

# Performance of Cellular CDMA with Voice/Data Traffic with an SIR based Admission Control

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**Abstract**— We analyze the performance of an SIR based admission control strategy in cellular CDMA systems with both voice and data traffic. Most studies in the current literature to estimate CDMA system capacity with both voice and data traffic do not take signal-to-interference ratio (SIR) based admission control into account. In this paper, we present an analytical approach to evaluate the outage probability for voice traffic, the average system throughput and the mean delay for data traffic for a voice/data CDMA system which employs an SIR based admission control. We show that for a data-only system, an improvement of about 25% in both the Erlang capacity as well as the mean delay performance is achieved with an SIR based admission control as compared to code availability based admission control. For a mixed voice/data system with 10 Erlangs of voice traffic, the improvement in the mean delay performance for data is about 40%. Also, for a mean delay of 50 ms with 10 Erlangs voice traffic, the data Erlang capacity improves by about 50%.

**Keywords** — Cellular CDMA, voice/data traffic, admission control, SIR.

## I. INTRODUCTION

Code division multiple access (CDMA) cellular systems with voice-only traffic have been known to offer higher system capacity than than the channelized systems [1]. Several studies analyzing the capacity of CDMA systems have been reported [2],[3]. However, these studies did not take into account admission control strategies based on signal-to-interference ratio (SIR) measurements. In [4], we had analyzed, using Chernoff bound and central limit theorem approximations, the capacity and outage performance of a *voice-only* cellular CDMA system with an SIR based admission control strategy. We showed that an improvement of about 30% in the system capacity is achieved for an outage probability of 1%. This study, however, did not consider the performance with mixed voice and data traffic, which is typical in the next generation CDMA cellular systems [5]. Performance of CDMA systems with voice and data traffic has been studied in [6],[7]. These studies have considered admission control, but based only on code availability. Admission control based on SIR measurements can offer improved performance [4].

Our focus in this paper is to develop an analytical approach to evaluate the performance of a *mixed voice/data* CDMA system which employs an SIR based admission control. We derive expressions for a) the outage probability of voice calls, b) the average system throughput, and c) the mean delay performance for data traffic. For deriving the outage probability, we

use a Chernoff bound approximation. For deriving the mean delay for data traffic, we model the system as a single *virtual buffer*, where all the buffered data (at all the mobiles in all the cells) are queued in the order of their arrival epochs. We compute the mean delay for the first departing data burst of this virtual buffer. We then model the rest of the buffer as an  $M/G/1$  queue with a mean service time equal to the mean delay of the first departing data burst. We show that, for a data-only system, an improvement of about 25% in both the Erlang capacity as well as the mean delay performance is achieved with an SIR based admission control as compared to code availability based admission control. For a mixed voice/data system with 10 Erlangs of voice traffic, the improvement in the mean delay performance is about 40%. Also, for a mean delay of 50 ms with 10 Erlangs voice traffic, the data Erlang capacity improves by about 50%.

## II. SYSTEM MODEL

Consider a voice/data CDMA cellular system with  $N = 61$  circular cells. The objective is to develop an analytical approach to evaluate the performance of this system with an SIR based admission control on the uplink (mobile-to-base station link). The performance measures of interest are the outage probability for voice calls, the average system throughput, and the mean delay for data traffic.

Voice calls are assumed to be of circuit-switched type. Each voice call uses a spreading code for transmission. The assigned code is held for the entire duration of the call, after which it is released. Data traffic, on the other hand, is assumed to arrive in bursts. Spreading codes are allocated and released on a burst-by-burst basis.

A voice call or a data burst originating from a mobile is admitted into the system if a) spreading codes are available for allocation, and b) the interference-to-signal ( $I/S$ ) ratio measured at the corresponding base station is less than a desired threshold. The  $I/S$  thresholds for voice and data are  $\epsilon_v$  and  $\epsilon_d$ , respectively, which can be chosen based on the transmission rates of the voice and data traffic. Voice calls which are not admitted are blocked, and data bursts which are not admitted are buffered.

