Channel Allocation for GPRS

Phone Lin and Yi-Bing Lin, *Senior Member, IEEE*

***Abstract*—Based on the GSM radio architecture, general packet radio service (GPRS) provides users data connections with variable data rates and high bandwidth efficiency. In GPRS service, allocation of physical channels is flexible, i.e., multiple channels can be allocated to a user. In this paper, we propose four algorithms for the GPRS radio resource allocation: fixed resource allocation (FRA), dynamic resource allocation (DRA), fixed resource allocation with queue capability (FRAQ), and dynamic resource allocation with queue capability (DRAQ). We develop analytic and simulation models to evaluate the performance for these resource allocation algorithms in terms of the acceptance rate of both GPRS packet data and GSM voice calls. Our study indicates that DRAQ (queuing for both new and handoff calls) outperforms other algorithms.**

***Index Terms*—Dynamic resource allocation, fixed resource allocation, general packet radio service, wireless data.**

α_1	Shape parameter of Gamma distributed packet transmission times.
α_2	Shape parameter of Gamma distributed packet inter arrival times.
α_3	Shape parameter of Gamma distributed GSM voice user cell residence times.
η_v	GSM voice user mobility rate.
$\lambda_p(\lambda_v)$	GPRS packet arrival rate to a cell (the new GSM voice call arrival rate to a cell).
$\lambda_{v,h}$	Voice handoff call arrival rate to a cell.
$1/\mu_p$ $(1/\mu_v)$	Expected GPRS packet transmission time if one channel is used to serve the packet (the expected GSM voice call holding time).
ρ_p (ρ_v)	GPRS packet traffic (the GSM voice traffic) to a cell.
$\Lambda_v = \lambda_v - \lambda_{v,h}$	Net new/handoff voice call arrival rate.
$1/M_v = 1/\mu_v + \eta_v$	Mean channel occupancy time of a voice call.
C	Number of channels in a cell.
c_p	Average number of channels for a served packet.
K	Maximum number of channels used to serve a GPRS packet.
L	Number of idle channels in a cell, where $0 \leq L \leq C$.
P_{b_p} (P_{b_v})	Dropping probability for the GPRS packet (the new call blocking probability for the GSM voice call).
P_{f_v}	Force-termination probability for the GSM voice call.
P_{nc_v}	Probability that a GSM voice call is not completed (either blocked or forced to terminate).
Q	Maximum number of voice call requests buffered in the queue.
$t_{c,p}$ $(t_{c,v})$	GPRS packet transmission time (the voice call holding time).
$t_{m,j}$	Residence time of an GSM voice user at a cell j.
v_{μ_p}	Variance of Gamma distributed packet transmission times.
v_{λ_p}	Variance of Gamma distributed packet inter arrival times.
v_{η_v}	Variance of Gamma distributed GSM voice user cell residence times.
W_{avg}	Average waiting time for the accepted voice call requests.

I. INTRODUCTION

General Packet Radio Service (GPRS) [6] is a new bearer service for mobile networks [such as Global System for Mobile Communications (GSM) [13] and IS-136 [8]], which greatly improves and simplifies the wireless access to packet data networks (e.g., the Internet). In this paper, we assume that the mobile network for GPRS is GSM. Compared with the previous mobile data services (e.g., circuit-switched data [4] and short message service [2]), users of GPRS benefit from shorter access times and higher data rates.

Fig. 1 illustrates the GPRS architecture based on the GSM network [7]. In a GSM network, a mobile station (MS) communicates with a base station subsystem (BSS) through the air interface. The BSS is connected to the mobile switching center (MSC) for the mobile applications. The MSC communicates with the visitor location register (VLR) and home location register (HLR) to track the locations of MSs. The reader is referred to [13] for GSM details. In the GPRS architecture, MS, BSS, VLR, and HLR in the GSM network are modified. For example, the HLR is enhanced to accommodate GPRS user information. Two GPRS support nodes (GSNs), a serving GPRS support node (SGSN), and a gateway GPRS support node (GGSN)

Manuscript received May 5, 2000; revised November 22, 2000. This work was sponsored in part by the MOE Program of Excellence Research under Contract 89-E-FA04-4, in part by CCL/ITRI under Contract 2-10B, in part by FarEastone, in part by NSC, and in part by the Lee and MTI Center for Networking Research, National Chiao Tung University.

The authors are with the Department of Computer Science and Information Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: liny@csie.nctu.edu.tw).

Publisher Item Identifier S 0018-9545(01)03068-7.

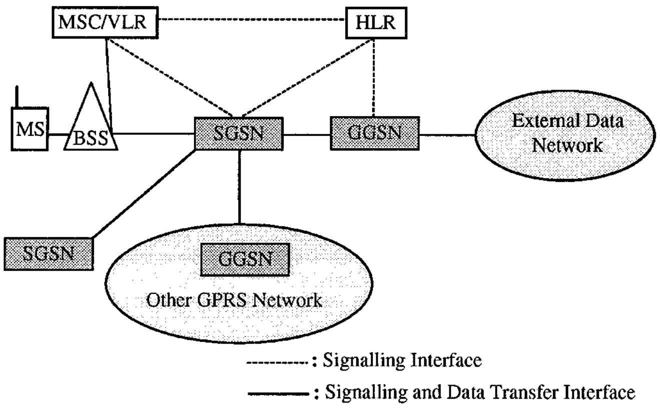


Fig. 1. GPRS architecture.

are introduced in GPRS. The SGSN is responsible for delivering packets to the MSs. The GGSN acts as a gateway between GPRS and the external data networks. Between different GSNs within the GPRS network, the GPRS tunneling protocol is used to tunnel user data and signaling message.

Based on the GSM architecture, the GPRS air interface [5] has been implemented for communication between the MS and BSS. The GPRS physical channel dedicated to packet data traffic is called a packet data channel (PDCH). Different packet data logical channels can camp on the same PDCH, which are packet data traffic channels (PDTCHs) used for data transfer, packet common control channels (PCCCHs) used to convey the GPRS common control signaling, and packet dedicated control channels (PDCCHs) used to convey the GPRS control signaling for a dedicated MS. Allocation of channels for GPRS is flexible where one to eight channels can be allocated to a user or one channel can be shared by several users.

Fig. 2 illustrates the message flow for the GPRS uplink packet transfer. The downlink packet transfer is similar and is not described. To initiate packet transfer, an MS negotiates with the network for the radio resource in the access and assignment phase via PCCCH and possibly PDCCH (see Step 1 in Fig. 2). After this phase, the MS starts to transmit data blocks to the network via PDTCH (see Step 2 in Fig. 2) according to the agreed resource assignment. If the MS requires more PDCHs, it can specify the request through an assigned uplink block (see Step 3 in Fig. 2). The network and the MS then exchange the PDCCHs to reallocate the resources for uplink transmission (see Steps 4 and 5 in Fig. 2). The amount of PDCHs for the request will be recorded in the quality of service (QoS) profile of the user at the SGSN. When the MS completes the transmission, it indicates the last data block (see Step 7 in Fig. 2). The network then terminates the uplink transmission by returning the final block acknowledgment (see Step 8 in Fig. 2). Note that in resource assignment (Step 1) and resource reassignment (Step 4), there are two alternatives: fixed resource allocation and dynamic resource allocation. In the fixed resource allocation, the requested amount of PDCHs is allocated for the packet request. The packet request is rejected if the BS does not have enough radio resources to accommodate the request. On the other hand, the network allocates partial resources in dynamic resource allocation.

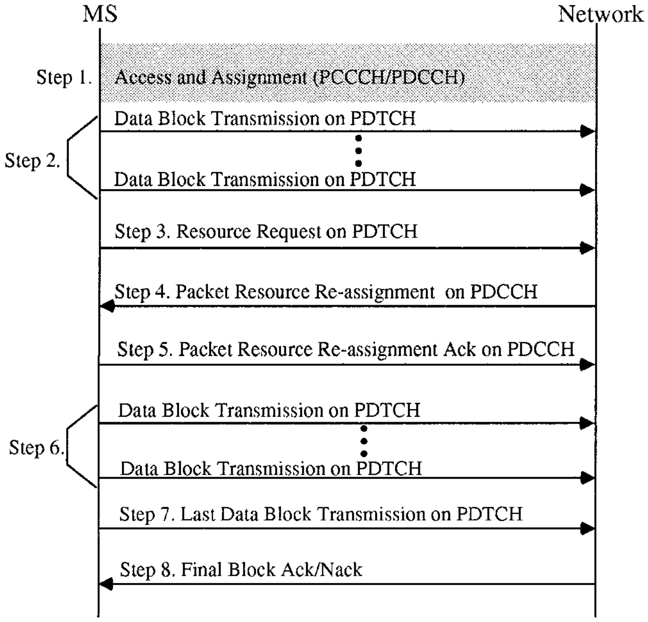


Fig. 2. GPRS uplink packet transfer.

In this paper, we propose four resource allocation algorithms: fixed resource allocation (FRA), fixed resource allocation with queue capability (FRAQ), dynamic resource allocation (DRA), and dynamic resource allocation with queue capability (DRAQ) for scheduling of the packet data and voice calls. Then we propose analytic and simulation models to evaluate the performance for these algorithms. Our study indicates that dynamic allocation for packet transmission and waiting queue for voice calls may significantly improve the performance of the network.

