# On Channel-Adaptive Multiple Burst Admission Control for Mobile Computing Based on Wideband CDMA *

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## ABSTRACT

Mobile computing systems built using third generation wireless standards 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 formulate the multiple-burst admission control problem as an integer programming problem, which induces our novel jointly adaptive burst admission algorithm, called the *jointly adaptive burst admission–spatial dimension* algorithm (JABA-SD), which is designed to effectively allocate valuable resources in wideband CDMA systems to burst requests. 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 hand-off.

## 1. INTRODUCTION

Traditional protocol stack design is based on the layering approach. System designers attempt to optimize individual protocol layers without considering the interaction between layers. The advantage of this approach is flexibility and modularity. This is fine for fixed wire systems where the performance of the physical layer is essentially time invariant. However, in wireless environment, performance gains could be achieved by considering joint design between protocol layers. In this paper, we extend our previous work on TDMA systems [5] 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.

Code division multiple access (CDMA) systems have been proposed [1] for 2nd generation wireless networks to support voice service. In contrast to orthogonal systems like TDMA or FDMA, frequency planning and channel allocation between cells are greatly simplified. In the voice situation, reuse in CDMA systems is based on the average interference seen from a large number of low-power users. Because of this interference averaging property, CDMA simply translates voice activity factor and antenna sectorization into capacity gains. In order to provide integrated voice and data services, the network must be able to statistically multiplex users with different rates and QoS requirements effectively. Naturally, CDMA systems offer a near perfect statistical multiplexing for voice users. As long as voice users are independent of each other and the number of voice users is sufficiently large, there is no need for voice packet coordination. Note that by law of large number, average number of voice users simultaneously transmitting voice packets is given by $\sum_{i=1}^{N} 1(v_n = 1) \longrightarrow \mathcal{E}[1(v_n = 1)] = Np_{on}$ where $\{v_n\}$ is an i.i.d. binary random sequence indicating whether the $n$-th voice user is on or off and $Np_{on}$ is the statistical multiplexing limit. On the other hand, CDMA has not been pursued as a viable method of providing high speed packet data services [2]. 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. Therefore, 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. Therefore, burst admission is very important in CDMA systems to support high speed packet data.

On the other hand, traditional physical layer delivers a constant throughput 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 [3, 4, 5]. 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

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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 [3] 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 [7] which is designed for CDMA systems with high bandwidth expansion based on orthogonal coding and modulation.

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 [1, 2, 8]. Most existing burst admission control algorithms are designed to handle single-burst assignment only. For example, in [1, 2], only a single data user is considered for the burst admission algorithm. In the cdma2000 system[1], the burst requests are handled on a first-come-first-serve manner. In [8], empirical scheduling such as equal sharing between multiple burst requests is considered. The major contribution in this paper is that 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. Based on the formulation, 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. Due to space limitations, we do not describe the details of the JABA-SD algorithm in this paper. The detailed design and analytical properties, as well as the performance of the proposed JABA-SD algorithm, can be found in [6]. To summarize, in [6], the performance of the burst admission algorithm is evaluated by dynamic simulations [2] which takes into account of the user mobility, power control and soft hand-off. 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, are also discussed in [6]. Specifically, in the physical layer of the JABA-SD algorithm, 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. The superior performance, in terms of average packet delay, data user capacity and coverage, of the JABA-SD algorithm illustrates that synergy could be attained by interactions between the adaptive physical layer and the burst admission layer.

This paper is organized as follows. In Section 2, we discuss the variable-throughout adaptive physical layer design and the wireless channel model. In Section 3, 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.

[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 [3].

## 2. 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[3]. In this section, we discuss the design and operation of the adaptive physical layer for CDMA systems.