For the buffered data (at all the mobiles in all the cells), the system behaves like a single *virtual queue* as follows. All the

base stations in the system co-ordinate among themselves and keep track of a virtual queue of data bursts, by assigning a priority index to each buffered data burst. The priority indices are assigned based on the order of the arrival epochs of the data bursts. When a code becomes free and the  $I/S$  conditions become favorable following the departure of an ongoing call, the base stations allow the mobile having the data burst with the least priority index to transmit the data burst using the assigned code, and the priority indices of all the other buffered data bursts in the system are decremented by 1.

In order to analyze the above system, we make the following assumptions.

- Each cell has a maximum of  $n = 64$  spreading codes available for allocation.
- Mobiles are uniformly distributed over the area of each cell. All the mobiles are assumed to have either very low mobility or no mobility.
- The voice call arrival process in each cell is Poisson with mean arrival rate  $\lambda_v$ . The voice call holding times are exponentially distributed with mean  $\mu_v^{-1}$  seconds.  $\rho_v \triangleq \lambda_v / \mu_v$  Erlangs/cell.
- The data burst arrival process in each cell is Poisson with mean arrival rate  $\lambda_d$ . The data burst lengths are exponentially distributed with mean  $\mu_d^{-1}$  seconds.  $\rho_d \triangleq \lambda_d / \mu_d$  Erlangs/cell.
- Voice calls are transmitted at a rate  $r_v$  bps, and data bursts are transmitted at a rate  $r_d$  bps. We consider  $r_d = k_d r_v$ ,  $k_d > 1$ . This leads to  $\epsilon_v = k_d \epsilon_d$ .
- The signal undergoes distance attenuation, shadow loss and multipath Rayleigh fading. For voice traffic, the Rayleigh fading is assumed to be averaged out because of the large holding times of voice calls.
- We assume perfect power control for voice traffic and no power control for data traffic.
- The path loss exponent is taken to be 4. The shadow loss is assumed to be log-normally distributed of the form  $10^{-\frac{\psi}{10}}$ , where  $\psi \sim \mathcal{N}(0, \sigma^2)$ .

### III. PERFORMANCE ANALYSIS

In cellular CDMA, the interference in a given cell is due to the in-cell and the other-cell active mobiles. Here, we assume that the interference seen by a base station is due to the mobiles in its first tier of neighboring cells, i.e., we ignore the interference due to the mobiles located in the cells other than the first tier neighboring cells as negligible<sup>1</sup>.

The number of interferers with voice traffic seen by cell  $k$ ,  $\Delta_k^{(v)}$ , can be written as

$$\Delta_k^{(v)} = \Delta_{I_k}^{(v)} + \Delta_{O_k}^{(v)}, \quad (1)$$

<sup>1</sup>Henceforth, we use the term neighboring cells to mean the first tier of cells around the cell-of-interest.

where  $\Delta_{I_k}^{(v)}$  is the number of in-cell voice interferers and  $\Delta_{O_k}^{(v)}$  is the number of neighboring-cell voice interferers to cell  $k$ . Similarly, the number of interferers with data traffic seen by cell  $k$ ,  $\Delta_k^{(d)}$ , is given by

$$\Delta_k^{(d)} = \Delta_{I_k}^{(d)} + \Delta_{O_k}^{(d)}, \quad (2)$$

where  $\Delta_{I_k}^{(d)}$  is the number of in-cell data interferers and  $\Delta_{O_k}^{(d)}$  is the number of neighboring-cell data interferers to cell  $k$ .

Let  $I_k'(\Delta_k^{(v)}, \Delta_k^{(d)})$  denote the  $I/S$  at the base station of cell  $k$ , due to  $\Delta_k^{(v)}$  voice interferers and  $\Delta_k^{(d)}$  data interferers.  $I_k'(\Delta_k^{(v)}, \Delta_k^{(d)})$  can be written as

$$I_k'(\Delta_k^{(v)}, \Delta_k^{(d)}) = \Delta_{I_k}^{(v)} + r_k(\Delta_{O_k}^{(v)}, \Delta_k^{(d)}), \quad (3)$$

where the first term is due to the perfectly power controlled in-cell voice interferers, and the second term is due to the neighboring-cell voice interferers and all the data interferers.