II. RESOURCE ALLOCATION ALGORITHMS FOR GPRS PACKET REQUESTS AND GSM VOICE CALLS

This section describes four resource allocation algorithms for GPRS packet requests and GSM voice calls. We assume that a GPRS data request specifies K channels for transmission. Based on the negotiated QoS profile, a cell may allocate resources on one or several physical channels to support the GPRS traffic, as described in Section I. We assume that the packets are transmitted at rate μ_p at a single channel. Consequently, if k channels are assigned to a GPRS data request, then this packet request will be delivered with rate $k\mu_p$. Suppose that there are L free channels at a cell when a GPRS data request or a GSM voice call request arrives. Algorithms FRA and FRAQ allocate the exact number of channels requested by the GPRS data requests. On the other hand, algorithms DRA and DRAQ may allocate partial resources. All four algorithms allocate one channel for a voice request. In FRA and DRA, if no channel is available, the voice request is rejected immediately. In FRAQ and DRAQ, on the other hand, the voice call requests can be buffered in a waiting queue if all channels at a cell are busy. The intuition behind FRAQ and DRAQ is that packet transmission times are typically short. Thus, with the buffer mechanism, a voice request can be served after a short waiting time (when GPRS completes

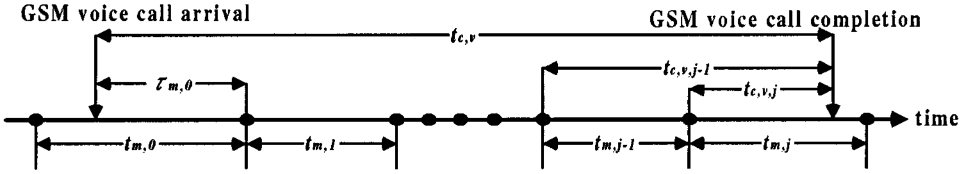


Fig. 3. The timing diagram.

a packet transmission) instead of being rejected immediately at its arrival. The four algorithms are described below.

Algorithm FRA	For a data request of K channels, the BS assigns K channels to the GPRS packet request if $K \leq L$. Otherwise, the GPRS packet request is rejected.
Algorithm DRA	For a data request of K channels, DRA allocates at most K channels to the request. Depending on the current available radio resources, the network shall negotiate with the GPRS MS for the QoS profile at the beginning of GPRS data transfer. Specifically, if $L \geq K$, then K channels are allocated to the request. If $0 < L < K$, then L channels are allocated to the request. If $L = 0$, then the request is rejected.
Algorithm FRAQ	FRAQ handles GPRS data requests in the same way as FRA. For GSM voice call requests, FRAQ provides a queue to hold GSM voice call requests when all channels are busy. These queued GSM requests are served immediately when idle channels are available. FRAQ may selectively queue the new calls only, the handoff calls only, or both, and the corresponding mechanisms are called FRAQ_N (for new calls only), FRAQ_H (for handoff calls only), and FRAQ_NH (for both new calls and handoff calls), respectively.
Algorithm DRAQ	DRAQ assigns channels to a GPRS data request in the same way as DRA and assigns channels to GSM voice call requests in the same way as FRAQ. Thus, there are also three DRAQ variations: DRAQ_N (for new calls only), DRAQ_H (for handoff calls only), and DRAQ_NH (for both new calls and handoff calls), respectively.

III. ANALYTIC MODELS

Several analytic models for circuit-switched-type channel allocation of mobile networks are described in [1] and [9] and references therein. We propose analytic models to investigate the performance of algorithms FRA, DRA, and FRAQ and validate these models by simulation experiments. The output measures of these models are the dropping probability P_{b_p} for the GPRS packets and the GSM voice call incompletion probability P_{nc_v} (i.e., the probability that a voice call is blocked or forced to terminate).

We assume that the GSM voice call arrivals and GPRS packet requests to a cell form Poisson streams with rates λ_v and λ_p, respectively. Let $t_{c,v}$ ($t_{c,p}$) be the voice call holding time (GPRS packet transmission time), which is assumed to be exponentially distributed with the density function $f_{c,v}(t_{c,v}) = \mu_v e^{-\mu_v t_{c,v}}$ ($f_{c,p}(t_{c,p}) = \mu_p e^{-\mu_p t_{c,p}}$) and the mean voice call holding time (packet transmission time) $E[t_{c,v}] = 1/\mu_v$ ($E[t_{c,p}] = 1/\mu_p$).

In the GSM (GPRS) network, if an MS moves to another cell during the conversation, then the radio link to the old BS is disconnected and a radio link to the new BS is required to continue the conversation. This process is called "handoff" [3]. If the new BS does not have any idle channel, the handoff call is "forced to terminate." In the analytic models, we consider the mobility of voice users but ignore the effect of mobility (handoff) on the GPRS packet transmission. Our assumption is justified as follows. Although a GPRS session can be elapsed for a long period, the individual packet transmission times are short, and the handoff procedure can be initiated after the current packet transmission is completed. On the other hand, voice call holding times are long enough so that handoffs may occur during the conversation. Thus the handoff effects of voice calls must be considered.

A. Analytic Model for FRA

This section proposes an analytic model for algorithm FRA. We first describe the handoff traffic model for voice users. Then we use the Zachary–Kelly model [15], [10] together with an iterative algorithm to derive the voice blocking probability and data dropping probability.

Consider the timing diagram in Fig. 3. Let $t_{m,j}$ be the residence time of a GSM voice user at a cell j (where $j \geq 0$). We assume that $t_{m,j} (j \geq 0)$ are independent and identically distributed random variables with a general function $f_m(t_{m,j})$ with mean $1/\eta_v$. Let $f_m^*(s) = \int_{t_{m,j}=0}^{\infty} f_m(t_{m,j}) e^{-st_{m,j}} dt_{m,j}$ be the Laplace transform of the cell residence time distribution. In the GSM voice call channel assignment of FRA, the handoff calls and the new calls are not distinguishable. Thus the new call blocking probability P_{b_v} and the handoff call force-termination probability P_{f_v} are the same (i.e., $P_{b_v} = P_{f_v}$). Let $\lambda_{v,h}$ be the voice handoff call arrival rate to a cell and P_{nc_v} be the voice call incompletion probability (i.e., the probability that a voice call is blocked as a new call attempt or forced to terminate as a connected call). From [12], $\lambda_{v,h}$ can be expressed as

$$\lambda_{v,h} = \frac{\eta_v (1 - P_{b_v})[1 - f_m^*(\mu_v)]\lambda_v}{\mu_v [1 - (1 - P_{f_v}) f_m^*(\mu_v)]}. \tag{1}$$

The GSM voice call traffic ρ_v to a cell is

$$\rho_v = \left(\frac{\lambda_v}{\mu_v}\right) \times \left\{1 - \frac{\eta_v[P_{b_v} + (P_{f_v} - P_{b_v}) f_m^*(\mu_v)][1 - f_m^*(\mu_v)]}{\mu_v[1 - (1 - P_{f_v}) f_m^*(\mu_v)]}\right\} \tag{2}$$

and P_{nc_v} is

$$\begin{aligned} P_{nc_v} &= P_{b_v} + \left(\frac{\lambda_{v,h}}{\lambda_v}\right) P_{f_v} \\ &= P_{b_v} + \left\{\frac{\eta_v(1 - P_{b_v})[1 - f_m^*(\mu_v)]}{\mu_v[1 - (1 - P_{f_v}) f_m^*(\mu_v)]}\right\} P_{f_v}. \end{aligned} \tag{3}$$

To derive the new call blocking probability P_{b_v} for GSM voice calls and the dropping probability P_{b_p} for the GPRS packets, we consider a stochastic process with state $\mathbf{n} = (n_v, n_p)$, where n_v and n_p represent the number of outstanding voice calls and GPRS packets at a cell, respectively. Suppose that there are C channels at a cell. Since the network assigns K channels to every GPRS packet request in FRA, the following constraints must be satisfied:

$$n_v + K n_p \le C, \; 0 \le n_v \le C, \text{ and } 0 \le n_p \le \left\lfloor \frac{C}{K} \right\rfloor$$

Thus the state space $\mathbf{S}_{\text{FRA}}$ of the stochastic process is

$$\mathbf{S}_{\text{FRA}} = \left\{ (n_v, n_p) \mid n_v + K n_p \le C, \; 0 \le n_v \le C, \text{ and } 0 \le n_p \le \left\lfloor \frac{C}{K} \right\rfloor \right\}.$$

According to the Zachary–Kelly model, the stationary probability $p(\mathbf{n})$ of the state $\mathbf{n} = (n_v, n_p)$ can be computed as

$$p(\mathbf{n}) = G^{-1} \left(\frac{\rho_v^{n_v}}{n_v!}\right) \left(\frac{\rho_p^{n_p}}{n_p!}\right) \tag{4}$$

where $\rho_p = \lambda_p / \mu_p$, ρ_v is obtained from (2) and G is

$$G = \sum_{\mathbf{n} \in \mathbf{S}_{\text{FRA}}} \left[\left(\frac{\rho_v^{n_v}}{n_v!}\right) \left(\frac{\rho_p^{n_p}}{n_p!}\right) \right]. \tag{5}$$

The second and third terms of the right-hand side in (4) are the weights contributed by the GSM voice call traffic and GPRS packet traffic, respectively. The normalized factor G in (5) is used to ensure that $\sum_{\mathbf{n} \in \mathbf{S}_{\text{FRA}}} p(\mathbf{n}) = 1$.

With the above stochastic process model, P_{b_v} is computed as follows. When a GSM voice call arrives at a cell, it is blocked if no free channel is available at the cell. That is, $n_v + K n_p = C$ when the GSM voice call arrives. Thus

$$P_{b_v} = \sum_{\mathbf{n} \in \{(n_v, n_p) \mid n_v + K n_p = C, \; 0 \le n_v \le C, \; 0 \le n_p \le \lfloor C/K \rfloor\}} p(\mathbf{n}). \tag{6}$$

Similarly, when a GPRS packet request arrives at a cell, it is dropped if the number of idle channels is smaller than K (i.e., $C - K < n_v + K n_p \le C$). (See (7) at the bottom of the page.) With (1), (2), (3), (6), and (7), the following iterative algorithm [12] computes $\lambda_{v,h}$, P_{nc_v}, and P_{b_p}.

