Optimal Admission Control Algorithms for Scheduling Burst Data in CDMA Multimedia Systems

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Abstract— **3rd generation mobile systems are mostly based on the wideband CDMA platform to support high bit rate packet data services. One important component to offer packet data service in CDMA is a *burst admission control* algorithm. In this paper, we propose and study a novel jointly adaptive burst admission algorithm, namely the *jointly adaptive burst admission–spatial dimension* algorithm (JABA-SD) to effectively allocate valuable resources in wideband CDMA systems to burst requests. In the physical layer, we have a variable rate channel-adaptive modulation and coding system which offers variable throughput depending on the instantaneous channel condition. In the MAC layer, we have an optimal multiple-burst admission algorithm. We demonstrate that synergy could be attained by interactions between the adaptive physical layer and the burst admission layer. We formulate the problem as an integer programming problem and derive an optimal scheduling policy for the jointly adaptive design. Both the forward link and the reverse link burst requests are considered and the system is evaluated by dynamic simulations which takes into account of the user mobility, power control and soft-handoff. We found that significant performance improvement, in terms of average packet delay, data user capacity and coverage, could be achieved by our scheme compared to the existing burst assignment algorithms.**

I. INTRODUCTION

Code division multiple access (CDMA) systems have been proposed [1] for 2nd generation wireless networks to support voice service. However, CDMA has not been pursued as a viable method of providing high speed packet data services [3]. This is because the following points. Firstly, spreading limits the permissible data rates in limited wireless spectrum. Yet, the allocated spectrum could be increased in order to support packet data services and this motivates the wideband CDMA systems. Secondly, law of large number does not hold for the relatively small number of packet data users. Thus, the intrinsic advantage of perfect statistical multiplexing in CDMA systems does not apply to high speed packet data users. In other words, packet data transmissions from data users have to be *coordinated* carefully and this motivates the need for *burst admission control* in wideband CDMA systems for packet data users. Thus, burst admission is very important in CDMA systems to support high speed packet data. In this paper, we extend our previous work on TDMA systems [7] and focus on the joint design of the physical layer and the burst admission layer in wideband CDMA systems to support high speed packet data. Both the physical layer and the burst admission layer are fully adaptive to the time varying channel condition.

In traditional physical layer design, a constant throughput is delivered in that the amount of error protection incorporated into a packet is fixed without regard to the time varying channel condition. However, the design proposed in the present paper is a channel-adaptive one in that a variable throughput channel adaptive encoder and modulator are used in the physical layer [5], [6], [7]. Specifically, a low capacity feedback channel is employed to convey estimated channel state information (CSI) to the transmitter. Thus, under good channel condition (i.e., signal attenuation is low), the amount of protection incorporated is reduced to boost the throughput. On the other hand, more protection is added when the channel condition becomes worse. Using this dynamically adjusted level of protection, the bit-error-rate (BER) is maintained at a constant target level over a range of channel condition[1]. It has been shown [5] that a significant gain in the average throughput can be achieved in these adaptive channel coding schemes. However, most previous adaptive coding schemes are designed for TDMA systems with high bandwidth efficiency. In this paper, the variable throughput adaptive physical layer follows from [9] which is designed for CDMA systems with high bandwidth expansion based on orthogonal coding and modulation.

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[1] When channel adaptive modulation and coding is employed, the penalty during poor channel condition is therefore a lower offered throughput instead of a higher error rate [5].

Burst admission control for CDMA systems is a relatively new research topic. Various burst admission control protocols have been proposed recently based on load and interference measurement [2], [3], [10]. Most existing burst admission control algorithms are designed to handle single-burst assignment only. For example, in [2], [3], only a single data user is considered for the burst admission algorithm. In the cdma2000 system[2], the burst requests are handled on a first-come-first-serve manner. In [10], empirical scheduling such as equal sharing between multiple burst requests is considered. Two major contributions are made in this paper. Firstly, we formulate the burst admission as an integer programming problem and propose a novel optimal burst scheduling algorithm for multiple burst requests to optimize the system throughput and the overall packet delay. Secondly, we illustrate the importance of interactions between the adaptive physical layer and the burst admission algorithm to achieve synergy on performance. We propose and study a novel jointly adaptive burst admission algorithm, namely the *jointly adaptive burst admission—spatial dimension* algorithm (JABA-SD) to effectively allocate valuable resources in wideband CDMA systems. The performance of the burst admission algorithm is evaluated by dynamic simulation[3] which takes into account of the user mobility, power control and soft-handoff.

