}\right) \zeta_j^{(p)}. \tag{38}$$

Intuitively, request that occupies small system resource or request that has a long waiting time should be given higher priority as indicated in (38). The iteration starts at $p = 1$ where $\vec{m}^{(0)} = [0, \ldots, 0]$. The algorithm tries to allocate δm resource to one of the competing requests according to their priorities, $[\gamma_1^{(p)}, \ldots, \gamma_{N_\mathrm{d}}^{(p)}]$. Suppose $j_*^{(p)}$ has the highest priority, then $m_{j_*^{(p)}}^{(p)} = \min[m_{j_*^{(p)}}^{(p-1)} + \delta m, M_0]$. Note that if $m_{j_*}^{(p)} = M_0$, this request is taken out of the competing list in the next iteration. After the allocation, the resource index $\vec{\zeta}$ is updated for the $(p+1)$th iteration. The iteration stops when there exists some j such that $\zeta_j^{(p+1)} \leqslant 0$.

3.3. Practical implementation issues

Burst requests are collected in a request queue. The optimal scheduling algorithm is performed at designated scheduling points for the N_d accumulated requests. Burst requests with resource allocated will start their transmission at the next frame boundary. On the other hand, requests with no resource allocated will stay in the queue. Together with any new requests generated, they are rescheduled at the next decision point.

Load and interference update. Since requests in the queue are accompanied with load and interference measurement, they need to be updated if the waiting time exceeds a certain threshold, T_e. For those requests with *expired measurement*, new set of measurement will be collected from the concerned base-stations and the mobile terminals (by *pilot strength measurement message*, PSMM).

Forced termination. The scheduling algorithm works on an assumption that the load and interference situation will be relatively stable for a brief period of time. However, in practice, the system load and interference level could exceed the maximum thresholds temporarily due to the statistical fluctuation of shadowing and speed of the mobile terminal. Thus, we need another mechanism – the *forced termination* – to safeguard the system from overloading. Forced termination is triggered by the unacceptable frame error rate performance of the data burst transmission and the concerned data link is terminated by a layer three message to the concerned mobile terminal.

Topological issues. Note that the measurement sub-layer and the scheduling sub-layer could reside at the base-station controller level (Selection and Distribution Unit (SDU) level) or at the base-station level. In the former case, namely the *centralized approach*, the burst scheduling problem concerns about the concurrent burst requests over the whole network (instead of a single cell). This increases the scheduling complexity and the associated delay. In this paper, we propose the latter approach, namely the *decentralized approach*. Both the measurement and the scheduling decision are decentralized to the base-station level, and hence, the burst scheduling problem concerns about the concurrent burst requests at a single cell only. This reduces the scheduling complexity. However, since admissions of the burst requests in adjacent cells are inter-related, we have to synchronize the load information between cells to avoid the problems of *concurrent transaction* [9]. Specifically, the system has to notify all the neighbor cells around cell k through the base-station controller for any changes in the forward link and the reverse link load information (P_k and L_k) of a cell k. The synchronization among cells requires a solution that can lead to a fast convergence of consensus on the settings of parameters. We believe this is by itself an interesting research problem.

4. Results

The proposed burst admission approach is compared with two baseline systems. Because the optimal version is not computationally efficient for large problem instances, we only tested the sub-optimal version, which is more practicable in a real world scenario (e.g., implementation in a base-station). In *baseline I*, we have the single burst admission algorithm, which is employed in the cdma2000 system. Specifically, concurrent burst requests are served on a first-come-first-served basis. In *baseline II*, we have a multiple burst admission algorithm but with a heuristic scheduling sub-layer. Specifically, resource is equally shared between concurrent burst requests. Furthermore, priority is given to the existing burst for new packet arrivals [18].

All the burst admission algorithms are evaluated based on static and dynamic simulations used in [9]. Specifically, we employ static Monte Carlo techniques for generating the coverage results for high speed data users. The cellular architecture is assumed to be a hexagonal grid with base-stations (sectorized with three sectors) located at the center of every hexagon. Distance loss is modeled by $d^{-\delta}$, where δ is the propagation constant. Shadow fading is modeled using the Mawira model [17] for an urban environment. We repeat the Monte Carlo simulations for 100 times to obtain the static coverage results. Throughout all experiments, we assume adjacent cell load is 50%. Note that for parameters Δ_j, λ, and β, one should set them to suit the goals to be achieved. For example, if the primary goal is to minimize the delay, then the parameters λ and β should have large values. On the other hand, if traffic type is a more important concern (e.g., some data users are privileged), the value of Δ_j should be increased appropriately to reflect the relative importance. In our experiments, we try to strike the balance between the two objectives. Table 2 summarizes the parameters used.