$I_k(\Delta_{O_k}^{(v)}, \Delta_k^{(d)})$  can be written, in terms of distance attenuation, shadow loss and multipath Rayleigh fading loss, as

$$I_k(\Delta_{O_k}^{(v)}, \Delta_k^{(d)}) = \frac{1}{k_d} \sum_{\substack{i \in S_k \\ i \neq k}} \sum_{j=1}^{\Delta_{i_k}^{(v)}} \frac{D^4(M_{ji}^v, B_k) 10^{-\frac{\psi_{ji}^v}{10}}}{D^4(M_{ji}^v, B_k) 10^{-\frac{\psi_{ji}^v}{10}}} + \sum_{i \in S_k} \sum_{j=1}^{\Delta_{i_k}^{(d)}} D^{-4}(M_{ji}^d, B_k) 10^{-\frac{\psi_{ji}^d}{10}} R_{jk}^2, \quad (4)$$

where  $\Delta_{i_k}^{(v)}$  and  $\Delta_{i_k}^{(d)}$  are the number of voice and data interferers, respectively, in cell  $i$  to cell  $k$ .  $S_k$  denotes the set of cells containing cell  $k$  and its neighboring cells. Note that  $\Delta_{O_k}^{(v)} = \sum_{i \in S_k, i \neq k} \Delta_{i_k}^{(v)}$  and  $\Delta_k^{(d)} = \sum_{i \in S_k} \Delta_{i_k}^{(d)}$ .  $D(M_{ji}^v, B_k)$  is the distance between the  $j^{\text{th}}$  voice interferer in cell  $i$  and the  $k^{\text{th}}$  base station,  $D(M_{ji}^d, B_k)$  is the distance between the  $j^{\text{th}}$  data interferer in cell  $i$  and the  $k^{\text{th}}$  base station, and  $\psi_{jk}^v, \psi_{jk}^d \sim \mathcal{N}(0, \sigma^2)$  correspond to the shadow loss from  $j^{\text{th}}$  mobile in cell  $i$  to the  $k^{\text{th}}$  base station for voice and data interferers, respectively.  $R_{jk}^2$  corresponds to the Rayleigh fading loss from the  $j^{\text{th}}$  mobile in cell  $i$  to the  $k^{\text{th}}$  base station. The  $k_d^{-1}$  factor in the first term accounts for the lesser transmit power for voice users relative to that of the data users, because of the difference in the transmission rates of the voice and data traffic. Note that  $I_k(\Delta_{O_k}^{(v)}, \Delta_k^{(d)})$  is conditioned on  $\Delta_{O_k}^{(v)}, \Delta_k^{(d)}, R_{jk}$  and the location of the interferers, and hence it needs to be averaged over these variables.

#### A. Data Burst Retransmission Probability

A data burst currently in transmission could be lost because of a new call being admitted in the system. Such lost data bursts enter the virtual queue and are retransmitted. We derive

the probability of such data burst retransmissions,  $p_o$ , which is needed to compute the average system throughput and the mean burst delay.

Let  $p_o^v$  and  $p_o^d$  denote the probabilities of data burst retransmission in cell  $k$  due to a newly admitted voice call and data burst, respectively, in cell  $i$ . These probabilities conditioned on  $\Delta_{O_k}^{(v)}$ ,  $\Delta_k^{(d)}$ , and  $\Delta_{I_k}^{(v)}$  are denoted by  $P_{vd}$  and  $P_{dd}$ , respectively.  $P_{vd}$  can be written as

$$P_{vd} = \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d \mid I_h \left( \Delta_{O_h}^{(v)} - 1, \Delta_h^{(d)} \right) \leq \epsilon'_d \right\}, \quad (5)$$

where  $\epsilon'_d = \epsilon_d - \frac{1}{k_d} \Delta_{I_k}^{(v)}$ . Similarly,  $P_{dd}$  can be written as

$$P_{dd} = \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d \mid I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} - 1 \right) \leq \epsilon'_d \right\}. \quad (6)$$

