Performance Analysis for Voice/Data Integration on a Finite-Buffer Mobile System

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***Abstract*—Personal communication service (PCS) networks offer mobile users diverse telecommunication applications, such as voice, data, and image, with different bandwidth and quality-of-service (QoS) requirements. This paper proposes an analytical model to investigate the performance of an integrated voice/data mobile network with finite data buffer in terms of voice-call blocking probability, data loss probability, and mean data delay. The model is based on the movable-boundary scheme that dynamically adjusts the number of channels for voice and data traffic. With the movable-boundary scheme, the bandwidth can be utilized efficiently while satisfying the QoS requirements for voice and data traffic. Using our model, the impact of hot-spot traffic in the heterogeneous PCS networks, in which the parameters (e.g., number of channels, voice, and data arrival rates) of cells can be varied, can be effectively analyzed. In addition, an iterative algorithm based on our model is proposed to determine the handoff traffic, which computes the system performance in polynomial-bounded time. The analytical model is validated by simulation.**

***Index Terms*—Handoff, hot-spot, movable-boundary, personal communication service, quality-of-service.**

I. INTRODUCTION

A PERSONAL communication service (PCS) [1]–[4] network offers integrated services where mobile users communicate via wireless links in the radio coverage of base stations. PCS networks are expected to support diverse applications, such as voice, data, and image, etc., demanding different quality-of-service (QoS) and bandwidth. The bandwidth of the wireless links is inherently limited and is generally much smaller than that in its wireline counterpart. Particularly, for integrated voice/data mobile networks, voice traffic results in call losses and data traffic suffers from longer delays should networks have insufficient bandwidth. Thus, it is essential to design mobile networks that furnish effective and dynamic allocation of the bandwidth to satisfy different services demands.

In integrated voice/data mobile networks, several proposed bandwidth allocation schemes [5]–[8] attempt to achieve improved system performance (e.g., voice-call blocking probability and data delay, etc.). Generally, these schemes are based on movable-boundary strategy with or without reservation for voice or data traffic. Although these schemes were evaluated extensively, the effect of handoff [1]–[4], [9] traffic due to the movement of portables was not taken into account. Handoff denotes the procedure of changing channels associated with current connection to maintain acceptable service quality. It is initiated by cell boundary crossing. When the cell size of PCS networks is relatively small [1]–[4], the handoff traffic has an important effect on the system performance.

This paper proposes an analytical model to study the system performance of an integrated voice/data mobile network with finite data buffer in terms of voice-call blocking probability, data loss probability, and mean data delay. Our model is based on the movable-boundary scheme, which considers both voice and data traffic with the handoff effects.

With the movable-boundary scheme, the available bandwidth (i.e., radio channels) of each cell is partitioned into three compartments, namely, designated voice channels, designated data channels, and shared channels. Designated voice and data channels are dedicated for voice and data traffic transmissions, respectively. The shared channels can be used by either type of traffic. The boundary between compartments is dynamically moved such that the bandwidth can be utilized efficiently while satisfying the QoS requirements for voice and data traffic.

Previous handoff studies [1], [3], [9], [10] assumed a homogeneous PCS network where all cells have the same number of channels and experience the same new and handoff call arrival rates. Our model accommodates the heterogeneity of a PCS network by relaxing the restrictions in those previously proposed models. With our model, the parameters (e.g., number of channels, voice, and data arrival rates) of cells can be varied, and hence the impact of hot-spot traffic can be effectively analyzed. Our model utilizes an iterative algorithm to determine the handoff traffic, which computes the system performance in polynomial-bounded time. Simulation experiments are conducted to validate the accuracy of the analytical model.

The paper is organized as follows. Section II presents the analysis of an integrated voice/data mobile network with finite data buffer. In Section III, extensive performance results are presented. In addition, the accuracy of analytical results are confirmed by simulation results. Finally, Section IV concludes the paper. The notation used in this paper is in Appendix I.

II. PERFORMANCE ANALYSIS

In this section, we analyze the system performance in terms of voice-call blocking probability, data loss probability, and mean data delay in each cell. The system under consideration is an integrated voice/data mobile network, in which the users move along an arbitrary topology of M cells according to the routing

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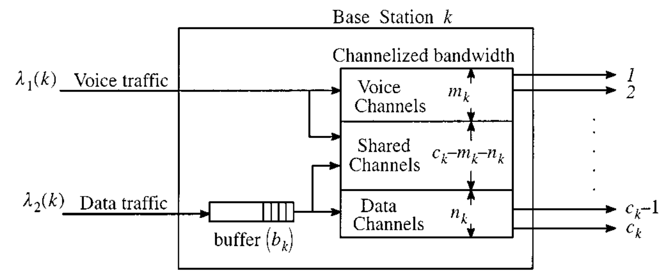


Fig. 1. Base station architecture.

probability r_{ij} (from cell i to cell j). In each cell k, the arrivals of new voice calls, handoff voice calls, new data packets, and handoff data packets are Poisson distributed with rates $\lambda_v(k)$, $\lambda_v^h(k)$, $\lambda_d(k)$, and $\lambda_d^h(k)$, respectively. In addition, we assume that the system uses the nonprioritized handoff scheme [1]–[4] where the channel assignment to the new and the handoff voice calls/data packets are not distinguishable.

It is assumed that voice and data traffic have exponential service-time (call holding time) distribution with means $1/\mu_v$ and $1/\mu_d$, respectively. Moreover, the residence times in a cell for voice and data portable are assumed to follow exponential distribution with means $1/\eta_v$ and $1/\eta_d$, respectively. Although the cell residence times are typically nonexponential in a particular mobile system, the analysis based on the simplified exponential assumption has been widely used [1], [3], [9]–[12] and does provide useful mean value information for the output measures. To relax the exponential assumptions, performance of the movable-boundary scheme can be investigated by the simulation experiments conducted in this paper.

A. The Model

For each cell k, the base station architecture is illustrated in Fig. 1. There are three types of traffic channels. Designated voice and data channels are dedicated for voice and data traffic transmissions, respectively. The shared channels can be used by either type of traffic. Voice traffic is balked from the system if legitimate channels are all in use upon its arrival. On the contrary, data traffic would be queued in a buffer should legitimate channels be busy.

In our study, the base station architecture (see Fig. 1) is modeled by a continuous-time model with *heterogeneous arrivals* (voice and data), *multiple designated channels* (voice, data, and shared channels), and *finite data buffer*. For analytical tractability, we assume that the buffer size is infinite and then compute the tail probability to approximate the data loss probability under finite buffer size. Starting with a guess of handoff rates $\lambda_v^h(k)$ and $\lambda_d^h(k)$, we assume that voice and data traffic in each cell k are Poisson distributed with arrival rates $\lambda_1(k)\ (=\ \lambda_v(k) + \lambda_v^h(k))$ and $\lambda_2(k)\ (=\ \lambda_d(k) + \lambda_d^h(k))$, respectively. Moreover, the channel occupancy times for voice and data traffic are assumed to have exponential distribution with means $1/\mu_1\ (= 1/(\mu_v + \eta_v))$ and $1/\mu_2\ (= 1/(\mu_d + \eta_d))$, respectively. Note that $\lambda_v^h(k)$ and $\lambda_d^h(k)$ will be determined by an iterative algorithm (to be elaborated later). Each base station k has finite buffer size b_k. Let c_k be the total number of channels in cell k and m_k and n_k be the number of channels designated for voice and data traffic, respectively (see Fig. 1). Thus, there are $c_k - m_k - n_k$ shared channels that can be used by either type of traffic. All channels are employed in a first-come first-serve (FCFS) manner.