Table 2
Simulation parameters.

Parameter	Value
Δ_j	5.0
λ	4.0
β	2.0
Path loss exponent	4
Average adjacent cell load	50%
Chip rate	7.3728 Mcps
FCH rate	14.4 Kbps
cdma2000–SCH rate	14.4 Kbps–1.8432 Mbps
PG[cdma2000–FCH]	512
PG[cdma2000–SCH]	512–4
BER[FCH]	10^{-2}
BER[SCH]	10^{-4}
E_s/I_0[cdma2000–FCH]	7 dB
E_s/I_0[cdma2000–SCH]	13 dB
PG[cdma2000–FCH]	512
PG[cdma2000–SCH]	512–4

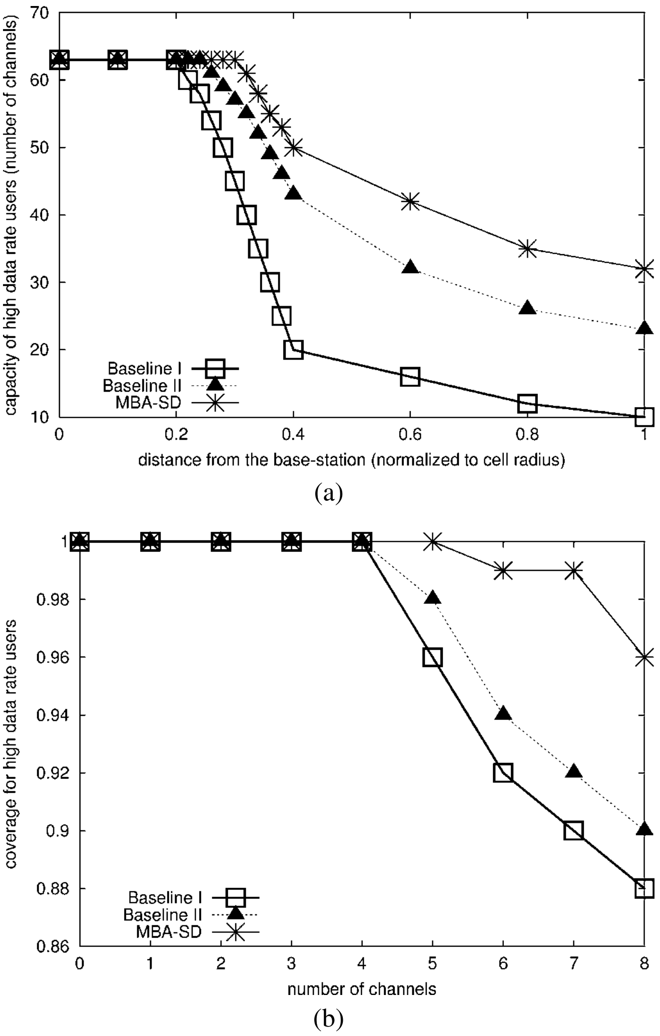
We use a simple model for the mobility of the users. Each user (voice or data) selects a random starting position, which is uniformly distributed over the cell. The direction of motion is also randomly selected. The motion is rectilinear until a call is finished. The speed of motion is assumed to be a constant (35 miles/hr). Soft handoff and perfect power control are assumed also. To obtain results of dynamic measurements such as admission and outage probabilities, we performed 10 independent simulations with 5000 calls each.

Figure 3(a) shows the forward link capacity of the three different burst admission control schemes generated by the static simulations. Here, the load by the voice users in the cell is also 50%. As can be seen, the proposed algorithm, called MBA-SD (Multiple-Burst Admission based on Spatial Dimension), outperforms the two baseline approaches by a considerable margin. This clearly demonstrates that if the extra processing requirements are affordable, optimizing the high data rate bursts scheduling is highly beneficial. On the other hand, as expected, the high capacity is not available throughout the entire cell but just the area near the base-station, as indicated in figure 3(b) (in these results, there is 1 high data rate user and the voice user load in the cell is 50%).

For the reverse link, we obtain results on admission and outage probabilities, as shown in figures 4(a) and (b). For the results on admission probabilities, the requested data rate is 57.6 Kbps and the voice load in the cell is 50%. The results on outage probabilities are obtained by dynamic simulations and there is 1 data user (with rate 57.6 Kbps). Again, we can see that the MBA-SD approach can allow a high admission probability, through its judicious merging of different requests arrived at different time periods. The MBA-SD approach can also support a much higher number of voice users.