The Iterative Algorithm for FRA

Step 1) Select an initial value for $\lambda_{v,h}$.
Step 2) $\lambda_{v,h,\text{old}} \leftarrow \lambda_{v,h}$.
Step 3) Compute P_{b_v} and P_{b_p} by using (2) and (4)–(7).
Step 4) Compute $\lambda_{v,h}$ by using (1).
Step 5) If $|\lambda_{v,h} - \lambda_{v,h,\text{old}}| > \delta \lambda_{v,h}$ then go to Step 2). Otherwise, go to Step 6). Note that δ is a predefined threshold set to 10^{-7}.
Step 6) The values for $\lambda_{v,h}$, P_{b_v} and P_{b_p} converge. Compute P_{nc_v} by using (3).

In all cases considered in this paper, the above algorithm always converges. The simulation experiments indicate that the algorithm converges to the correct values (see Section III-D).

B. Analytic Model for DRA

This section proposes an analytic model for DRA. To simplify our discussion, the cell residence time for a GSM voice user is assumed to be exponentially distributed with mean $1/\eta_v$ and Laplace transform

$$f_m^*(s) = \frac{\eta_v}{\eta_v + s}. \tag{8}$$

In the real world, the cell residence time distribution may not be exponential. By using exponential assumptions, our analytic model serves for two purposes. First, exponential distribution provides the mean value analysis, which indicates the performance trend of DRA. Second, the analytic model is used to validate the simulation model that we use to study the performance of DRA with a general cell residence time distribution.

Algorithm DRA is modeled by a $(K+1)$-state Markov process. In this process, a state $(n_v, n_{p_K}, n_{p_{K-1}}, n_{p_{K-2}}, n_{p_{K-3}}, \ldots, n_{p_1})$ denotes that a cell is occupied by n_v voice calls, n_{p_K} GPRS packets (each allocated K channels), $n_{p_{K-1}}$ GPRS packets (each allocated $K-1$ channels), $n_{p_{K-2}}$ GPRS packets (each allocated $K-2$ channels), $\ldots$, and n_{p_1} GPRS packets (each allocated one channel), respectively. For the illustration purpose, we consider $K = 3$ in our discussion. In this Markov process, a state is represented by (i, j, k, l), where $i = n_v, j = n_{p_3}, k = n_{p_2}$ and

$$P_{b_p} = \sum_{\mathbf{n} \in \{(n_v, n_p) \mid C - K n_v + K n_p \le C, \; 0 \le n_v \le C, \; 0 \le n_p \le \lfloor C/K \rfloor\}} p(\mathbf{n}). \tag{7}$$

$l = n_{p_1}$. Based on DRA described in the previous section, it is clear that the state space $\mathbf{S}_{\mathrm{DRA}}$ for this Markov process is

$$\mathbf{S}_{\mathrm{DRA}} = \Bigg\{ (i,j,k,l) \mid 0 \le i + 3j + 2k + l \le C, \\ 0 \le i \le C,\ 0 \le j \le \left\lfloor \frac{C}{3} \right\rfloor, \\ 0 \le k \le \left\lfloor \frac{C}{2} \right\rfloor, \text{ and } 0 \le l \le C \Bigg\}.$$

Let $\pi_{i,j,k,l}$ be the steady-state probability for state (i,j,k,l). By convention $\pi_{i,j,k,l} = 0$ if state $(i,j,k,l) \notin \mathbf{S}_{\mathrm{DRA}}$. For all legal states $(i,j,k,l) \in \mathbf{S}_{\mathrm{DRA}}$, we have

$$\sum_{(i,j,k,l) \in \mathbf{S}_{\mathrm{DRA}}} \pi_{i,j,k,l} = 1.$$

Fig. 4 illustrates the state transition diagram for DRA. The transitions of the Markov process are described as follows. If state $(i,j,k,l) \in \mathbf{S}_{\mathrm{DRA}}$, the following transitions should be considered. Let $\Lambda_v = \lambda_v + \lambda_{v,h}$ be the net new/handoff voice call arrival rate to a cell. Let $M_v = \mu_v + \eta_v$. Then $1/M_v$ is the mean channel occupancy time of a voice call at a cell.

1) At state $(i-1,j,k,l) \in \mathbf{S}_{\mathrm{DRA}}$, if a new voice call or handoff call arrives, the process moves from state $(i-1,j,k,l)$ to (i,j,k,l) with rate Λ_v. The process moves from state (i,j,k,l) to $(i-1,j,k,l)$ with rate iM_v for a voice call completion (or when the voice user moves to another cell).

2) If a GPRS request arrives when the process is at state $(i,j,k,l-1) \in \mathbf{S}_{\mathrm{DRA}}$ where $i+3j+2k+(l-1) = C-1$, then one channel is allocated. Define δ_1 as

$$\delta_1 = \begin{cases} 1, & \text{if } i+3j+2k+(l-1) = C-1 \text{ and} \\ & (i,j,k,l-1) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

Then the process moves from state $(i,j,k,l-1)$ to (i,j,k,l) with rate $\delta_1\lambda_p$. The process moves from state (i,j,k,l) to $(i,j,k,l-1)$ with rate $l\mu_p$ when the transmission is completed for a GPRS data request utilizing one channel.

3) If a GPRS request arrives when the process is at state $(i,j,k-1,l) \in \mathbf{S}_{\mathrm{DRA}}$, where $i+3j+2(k-1)+l = C-2$, then two channels are allocated. Define δ_2 as

$$\delta_2 = \begin{cases} 1, & \text{if } i+3j+2(k-1)+l = C-2 \text{ and} \\ & (i,j,k-1,l) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

The process moves from state $(i,j,k-1,l)$ to (i,j,k,l) with rate $\delta_2\lambda_p$. The process moves from state (i,j,k,l) to $(i,j,k-1,l)$ with rate $2k\mu_p$ when the transmission is completed for a GPRS data request occupying two channels.

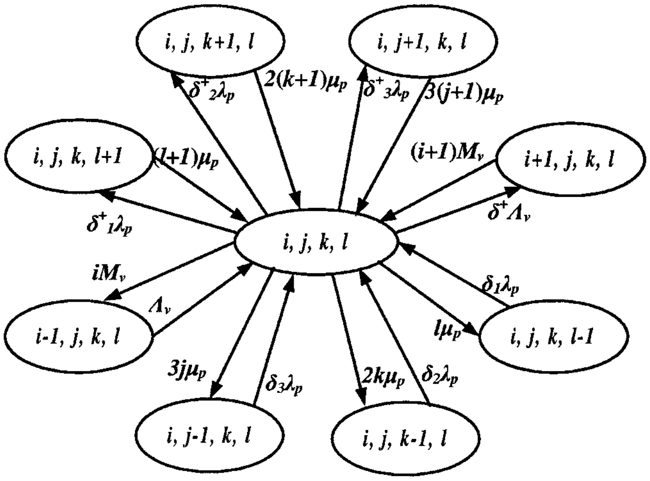


Fig. 4. The state transition diagram for DRA.

4) At state $(i,j-1,k,l) \in \mathbf{S}_{\mathrm{DRA}}$, where $i+3(j-1)+2k+l \le C-3$, if a GPRS data request arrives, then three channels are allocated. Define δ_3 as

$$\delta_3 = \begin{cases} 1, & \text{if } i+3(j-1)+2k+l \le C-3 \text{ and} \\ & (i,j-1,k,l) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

The process moves from state $(i,j-1,k,l)$ to (i,j,k,l) with rate $\delta_3\lambda_p$. The process moves from state (i,j,k,l) to $(i,j-1,k,l)$ with rate $3j\mu_p$ when the transmission is completed for a GPRS data request with three channels.

The transitions between (i,j,k,l) and $(i+1,j,k,l)$, $(i,j+1,k,l)$, $(i,j,k+1,l)$, $(i,j,k,l+1)$ are similar to that between (i,j,k,l) and $(i-1,j,k,l)$, $(i,j-1,k,l)$, $(i,j,k-1,l)$, $(i,j,k,l-1)$. The balance equations for the Markov process are expressed as

$$\begin{aligned} &(\delta^+\Lambda_v + iM_v + 3j\mu_p + 2k\mu_p + l\mu_p \\ &\quad + \delta_1^+\lambda_p + \delta_2^+\lambda_p + \delta_3^+\lambda_p)\pi_{i,j,k,l} \\ &\qquad = \Lambda_v\pi_{i-1,j,k,l} + \delta_3\lambda_p\pi_{i,j-1,k,l} \\ &\qquad\quad + \delta_2\lambda_p\pi_{i,j,k-1,l} + \delta_1\lambda_p\pi_{i,j,k,l-1} \\ &\qquad\quad + (i+1)M_v\pi_{i+1,j,k,l} + 3(j+1)\mu_p\pi_{i,j+1,k,l} \\ &\qquad\quad + 2(k+1)\mu_p\pi_{i,j,k+1,l} + (l+1)\mu_p\pi_{i,j,k,l+1} \end{aligned} \tag{12}$$

where δ_1, δ_2, and δ_3 are obtained from (9), (10), and (11), respectively, and

$$\delta^+ = \begin{cases} 1, & \text{if } i+3j+2k+l \le C-1 \text{ and} \\ & (i+1,j,k,l) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise} \end{cases}$$

$$\delta_1^+ = \begin{cases} 1, & \text{if } i+3j+2k+l = C-1 \text{ and} \\ & (i,j,k,l+1) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise} \end{cases}$$

$$\delta_2^+ = \begin{cases} 1, & \text{if } i+3j+2k+l = C-2 \text{ and} \\ & (i,j,k+1,l) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise} \end{cases}$$

$$\delta_3^+ = \begin{cases} 1, & \text{if } i+3j+2k+l \le C-3 \text{ and} \\ & (i,j+1,k,l) \in \mathbf{S}_{\mathrm{DRA}} \\ 0, & \text{otherwise} \end{cases}$$