Averaging (5) and (6) over  $\Delta_{O_h}^{(v)}$  and  $\Delta_k^{(d)}$ , we can write

$$p_o^v \left( \Delta_{I_k}^{(v)} \right) = 1 - \prod_{\substack{i \in S_k \\ i \neq h}} \left[ 1 - \sum_{M_v} \sum_{M_d} P_{vd} P_1 P_2 \right], \quad (7)$$

$$p_o^d \left( \Delta_{I_k}^{(v)} \right) = 1 - \prod_{\substack{i \in S_k \\ i \neq h}} \left[ 1 - \sum_{M_v} \sum_{M_d} P_{dd} P_1 P_2 \right], \quad (8)$$

where

$$P_1 \triangleq \Pr \left\{ \Delta_{O_h}^{(v)} = M_v \right\} = \frac{e^{-\hat{\rho}_v} \hat{\rho}_v^{M_v}}{M_v!}, \quad (9)$$

$$P_2 \triangleq \Pr \left\{ \Delta_h^{(d)} = M_d \right\} = \frac{e^{-\hat{\rho}_d} \hat{\rho}_d^{M_d}}{M_d!}. \quad (10)$$

In the above,  $\hat{\rho}_v = N_k \rho_v$ , and  $\hat{\rho}_d = (N_k + 1) \rho_d$ , where  $N_k$  is the number of neighboring cells to cell  $k$  (here,  $N_k = 6$ ).

Averaging (7) and (8) over  $\Delta_{I_k}^{(v)}$ , we have

$$p_o^v = \sum_{m_v} p_o^v \left( \Delta_{I_k}^{(v)} \right) P_3, \quad (11)$$

$$p_o^d = \sum_{m_v} p_o^d \left( \Delta_{I_k}^{(v)} \right) P_3, \quad (12)$$

where

$$P_3 \triangleq \Pr \left\{ \Delta_{I_k}^{(v)} = m_v \right\} = \frac{e^{-\rho_v} \rho_v^{m_v}}{m_v!}. \quad (13)$$

The data burst retransmission probability,  $p_o$ , is then given by

$$p_o = \frac{\lambda_v p_o^v + \lambda_d p_o^d}{\lambda_v + \lambda_d}. \quad (14)$$

It is noted that the key step in the computation of the retransmission probability in the above is the evaluation of (5) and (6). In order to evaluate (5) and (6), we need to compute the joint probabilities

$$P_v^J \triangleq \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d, I_h \left( \Delta_{O_h}^{(v)} - 1, \Delta_h^{(d)} \right) \leq \epsilon'_d \right\}, \quad (15)$$

$$P_d^J \triangleq \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d, I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} - 1 \right) \leq \epsilon'_d \right\}, \quad (16)$$

and the marginal probabilities

$$P_v^M \triangleq \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)} - 1, \Delta_h^{(d)} \right) \leq \epsilon'_d \right\}, \quad (17)$$

$$P_d^M \triangleq \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} - 1 \right) \leq \epsilon'_d \right\}. \quad (18)$$

In [4], we made approximations based on Fenton's method to evaluate an expression similar to the joint probability expressions in (15) and (16). Also, an approximation based on Chernoff bound (CB) was used to evaluate an expression similar to the marginal probabilities in (17) and (18). We use our approach in [4] to evaluate  $P_v^J$ ,  $P_d^J$ ,  $P_v^M$  and  $P_d^M$  here, which are used to compute  $p_o$ . Note that  $p_o$  is also equal to the voice call outage probability. This is because, for voice, the  $k_d$  factor multiplies both the  $I/S$  and the comparison threshold in (5) and (6).

The probability that a data burst is not admitted due to  $I/S$  constraint, and hence buffered,  $p_b$ , can be written as

$$p_b = \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon_d \right\}. \quad (19)$$

As explained before,  $p_b$  is also equal to the voice call blocking probability.