The paper is organized as follows. In Section II, we discuss the variable-throughout adaptive physical layer design and the wireless channel model. In Section III, we discuss the ABA-SD burst admission algorithm and formulate the scheduling sub-layer as an integer programming problem with various objective measures. The implications of the MAC states to the burst admission algorithm design is also addressed. In Section IV, we derive the optimal solution to the burst admission problem. In Section V, we briefly summarize and discuss the simulation results on comparison of the performance of the proposed ABA-SD with two baseline systems. Finally, we provide some concluding remarks in Section VI.

II. THE ADAPTIVE PHYSICAL LAYER

It has been shown that variable throughput adaptive channel coding could achieve a higher average throughput compared with traditional fixed throughput systems[5]. In this section, we discuss the design and operation of the adaptive physical layer for CDMA systems.

A. Wireless Channel Model

The wireless link between a mobile terminal and the base-station is characterized by two components, namely the *fast fading* component and the *long-term shadowing* component. Fast fading is caused by the superposition of multipath components and is therefore fluctuating in a very fast manner (on the order of a few msec). Long-term shadowing is caused by terrain configuration or obstacles and is fluctuating only in a relatively much slower manner (on the order of one to two seconds). Examples of measured fading signals can be found in [11].

Let $\lambda(t)$ be the combined channel fading which is given by:

$$\lambda(t) = \lambda_l(t)\lambda_s(t) \tag{1}$$

where $\lambda_l(t)$ and $\lambda_s(t)$ are the long-term and short-term fading components, respectively. Both $\lambda_s(t)$ and $\lambda_l(t)$ are random processes with a coherent time on the order of a few milli-seconds and seconds, respectively.

B. Variable Throughput Adaptive Coding and Modulation for CDMA

The system consist of two stages, namely the *adaptive coding stage* and the *spreading stage*. In the adaptive coding stage, redundancy is incorporated to the information packet for error protection. Orthogonal coding and modulation is employed to achieve the high bandwidth expansion requirement in CDMA. To exploit the time-varying nature of the wireless channel, a variable rate channel-adaptive physical layer is employed. Channel state information (CSI), which is estimated at the receiver, is feedback to the transmitter via a low-capacity *feedback channel*. Based on the CSI, the level of redundancy and the modulation applied to the information packets are adjusted accordingly by choosing a suitable transmission mode. Thus, the instantaneous throughput is varied according to the instantaneous channel state. In this paper, a 8-mode (symbol-by-symbol) variable throughput adaptive orthogonal coding scheme (VTAOC) is employed [5]. Thus, the available instantaneous throughput, which is defined as the number of information bits carried per modulation symbol, ranges from $1/2^2$ to $1/2^9$ depending on the channel condition. Specifically, transmission mode-q is chosen for the current information bit if the feedback CSI, falls within the *adaptation thresholds*, (ζ_{q-1}, ζ_q). Here, the operation and the performance of the VTAOC scheme is determined by the set of adaptation thresholds $\{\zeta_0, \zeta_1, \ldots, \zeta_M\}$. In this paper, it is assumed that the VTAOC scheme is operated in the *constant BER* mode [5]. That is, the adaptation thresholds are set optimally to maintain a target transmission error level over a range of CSI values [5]. When the channel condition is good, a higher transmission mode could be used and the system enjoys a higher throughput. On the other hand, when the channel condition is bad, a lower mode is used to maintain the target error level at the expense of a lower transmission throughput.