### 2.1 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).

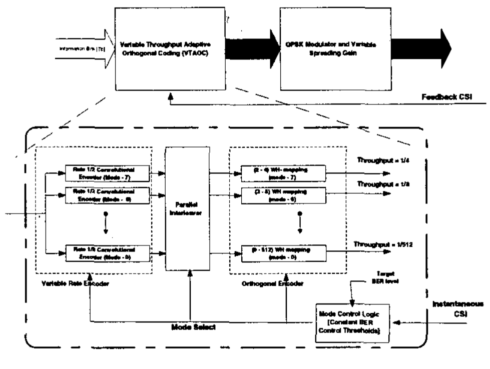
Let $\lambda(t)$ be the combined channel fading which is given by:

$$\lambda(t) = \lambda_l(t)\lambda_s(t) \quad (1)$$

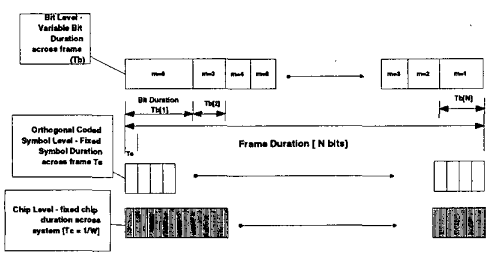
where $\lambda_l(t)$ and $\lambda_s(t)$ are the long-term and short-term fading components, respectively. Both $\lambda_s(t)$ and $\lambda_l(t)$ are random processes with a coherent time on the order of a few milli-seconds and seconds, respectively.

### 2.2 Variable Throughput Adaptive Coding and Modulation for CDMA

The system consist of two stages, namely the *adaptive coding stage* and the *spreading stage* as illustrated in Figure 1(a). 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 as illustrated in Figure 1(a). 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 [3]. Therefore, 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*, $(\zeta_{q-1}, \zeta_q)$. The typical mode sequence of a transmitted frame is illustrated in Figure 1(b). 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 [3]. That is, the adaptation thresholds are set optimally to maintain a target transmission error level over a range of CSI values. 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.




(a) Conceptual system block diagram




(b) A typical transmitted frame

**Figure 1: Block diagram of variable throughput adaptive physical layer.**

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 as illustrate in Figure 1. 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 $\lambda_l$ 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 $\rho_f$, 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, $P_b$. Thus, the fast fading component ($\lambda_l$) 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 ($\bar{c}_s$) as illustrated in Figure 1.

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 $\gamma_s$ 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 $\gamma_s$ is a fixed parameter which is dependent only on the target error levels of the FCH and SCH as well as the FCH throughput ($\rho_f$). Thus, $\gamma_s$ is independent of the local mean CSI ($\bar{c}_s$) and the SCH bit rate, $\mathcal{R}_s$.

## 3. 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.

### 3.1 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.

[2]This is a valid assumption based on the cdma2000 design [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 SCH[5]. Thus, a burst should be admitted if there is available power in all the base stations (involved in soft hand-off) 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[1]. 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:

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

Therefore, as illustrated in Figure 2(a), 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.

**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. Therefore, we deal with reverse link burst assignment in the following two cases:

**Soft hand-off cells:** For the base station (k) in soft hand-off with a mobile station (j), it measures (i) the total received power from the reverse link ($L_k$) and (ii) the reverse link pilot strength, $t_{j,k}^{(RL)} = \frac{E_c}{I_{or}}$ from the mobile station-$j$. This is illustrated in Figure 2(b). 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 $\xi_j$ 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:

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

Therefore, 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 hand-off effect. Substituting from (10), we have:

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

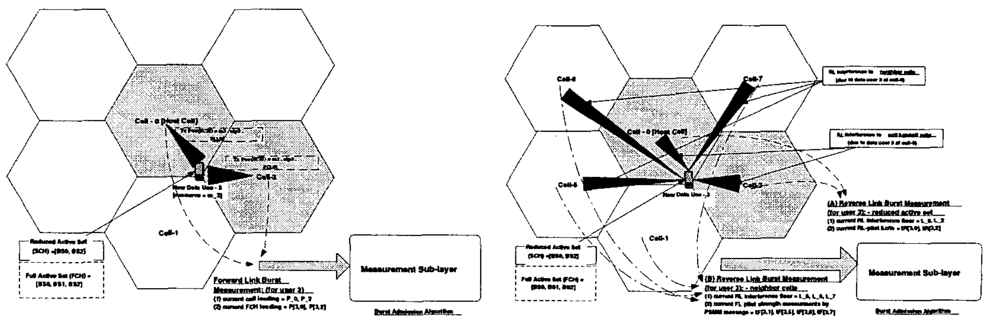
where $m_j \in [0, M]$ is the ratio of the spreading gain of FCH to SCH. Note that $m_j = 0$ denotes that the burst request is rejected.