We define the average system throughput,  $\bar{U}$ , to be the fraction of time during which the system carries voice traffic and successful data bursts.  $\bar{U}$  is given by

$$\bar{U} = \frac{\rho_v r_v (1 - p_b) + \rho_d r_d (1 - p_b)(1 - p_o)}{n r_d}. \quad (20)$$

## B. Mean Delay

In this subsection, we present the analysis for deriving the mean data burst delay. The first departing data burst in the virtual queue waits till  $a$ ) a code is available for allocation, and  $b$ ) the  $I/S$  at the corresponding base station is below threshold. However, for the loads under consideration, the probability of a code not being available is small. Hence, the first departing data burst waits till the  $I/S$  at its corresponding base station (in this case, base station  $k$ ) goes below threshold. This happens only if an ongoing call departs from the system. We define  $p_f \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  to be the probability that the  $I/S$  at the base station of cell  $k$  goes below threshold following the departure of either a voice call or a data burst.  $p_f \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  can be written as

$$p_f \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) = p_f^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) p_d^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) + p_f^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) p_d^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right), \quad (21)$$

where  $p_f^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  and  $p_f^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  are the probabilities that the  $I/S$  going below threshold is due to the departure of a voice call and a data burst, respectively. Likewise,  $p_d^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  and  $p_d^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  are the probabilities that the departing call is a voice call and a data burst, respectively.  $p_f^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  and  $p_f^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right)$  are given by

$$p_f^v \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) = \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)} - 1, \Delta_h^{(d)} \right) \leq \epsilon'_d \mid I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d \right\},$$

$$p_f^d \left( \Delta_k^{(v)}, \Delta_k^{(d)} \right) = \Pr \left\{ I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} - 1 \right) \leq \epsilon'_d \mid I_h \left( \Delta_{O_h}^{(v)}, \Delta_h^{(d)} \right) > \epsilon'_d \right\}.$$

The above two equations are evaluated by the method applied to evaluate  $p_o^v$  and  $p_o^d$  in the previous subsection. The probabilities  $p_d^v(\Delta_k^{(v)}, \Delta_k^{(d)})$  and  $p_d^d(\Delta_k^{(v)}, \Delta_k^{(d)})$  are given by

$$p_d^v(\Delta_k^{(v)}, \Delta_k^{(d)}) = \frac{\Delta_k^{(v)} \mu_v}{\Delta_k^{(v)} \mu_v + \Delta_k^{(d)} \mu_d}, \quad (22)$$

$$p_d^d(\Delta_k^{(v)}, \Delta_k^{(d)}) = \frac{\Delta_k^{(d)} \mu_d}{\Delta_k^{(v)} \mu_v + \Delta_k^{(d)} \mu_d}. \quad (23)$$

The arrival rate into the virtual queue is  $p_b N \lambda_d$ . Let  $m$  be the number of departures that need to occur for the  $I/S$  at the base station of cell  $k$  to go below threshold. Let  $T$  be the random variable that denotes the delay experienced by the first departing data burst in the virtual queue. The characteristic function,  $\phi_T(\omega | m, \Delta_k^{(v)}, \Delta_k^{(d)})$ , of  $T$  conditioned on  $m$ ,  $\Delta_k^{(v)}$  and  $\Delta_k^{(d)}$ , is given by

$$\phi_T(\omega | m, \Delta_k^{(v)}, \Delta_k^{(d)}) = \prod_{i=1}^m \phi_i(j\omega), \quad (24)$$

where

$$\phi_i(\omega) = \sum_{l=1}^i \left[ \frac{\mu_i^l}{\mu_i^l - \omega} \right] \binom{m-1}{i-1} \cdot (p_d^v)^{m-l} (p_d^d)^{l-1}, \quad (25)$$

$\mu_i^l = (\Delta_k^{(v)} - (i-1)\mu_v + (\Delta_k^{(d)} - (i-1)\mu_d)$ , and  $p_d^v$  and  $p_d^d$  are obtained by averaging (22) and (23) over  $\Delta_k^{(v)}$  and  $\Delta_k^{(d)}$ . To average (24) over  $m$ , we use  $\Pr\{m=K\} = (1-p_f)^{K-1} p_f$ , where  $p_f$  is obtained by averaging  $p_f(\Delta_k^{(v)}, \Delta_k^{(d)})$  over  $\Delta_k^{(v)}$  and  $\Delta_k^{(d)}$ . Averaging (24) over  $m$ ,  $\Delta_k^{(v)}$  and  $\Delta_k^{(d)}$ , we obtain the characteristic function,  $\phi_T(\omega)$ , of  $T$ . The density function of the delay  $T$ ,  $f_T(t)$ , is then given by

$$f_T(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \phi_T(\omega) e^{-j\omega t} d\omega. \quad (26)$$