In (12), the state probability $\pi_{a,b,c,d} = 0$ if state $(a, b, c, d) \notin \mathbf{S}_{\mathrm{DRA}}$. The new voice call blocking probability P_{b_v}, handoff voice call force-termination probability P_{f_v} for voice calls, and dropping probability P_{b_p} for the GPRS packet are derived as follows. A new voice call is blocked, a handoff call is forced to terminate, or a packet request is dropped if no free channel is available when the request arrives. Let $\mathbf{E}_1$ be the set of the states where no free channel is available. Then

$$\mathbf{E}_1 = \Big\{ (i, j, k, l) \mid i + 3j + 2k + l = C, \\ 0 \leq i \leq C,\ 0 \leq j \leq \left\lfloor \frac{C}{3} \right\rfloor, \\ 0 \leq k \leq \left\lfloor \frac{C}{2} \right\rfloor, \text{ and } 0 \leq l \leq C \Big\}$$

and P_{b_p}, P_{b_v}, and P_{f_v} can be expressed as

$$P_{b_p} = P_{b_v} = P_{f_v} = \sum_{(i,j,k,l) \in \mathbf{E}_1} \pi_{i,j,k,l}. \tag{13}$$

By substituting (8) and (13) into (1), we obtain $\lambda_{v,h}$. The voice call incompletion probability P_{nc_v} can be obtained by using (3). The probabilities $\pi_{i,j,k,l}$, P_{nc_v}, and P_{b_p} can be computed by an iterative algorithm similar to the one described in Section III-A, where $\pi_{i,j,k,l}$ are computed by (12) and P_{b_v}, P_{f_v}, and P_{b_p} are computed by (13).

C. Analytic Model for FRAQ

This section proposes an analytic model for FRAQ_N. As in Section III-B, we assume that the cell residence time for a GSM voice user is exponentially distributed. Algorithm FRAQ_N can be modeled by a two-dimensional Markov process. A state in this process is defined as (x, y), where x is the number of voice calls (either being served on the channels or buffered in the queue) at the cell and y is the number of packets being transmitted on the channels. Let Q denote the size of the finite queuing mechanism (i.e., at most Q requests can be buffered in the queue). Based on the description of FRAQ_N in the previous section, it is clear that the state space $\mathbf{S}_{\mathrm{FRAQ\_N}}$ for this Markov process is

$$\mathbf{S}_{\mathrm{FRAQ\_N}} = \Big\{ (x, y) \mid 0 \leq x + Ky \leq C + Q, \\ 0 \leq x \leq C + Q,\ 0 \leq y \leq \left\lfloor \frac{C}{K} \right\rfloor \Big\}.$$

Let $\pi_{x,y}$ denote the steady-state probability for state (x, y), where $\pi_{x,y} = 0$ if state $(x, y) \notin \mathbf{S}_{\mathrm{FRAQ\_N}}$. For all legal states $(x, y) \in \mathbf{S}_{\mathrm{FRAQ\_N}}$, $\sum_{(x,y) \in \mathbf{S}_{\mathrm{FRAQ\_N}}} \pi_{x,y} = 1$. Fig. 5 illustrates the transition diagram for FRAQ_N. The transitions of the process are described as follows. For state $(x, y) \in \mathbf{S}_{\mathrm{FRAQ\_N}}$, if states $(x, y-1)$, $(x, y+1)$, $(x-1, y)$, $(x+1) \in \mathbf{S}_{\mathrm{FRAQ\_N}}$, the transitions between (x, y) and $(x, y-1)$, $(x, y+1)$, $(x-1, y)$, and $(x+1, y)$ are considered, respectively. Otherwise, for a state $(a, b) \notin \mathbf{S}_{\mathrm{FRAQ\_N}}$, the transitions between state (x, y) and (a, b) do not exist. We consider the following cases.

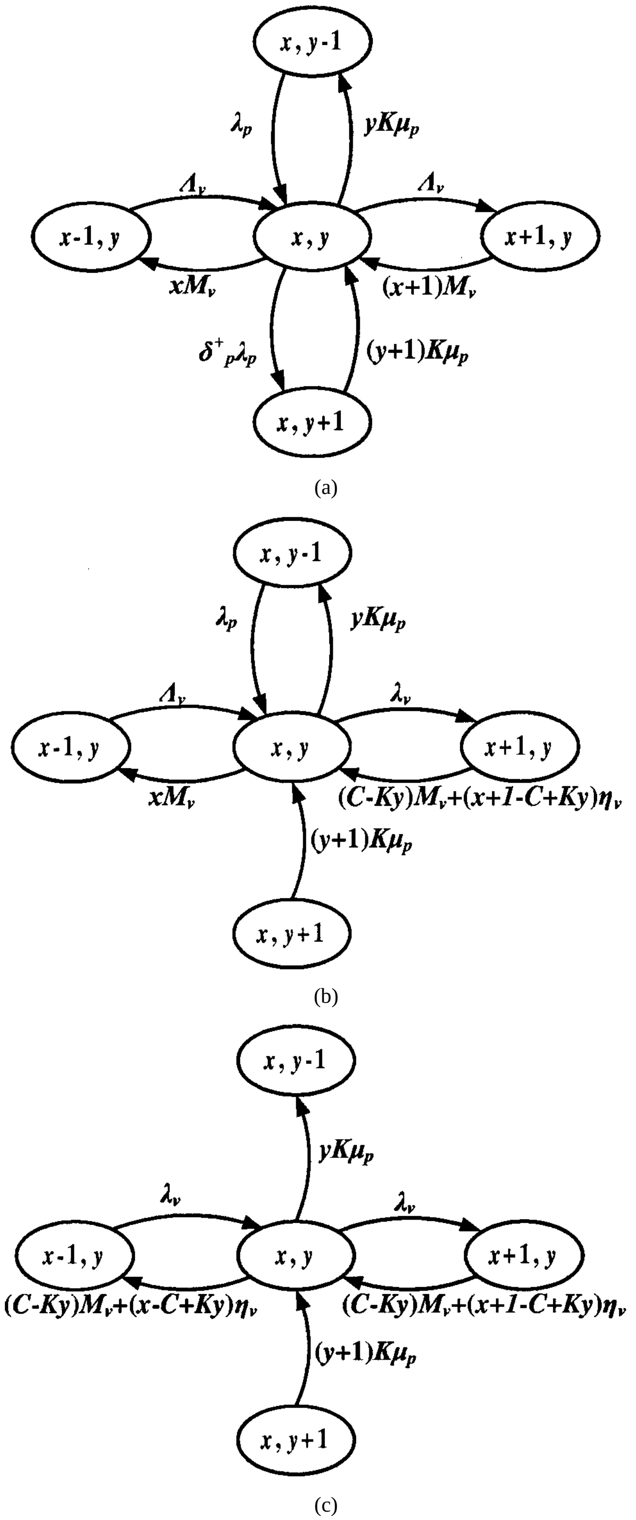


Fig. 5. The state transition diagram for FRAQ_N. (a) Case I: $0 \leq x + K_y < C$. (b) CaseII: $x + K_y = C$. (c) Case III: $C < x + K_y \leq C + Q$.

Case 1) $0 \leq x + Ky < C$ [Fig. 5(a)]. In this case, free channels are available at the cell and no voice call requests are buffered in the queue. If a GPRS request arrives when the process is at state $(x, y-1)$, then K channels are allocated. The process moves from state $(x, y-1)$ to (x, y) with rate λ_p. For a GPRS data request with K channels, when the transmission is completed at state (x, y), the process moves from state (x, y) to $(x, y-1)$ with rate $yK\mu_p$.

If a GPRS request arrives at state (x, y) and $0 \le x + Ky \le C - K$, then K channels are allocated. Define δ_p^+ as

$$\delta_p^+ = \begin{cases} 1, & \text{if } 0 \le x + Ky \le C - k \\ 0, & \text{otherwise.} \end{cases}$$

The process moves from state (x, y) to $(x, y+1)$ with rate $\delta_p^+ \lambda_p$. At state $(x, y{+}1)$, if the transmission for a K-channel GPRS data request is completed, the process moves from state $(x, y{+}1)$ to (x, y) with rate $(y+1)K\mu_p$. At state $(x-1, y)$, if a new or handoff voice call arrives, then one channel is allocated to the voice call. In this case, the process moves from state $(x-1, y)$ to (x, y) with rate Λ_v. At state (x, y), if a voice call is completed or the GSM voice user moves to another cell, the process moves from state (x, y) to $(x-1, y)$ with rate xM_v. At state $(x+1, y)$, if a voice call is completed or the voice user moves to another cell, the process moves from state $(x+1, y)$ to (x, y) with rate $(x+1)M_v$. The process moves from state (x, y) to $(x+1, y)$ with rate Λ_v for a new or handoff voice call arrival.