In the spreading stage, the orthogonal coded symbols from the VTAOC is spreaded by a PN sequence to achieve the target spread spectrum. Spreaded chips are QPSK modulated and transmitted to the wireless channel. We assume the presence of pilot channel[2] and therefore, channel state estimation and coherent demodulation could be done at the receiver based on the pilot signal. Let T_b, T_s and T_c be the bit-duration, orthogonal coded symbol duration and the chip-duration. The *overall processing gain*, $\mathcal{G}$, is given by:

$$\mathcal{G} = \frac{T_b}{T_c} = \frac{T_b}{T_s} \times \frac{T_s}{T_c} = \frac{T_b}{T_s} \times g = \frac{W}{\mathcal{R}_b} \qquad (2)$$

where W, $\mathcal{R}_b$, g and $\frac{T_s}{T_b}$ are the system bandwidth, the instantaneous bit rate, the processing gain of the spreading stage and the throughput offered by the VTAOC block respectively. Note that the instantaneous symbol energy-to-interference ratio, $\frac{E_s}{I_0}$, is given by:

$$\frac{E_s}{I_0} = \lambda_l \bar{c} \qquad (3)$$

where λ_l and $\bar{c}$ are the fast fading component and the short-term average symbol energy-to-interference ratio. Suppose the fundamental channel (FCH) is operating at a fixed-rate transmission with a fixed throughput of ρ_f, spreading gain of g_f and bit rate of $\mathcal{R}_f$. The relative average bit rate of the supplemental channel (SCH) for burst data, $\delta\mathcal{R}_b = \frac{\mathcal{R}_s}{\mathcal{R}_f}$, is given by:

$$\frac{\mathcal{R}_s}{\mathcal{R}_f} = \delta\mathcal{R}_b = \frac{\mathcal{E}[T_s^s/T_b^s][W/g_s]}{\rho_f[W/g_f]} = \frac{\rho_s(\bar{c}_s)}{\rho_f} \times \frac{g_f}{g_s} = \delta\rho_s(\bar{c}_s)m \qquad (4)$$

where $\delta\rho_s$ and m are the relative average throughput($\frac{\rho_s}{\rho_f}$) and the relative spreading gain ($\frac{g_f}{g_s}$) between the SCH and FCH respectively. Thus, high speed transmission of the SCH is accomplished by the reduced spreading gain (m) and the higher average throughput ($\delta\rho$) of the VTAOC. Note that the average throughput offered by the VTAOC is a function of the *short-term average CSI* ($\bar{c}_s$) and the target BER, P_b [5]. Thus, the fast fading component (λ_l) is handled by the VTAOC system while the offered SCH bit rate (short-term average), $\mathcal{R}_s$, is varying in accordance with the local mean CSI ($\bar{c}_s$).

Let X_s and X_f be the required transmission power of the SCH and FCH respectively. The ratio of X_s to X_f is given by:

$$\frac{X_s}{X_f} = \frac{\bar{c}_s}{\bar{c}_f} \times m = \gamma_s \times m \qquad (5)$$

where γ_s is the relative symbol energy-to-interference ratio between the SCH and the FCH to support their required error rates and throughput in the VTAOC system. Note that γ_s is a fixed parameter which is dependent only on the target error levels of the FCH and SCH as well as the FCH throughput (ρ_f). Thus, γ_s is independent of the local mean CSI ($\bar{c}_s$) and the SCH bit rate, $\mathcal{R}_s$.

III. FORMULATION OF THE BURST ADMISSION PROBLEM

A generic burst admission algorithm could be decomposed into two sub-layers, namely the *measurement sub-layer* and the *scheduling sub-layer*. We first discuss the measurement sub-layer followed by the scheduling sub-layer.

A. 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 loading 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.

A.1 Forward Link Measurement

Consider we have N_d high speed data users in a cell. The mobile users are labelled by the index $j \in [1, N_d]$ and the cell is labeled by the index k. Assume the maximum loading of a cell is P_{max} and the loading[3] of the base station-k to support the FCH of the mobile state-j is $P_{j,k}$. Note that $P_{j,k} = 0$ if cell-k is not in the reduced active set[4] of the mobile-j. Let P_k be the existing loading in the cell-k and m_j be the ratio of the spreading gain of FCH to

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[2] This is a valid assumption based on the cdma2000 design [2].

[3] Since the constraint in forward link is the available transmitted power, forward link loading refers to the transmission power required at the base station.

[4] 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 in cdma2000. The reduced active set is assumed to be the set of the 2 base stations with the strongest pilot E_c/I_{or} and is a subset of the active set of FCH.