The mean delay,  $T_{ave}$ , and the delay variance,  $T_{var}$ , of the first departing data burst are given by

$$T_{ave} = \int_0^{\infty} t f_T(t) dt, \quad (27)$$

$$T_{var} = \int_0^{\infty} (t - T_{ave})^2 f_T(t) dt. \quad (28)$$

The rest of the virtual queue, other than the first departing burst, is modeled as an  $M/G/1$  queue with mean service time  $T_{ave}$ . Hence, the mean waiting time,  $W_{ave}$ , in the  $M/G/1$  queue can be written as,

$$W_{ave} = \frac{r T_{ave}}{2(1-r)} (1 + c_T^2), \quad (29)$$

where  $c_T^2 = \frac{T_{var}}{T_{ave}^2}$  and  $r = p_b N \lambda_d T_{ave}$ . Finally, the mean data burst delay,  $\bar{D}$ , is given by

$$\bar{D} = p_b (W_{ave} + T_{ave}) N_{tx}, \quad (30)$$

where  $N_{tx}$  is the average number of transmissions per packet, given by  $N_{tx} = 1/(1-p_o)$ .

## IV. RESULTS AND DISCUSSION

In this section, we present the analytical and simulation results of the performance of a voice/data CDMA system with SIR based admission control. The performance of the system with code availability (CA) based admission control is also presented for comparison. The following system parameter values are used in all the analytical computations and simulations:  $N = 61$  cells,  $n = 64$  spreading codes,  $\mu_v^{-1} = 100$  seconds,  $\rho_v$  in the range 1 to 10 in steps of 1,  $\mu_d^{-1} = 1$  second,  $\rho_d$  in the range 1 to 9 in steps of 1,  $r_v = 8$  kbps,  $r_d = 16$  kbps (i.e.,  $k_d = 2$ ),  $\sigma = 8$  dB, and  $\epsilon_v = 14$  dB (i.e.,  $\epsilon_d = 11$  dB). We define the voice and data Erlang capacities as the offered voice traffic for a desired voice call outage probability and the offered data traffic for a desired mean data burst delay performance, respectively. We specifically consider a data-only system (for which  $\rho_v = 0$ ), as well as a mixed voice/data system with  $\rho_v = 10$  Erlangs per cell, both with varying  $\rho_d$ .

Fig. 1 gives the voice call outage probability performance as a function of voice traffic load,  $\rho_v$ , in a mixed voice/data system with a data traffic of  $\rho_d = 5$  Erlangs per cell. The SIR based admission control is seen to perform better than the CA based admission control. For example, a 1% outage probability occurs at a voice traffic of about 2 Erlangs per cell using CA based admission control, whereas, for the same outage performance of 1%, the SIR based admission control supports an increased voice traffic of about 6 Erlangs per cell. It is noted that, in the voice-only system that we studied in [4], a voice traffic load of about 20 Erlangs per cell was achieved at a 1% voice call outage probability. However, in the mixed voice/data system that we consider in this paper, the voice Erlang capacity achieved is 6 Erlangs per cell in the presence of 5 Erlangs per cell of data traffic. Thus, the voice Erlang capacity comes down while supporting higher rate data users, which is expected.

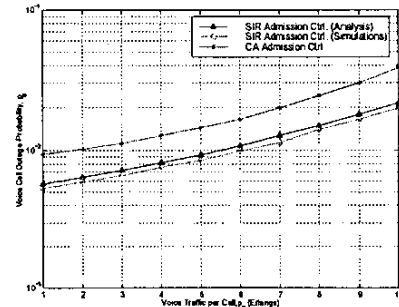


Fig. 1. Voice call outage probability,  $p_o$ , vs  $\rho_v$  for  $\rho_d = 5$  Erlangs per cell.