Case 2) $x + Ky = C$ [Fig. 5(b)]. In this case, no free channels are available at the cell. If a new voice call request arrives, it will be buffered in the queue. On the other hand, if a handoff call or packet request arrives, it will be dropped. Thus the process moves from state (x, y) to $(x+1, y)$ with rate λ_v. At state $(x+1, y)$, there are $C - Ky$ voice calls served on the channels and $x + 1 - C + Ky$ voice call requests buffered in the queue. A served voice call releases the channel with rate M_v, and the voice user of a queued request leaves the cell with rate η_v. Thus the process moves from state $(x+1, y)$ to (x, y) with rate $(C - Ky)M_v + (x + 1 - C + Ky)\eta_v$. At state $(x, y{+}1)$, if the transmission for a K-channel GPRS data request is completed, the process moves from state $(x, y+1)$ to (x, y) with rate $(y+1)K\mu_p$. The transition between $(x, y-1)$ and (x, y) and the transition between $(x-1, y)$ and (x, y) in this case are the same as that in Case 1).

Case 3) $C < x + Ky \le C + Q$ [Fig. 5(c)]. In this case, no free channels are available at the cell. $C - Ky$ voice calls are served and $x - C + Ky$ voice call requests are buffered in the queue. At state (x, y), a served voice call releases the channel with rate M_v, and the voice user of a queued request leaves the cell with rate η_v. The process moves from state (x, y) to $(x-1, y)$ with rate $(C - Ky)M_v + (x - C + Ky)\eta_v$. At state $(x-1, y)$, if a new voice call request arrives, it is buffered in the queue. The process moves from state $(x-1, y)$ to (x, y) with rate λ_v. When the transmission for a GPRS data request with K channels is completed at state (x, y), the process moves from state (x, y) to $(x, y-1)$ with rate $yK\mu_p$. The transition between (x, y) and $(x+1, y)$ and the transition between (x, y) and $(x, y+1)$ are the same as that in Case 2).

From the above state transitions, we write the balance equations and compute the probability $\pi_{x,y}$ by using the same iterative algorithm described in Section III-B.

The new voice call blocking probability P_{b_v}, the handoff voice call force-termination probability P_{f_v}, and the dropping probability P_{b_p} for the GPRS packet are derived as follows. A packet request is dropped if the number of free channels is smaller than K. Let $\mathbf{E}_2$ be

$$\mathbf{E}_2 = \Bigg\{ (x, y) \mid C - K < x + Ky \le C + Q, \\ 0 \le x \le C + Q,\ 0 \le y \le \left\lfloor \frac{C}{K} \right\rfloor \Bigg\}.$$

Then P_{b_p} can be expressed as

$$P_{b_p} = \sum_{(x,y) \in \mathbf{E}_2} \pi_{x,y}. \tag{14}$$

Since FRAQ_N queues the new calls only, the new voice calls and the handoff voice calls are distinguishable, and $P_{b_v} \ne P_{f_v}$. From [14], P_{b_v} can be expressed as shown in (15) at the bottom of the next page.A handoff voice call is forced to terminate if no free channel is available when the handoff request arrives. Thus P_{f_v} can be expressed as

$$P_{f_v} = \sum_{y=0}^{\lfloor C/K \rfloor} \left(\sum_{x=C-Ky}^{C+Q-Ky} \pi_{x,y} \right). \tag{16}$$

From (1), (8), (15), and (16), we can obtain $\lambda_{v,h}$. The voice call incompletion probability P_{nc_v} can be obtained from (3). The probabilities P_{nc_v} and P_{b_p} can be computed by an iterative algorithm similar to the one in Section III-A.The analytic model for FRAQ_H is similar to the one for FRAQ_N except that the handoff calls can be buffered instead of the new calls. The details are not presented.

D. Simulation Validation

The analytic models are validated by simulation experiments. Furthermore, algorithms such as FRAQ_NH, DRAQ_N, DRAQ_H, and DRAQ_NH are evaluated by simulation experiments without analytic modeling. In the simulation experiments, we consider a 6 × 6 wrapped mesh cell structure.

$$P_{b_v} = \sum_{y=0}^{\lfloor C/K \rfloor} \left\{ \sum_{x=C-Ky}^{C+Q-Ky} \left[\frac{(x + 1 - C + Ky)\eta_v \pi_{x,y}}{(C - Ky)M_v + (x + 1 - C + Ky)\eta_v} \right] \right\}. \tag{15}$$

TABLE I
COMPARISON OF THE ANALYTIC AND THE SIMULATION RESULTS FOR FRA ($\lambda_v = \mu_v$; $\mu_p = 100\mu_v$; $\eta_v = 0.2\mu_v$; $C = 7$; $K = 3$)

	λ_p (units: μ_v)	Analytic	Simulation	Error
P_{b_p}	1	0.450694%	0.458499%	1.7023%
P_{nc_v}	1	0.0150834%	0.0158931%	5%
P_{b_p}	10	1.2326%	1.23912%	0.526%
P_{nc_v}	10	0.0914728%	0.0957999%	4.5%
P_{b_p}	25	2.56993%	2.58131%	0.44%
P_{nc_v}	25	0.290101%	0.2919%	0.61%

The model follows the discrete event simulation approach in [11]. Table I lists P_{b_p} and P_{nc_v} values for both analytic and simulation models for FRA. The details of the parameter setup in this table will be described in the following section. In this table, the errors between simulation and analytic models are below 1% in most cases and are always less than 5%. The table indicates that the analytic results match closely with the simulation data. Similar results for DRA, FRAQ_N, and FRAQ_H are observed and are not presented.

IV. PERFORMANCE EVALUATION

This section investigates the performance of the resource allocation algorithms. In our study, the input parameters λ_v, λ_p, η_v, and μ_p are normalized by μ_v. For example, if the expected GSM voice call holding time is $1/\mu_v = 3$ min, then $\lambda_v = \mu_v$ means that the expected inter voice call arrival time for GSM at a cell is 3 min. We assume that there is one frequency carrier (or seven channels) per cell, i.e., $C = 7$. For the cases where $C > 7$, similar results are observed and are not presented. Our study indicates that for the GPRS data acceptance rate and the GSM voice call completion, DRAQ_NH outperforms other algorithms in most cases. This high acceptance rate is achieved by reasonably slowing down the packet transmission.

A. Performance of FRA

In this section, we use FRA to investigate the performance of GPRS data transmission and GSM voice call completion. Similar results are observed in other algorithms and are not presented.

1) Performance of GPRS Data Transmission: Fig. 6 plots P_{b_p} as a function of K and λ_p, where $C = 7$. Fig. 6(a) and (b) shows the effects of packet sizes, where $\mu_p = 100\mu_v$ (small packet size) and $10\mu_v$ (large packet size). Fig. 6(a) and (c) shows the effects of voice arrival rates, where $\lambda_v = \mu_v$ (small arrival rate) and $5\mu_v$ (large arrival rate). Fig. 6(a) and (d) shows the effects of GSM voice user mobility rates, where $\eta_v = 0.2\mu_v$ (low mobility rate) and $\eta_v = 2\mu_v$ (high mobility rate). Since the packet transmission rate is $K\mu_p$, the traffic becomes bursty when K increases (i.e., a data transmission occupies more radio channels with shorter transmission time). A general phenomenon in Fig. 6 is that P_{b_p} increases as K increases. This phenomenon reflects the well-known result that the performance of a system (packet dropping probability) becomes worse as the packet arrival becomes bursty since each packet requests more channels. We also observe an intuitive result that P_{b_p} increases as λ_p increases.

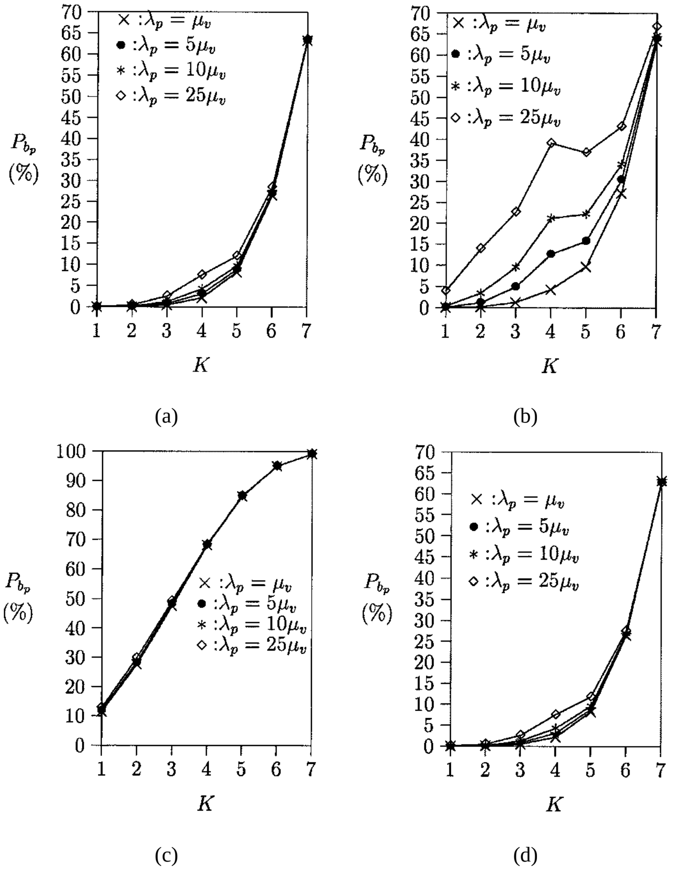


Fig. 6. Impact of GPRS data transmission for FRA ($C = 7$). (a) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (b) $\mu_p = 10\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (c) $\mu_p = 100\mu_v$; $\lambda_v = 5\mu_v$; $\eta_v = 0.2\mu_v$. (d) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 2\mu_v$.