B. The Analysis

The queueing system shown in Fig. 1 is ergodic [13] if $\lambda_2(k) < (c_k - m_k)\mu_2$. Let p_{ij} $(0 \le i \le c_k - n_k; j \ge 0)$ be the steady-state probability that simultaneously there are i voice calls and j data packets in cell k; the corresponding balance equations are shown as follows.

Case I: If the number of voice calls in cell k is less than m_k, i.e., $0 \le i \le m_k - 1$, then

$$\begin{aligned}
&[\lambda_1(k) + \lambda_2(k) + i\mu_1]p_{i0}\\
&\quad = (i+1)\mu_1 p_{i+1,0} + \mu_2 p_{i1} + \lambda_1(k)p_{i-1,0}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + \mu_2]p_{i1}\\
&\quad = (i+1)\mu_1 p_{i+1,1} + 2\mu_2 p_{i2} + \lambda_1(k)p_{i-1,1} + \lambda_2(k)p_{i0}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + 2\mu_2]p_{i2}\\
&\quad = (i+1)\mu_1 p_{i+1,2} + 3\mu_2 p_{i3} + \lambda_1(k)p_{i-1,2} + \lambda_2(k)p_{i1}\\
&\quad \vdots\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + (c_k - m_k - 1)\mu_2]p_{i,c_k-m_k-1}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k-1} + (c_k - m_k)\mu_2 p_{i,c_k-m_k}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k-1} + \lambda_2(k)p_{i,c_k-m_k-2}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + (c_k - m_k)\mu_2]p_{i,c_k-m_k}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k} + (c_k - m_k)\mu_2 p_{i,c_k-m_k+1}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k} + \lambda_2(k)p_{i,c_k-m_k-1}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + (c_k - m_k)\mu_2]p_{i,c_k-m_k+1}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k+1} + (c_k - m_k)\mu_2 p_{i,c_k-m_k+2}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k+1} + \lambda_2(k)p_{i,c_k-m_k}\\
&\quad \vdots
\end{aligned} \tag{1}$$

Case II: If the number of voice calls in cell k is equal to m_k, i.e., $i = m_k$, then

$$\begin{aligned}
&[\lambda_1(k) + \lambda_2(k) + i\mu_1]p_{i0}\\
&\quad = (i+1)\mu_1 p_{i+1,0} + \mu_2 p_{i1} + \lambda_1(k)p_{i-1,0}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + \mu_2]p_{i1}\\
&\quad = (i+1)\mu_1 p_{i+1,1} + 2\mu_2 p_{i2} + \lambda_1(k)p_{i-1,1} + \lambda_2(k)p_{i0}\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + 2\mu_2]p_{i2}\\
&\quad = (i+1)\mu_1 p_{i+1,2} + 3\mu_2 p_{i3} + \lambda_1(k)p_{i-1,2} + \lambda_2(k)p_{i1}\\
&\quad \vdots\\
&[\lambda_1(k) + \lambda_2(k) + i\mu_1 + (c_k - m_k - 1)\mu_2]p_{i,c_k-m_k-1}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k-1} + (c_k - m_k)\mu_2 p_{i,c_k-m_k}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k-1} + \lambda_2(k)p_{i,c_k-m_k-2}\\
&[\lambda_2(k) + i\mu_1 + (c_k - m_k)\mu_2]p_{i,c_k-m_k}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k} + (c_k - m_k)\mu_2 p_{i,c_k-m_k+1}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k} + \lambda_2(k)p_{i,c_k-m_k-1}\\
&[\lambda_2(k) + i\mu_1 + (c_k - m_k)\mu_2]p_{i,c_k-m_k+1}\\
&\quad = (i+1)\mu_1 p_{i+1,c_k-m_k+1} + (c_k - m_k)\mu_2 p_{i,c_k-m_k+2}\\
&\qquad + \lambda_1(k)p_{i-1,c_k-m_k+1} + \lambda_2(k)p_{i,c_k-m_k}\\
&\quad \vdots
\end{aligned} \tag{2}$$

Case III: If the number of voice calls in cell k exceeds m_k but is less than the total number of channels eligible for voice traffic, i.e., $m_k+1 \le i \le c_k-n_k-1$, then

$$\begin{aligned}
&[\lambda_1(k)+\lambda_2(k)+i\mu_1]p_{i0}\\
&\quad=(i+1)\mu_1 p_{i+1,0}+\mu_2 p_{i1}+\lambda_1(k)p_{i-1,0}\\
&[\lambda_1(k)+\lambda_2(k)+i\mu_1+\mu_2]p_{i1}\\
&\quad=(i+1)\mu_1 p_{i+1,1}+2\mu_2 p_{i2}+\lambda_1(k)p_{i-1,1}+\lambda_2(k)p_{i0}\\
&[\lambda_1(k)+\lambda_2(k)+i\mu_1+2\mu_2]p_{i2}\\
&\quad=(i+1)\mu_1 p_{i+1,2}+3\mu_2 p_{i3}+\lambda_1(k)p_{i-1,2}+\lambda_2(k)p_{i1}\\
&\quad\vdots\\
&[\lambda_1(k)+\lambda_2(k)+i\mu_1+(c_k-i-1)\mu_2]p_{i,c_k-i-1}\\
&\quad=(i+1)\mu_1 p_{i+1,c_k-i-1}+(c_k-i)\mu_2 p_{i,c_k-i}\\
&\qquad+\lambda_1(k)p_{i-1,c_k-i-1}+\lambda_2(k)p_{i,c_k-i-2}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i}\\
&\quad=(i+1)\mu_1 p_{i+1,c_k-i}+(c_k-i)\mu_2 p_{i,c_k-i+1}\\
&\qquad+\lambda_1(k)p_{i-1,c_k-i}+\lambda_2(k)p_{i,c_k-i-1}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i+1}\\
&\quad=(i+1)\mu_1 p_{i+1,c_k-i+1}+(c_k-i)\mu_2 p_{i,c_k-i+2}\\
&\qquad+\lambda_2(k)p_{i,c_k-i}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i+2}\\
&\quad=(i+1)\mu_1 p_{i+1,c_k-i+2}+(c_k-i)\mu_2 p_{i,c_k-i+3}\\
&\qquad+\lambda_2(k)p_{i,c_k-i+1}\\
&\quad\vdots
\end{aligned}\tag{3}$$

Case IV: If the number of voice calls in cell k is equal to c_k-n_k, i.e., $i=c_k-n_k$, then

$$\begin{aligned}
&[\lambda_2(k)+i\mu_1]p_{i0}\\
&\quad=\mu_2 p_{i1}+\lambda_1(k)p_{i-1,0}\\
&[\lambda_2(k)+i\mu_1+\mu_2]p_{i1}\\
&\quad=2\mu_2 p_{i2}+\lambda_1(k)p_{i-1,1}+\lambda_2(k)p_{i0}\\
&[\lambda_2(k)+i\mu_1+2\mu_2]p_{i2}\\
&\quad=3\mu_2 p_{i3}+\lambda_1(k)p_{i-1,2}+\lambda_2(k)p_{i1}\\
&\quad\vdots\\
&[\lambda_2(k)+i\mu_1+(c_k-i-1)\mu_2]p_{i,c_k-i-1}\\
&\quad=(c_k-i)\mu_2 p_{i,c_k-i}+\lambda_1(k)p_{i-1,c_k-i-1}\\
&\qquad+\lambda_2(k)p_{i,c_k-i-2}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i}\\
&\quad=(c_k-i)\mu_2 p_{i,c_k-i+1}+\lambda_1(k)p_{i-1,c_k-i}\\
&\qquad+\lambda_2(k)p_{i,c_k-i-1}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i+1}\\
&\quad=(c_k-i)\mu_2 p_{i,c_k-i+2}+\lambda_2(k)p_{i,c_k-i}\\
&[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]p_{i,c_k-i+2}\\
&\quad=(c_k-i)\mu_2 p_{i,c_k-i+3}+\lambda_2(k)p_{i,c_k-i+1}\\
&\quad\vdots
\end{aligned}\tag{4}$$

Define the probability generating function of the occupancy distribution of data traffic as

$$\Pi_i(z)=\sum_{j=0}^{\infty} p_{ij}z^j \tag{5}$$

where $|z|\le 1$ and $0\le i\le c_k-n_k$. By using (1)–(4), we derive $\Pi_i(z)$ in four cases.