SCH[5]. 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 loading of the burst requesting mobile. 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. From (5), the additional forward link power required at the k-th base station to accommodate the j-th data user is given by:

$$\Delta P = m_j P_{j,k} \gamma_s \alpha_j^{(FL)} \tag{6}$$

where $\alpha_j^{(FL)}$ is the adjustment factor taking into account of the reduced active set[2]. Thus, for N_d concurrent data users, the *admissible region* is given by:

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

or

$$\mathcal{A}\vec{m} \leq \vec{P} \tag{7}$$

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:

$$a_{jk} = \gamma_s P_{jk} \alpha_j^{(FL)} \tag{8}$$

Thus, the measurements accomplished with the forward burst request includes (1) the current cell loading P_k and (2) the current forward link loading associated with the mobile-j, $P_{j,k}$, which could be obtained directly from the base stations in the reduced active set.

A.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 (1) the extra reverse link interference caused by the data burst transmission in the host cell is within threshold and (2) 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:

Soft-Handoff Cells: For the base station (k) in soft-handoff with a mobile station (j), it measures (1) the total received power from the reverse link (L_k) and (2) the reverse link pilot strength, $t_{j,k}^{(RL)} = \frac{E_c}{I_{or}}$ from the mobile station-j. Let $X_{j,k}(FCH)$ be the received power at base station k from mobile station j, supporting the fundamental channel (FCH). The received bit energy to interference ratio of the reverse FCH, $(E_b/I_o)_{j,k}[FCH]$ is given by:

$$\left(\frac{E_b}{I_0}\right)_{j,k}[FCH] = G_{FCH}\frac{X_{j,k}(FCH)}{L_k} \tag{9}$$

Thus, the reverse link received power at base station k due to the FCH of the j-th mobile station, $X_{j,k}(FCH)$, is given by:

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

However, we do not have $\left(\frac{E_b}{I_0}\right)_{j,k}[FCH]$ measurement directly. Instead, we have the reverse link pilot strength measurement, $t_{j,k}^{(RL)} = E_c/I_0$. Since we have:

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

where ξ_j is the transmit power ratio of FCH and pilot at the mobile state j, the reverse link loading of FCH of the j-th mobile could be expressed as follows:

$$X_{j,k}(FCH) = L_k t_{j,k}^{(RL)} \xi_j \tag{10}$$

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

$$Y_{j,k} = m_j X_{j,k}(FCH)\alpha_j \gamma_s \tag{11}$$

where $\alpha_j^{(RL)}$ is the power adjustment factor to account for the reduced active set soft-handoff effect. Substituting from (10), we have:

$$Y_{j,k} = m_j \gamma_s \alpha_j^{(RL)} \xi_j t_{j,k}^{(RL)} L_k \tag{12}$$

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 user j ($t_{j,k'}$). Instead, 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

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[5] 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.

neighbor cell and the host cell. Since path loss depends on the distance of the mobile user and the base station, path loss is symmetrical for the forward and the reverse link and could be estimated as follows.

When there is a reverse burst request, the mobile user will send a supplemental channel request message (SCRM) to the base station. The SCRM message contains the forward link pilot strength measurements, $t_{j,k'}^{(FL)} = (E_c/I_0)_{jk}$, for a number of neighbor cells[6]. These pilot strength measurements are used to estimate the relative path loss. Let $\rho_{k'}$ be the path loss of the cell (k').

$$\rho_{k'} \propto t_{j,k'}^{(FL)} \tag{13}$$

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

$$\delta\rho_{k,k'} = \frac{t_{j,k'}^{(FL)}}{t_{j,k}^{(FL)}} \tag{14}$$

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

$$\begin{aligned} Y_{j,k'} &= L_k(m_j\gamma_s\alpha_j^{(RL)}\xi_j t_{j,k}^{(RL)})\kappa\delta\rho_{k,k'} \\ &= L_k m_j\gamma_s\alpha_j^{(RL)}\xi_j\kappa t_{j,k}^{(RL)}\frac{t_{j,k'}^{(FL)}}{t_{j,k}^{(FL)}} \end{aligned} \tag{15}$$

where κ 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:

$$L_k + \sum_{j=1}^{N_d} Y_{j,k} \le L_{max}, \quad \forall k \in [1, K]$$

where $Y_{j,k}$ is given by (12) if k is in soft-handoff with mobile j or is given by (15) if k is not in soft-handoff. Rearranging the terms, the *admissible region* for the $N-d$ concurrent data users is given by:

$$\sum_{j=1}^{N_d} b_{jk}m_j \le \frac{L_{max}}{L_k} - 1 \tag{16}$$

or

$$\mathcal{B}\vec{m} \le \vec{L} \tag{17}$$

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

$$b_{jk} = \gamma_s \begin{cases} \alpha_j^{(RL)}\xi_j t_{j,k}^{(RL)} & \text{cell-}k\text{ in soft-handoff} \\ \alpha_j^{(RL)}\xi_j\gamma_j t_{j,k}^{(RL)}\frac{t_{j,k'}^{(FL)}}{t_{j,k}^{(FL)}} & \text{cell-}k\text{ not in soft-handoff} \end{cases} \tag{18}$$

Thus, the measurements accomplished with the reverse burst request includes (1) the reverse interference, L_k, from the cells and (2) the reverse pilot strength measurements, $t_{j,k}^{(RL)}$, from the soft-handoff cells, and (3) the forward link pilot strength measurement reported from the mobile user, $t_{j,k}^{(FL)}$.

B. Scheduling Sub-Layer

The measurement sub-layer defines the *admissible regions* for both the forward link and the reverse link burst admission. The optimal scheduling solution should be designed with respect to an objective function. In general, an objective function should be a compromise of (1) system resource utilization and (2) overall system delay. In this paper, we consider the following two objective functions.

$$\mathcal{J}_1(\vec{\mathcal{R}}) = \sum_{j=1}^{N_d}\mathcal{R}_j \propto \sum_{j=1}^{N_d} m_j\delta\rho_j \tag{19}$$

and

$$\begin{aligned} \mathcal{J}_2(\vec{\mathcal{R}}, \vec{w}) &= \sum_{j=1}^{N_d}[\mathcal{R}_j(1+\Delta_j) - f(w_j, \mathcal{R}_j) \\ &\propto \sum_{j=1}^{N_d}[m_j\delta\rho_j(1+\Delta_j) - f(w_j, m_j\delta\rho_j) \end{aligned} \tag{20}$$

where $\vec{w}$, $f(w_j, m_j\delta\rho_j)$ and Δ_j are the waiting time vector for N_d data users, the waiting time penalty function (linear in $m_j\delta\rho_j$), as well as the priority due to traffic type respectively. The first objective function focuses on the overall system transmission rate. Intuitively, those requests resulting in high transmission rate 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. For instance, we have to minimize the delay penalty ($f(w_j, m_j\delta\rho_j)$) despite the fact that those requests may be at poor transmission rate. Note that $\mathcal{J}_1(\vec{\mathcal{R}})$ is a special case of $\mathcal{J}_2(\vec{\mathcal{R}}, \vec{w})$.

The delay penalty function is given by:

$$f(w_j, m_j\delta\rho_j) = D_0 - \lambda(w_j)^{\beta} m_j\delta\rho_j \tag{21}$$

where λ and β are the scaling factor and the delay forgetting factor. The delay penalty increases with the overall

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[6] In cdma2000, the SCRM message contains at most 8 pilot strength measurements.

request delay, w_j and decreases with $\delta\rho_j$. With reference to the state diagram of cdma2000 [1], a huge set up delay penalty will be imposed if the waiting time exceeds time out values. To take into account of the set up delay penalty due to MAC states time out, the overall request delay is given by:

$$w_j = t_w + D_s \tag{22}$$

where t_w is the request waiting time and D_s is the MAC setup delay penalty given by:

$$D_s = \begin{cases} 0 & t_w < T_2 \\ D_1 & t_w \in [T_2, T_3) \\ D_2 & t_w > T_3 \end{cases} \tag{23}$$

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:

$$m_j \leq \min\left\{M, \frac{Q_j}{T_l \delta\rho_j}\right\} \tag{24}$$

where Q_j is the burst packet size for the j-th request. Thus, the objective functions ($\mathcal{J}_1, \mathcal{J}_2$) together with the admissible region constraint, (17) and (7), and the burst duration constraint and (24), form an integer programming problem in $\vec{m}$. 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 $Q_j/(m_j \delta\rho_j)$.