2) The Base Case: Consider Fig. 6(a) where the packet size is small ($\mu_p = 100\mu_v$). In this case, the offered load of GPRS packets is small for $\lambda_p \leq 25\mu_v$, and it is not likely that multiple GPRS packets will arrive and be processed at the same time. That is, the packets do not compete among themselves. Instead, they compete with voice requests. For a large K, it is more difficult for packets to compete channels with the voice requests. Thus P_{b_p} increases as K increases.

3) Effects of Packet Size: In Fig. 6(b), the average packet size is ten times of that in Fig. 6(a). In this case, the packet traffic is large and the arrival packets compete with each other as well as the voice requests for the radio channels. The figure indicates that the increase of P_{b_p} is very significant in two cases: when K increases from three to four and from six to seven. This phenomenon is described as follows.

1) When $K \leq 3$, the GPRS network may accommodate two or more packets simultaneously (because the total number of channels is $C = 7$). When $K = 4$, the GPRS can at most accommodate one packet at a time. Thus, when K increases from three to four, P_{b_p} significantly increases.

2) When $K = 7$, a packet arrival is dropped if some radio channels are already occupied by voice requests or another packet. Since $\lambda_v = \mu_v$, the probability that the system is serving one voice request is high. On the other hand, the probability of serving more than one voice call is relative low. Thus P_{b_p} significantly increases when K increases from six to seven. This phenomenon is also observed in Fig. 6(a).

When K increases from four to five, P_{b_p} only insignificantly increases (for $\lambda_p \leq 10\mu_v$) or even decreases (for $\lambda_p = 25\mu_v$). In this case, the effect of short data transmission time (i.e., the data transmission time decreases by 20% when K increases from four to five) has balanced against the effect that more channels are occupied to accommodate a packet arrival. This effect diminishes as K continues to increase.

4) Effects of Voice Call Arrival Rate: In Fig. 6(c), the voice traffic is five times that in Fig. 6(a). In this case, the voice traffic is large and the arrival packets become less competitive compared with the voice requests. The consequence is that the bursty data effect occurs when K is smaller than that in Fig. 6(a). That is, P_{b_p} increases quickly and then slowly as K increases. On the other hand, when the voice traffic is small, the bursty data effect occurs when K is large. Thus, in Fig. 6(a), P_{b_p} curves are concave (i.e., P_{b_p} increases slowly and then quickly as K increases).

5) Effects of Voice User Mobility: In Fig. 6(d), the GSM voice user mobility is ten times of that in Fig. 6(a). With a higher mobility, handoffs are more likely to occur in a voice call. However, Fig. 6(a) and (d) indicates that the mobility of voice users does not affect the GPRS data transmission. When the voice user mobility rate η_v increases, the voice users are more likely to move to another cell during the conversation, and two effects are observed.

Effect 1) The channel occupancy times for voice calls become shorter.

Effect 2) The voice call handoff arrival rate at a cell becomes higher.

Effect 1) allows GPRS packets to have a better chance to be served. Effect 2) results in more voice calls to compete radio channels with packets. These two conflicting effects balance against each other. Thus, we observe that voice user mobility has no apparent effect on P_{b_p}.

6) Performance of Voice Call Completion: Fig. 7 plots P_{nc_v} as a function of K and λ_p, where $C = 7$. Like Fig. 6, Fig. 7 shows the effects of various packet sizes, voice call arrival rates, and GSM voice user mobility rates. A general phenomenon in Fig. 7 is that P_{nc_v} increases as λ_p increases. This result also reflects the bursty data effect as observed in Fig. 6.

7) The Base Case: Consider Fig. 7(a), where the packet size is small ($\mu_p = 100\mu_v$) and the voice traffic is low ($\lambda_v = \mu_v$). This figure indicates that P_{nc_v} increases as K increases for $1 \leq K \leq 6$. In this case, since voice traffic is low, it is less likely that multiple voice calls will arrive and be processed at the same time. That is, the voice calls do not compete among themselves. Instead, they compete with packet requests. For a larger K, the packet traffic becomes more bursty. Therefore, it is more difficult for voice requests to be accepted. When $K = 7$, a packet arrival is dropped if any radio channel is occupied by a voice request or another packet. Thus voice requests have a better chance to be served, and the packets are likely to be blocked as K increases from six to seven. Consequently, P_{nc_v} decreases as K increases from six to seven.

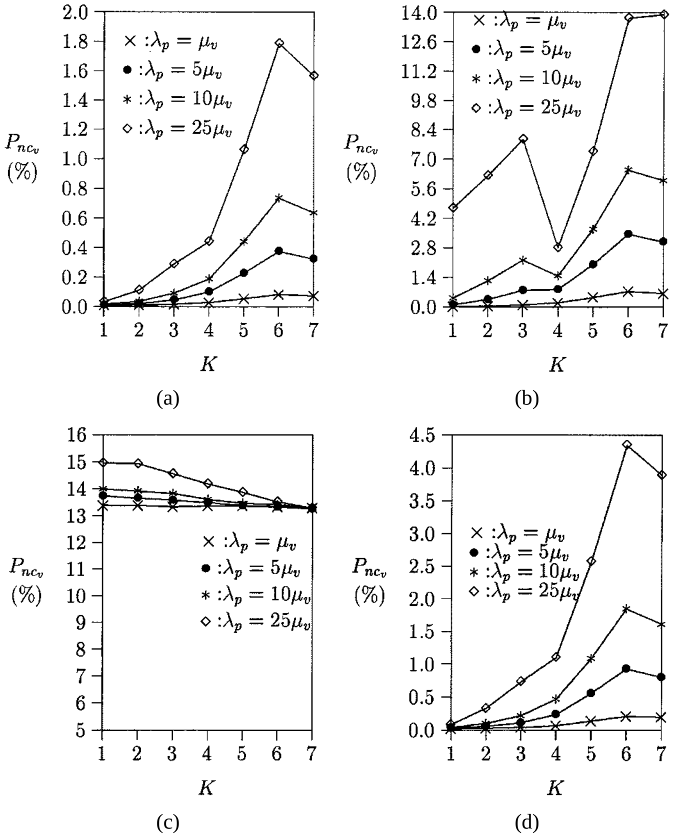
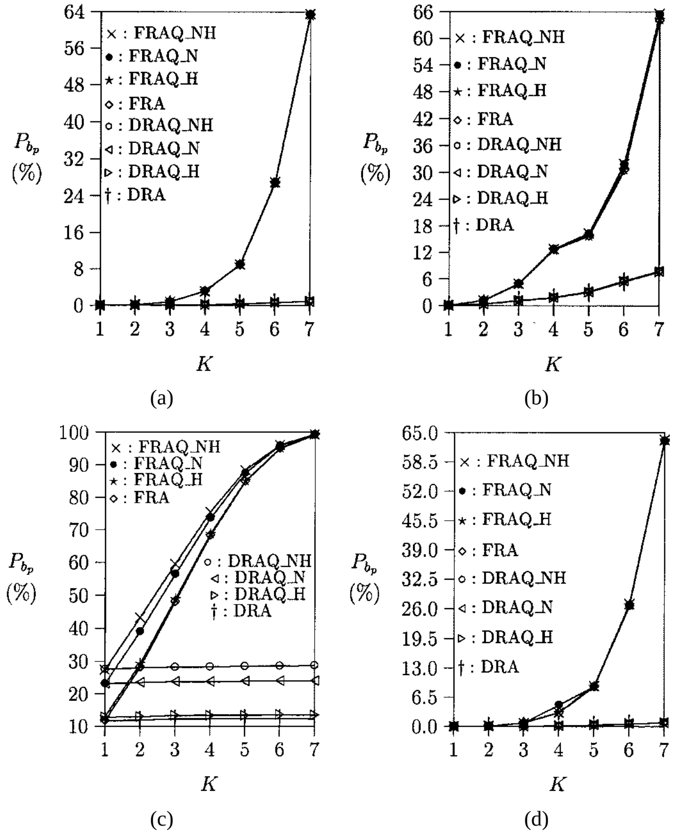


Fig. 7. Impact of voice call completion for FRA ($C = 7$). (a) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (b) $\mu_p = 10\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (c) $\mu_p = 100\mu_v$; $\lambda_v = 5\mu_v$; $\eta_v = 0.2\mu_v$. (d) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 2\mu_v$.

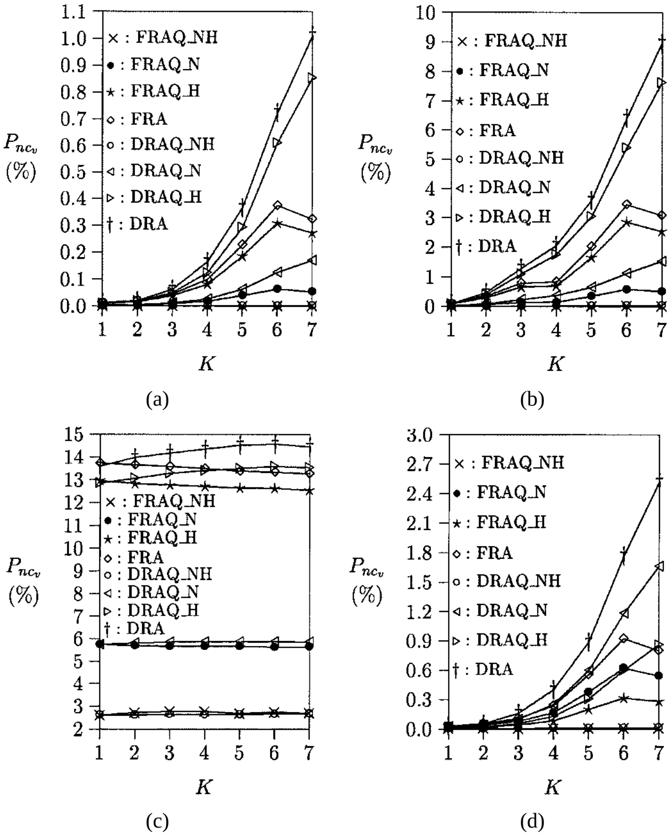
8) Effects of Packet Size: In Fig. 7(b), the average packet size is ten times of that in Fig. 7(a). In this case, the offered load of GPRS packets becomes larger, and voice requests are likely to compete with more than one packet request at the same time. The figure indicates that the decrease of P_{nc_v} is very significant in two cases: when K increases from three to four and from six to seven.