Case I: If $0\le i\le m_k-1$, then

$$\begin{aligned}
&D_i(z)\Pi_i(z)\\
&\quad=(i+1)\mu_1 z\Pi_{i+1}(z)+\lambda_1(k)z\Pi_{i-1}(z)\\
&\qquad+(z-1)\mu_2\sum_{j=0}^{c_k-m_k-1}(c_k-m_k-j)p_{ij}z^j
\end{aligned}\tag{6}$$

where $D_i(z)=-\lambda_2(k)z^2+[\lambda_1(k)+\lambda_2(k)+i\mu_1+(c_k-m_k)\mu_2]z-(c_k-m_k)\mu_2$ and $\Pi_{-1}(z)=0$.

Case II: If $i=m_k$, then

$$\begin{aligned}
D_i(z)\Pi_i(z)&=(i+1)\mu_1 z\Pi_{i+1}(z)+\lambda_1(k)z\Pi_{i-1}(z)\\
&\quad+(z-1)\mu_2\sum_{j=0}^{c_k-m_k-1}(c_k-m_k-j)p_{ij}z^j\\
&\quad-\lambda_1(k)\sum_{j=0}^{c_k-m_k-1}p_{ij}z^{j+1}
\end{aligned}\tag{7}$$

where $D_i(z)=-\lambda_2(k)z^2+[\lambda_2(k)+i\mu_1+(c_k-m_k)\mu_2]z-(c_k-m_k)\mu_2$ and $\Pi_{-1}(z)=0$.

Case III: If $m_k+1\le i\le c_k-n_k-1$, then

$$\begin{aligned}
D_i(z)\Pi_i(z)&=(i+1)\mu_1 z\Pi_{i+1}(z)\\
&\quad+(z-1)\mu_2\sum_{j=0}^{c_k-i-1}(c_k-i-j)p_{ij}z^j\\
&\quad-\lambda_1(k)\sum_{j=0}^{c_k-i-1}p_{ij}z^{j+1}\\
&\quad+\lambda_1(k)\sum_{j=0}^{c_k-i}p_{i-1,j}z^{j+1}
\end{aligned}\tag{8}$$

where $D_i(z)=-\lambda_2(k)z^2+[\lambda_2(k)+i\mu_1+(c_k-i)\mu_2]z-(c_k-i)\mu_2$.

Case IV: If $i=c_k-n_k$, then

$$\begin{aligned}
D_i(z)\Pi_i(z)&=(z-1)\mu_2\sum_{j=0}^{c_k-i-1}(c_k-i-j)p_{ij}z^j\\
&\quad+\lambda_1(k)\sum_{j=0}^{c_k-i}p_{i-1,j}z^{j+1}
\end{aligned}\tag{9}$$

where $D_i(z) = -\lambda_2(k)z^2 + [\lambda_2(k) + i\mu_1 + (c_k - i)\mu_2]z - (c_k - i)\mu_2$. From (6) to (9), we obtain

$$\begin{aligned}[](c_k - m_k)\mu_2 - \lambda_2(k)z] \sum_{i=0}^{m_k} \Pi_i(z) &+ \sum_{i=m_k+1}^{c_k-n_k} [(c_k - i)\mu_2 - \lambda_2(k)z]\Pi_i(z) \\ &= \sum_{i=0}^{m_k} \sum_{j=0}^{c_k-m_k-1} (c_k - m_k - j)\mu_2 p_{ij} z^j \\ &+ \sum_{i=m_k+1}^{c_k-n_k} \sum_{j=0}^{c_k-i-1} (c_k - i - j)\mu_2 p_{ij} z^j. \end{aligned} \tag{10}$$

After rearrangement, (10) is rewritten as

$$\begin{aligned}\sum_{i=0}^{c_k-n_k} \Pi_i(z) = &\left[\sum_{i=1}^{c_k-m_k-n_k} (i\mu_2)\Pi_{i+m_k}(z) + \sum_{i=0}^{m_k} \sum_{j=0}^{c_k-m_k-1} (c_k - m_k - j)\mu_2 p_{ij} z^j + \sum_{i=m_k+1}^{c_k-n_k} \sum_{j=0}^{c_k-i-1} (c_k - i - j)\mu_2 p_{ij} z^j \right] \\ &\times [(c_k - m_k)\mu_2 - \lambda_2(k)z]^{-1}. \end{aligned} \tag{11}$$

Consider the voice-call blocking probability and the handoff voice-call arrival rate in cell k. Since the nonprioritized handoff scheme is adopted, the voice-call blocking probability $P_B(k)$ is equal to the voice-call forced termination probability, which is given by

$$P_B(k) = 1 - \left[\Pi_0(1) + \Pi_1(1) + \cdots + \Pi_{m_k-1}(1) + \sum_{i=m_k}^{c_k-n_k-1} \sum_{j=0}^{c_k-i-1} p_{ij} \right]. \tag{12}$$

Note that $\sum_{i=0}^{c_k-n_k} \Pi_i(1) = 1$. By setting $z = 1$ in (6)–(8) and after manipulations, $P_B(k)$ can be expressed as

$$P_B(k) = \Pi_{m_k}(1) + \sum_{i=m_k+1}^{c_k-n_k} \left[1 - \frac{i}{\lambda_1(k)/\mu_1} \right] \Pi_i(1). \tag{13}$$

Since the probability that an accepted voice call will attempt to hand off is $\eta_v/(\mu_v + \eta_v)$, the rate of the handoff voice calls moving out of cell j is given by

$$(\lambda_v(j) + \lambda_v^h(j))(1 - P_B(j)) \left(\frac{\eta_v}{\mu_v + \eta_v} \right). \tag{14}$$

By using (14), the rate of handoff voice calls moving into cell k, $\lambda_v^h(k)$, is expressed as

$$\lambda_v^h(k) = \sum_{j \neq k} r_{jk} \left[(\lambda_v(j) + \lambda_v^h(j))(1 - P_B(j)) \cdot \left(\frac{\eta_v}{\mu_v + \eta_v} \right) \right]. \tag{15}$$

After the voice-call blocking probability in each cell j $(j \neq k)$ is determined, $\lambda_v^h(k)$ can be calculated using (15).