5. Concluding remarks

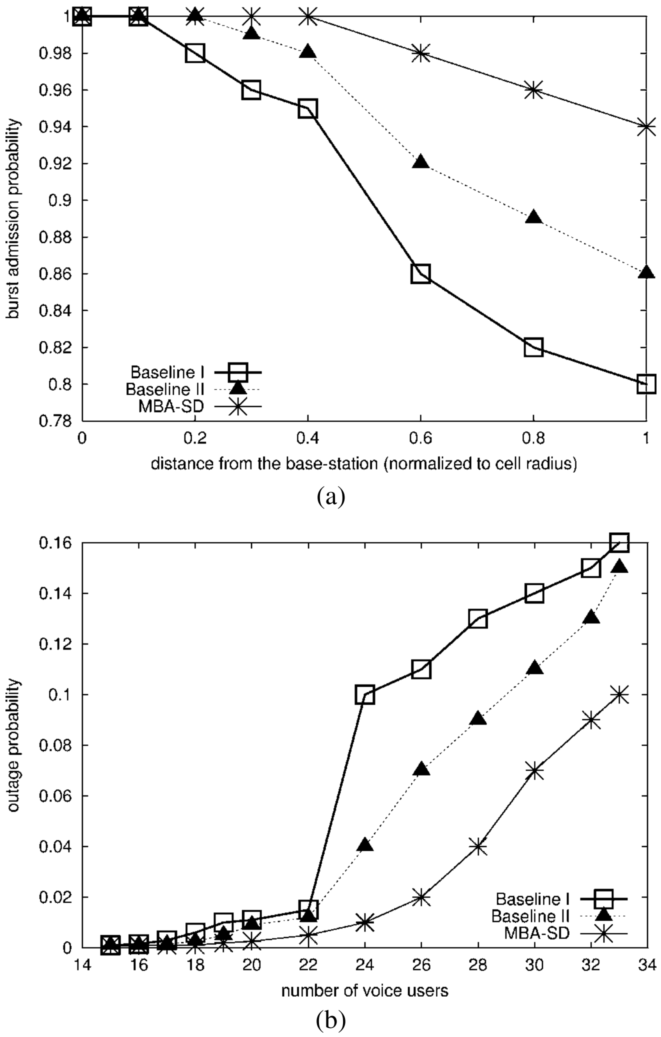
We have presented the design and analysis of a new approach for multiple high data rate burst admission control in a CDMA cellular system. Using a combinatorial optimization technique, we devise the algorithm for obtaining optimal scheduling of high data rate bursts. The proposed algorithm works by arranging the data bursts judiciously in the spatial dimension such that the optimal allocation of channels can be done. Simulation results indicate that our scheme outperforms the



(a)

(b)

Figure 3. Forward link results. (a) Number of FCHs available on the forward link with varying distances from the base-station. (b) Forward link coverage area as a function of number of FCHs.



(a)

(b)

Figure 4. Reverse link results. (a) Average admission probabilities on the reverse link. (b) Outage probabilities for voice users.

FCFS scheduling scheme and the allocation method used in cdma2000. In another study of further improving the admission control algorithm, we are currently investigating the exploitation of the synergy [14,15] between the multiple burst admission control and a channel adaptive physical layer design [11–13]. Furthermore, a genetic algorithm based optimization approach [10] is also being considered for improving the efficiency and solution quality of the sub-optimal approach.

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Appendix. Proof of theorem 2

We have to prove the following results for *complete partitioning*:

$$\bigcup_{n\in[0,N_\mathrm{d}],[j_1,\ldots,j_n]\in\mathcal{C}^{N_\mathrm{d}}_{n([1,\ldots,N_\mathrm{d}])}} \mathcal{S}\big(n,[j_1,\ldots,j_n]\big)=\mathcal{R}^K_+, \tag{A.1}$$

$$\mathcal{S}\big(n_1,[j_1,\ldots,j_{n_1}]\big)\bigcap\mathcal{S}\big(n_2,[j'_1,\ldots,j'_{n_2}]\big)=\emptyset. \tag{A.2}$$

To prove equation (A.1), we consider the following backward induction formulation. At the N_dth step, we have, $\mathcal{S}(N_\mathrm{d},[1,\ldots,N_\mathrm{d}])$ given by

$$\mathcal{S}\big(N_\mathrm{d},[1,\ldots,N_\mathrm{d}]\big)=\bigcup_{[j_1,\ldots,j_{N_\mathrm{d}}]\in\mathcal{C}^{N_\mathrm{d}}_{N_\mathrm{d}}}\left[\bigcap_{p=1}^{N_\mathrm{d}}\mathcal{A}_{j_p}\right]=\left[\bigcap_{j=1}^{N_\mathrm{d}}\mathcal{A}_j\right]. \tag{A.3}$$