1) Since P_{b_p} increases significantly as K increases from three to four [Fig. 6(b)], the voice requests have a better chance to be served. Thus P_{nc_v} decreases significantly. This effect is pronounced when λ_p is large.
2) We observe local minimum in the curves of Fig. 7(b). The phenomenon is explained as follows. For $C = 7$, when $K = 4$, the system can at most accommodate one packet transmission at a time. In this case, at most three channels are available for voice call requests. Similarly, for $K > 4$, $7-K$ channels can be used for voice calls when a packet is in transmission. Compared with the cases where $K = 5, 6$, or 7, more channels are available to serve voice call requests for the case when $K = 4$. For the case where $K = 3$, more than one packet can be processed at a time, and fewer channels are likely to be available for the voice



(a) (b) (c) (d)

Fig. 8. Comparing P_{b_p} for the resource allocation algorithms ($\lambda_p = 5\mu_v$; $C = 7$; $Q = 7$). (a) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (b) $\mu_p = 10\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (c) $\mu_p = 100\mu_v$; $\lambda_v = 5\mu_v$; $\eta_v = 0.2\mu_v$. (d) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 2\mu_v$.



(a) (b) (c) (d)

Fig. 9. Comparing P_{nc_v} for the resource allocation algorithms ($\lambda_p = 5\mu_v$; $C = 7$; $Q = 7$). (a) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (b) $\mu_p = 10\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (c) $\mu_p = 100\mu_v$; $\lambda_v = 5\mu_v$; $\eta_v = 0.2\mu_v$. (d) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 2\mu_v$.

call requests as compared with the case where $K = 4$. Thus a local minimum can be observed at $K = 4$ for every P_{nc_v} curve in Fig. 7(b). This phenomenon is observed when packet size is large (i.e., $\mu_p = 10\mu_v$).

3) Following the same reasoning in Fig. 7(a), P_{nc_v} decreases as K increases from six to seven.

9) Effects of Voice Call Arrival Rate: In Fig. 7(c), the voice traffic is five times of that in Fig. 7(a). In this case, the voice traffic is large and the arrival packets become less competitive compared with the voice requests. Thus packet requests have less chance to be served as K increases, and P_{nc_v} decreases as K increases.

10) Effects of Voice User Mobility: In Fig. 7(d), the GSM voice user mobility is ten times that in Fig. 7(a). With a higher mobility, handoffs are more likely to occur in a voice call. Thus P_{nc_v} for high mobility [Fig. 7(d)] is larger than that for low mobility [Fig. 7(a)].

It is interesting to note a general trend that both P_{b_p} and P_{nc_v} increase as K increases. Thus the operators should think carefully if they would provide quick GPRS transmission service at the cost of increasing packet and voice call blocking/dropping rates.

B. Comparison for the FRA and DRA Algorithms

This section compares the performance for FRA algorithms (i.e., FRA, FRAQ_N, FRAQ_H, and FRAQ_NH) and DRA algorithms (i.e., DRA, DRAQ_N, DRAQ_H, and DRAQ_NH). In our study, the buffer size of the waiting queue is $Q = 7$.

1) Effects of Dynamic and Fixed Allocations: Figs. 8 and 9 plot P_{b_p} and P_{nc_v} as functions of K. The parameter setups in these two figures are the same as in Fig. 6. Fig. 8 indicates that in terms of the P_{b_p} performance, DRA algorithms (with or without queuing) always outperform FRA algorithms (with or without queuing). This result is explained as follows. By partially allocating resources to packet transmissions, dynamic allocation can accommodate more packet requests than fixed allocation does. Fig. 9 indicates that in terms of P_{nc_v}, the results are opposite to that in Fig. 8. It is interesting to note that FRAQ_NH and DRAQ_NH have similar P_{nc_v} performance that is much better than other algorithms. Since both new calls and handoff calls can be buffered and have better opportunity to survive, small P_{nc_v} for both FRAQ_NH and DRAQ_NH are expected.

2) Effects of the Queuing Mechanisms: Fig. 9 indicates that queuing mechanisms may significantly affect the P_{nc_v} performance. When voice user mobility is low [i.e., $\eta_v = 0.2\mu_v$ in Fig. 9(a)–(c)], the P_{nc_v} performance for fixed allocation from the best to the worst are FRAQ_NH, FRAQ_N, FRAQ_H, and FRA. When the voice user mobility is high (i.e., $\eta_v = 2\mu_v$ in Fig. 9(d)), the P_{nc_v} performance from the best to the worst are FRAQ_NH, FRAQ_H, FRAQ_N, and FRA. With small η_v, it is more effective to buffer new calls, and FRAQ_N outperforms FRAQ_H. On the other hand, when η_v is large, FRAQ_H outperforms FRAQ_N. Same results are observed for dynamic allocation algorithms. Fig. 8(a), (b), and (d) indicate that when the voice call arrival rate is small (i.e., $\lambda_v = \mu_v$), P_{b_p} is not affected by the queuing mechanisms. When the voice call arrival rate is large [$\lambda_v = 5\mu_v$ in Fig. 8(c)], the P_{b_p} performance from the best to the worst are FRA (DRA), FRAQ_H (DRAQ_H), FRAQ_N (DRAQ_N), and FRAQ_NH (DRAQ_NH). This order is opposite to the results observed in Fig. 9(c).

Figs. 8 and 9 indicate that DRAQ_NH outperforms other algorithms in terms of P_{b_p} and P_{nc_v} performance.

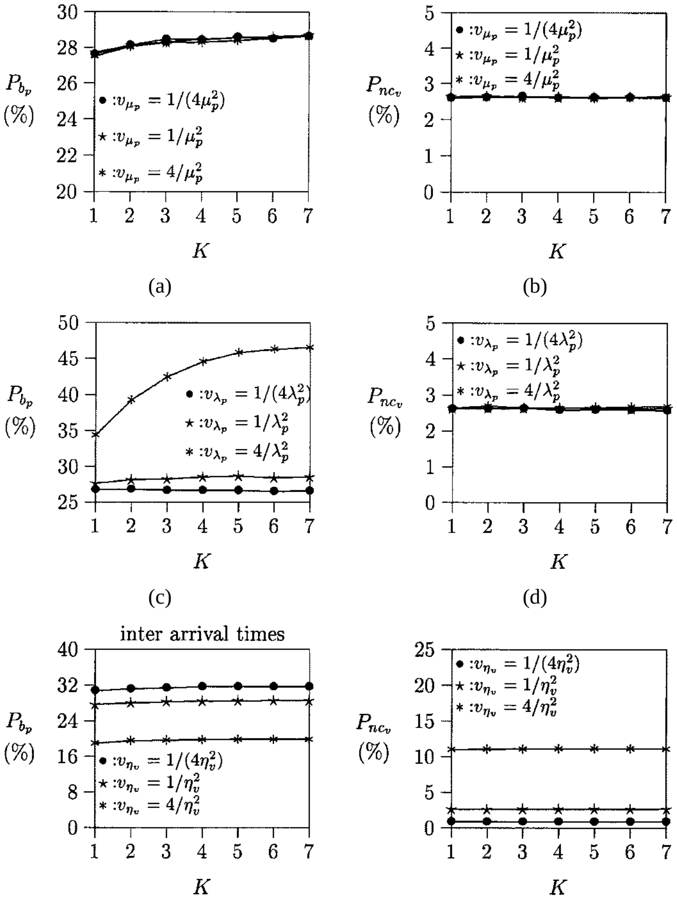
C. Effects of the Variations of the Distributions for Input Parameters

This section studies the effects of the variances of the distributions for packet transmission times, packet interarrival times and cell residence times for GSM voice users. We consider DRAQ_NH in this section. Results for other algorithms are similar and are omitted. We assume that packet transmission times, packet interval times, and cell residence times for GSM voice users have Gamma distributions with means $1/\mu_p$, $1/\lambda_p$, and $1/\eta_v$ and variances $v_{\mu_p} = 1/(\mu_p^2\alpha_1)$, $v_{\lambda_p} = 1/(\lambda_p^2\alpha_2)$, and $v_{\eta_v} = 1/(\eta_v^2\alpha_3)$, respectively, where α_1, α_2, and $\alpha_3 > 0$ are the shape parameters. Gamma distributions are considered because they can be used to approximate many other distributions as well as measured data from GSM field trials. Fig. 10 plots P_{b_p} and P_{nc_v} as functions of K, where $\lambda_p = 5\mu_v$, $\lambda_v = 5\mu_v$, $\mu_p = 100\mu_v$, $\eta_v = 0.2\mu_v$, $C = 7$, and $Q = 7$. To investigate the variance of the distribution for one input parameter, the distributions for the other two parameters are set to exponential (i.e., the shape parameters are set to one). For example, in Fig. 10(a), the distribution for the packet transmission times is Gamma, and the distributions for the packet interarrival times and voice user cell residence times are exponential. We note that the data packet transmission times are often modeled by Pareto distributions. In terms of variance impact, both Pareto and Gamma show the same trend. To be consistent, we use Gamma distributions for the three input parameters.