To evaluate the data loss probability in cell k, we follow the approach described in [15]. Let q_{ij} be the tail probability of the number of data packets when there are i voice calls in cell k, i.e., $q_{ij} = \sum_{l=1}^{\infty} p_{i,j+l}$. The generating function for q_{ij} is expressed as

$$Q_i(z) = \sum_{j=0}^{\infty} q_{ij} z^j \tag{16}$$

where $|z| \le 1$ and $0 \le i \le c_k - n_k$. After some manipulations, we have

$$\sum_{i=0}^{c_k-n_k} Q_i(z) = \frac{1}{z-1} \left[\sum_{i=0}^{c_k-n_k} \Pi_i(z) - 1 \right] \tag{17}$$

where $\sum_{i=0}^{c_k-n_k} \Pi_i(z)$ is given in (11). Based on the algorithm proposed in [15], the data loss probability $L(k)$ in cell k can be expressed as

$$\begin{aligned} L(k) &= \sum_{i=0}^{c_k-n_k} q_{i,b_k} \\ &= \frac{1}{2b_k r^{b_k}} \sum_{j=1}^{2b_k} (-1)^j Re \left[\sum_{i=0}^{c_k-n_k} Q_i(re^{\pi j\sqrt{-1}/b_k}) \right] \end{aligned} \tag{18}$$

where $Re[z]$ is the real part of the complex number z. To limit the error within $10^{-\epsilon}$, we let $r = 10^{-\epsilon/2b_k}$. Following the same reasoning for the handoff voice calls, the rate of handoff data packets moving into cell k is related to $L(j)$ $(j \neq k)$ by

$$\lambda_d^h(k) = \sum_{j \neq k} r_{jk} \left[(\lambda_d(j) + \lambda_d^h(j))(1 - L(j)) \cdot \left(\frac{\eta_d}{\mu_d + \eta_d} \right) \right]. \tag{19}$$

Differentiating (10) with respect to z and setting $z = 1$, the mean number of data packets in cell k can thus be derived as

$$\begin{aligned} \sum_{i=0}^{c_k-n_k} \Pi_i'(1) &= \left[\sum_{i=m_k+1}^{c_k-n_k} (i - m_k)\Pi_i'(1) + \sum_{i=0}^{m_k} \sum_{j=1}^{c_k-m_k-1} j(c_k - m_k - j)p_{ij} + \sum_{i=m_k+1}^{c_k-n_k} \sum_{j=1}^{c_k-i-1} j(c_k - i - j)p_{ij} + \frac{\lambda_2(k)}{\mu_2} \right] \\ &\times \left[c_k - m_k - \frac{\lambda_2(k)}{\mu_2} \right]^{-1}. \end{aligned} \tag{20}$$

Using (20) and applying Little's Formula, we obtain the mean data delay, $T(k)$, in cell k as

$$T(k) = \frac{\sum_{i=0}^{c_k-n_k} \Pi_i'(1)}{(\lambda_d(k) + \lambda_d^h(k))(1 - L(k))} \tag{21}$$

where $L(k)$ and $\lambda_d^h(k)$ are given in (18) and (19), respectively.

Consequently, as shown in (13), (18), and (21), to compute $P_B(k), L(k)$, and $T(k)$, we have to calculate $\Pi_i(1)$ $(m_k \le i \le c_k - n_k)$, $\Pi'_i(1)$ $(m_k+1 \le i \le c_k - n_k)$, and the steady-state probabilities p_{ij} $(0 \le i \le m_k, 0 \le j \le c_k - m_k - 1$ and $m_k + 1 \le i \le c_k - n_k, 0 \le j \le c_k - i - 1)$. The reader is referred to [14] for the details of these calculations. We will, however, provide the major computational steps in Appendix II. It is worth noting that, since these calculations are polynomial bounded, the performance measures of the mobile system can be computed in polynomial-bounded time.

C. The Iterative Algorithm

In this section, we propose an iterative algorithm to compute the voice-call blocking probability, the data loss probability, and the mean data delay in cell k using the equations derived in Section II-B. Recall that the voice-call blocking probability $P_B(k)$ is derived based on the amount of traffic contending for the available channels. $P_B(k)$ is changed if some data packets are lost, resulting in a reduction in the contending traffic.

Beginning with an initial data arrival rate, $\lambda_2^{(0)}(k)$, with no loss, we first derive $L^{(0)}(k)$ and $P_B^{(0)}(k)$. Based on arrival rate $\lambda_2^{(1)}(k)$ $(= \lambda_2^{(0)}(k)(1 - L^{(0)}(k))$, new data loss probability and voice-call blocking probability [$L^{(1)}(k)$ and $P_B^{(1)}(k)$, respectively] can then be obtained. We iterate this procedure until $L^{(i)}(k)$ and $P_B^{(i)}(k)$ converge and use these two quantities as estimates for the data loss probability and the voice-call blocking probability, respectively. After $L(k)$ and $P_B(k)$ are determined, the handoff data and voice-call arrival rates [$\lambda_d^{h(0)}(k)$ and $\lambda_v^{h(0)}(k)$, respectively] can then be calculated by using (19) and (15), respectively. To obtain the convergent values of $\lambda_d^h(k)$ and $\lambda_v^h(k)$, we follow an iterative technique proposed in [1].

Assume that there are M cells in the mobile system, and a mobile user moves from cell i to cell j with the routing probability r_{ij}. The iterative algorithm is shown as follows:

D. The Iterative Algorithm

Input Parameters: $R = [r_{ij}]_{M\times M}$ (routing matrix), $\lambda_v(k)$ (new voice-call arrival rate to cell k), $\lambda_d(k)$ (new data arrival rate to cell k), $1/\mu_v$ (mean voice-call service time), $1/\mu_d$ (mean data service time), $1/\eta_v$ (mean voice-portable residence time), $1/\eta_d$ (mean data-portable residence time), c_k (number of channels of cell k), m_k (number of channels designated for voice traffic), n_k (number of channels designated for data traffic), and b_k (buffer size for cell k).

Output Measures: $\lambda_v^h(k)$ (handoff voice-call arrival rate to cell k), $\lambda_d^h(k)$ (handoff data arrival rate to cell k), $P_B(k)$ (voice-call blocking probability in cell k), $L(k)$ (data loss probability in cell k), and $T(k)$ (mean data delay in cell k).

Step 1): $\mu_1 \leftarrow \mu_v + \eta_v$ and $\mu_2 \leftarrow \mu_d + \eta_d$.
Step 2): For $1 \le k \le M$, select initial values for $\lambda_v^h(k)$ and $\lambda_d^h(k)$ and perform the following steps.
Step 3): $\lambda_1(k) \leftarrow \lambda_v(k) + \lambda_v^h(k)$ and $\lambda_2(k) \leftarrow \lambda_d(k) + \lambda_d^h(k)$.
Step 4): Compute $\sum_{i=0}^{c_k-n_k} \Pi_i(z)$ by using (11).
Step 5): Compute $\sum_{i=0}^{c_k-n_k} Q_i(z)$ by using (17).
Step 6): Compute $P_B(k)$ and $L(k)$ by using (13) and (18), respectively.
Step 7): $\lambda_2(k) \leftarrow (\lambda_d(k) + \lambda_d^h(k))(1 - L(k))$.
Step 8): Iterate steps 4)–7) until $P_B(k)$ and $L(k)$ converge.
Step 9): Compute $\lambda_v^h(k)$ and $\lambda_d^h(k)$ by using (15) and (19), respectively.
Step 10): Iterate steps 3)–9) until $\lambda_v^h(k)$ and $\lambda_d^h(k)$ converge.
Step 11): Compute $T(k)$ by using (21).

For all cases studied in this paper, the iterative procedure converges within ten iterations of steps 3)–9), where each iteration of steps 3)–9) converges within 13 iterations of steps 4)–7). Moreover, we observe that numbers of iterations required for homogeneous systems are smaller than heterogeneous systems, but the difference is not significant. Since the run time complexity of steps 4)–7) is polynomial bounded, the iterative algorithm is a polynomial-bounded algorithm. Accordingly, the recomputation of the system performance due to the bandwidth reallocation can be performed in polynomial-bounded time.