IV. JOINTLY ADAPTIVE BURST ADMISSION ALGORITHM

A. Optimal Solution

In this section, we derive the optimal solution to the burst admission problem based on a jointly adaptive design. Specifically, both the physical layer and the burst admission layer is fully adaptive to the short-term average CSI, $\bar{c}_s$. Furthermore, the burst admission layer interacts closely with the variable throughput adaptive physical layer by exchanging the instantaneous throughput information ($\delta\rho_j$).

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:

$$\begin{aligned} \mathcal{F}(\vec{\mu}) &= \max_{\vec{m}} \{\mathcal{J}_2(\vec{m}, \vec{w})\} \\ &= \max_{\vec{m}} \sum_{j=1}^{N_d} (1 + \Delta_j + \lambda(w_j)^\beta)\delta\rho_j m_j \end{aligned} \tag{25}$$

with the constraint given by the *admissible region*:

$$\sum_{j=1}^{N_d} a_{kj} m_j \leq \mu_k, \forall k \in [1, K] \tag{26}$$

Theorem 1: The optimization problem (25) could be expressed into the following recursive form:

$$\mathcal{F}(\vec{\mu}) = \max\left\{0, \max_{j:\vec{\mu} \geq \vec{a}_j} [(1 + \Delta_j + \lambda(w_j)^\beta)\delta\rho_j + \mathcal{F}(\vec{\mu} - \vec{a}_j)]\right\} \tag{27}$$

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

Proof: Omitted due to space limitations (can be found in [8]). ■

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 (27) 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.

A.1 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:

$$\mathcal{R}_+^K = \mathcal{R}_1 \times \mathcal{R}_2 \times \ldots \mathcal{R}_K \tag{28}$$

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

$$\begin{aligned} \mathcal{P} = \{&\mathcal{S}(0), \mathcal{S}(1, [j_1]), \mathcal{S}(2, [j_1, j_2]), \ldots, \\ &\mathcal{S}(N_d, [j_1, \ldots, j_{N_d}]) : \\ &j_n \in [1, N_d], j_1 \neq j_2 \neq \ldots \neq j_{N_d}\} \end{aligned} \tag{29}$$

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

$$\mathcal{S}(n, [j_1, \ldots, j_n]) = \bigcap_{i=1}^{n} \mathcal{A}_{j_i} - \bigcup_{j \neq [j_1, \ldots, j_n]} \mathcal{A}_j \tag{30}$$

Note that *complete partition* means that

$$\bigcup_{n \in [0, N_d], [j_1, \ldots, j_n] \in \mathcal{C}_n^{N_d}([1, \ldots, N_d])} \mathcal{S}(n, [j_1, \ldots, j_n]) = \mathcal{R}_+^K \tag{31}$$

and

$$\mathcal{S}(n_1,[j_1,\ldots,j_{n_1}])\bigcap\mathcal{S}(n_2,[j_1^{'},\ldots,j_{n_2}^{'}])$$
$$=\Phi \text{ for } \mathcal{S}(n_1,[])\neq\mathcal{S}(n_2)[] \tag{32}$$

Proof: Omitted due to space limitations (can be found in [8]). ■

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

A.2 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

$$\mathcal{F}(\vec{\mu}\in\mathcal{S}(0))=0 \tag{33}$$

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

$$\begin{aligned}&\mathcal{Q}(n,[j_1,\ldots,j_n])=\{(\mu_1,\ldots,\mu_K)\in\mathcal{S}(n,[j_1,\ldots,j_n])\\ &\text{and:}\\ &\mu_k=0 \text{ if } a_{kj}=0\forall j\in[j_1,\ldots,j_n],\\ &\mu_k=\max_{j\in[j_1,\ldots,j_n]}[a_{kj}]+i\delta q_n \text{ for some } i\in[0,1,\ldots],\\ &\text{if } a_{kj}\neq 0.\}\end{aligned} \tag{34}$$