**Neighbor cells not in soft hand-off:** For a neighbor cell ($k'$) not in soft hand-off, the base station does not have the reverse link pilot measurement from the mobile user j ($t_{j,k'}$). This is illustrated in Figure 2(b). Instead, the base station only have the current reverse

[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 hand-off 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.

[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. Therefore, we assume single SCH assignment with variable spreading gain in this paper to support high speed data transmission.



(a) Forward link burst measurements (b) Reverse link burst measurements

**Figure 2: Forward and reverse link measurements needed for burst request.**

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 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, $t^{(FL)}_{j,k'} = (E_c/I_0)_{jk}$, 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').

$$\rho_{k'} \propto t^{(FL)}_{j,k'} \tag{13}$$

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

$$\delta\rho_{k,k'} = \frac{t^{(FL)}_{j,k'}}{t^{(FL)}_{j,k}} \tag{14}$$

Therefore, 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:

$$\begin{aligned} Y_{j,k'} &= (m_j \gamma_s \alpha^{(RL)}_j \xi_j t^{(RL)}_{j,k}) \kappa \delta\rho_{k,k'} \\ &= m_j \gamma_s \alpha^{(RL)}_j \xi_j \kappa t^{(RL)}_{j,k} \frac{t^{(FL)}_{j,k'}}{t^{(FL)}_{j,k}} \end{aligned} \tag{15}$$

where $\kappa$ is the additional margin to take into account of the attenuation fluctuations due to shadowing.

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

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 hand-off with mobile $j$ or is given by (15) if $k$ is not in soft hand-off. 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:

$$b_{jk} = \gamma_s \begin{cases} \alpha^{(RL)}_j \xi_j t^{(RL)}_{j,k} & \text{cell-}k \text{ in soft hand-off} \\ \alpha^{(RL)}_j \xi_j \gamma_j t^{(RL)}_{j,k} \frac{t^{(FL)}_{j,k'}}{t^{(FL)}_{j,k}} & \text{cell-}k \text{ not in soft hand-off} \end{cases} \tag{18}$$

Therefore, as illustrated in Figure 2(b), 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, $t^{(RL)}_{j,k}$, from the soft hand-off cells, and (3) the forward link pilot strength measurement reported from the mobile user, $t^{(FL)}_{j,k}$.

## 3.2 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 (i) system resource utilization and (ii) overall system delay. In this paper, we consider the following two objective functions.

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

and

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

where $\vec{w}$, $f(w_j, m_j\delta\rho_j)$ and $\Delta_j$ 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:

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

where $\lambda$ and $\beta$ are the scaling factor and the delay forgetting factor. The delay penalty increases with the overall request delay, $w_j$ and decreases with $\delta\rho_j$. As illustrated in Figure 3, 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:

$$w_j = t_w + D_s \qquad (22)$$

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

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

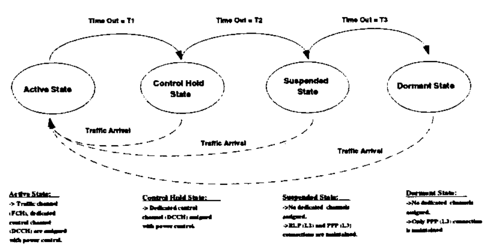



**Figure 3: MAC states of cdma2000 to support high speed packet data.**

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. Therefore, we have a lower bound ($T_l$) on the assigned burst duration. That is:

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

where $Q_j$ is the burst packet size for the $j$-th request. Therefore, 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 $Q_j/(m_j\delta\rho_j)$.

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