III. Numerical Results

To verify the accuracy of the analysis, we carried out an event-driven simulation. In the simulation, we considered the movements of users along a one-dimensional (1-D) cellular system [9], [11], [16], which consists of six cells arranged as a ring. We assume that a mobile user moves to its left neighboring cell with the same probability as to its right neighboring cell. To simplify our results, the cellular system is assumed to be homogeneous, although the simulation can accommodate arbitrary heterogeneous PCS network structure. For a homogeneous PCS network, we have

$$\begin{aligned}
\frac{\lambda_v(i)}{\mu_v} &= \frac{\lambda_v(j)}{\mu_v} = \frac{\lambda_v}{\mu_v} = \varrho_v \\
\frac{\lambda_d(i)}{\mu_d} &= \frac{\lambda_d(j)}{\mu_d} = \frac{\lambda_d}{\mu_d} = \varrho_d \\
\lambda_v^h(i) &= \lambda_v^h(j) = \lambda_v^h, \quad \lambda_d^h(i) = \lambda_d^h(j) = \lambda_d^h \\
c_i &= c_j = c, \quad m_i = m_j = m \\
n_i &= n_j = n, \quad b_i = b_j = b \\
P_B(i) &= P_B(j) = P_B, \quad L(i) = L(j) = L, \quad \text{and} \\
T(i) &= T(j) = T.
\end{aligned}$$

The simulation was run for a relatively long duration, and appropriate statistics (i.e., voice-call blocking probability, data loss probability, and mean data delay) were obtained after allowing sufficient time to reach a steady state (i.e., all cells experienced almost the same voice-call blocking and data loss probabilities).

The effect of voice- and data-portable mobilities on the system performance can be seen in Fig. 2 where $\alpha = 500$ $(= \mu_d/\mu_v)$, i.e., the ratio of voice service time to data service time). The figure indicates that analytical results agree with simulation results with negligible discrepancy. Moreover, from Fig. 2(a) and (c), we observe that the voice-call blocking probability and the mean data delay decrease as voice- or data-portable mobilities increase. This phenomenon is consistent with known results [1], [17] for pure voice system where the nonprioritized handoff scheme is adopted. As η_v or η_d increases, the system experiences larger handoff arrivals and

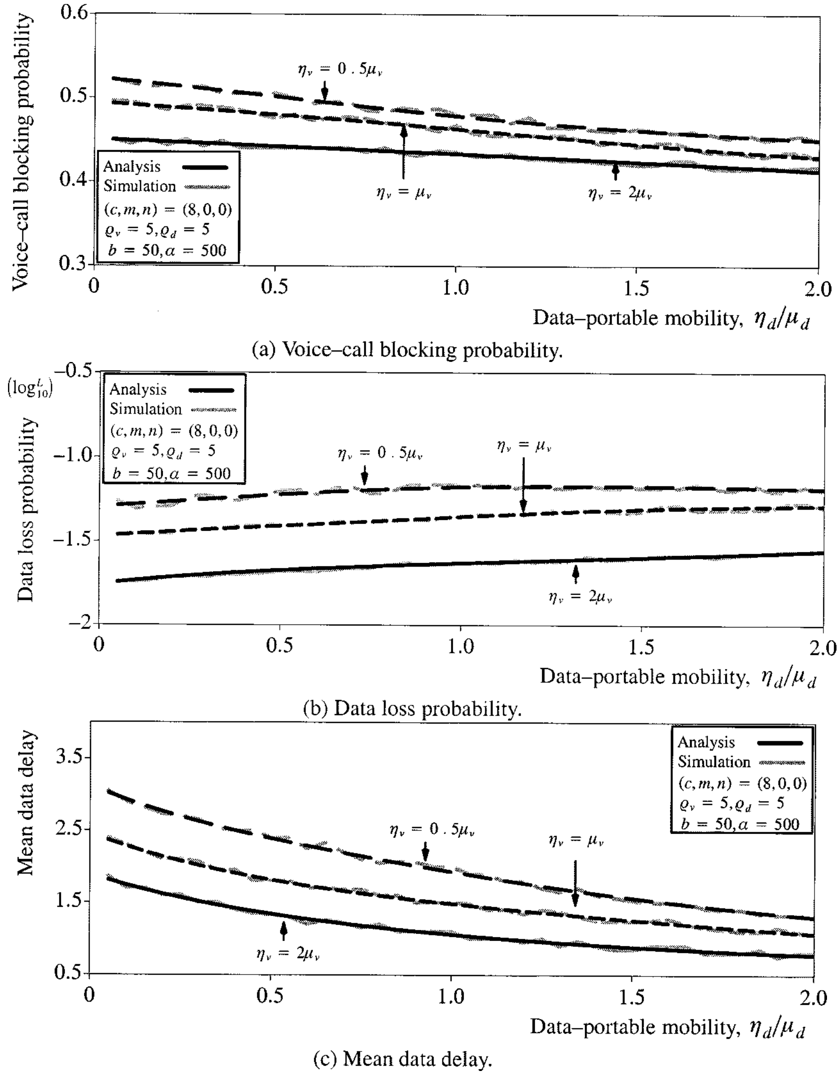


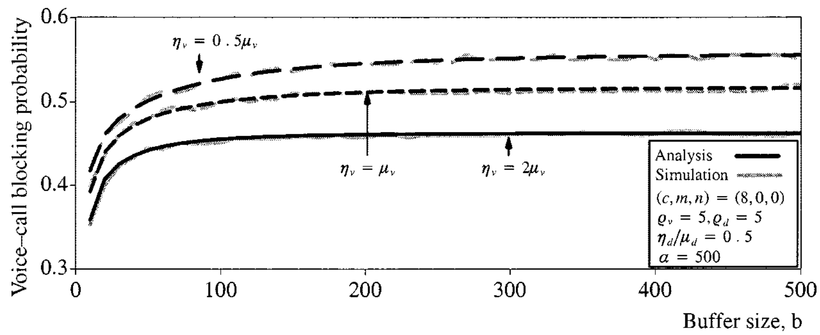
Fig. 2. System performance versus data-portable mobility.

shorter channel occupancy times where the total offered load (new plus handoff arrivals) is about the same. For the same offered load, P_B and T decrease as the service times decrease.

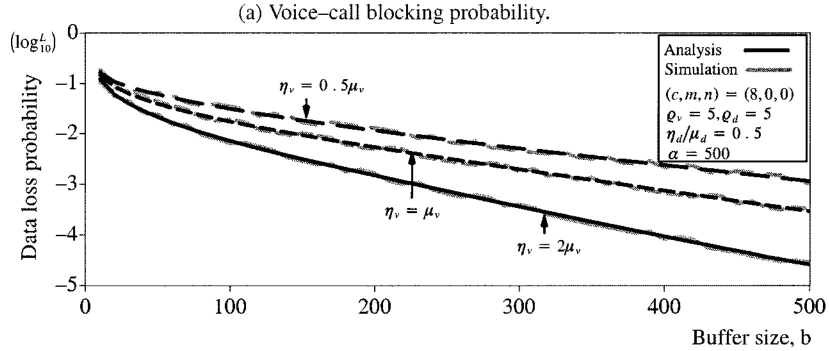
Fig. 2(b) shows that the data loss probability decreases as voice-portable mobility increases. As η_v increases the channel occupancy times decrease, resulting in the associated decrease in L. Moreover, it is seen that L is insensitive to η_d under smaller voice-portable mobility, say $\eta_v \leq 0.5\mu_v$, and slightly increases as η_d increases under larger voice-portable mobility, say $\eta_v \geq \mu_v$. This phenomenon is due to the fact that large values of η_d correspond to large values of λ_d^h, resulting in an increase in the data queue length and hence an increase in the data loss probability. Note that as η_v increases the contending voice traffic increases, the effect of η_d on L becomes significant.