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

A.3 Step III: Partial Resource Allocation

We solve the iterative equation (27) 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:

$$\mathcal{F}(\vec{\mu})=\max_{j\in[j_1,\ldots,j_n]}\{(1+\Delta_j+\lambda(w_j)^{\beta})\delta\rho_j+\mathcal{F}(-_n[\vec{\mu}-\vec{a}_j)]\} \tag{35}$$

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

$$\begin{aligned}&|\vec{x}-\hat{\vec{x}}|\leq|\vec{x}-\vec{y}|\\ &\forall\vec{y}\in\mathcal{S}(0)\\ &\bigcup_{r=1}^{n}\;\bigcup_{(p_1,\ldots,p_r)\in\mathcal{Q}_r^n([j_1,\ldots,j_n])}\mathcal{Q}(r,[p_1,\ldots,p_r])\end{aligned} \tag{36}$$

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

$$\begin{aligned}\mathcal{C}_r^n([j_1,\ldots,j_n]) \;=\;& \{(p_1,\ldots,p_r):\\ & p_i\in[j_1,\ldots,j_n],p_{i_1}\neq p_{i_2}\}\end{aligned} \tag{37}$$

Denote the *allocation index*, j^* as $j^*=f(\vec{\mu})$ where j^* is the result of the $\max$ operation in (35). The *allocation vector*, $g(\vec{\mu})$, is defined as $(m_1,m_2,\ldots,m_{N_d})$ such that $m_{j^*}=1$ and $m_{j'}=0\forall j'\neq j^*$.

A.4 Step IV: Termination

Define the initial resource vector, $\vec{\mu}_1$ as $-_{N_d}[(P_{max}-P_1),(P_{max}-P_2),\ldots,(P_{max}-P_K)]$. ¿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 p-th resource vector and the p-th allocation index given by:

$$\vec{\mu}_p=\vec{\mu}_{p-1}-\vec{a}_{j_{p-1}^*} \tag{38}$$

and

$$j_p^*=f(\vec{\mu}_p) \tag{39}$$

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.

B. Sub-Optimal Solution

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

$$\zeta_j^{(p)}=\min_{k:a_{kj}>0}\left[M_0,\frac{P_{max}-P_k-\sum_{j'=1}^{N_d}a_{kj'}m_{j'}^{(p-1)}}{a_{kj}}\right] \tag{40}$$

where $M_0=\min[M,\lfloor Q_{j*}/(T_l\delta\rho_j)\rfloor]$ and $\vec{m}^{(p-1)}=[m_1^{(p-1)},\ldots,m_{N_d}^{(p-1)}]$ is the allocation vector at the $(p-1)$-th iteration. Let $\xi_j^{(p)}$ be the priority function at the p-th iteration, which is given by:

$$\xi_j^{(p)}=(1+\Delta_j+\lambda(w_j)^{\beta})\delta\rho_j\zeta_j^{(p)} \tag{41}$$

Intuitively, request that occupies small system resource or request that have a long waiting time should be given higher priority as indicated in (41). The iteration starts at $p=1$ where $\vec{m}^{(0)}=[0,\ldots,0]$. The algorithm try to allocate δm resource to one of the competing requests according to their priorities, $[\xi_1^{(p)},\ldots,\xi_{N_d}^{((p))}$. 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 exist some j such that $\zeta_j^{(p+1)} \leq 0$.

V. PERFORMANCE RESULTS

The proposed burst admission algorithm is compared with two baseline systems at the same bandwidth and error probability levels. In *baseline I*, we consider the cdma2000 system which assign burst requests on a first-come-first-serve basis. The underlying physical layer is fixed throughput and hence, high speed SCH transmission is accomplished by the reduction of spreading gain only. On the other hand, it is shown in [9] that variable throughput adaptive physical layer could offer a higher average throughput relative to the fixed throughput systems at the same average energy and error level. Thus, in order to demonstrate that the reported performance gain of the proposed JABA scheme is not entirely due to the underlying adaptive physical layer, we compare the JABA scheme with a second baseline system as well. In the *baseline II* system, we have the same adaptive physical layer as the JABA scheme. However, the physical layer and the burst admission layer are isolated. Thus, the burst admission layer does not have the instantaneous offered throughput information ($\delta\rho_j$) from the adaptive physical layer. The corresponding scheduling algorithm would be the same as in Section IV-B except (41) becomes:

$$\xi_j^{(p)} = (1 + \Delta_j + \lambda(w_j)^{\beta})\zeta_j^{(p)} \tag{42}$$

All the burst admission algorithms are evaluated based on static and dynamic simulations used in [3]. For brevity, we do not describe the simulation details here but refer the readers to [3] for more information about the models. Specifically, we employ static Monte Carlo techniques for generating the coverage results for high speed data users. The celluar 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 [4] for an urban environment. We repeat the Monte Carlo simulations for 100 times to obtain the static coverage results. The simulation as well as the physical layer parameters of the *VTAOC* scheme and the cdma2000 scheme are shown in Table I.

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.

TABLE I
PHYSICAL LAYER PARAMETERS.

Parameter	Value
Path loss exponent	4
Average adjacent cell load	50%
Chip rate	7.3728Mcps
FCH rate	14.4kbps
cdma2000 - SCH rate	[14.4kbps - 1.8432Mbps]
VTAOC - SCH rate	[14.4kbps - 460.8kbps]^7
PG[cdma2000-FCH]	512
PG[cdma2000-SCH]	[512 - 4]
BER[FCH]	10^{-2}
BER[SCH]	10^{-4}
E_s/I_0[cdma2000 - FCH]	7dB
E_s/I_0[cdma2000 - SCH]	13dB
PG[cdma2000-FCH]	512
PG[cdma2000-SCH]	[512 - 4]
ρ[VTAOC-FCH, VTAOC-SCH]	$1/16$
E_s/I_0[VTAOC - FCH]	-7dB
E_s/I_0[VTAOC - SCH]	-3dB
PG[VTAOC-FCH]	32
PG[VATOC-SCH]	[32 - 1]

Figure 1 shows the forward link capacity of the three different burst admission control schemes. As can be seen, the proposed JABA-SD algorithm 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 2.

For the reverse link, we obtain results on admission and outage probabilities, as shown in Figures 3 and 4. Again, we can see that the JABA-SD approach can allow a high admission probability, through its judicious merging of different requests arrived at different time periods. The JABA-SD approach can also support a much higher number of voice users.

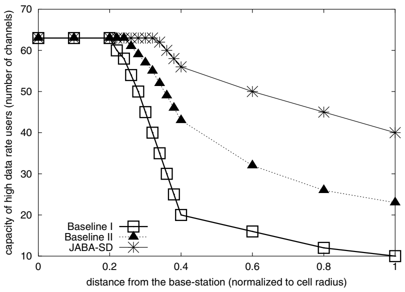

Fig. 1. Number of channels available on the forward link with varying distances from the base-station.

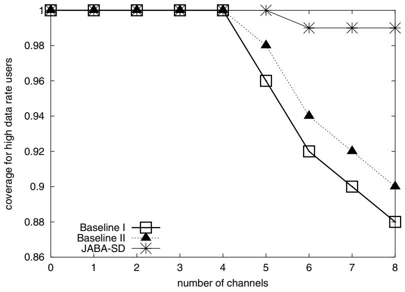

Fig. 2. Forward link coverage area as a function of number of channels.

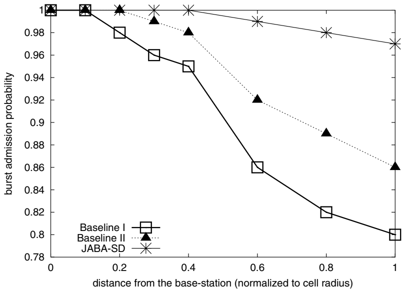

Fig. 3. Average admission probabilities on the reverse link.

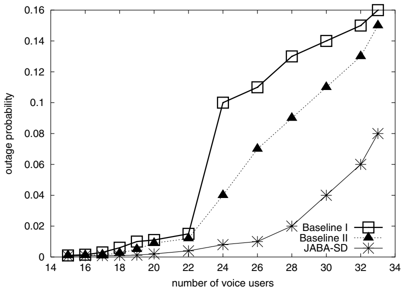

Fig. 4. Outage probabilities for voice users.

VI. CONCLUSIONS

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, called JABA-SD, 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 the JABA-SD scheme outperforms the FCFS scheduling scheme and the allocation method used in cdma2000.

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