In Figs. 2 and 3, we compare the mean data burst delay performance of the SIR based admission control with that of the CA based admission control, as a function of data traffic,  $\rho_d$ . Fig. 2 corresponds to a data-only system (i.e.,  $\rho_v = 0$ ) and Fig. 3 corresponds to a mixed voice/data system with a voice

traffic of  $\rho_v = 10$  Erlangs per cell. From Fig. 2, we observe that, in the absence of voice traffic, we obtain an improvement of about 25% in the mean delay performance due to SIR based admission control compared to CA based admission control (about 70 ms mean delay for CA based admission control and about 53 ms mean delay for SIR based admission control, at  $\rho_d = 8$  Erlangs per cell). This is because, in CA based admission control, calls are admitted into the system regardless of the SIR conditions. This may allow a faster first time transmission of a data burst, but it will encounter a larger number of retransmissions due to data loss because of more interference. This results in a larger overall delay for CA based admission control. SIR based admission control, on the other hand, does not admit calls (i.e., buffers data bursts) if SIR conditions are not favorable. This may possibly delay the first transmission attempt more, but the transmission attempts will have a larger probability of success, because of the controlled SIR conditions. This results in a lesser overall delay compared to that of CA based admission control. When  $\rho_v = 10$  Erlangs per cell, the mean delay performance of SIR based admission control improves by about 40% compared to CA based admission control, as observed in Fig. 3. This is because, at increased voice traffic loads, the CA based admission control performs poorer because it now admits more calls (subject to code availability) than in a data-only system, which causes more retransmissions and more delay compared to SIR based admission control.

From Figs. 2 and 3, it is also observed that at a mean delay of 50 ms, the SIR based admission control offers about 25 to 50% improvement in the data Erlang capacity, compared to CA based admission control. For example, for  $\rho_v = 0$  (Fig. 2), at  $\bar{D} = 50$  ms, the data Erlang capacity improves from 6.5 Erlangs to 8.2 Erlangs. Similarly, for  $\rho_v = 10$  (Fig. 3), the data Erlang capacity improves from 4 Erlangs to 6 Erlangs. Fig. 4 gives the average system throughput (Eqn.(20)) as a function of  $\rho_d$  for  $\rho_v = 10$  Erlangs. We observe that because of lesser retransmission and outage probability, the SIR based admission control utilizes the system more efficiently than the CA based admission control.

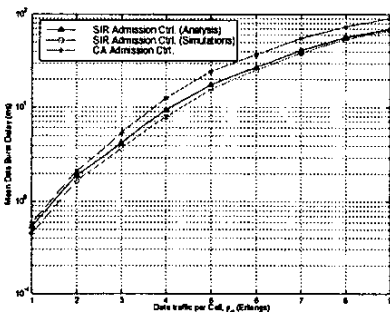


Fig. 2. Mean data burst delay,  $\bar{D}$ , vs  $\rho_d$  in the absence of voice traffic (i.e.,  $\rho_v = 0$ ).

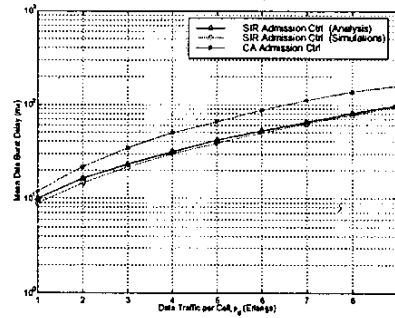


Fig. 3. Mean data burst delay,  $\bar{D}$ , vs  $\rho_d$  for  $\rho_v = 10$  Erlangs per cell.

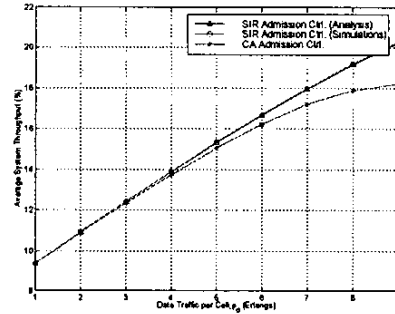


Fig. 4. Average system throughput,  $\bar{U}$ , vs  $\rho_d$  for  $\rho_v = 10$  Erlangs per cell.

## V. CONCLUSIONS

We analyzed the performance of an SIR based admission control strategy in cellular CDMA systems with both voice and data traffic. We derived the expressions for the outage probability for voice traffic, the mean delay for data traffic and the average system throughput for a mixed voice/data CDMA system which employs an SIR based admission control. We showed that significant performance improvement both in terms of mean delay as well as Erlang capacity could be achieved using the SIR based admission control as compared to that of code availability based admission control.

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