Fig. 3 plots the system performance for different voice-portable mobilities as a function of buffer size. Again, the figure shows that analytical and simulation results are consistent. From Fig. 3(b), it is clear that as the buffer size increases the data loss probability decreases. The tradeoff is the associated increases in the voice-call blocking probability and the mean data delay as shown in Fig. 3(a) and (c). This phenomenon is due to the fact that as the data loss probability decreases the contending traffic increases, resulting in the associated increases in P_B and T. In addition, to guarantee a prescribed data loss probability, the buffer size is expected to increase with decreasing η_v. Fig. 3(b) shows this quantitatively. On the other hand, as we have seen previously, the data loss probability increases as η_d increases. Thus, as η_d increases, larger buffer size is required to guarantee a prescribed data loss probability.

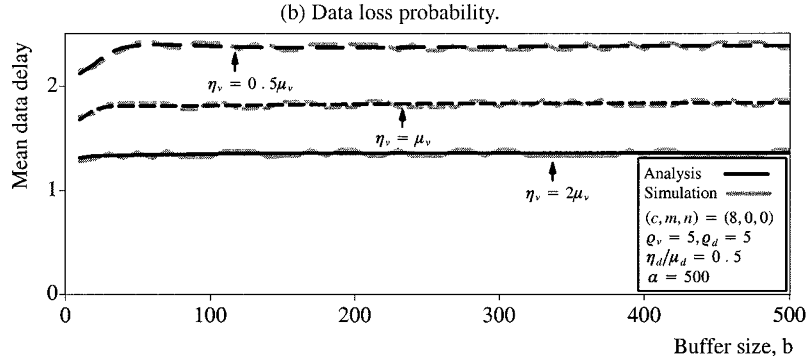
Figs. 4 and 5 depict the system performance for various bandwidth allocation paradigms (c, m, n) as a function of the new data-traffic intensity ϱ_d. The figures show that the voice-call blocking probability increases as n increases and decreases as m increases, while the data loss probability and the mean data delay increase as m increases and decrease as n increases. Another observation from Figs. 4(b) and (c) and 5(b) and (c) is that the data loss probability and the mean data delay oscillate as ϱ_d increases. In addition, the figures reveal the high sensitivity of L and T to α. Recall that α is the ratio of voice service time to data service time. For example, with $(c, m, n) = (8, 2, 1)$, it is seen that the larger α, the more L and T oscillate. This phenomenon is also observed in [14]. This salient phenomenon can be inferred from the following fact. Since voice calls often last on the order of minutes, while the duration of data transmission



(a) Voice–call blocking probability.



(b) Data loss probability.



(c) Mean data delay.

Fig. 3. System performance versus buffer size.

may elapse only on the order of milliseconds, the termination of voice calls can decrease data losses and delays profoundly. On the other hand, with $(c, m, n) = (8, 2, 1)$, from Figs. 4(a) and 5(a), we observe that the voice-call blocking probability is irrelevant to α. For more numerical results relating to α, the readers are referred to [14].

From the point of view of a mobile user, forced termination of an ongoing call is less desirable than blocking a new call. As a result, it needs to impose explicit control on the admission of new calls in order to keep the probability of forced termination at an acceptable level, in addition to allocating bandwidth dynamically and efficiently. The schedulable region (i.e., the acceptable load region) [18], which has been used for call admission control, can be calculated based on the bandwidth allocation scheme employed, portable mobility, channel occupancy time distribution, buffer size, and QoS constraints. For example, with $(c, m, n) = (8, 0, 0)$, $\eta_d = 0.5\mu_d$, $\alpha = 500$, and $b = 50$, Fig. 6 presents the schedulable regions for different voice-portable mobilities under the QoS constraints $P_B < 0.1$, $L < 10^{-3}$, and $T < 5$. The figure indicates that the larger η_v, the larger size of the schedulable region (area under the curve).

Finally, in order to illustrate the impact of hot-spot traffic on system performance, we carried out a numerical example for a heterogeneous cellular system. We assume that the mobile users move along a ring of six cells according to the routing matrix

$$R = \begin{bmatrix} 0 & \frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} \\ \frac{2}{5} & 0 & \frac{3}{5} & 0 & 0 & 0 \\ 0 & \frac{1}{4} & 0 & \frac{3}{4} & 0 & 0 \\ 0 & 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & \frac{4}{5} & 0 & \frac{1}{5} \\ \frac{1}{3} & 0 & 0 & 0 & \frac{2}{3} & 0 \end{bmatrix}.$$

For ease of illustrating the effects of hot-spot traffic caused by users' movements, we assume

$$\frac{\lambda_v(i)}{\mu_v} = \frac{\lambda_v(j)}{\mu_v} = \frac{\lambda_v}{\mu_v} = \varrho_v,$$
$$\frac{\lambda_d(i)}{\mu_d} = \frac{\lambda_d(j)}{\mu_d} = \frac{\lambda_d}{\mu_d} = \varrho_d,$$
$$c_i = c_j = c, \quad m_i = m_j = m,$$
$$n_i = n_j = n, \quad \text{and} \quad b_i = b_j = b.$$

Fig. 7 shows the system performance for six cells as a function of the new data-traffic intensity ϱ_d. Again, the figure indicates

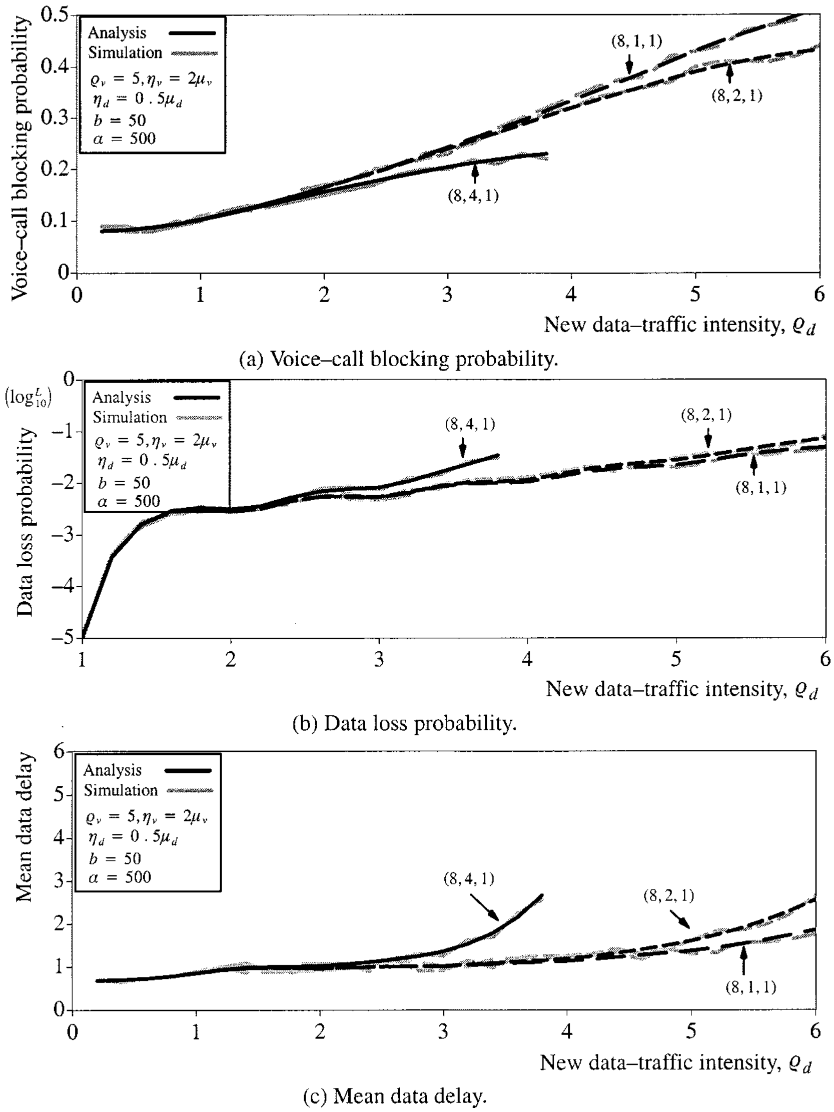


Fig. 4. System performance for various number of designated voice channels.