At the rth step, we have

$$\begin{aligned}
&\Biggl[\bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}([1,\ldots,N_\mathrm{d}])} \mathcal{S}\bigl(r,[j_1,\ldots,j_r]\bigr)\Biggr] \\
&\quad\bigcup_{[j_1,\ldots,j_{r+1}]\in\mathcal{C}_{r+1}^{N_\mathrm{d}}([1,\ldots,N_\mathrm{d}])}\Biggl[\bigcap_{p=1}^{r+1}\mathcal{A}_{j_p}\Biggr] \\
&= \bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}}\Biggl[\bigcap_{p=1}^{r}\mathcal{A}_{j_p} - \bigcup_{j=1:j\neq[j_1,\ldots,j_r]}^{N_\mathrm{d}}\mathcal{A}_j\Biggr] \\
&\quad\bigcup_{[j_1,\ldots,j_{r+1}]\in\mathcal{C}_{r+1}^{N_\mathrm{d}}([1,\ldots,N_\mathrm{d}])}\Biggl[\bigcap_{p=1}^{r+1}\mathcal{A}_{j_p}\Biggr] \\
&= \bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}}\Biggl[\bigcap_{p=1}^{r}\mathcal{A}_{j_p}\Biggr].
\end{aligned}\tag{A.4}$$

Thus, inductively, we have:

$$\begin{aligned}
&\mathcal{S}(0)\bigcup\Biggl[\bigcup_{r=1}^{N_\mathrm{d}}\bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}}\mathcal{S}\bigl(r,[j_1,\ldots,j_r]\bigr)\Biggr] \\
&= \mathcal{S}(0)\bigcup\bigcup_{r=1}^{N_\mathrm{d}-1}\Biggl[\bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}}\mathcal{S}\bigl(r,[j_1,\ldots,j_r]\bigr)\Biggr] \\
&\quad\bigcup\Biggl[\bigcap_{j=1}^{N_\mathrm{d}}\mathcal{A}_j\Biggr] \\
&= \mathcal{S}(0)\bigcup\bigcup_{r=1}^{N_\mathrm{d}-2}\Biggl[\bigcup_{[j_1,\ldots,j_r]\in\mathcal{C}_r^{N_\mathrm{d}}}\mathcal{S}\bigl(r,[j_1,\ldots,j_r]\bigr)\Biggr] \\
&\quad\bigcup\Biggl\{\bigcup_{[j_1,\ldots,j_{N_\mathrm{d}-1}]\in\mathcal{C}_{N_\mathrm{d}-1}^{N_\mathrm{d}}}\mathcal{S}\bigl(N_\mathrm{d}-1,[j_1,\ldots,j_{N_\mathrm{d}-1}]\bigr) \\
&\qquad\bigcup\Biggl[\bigcap_{j=1}^{N_\mathrm{d}}\mathcal{A}_j\Biggr]\Biggr\} \\
&= \cdots \\
&= \mathcal{S}(0)\bigcup_{j=1}^{N_\mathrm{d}}\mathcal{A}_j \\
&= \mathcal{R}_+^K.
\end{aligned}\tag{A.5}$$

Note that the first equality in (A.5) follows from (A.3). The second to the last equality follow by repeatedly applying (A.4).

We prove (A.4) by contradiction. Assume there exists an element $\vec{x}\in\mathcal{S}(n_1,[j_1,\ldots,j_{n_1}])\bigcap\mathcal{S}(n_2,[j_1',\ldots,j_{n_2}'])$. Since $\mathcal{S}(n_1,[j_1,\ldots,j_{n_1}]) = [\bigcap_{p=1}^{n_1}\mathcal{A}_{j_p} - \bigcup_{j=1:j\neq[j_1,\ldots,j_{n_1}]}^{N_\mathrm{d}}\mathcal{A}_j]$, we have:

$$\vec{x}\in\mathcal{A}_{j_p}\quad\forall p\in[1,n_1],\tag{A.6}$$

$$\vec{x}\notin\mathcal{A}_j\quad\forall j\neq\{j_1,\ldots,j_{n_1}\},\tag{A.7}$$

$$\vec{x}\in\mathcal{A}_{j_p'}\quad\forall p\in[1,n_2],\tag{A.8}$$

$$\vec{x}\notin\mathcal{A}_j\quad\forall j\neq\bigl\{j_1',\ldots,j_{n_2}'\bigr\}.\tag{A.9}$$

Without loss of generality, assume that $j_1\neq\{j_1',\ldots,j_{n_2}'\}$. We have from (A.6) and (A.9) that $\vec{x}\in\mathcal{A}_{j_1}$ and $\vec{x}\notin\mathcal{A}_{j_1}$. This results in a contradiction.

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