that analytic results are consistent with simulation results. Moreover, it is observed that the system performance of cell 3 (hot-spot cell) is significantly impaired by hot-spot traffic.

IV. Conclusions

This paper presented a traffic model for an integrated voice/data mobile system with finite data buffer, and validated its accuracy by simulation. With our model, the system performance (i.e., voice-call blocking probability, data loss probability, and mean data delay) based on the movable-boundary scheme and the impact of hot-spot traffic in a heterogeneous PCS network can be effectively analyzed. In addition, we proposed an iterative algorithm to determine the handoff traffic and compute the system performance, and proved that its run time complexity is polynomial bounded. This fact allows the recomputation of the system performance due to the bandwidth reallocation to be performed in polynomial-bounded time. According to the numerical results, we observed the following.

- The voice-call blocking probability and the mean data delay decrease as voice- or data-portable mobilities increase, while the data loss probability decreases as voice-portable mobility increases and slightly increases as data-portable mobility increases.
- The data loss probability decreases as the buffer size increases. The tradeoff is the associated increases in the voice-call blocking probability and the mean data delay.
- The voice-call blocking probability decreases as m increases (i.e., number of channels designated for voice traffic) and increases as n increases (i.e., number of channels designated for data traffic), while the data loss probability and the mean data delay decrease as n increases and increase as m increases.

Recall that the goal of voice/data integration on a mobile system is to share the bandwidth efficiently while keeping the probability of forced termination at an acceptable level. As a result, in addition to allocating bandwidth dynamically and efficiently, it also needs to impose explicit control on the admission of new calls. We have shown an example of the schedulable region

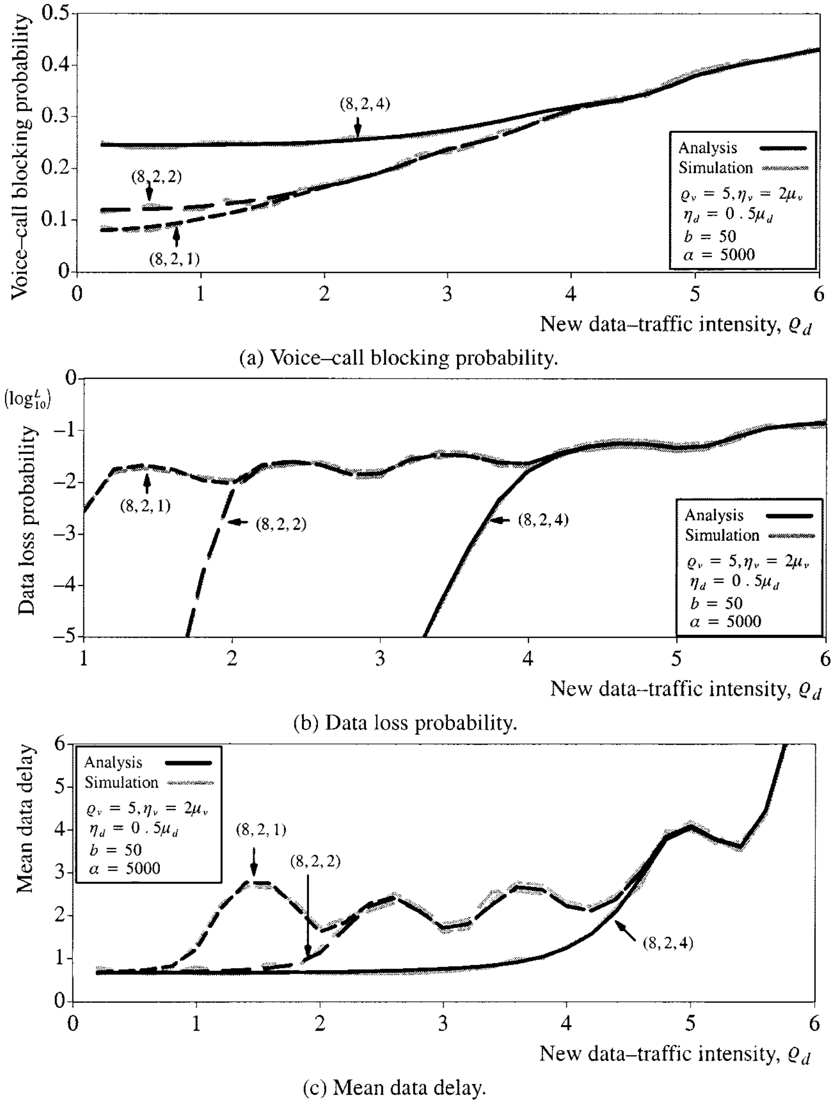


Fig. 5. System performance for various number of designated data channels.

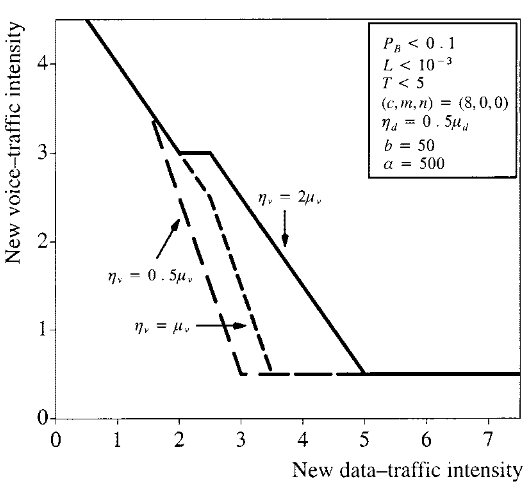


Fig. 6. Schedulable region with QoS guarantees.

which can be used for call admission control. Based on our model, we are developing a scheduling algorithm which combines bandwidth allocation scheme and call admission control in an integrated, efficient, and intelligent manner to satisfy diverse QoS requirements.

APPENDIX I
NOTATION

In this Appendix, we outline the notation used for the analysis. For each cell k, we define the following notation.

M	Number of cells in the mobile system.
k	kth cell where $1 \leq k \leq M$.
$R = [r_{ij}]_{M \times M}$	Routing matrix.
$\lambda_v(k)$	New voice-call arrival rate.
$\lambda_d(k)$	New data arrival rate.
$\lambda_v^h(k)$	Handoff voice-call arrival rate.
$\lambda_d^h(k)$	Handoff data arrival rate.
$\lambda_1(k) = \lambda_v(k) + \lambda_v^h(k)$	
$\lambda_2(k) = \lambda_d(k) + \lambda_d^h(k)$	
$1/\mu_v$	Mean voice-call service time.
$1/\mu_d$	Mean data service time.

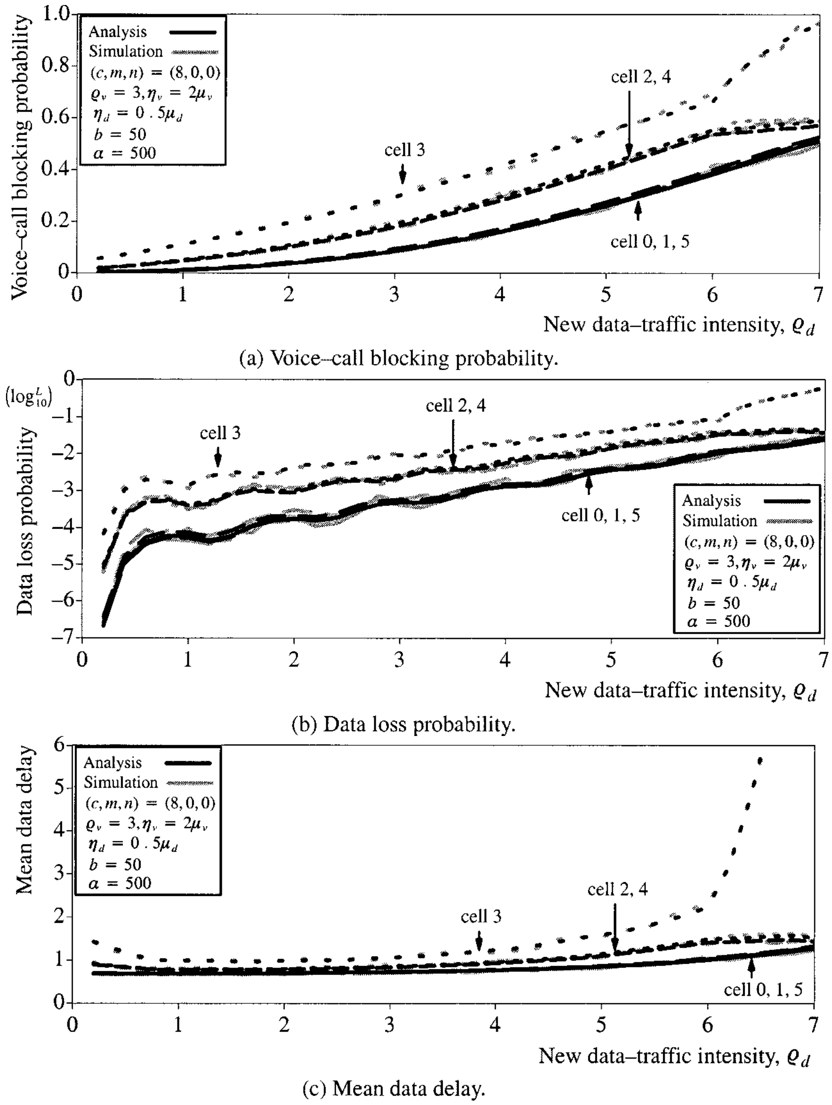


Fig. 7. System performance for six cells.

$1/\eta_v$	Mean voice-portable residence time.
$1/\eta_d$	Mean data-portable residence time.
$\mu_1 = \mu_v + \eta_v$	
$\mu_2 = \mu_d + \eta_d$	
c_k	Number of channels.
m_k	Number of channels designated for voice traffic.
n_k	Number of channels designated for data traffic.
b_k	Buffer size.
p_{ij}	Steady-state probability of having i voice calls and j data packets in cell k.
$\Pi_i(z) = \sum_{j=0}^{\infty} p_{ij} z^j$	Probability generating function of p_{ij}.
q_{ij}	Tail probability of p_{ij} (i.e., $q_{ij} = \sum_{l=1}^{\infty} p_{i,j+l}$).
$Q_i(z) = \sum_{j=0}^{\infty} q_{ij} z^j$	Probability generating function of q_{ij}.
$P_B(k)$	Voice-call blocking probability.
$L(k)$	Data loss probability.
$T(k)$	Mean data delay.

Appendix II
Derivation for $\Pi_i(1)$, $\Pi_i'(1)$, and p_{ij}

This Appendix provides the major computational steps for the derivation of $\Pi_i(1)$ $(m_k \leq i \leq c_k - n_k)$, $\Pi_i'(1)$ $(m_k + 1 \leq i \leq c_k - n_k)$, and p_{ij} $(0 \leq i \leq m_k,\ 0 \leq j \leq c_k - m_k - 1$ and $m_k + 1 \leq i \leq c_k - n_k,\ 0 \leq j \leq c_k - i - 1)$. First, setting $z = 1$ in (8) and (9), one can derive $\Pi_i(1)$ $(m_k + 1 \leq i \leq c_k - n_k)$ recursively. Since $\sum_{i=0}^{c_k - n_k} \Pi_i(1) = 1$, from (6) to (8), $\Pi_{m_k}(1)$ can be expressed as

$$\Pi_{m_k}(1) = \frac{1 - \displaystyle\sum_{i=m_k+1}^{c_k-n_k} \Pi_i(1)}{\displaystyle\sum_{j=0}^{m_k} \left(\frac{m_k!}{j!}\right)\left(\frac{\mu_1}{\lambda_1(k)}\right)^{m_k - j}}.$$

By differentiating (8) and (9) with respect to z and setting $z = 1$, we obtain $\Pi'_i(1)$ $(m_k + 1 \le i \le c_k - n_k)$ recursively.

We now calculate the steady-state probabilities p_{ij} from (1)–(4). However, (1)–(4) do not provide enough independent equations to solve these probabilities. This is because $c_k - n_k + 1$ additional unknowns, p_{i,c_k-m_k} $(0 \le i \le m_k)$ and p_{i,c_k-i} $(m_k + 1 \le i \le c_k - n_k)$, have to be solved. Thus, we must discover another $c_k - n_k + 1$ additional independent equations. Setting $z = 1$ in (10), we obtain one additional equation. Moreover, equating the zeros on both sides of (8) and (9) provides $c_k - m_k - n_k$ additional equations. Finally, let

$$A_i(z) = D_i(z) - \frac{i\lambda_1(k)\mu_1 z^2}{A_{i-1}(z)} \tag{22}$$

where $0 \le i \le m_k$ and $A_{-1}(z) = 1$. From (6), (7), and (22), we have

$$\begin{aligned} A_{m_k}(z)\Pi_{m_k}(z) &= (m_k+1)\mu_1 z \Pi_{m_k+1}(z) \\ &\quad - \lambda_1(k) \sum_{j=0}^{c_k-m_k-1} p_{m_k,j} z^{j+1} + (z-1)\mu_2 \\ &\quad \times \left[\sum_{i=0}^{m_k} \frac{[\lambda_1(k)z]^{m_k-i} \sum_{j=0}^{c_k-m_k-1} (c_k - m_k - j) p_{ij} z^j}{\Pi_{l=i}^{m_k-1} A_l(z)} \right] \end{aligned} \tag{23}$$

where $\Pi_{l=m_k}^{m_k-1} A_l(z) = 1$. Notice that $A_{m_k}(z)$ has m_k distinct roots between (0,1). For a rigorous proof, the reader is again referred to [14]. Equating the zeros on both sides of (23) provides the last m_k equations needed.

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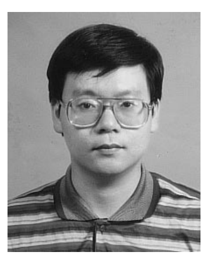

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