1) Variance of Packet Transmission Times: In Fig. 10(a) and (b), packet transmission times have Gamma distributions with variances $v_{\mu_p} = 1/(4\mu_p^2)$, $1/\mu_p^2$, and $4/\mu_p^2$, respectively. The two figures indicate that P_{b_p} and P_{nc_v} are insensitive to the variance of packet transmission times. As proven by the Zachary–Kelly model [15], [10], for FRA, when the voice calls and packet arrivals are Poisson streams, the packet dropping probability and the voice blocking probability are not affected by the distributions of the packet sizes and call holding times and are only affected by the means of the packet sizes and call holding times. Our simulation experiments indicated that DRAQ_NH and other algorithms also preserve this property.

2) Variance of Packet Interarrival Times: In Fig. 10(c) and (d), the packet interarrival times are Gamma distributed with variances $v_{\lambda_p} = 1/(4\lambda_p^2)$, $v_{\lambda_p} = 1/\lambda_p^2$, and $v_{\lambda_p} = 4/\lambda_p^2$, respectively. Fig. 10(d) indicates that P_{nc_v} is not affected by v_{λ_p}. In Fig. 10(c), we observe the following.

1) P_{b_p} increases as v_{λ_p} increases.
2) When $v_{\lambda_p} > 1/\lambda_p^2$, P_{b_p} increases as K increases.



(a) (b) (c) (d) (e) (f)

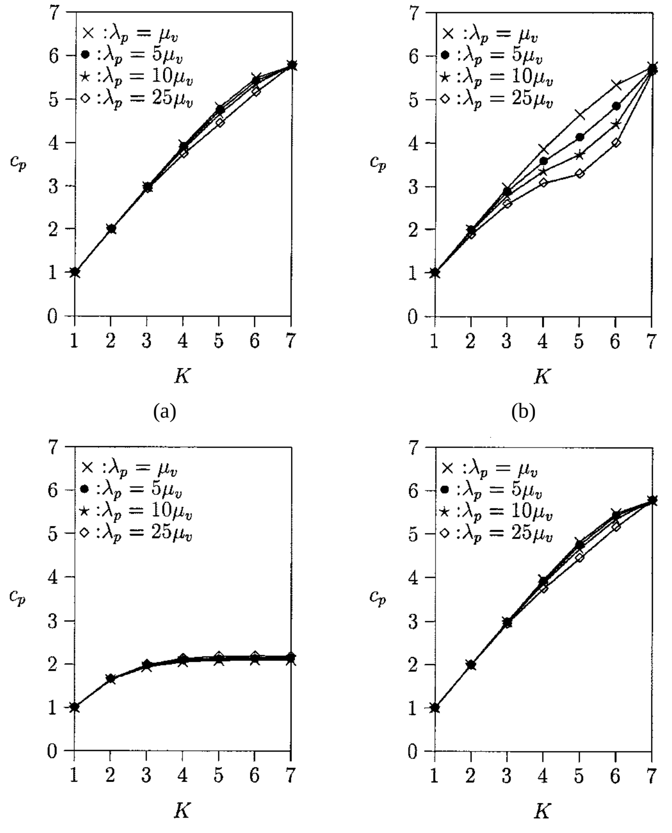
Fig. 10. Effects of the variances of packet transmission times, packet interarrival times, and GSM voice user cell residence times (DRAQ_NH; $\lambda_p = 5\mu_v$; $\lambda_v = 5\mu_v$; $\mu_p = 100\mu_v$; $\eta_v = 0.2\mu_v$; $C = 7$; $Q = 7$). (a) Gamma distributed packet transmission times. (b) Gamma distributed packet transmission times. (c) Gamma distributed packet interarrival times. (d) Gamma distributed packet interarrival times. (e) Gamma distributed GSM voice-user cell residence times. (f) Gamma distributed GSM voice-user cell residence times.

Phenomenon 1) indicates that with a larger variance v_{λ_p}, more small packet interarrival times are observed. Thus more packets arrive in a short period, and the packet traffic becomes more bursty. Phenomenon 2) states that the bursty effect due to the increase of K becomes insignificant when the variance v_{λ_p} is small.

3) Variance of Cell Residence Times for GSM Voice Users: In Fig. 10(e) and (f), GSM voice user cell residence times are Gamma distributed with variances $v_{\eta_v} = 1/(4\eta_v^2)$, $v_{\eta_v} = 1/\eta_v^2$, and $v_{\eta_v} = 4/\eta_v^2$, respectively. These figures indicate that:

1) P_{b_p} decreases as v_{η_v} increases;
2) P_{nc_v} increases as v_{η_v} increases.

The above results indicate that with a larger v_{η_v}, more short cell residence times for GSM voice users are observed. Thus voice calls are more likely to hand off to another cell, and voice handoff traffic becomes more bursty. Consequently, voice calls become less likely to be completed. On the other hand, packet data requests have better chance to be accepted in this case.



(a) (b) (c) (d)

Fig. 11. The average number of channels for a served packet in DRAQ_NH ($C = 7; Q = 7$). (a) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (b) $\mu_p = 10\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$. (c) $\mu_p = 100\mu_v$; $\lambda_v = 5\mu_v$; $\eta_v = 0.2\mu_v$. (d) $\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 2\mu_v$.

D. The Average Number of Channels Assigned to Packet Transmission

By allocating partial resources to packet transmissions, dynamic allocation accommodates more packet requests. However, the number of channels allocated to a packet data request may be smaller than K. Consequently, a packet data is transmitted at a slower rate than that in fixed allocation. In this section, we evaluate the average number c_p of channels for a served packet in DRAQ_NH. Fig. 11 plots c_p as a function of K with the same input parameter setups of the experiments in Fig. 8. We observe the following.

1) In Fig. 11(a), (b), and (d), the voice call arrival rate ($\lambda_v = \mu_v$) is small and c_p decreases as λ_p increases. With a small call arrival rate, when λ_p increases, it is more likely that the BS processes multiple packets at the same time, and thus the channels of the BS are shared by multiple packets. This phenomenon is pronounced when the packet transmission times become large, as shown in Fig. 11(b).
2) In Fig. 11(c), the voice call arrival rate ($\lambda_v = 5\mu_v$) is large. In this case, c_p is not significantly affected by an increasing λ_p. This phenomenon indicates that when voice call arrival rate is large, the voice call requests are more likely to be buffered before being served, and thus the voice traffic becomes more bursty. In this case, packets compete with a large number of voice calls, and poor c_p performance is observed for $\lambda_p \leq 25\mu_p$.

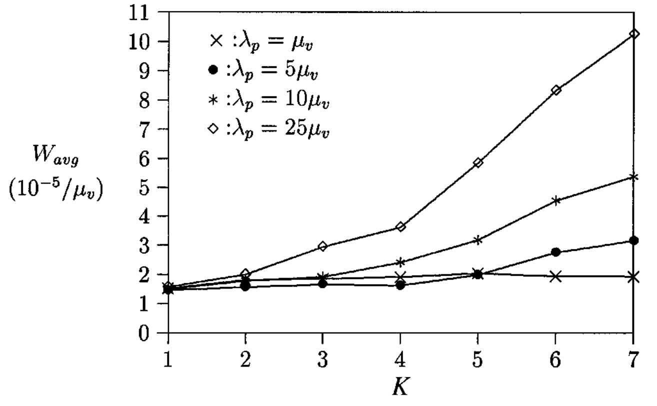


Fig. 12. The average waiting time for the accepted voice call requests in DRAQ_NH ($\mu_p = 100\mu_v$; $\lambda_v = \mu_v$; $\eta_v = 0.2\mu_v$; $C = 7$; $Q = 7$).

E. The Average Waiting Time for the Accepted Voice Call Requests

The buffering mechanism for voice calls can effectively reduce P_{nc_v}. In this section, we evaluate the average waiting time W_{avg} for the accepted voice call requests in DRAQ_NH. Fig. 12 plots W_{avg} as a function of K with the same input parameter values for the experiments in Fig. 8. We observe the following.

1) For most cases in Fig. 12, the W_{avg} values are below $10^{-4}/\mu_v$, which implies that the accepted voice calls are served with short waiting times. Thus, the buffering mechanism effectively improves the voice system performance by slightly increasing the waiting time.
2) When λ_p is small (i.e., $\lambda_p = \mu_v$ and $\lambda_p = 5\mu_v$ in Fig. 12), the packet data traffic is low and the effect of K (i.e., burstness of traffic) is not significant. In this case, W_{avg} is only slightly affected by the change of K.
3) When λ_p becomes large (i.e., $\lambda_p = 10\mu_v$ and $\lambda_p = 25\mu_v$), W_{avg} increases as K increases. That is, when packet data traffic becomes high, the effect of bursty data traffic becomes significant, and W_{avg} is an increasing function of K.

V. CONCLUSION

This paper studied the impact of GPRS service on the GSM network. Specifically, we proposed analytic and simulation models to investigate the performance for GPRS and GSM networks. We considered fixed and dynamic GPRS resource allocation algorithms as specified in the GPRS standard. We also proposed to include a waiting queue that buffers the voice requests when no radio channel is available. Our study indicated that dynamic allocation effectively increases the GPRS packet acceptance rate, and the queuing mechanism significantly reduces the voice call incompletion probability. By integrating both mechanisms, the best packet/voice call acceptance is expected. Our study also indicated that if too many channels are allocated to a packet transmission, both packet and voice call droppings will increase. Thus the operator should think carefully if he would provide quick GPRS transmission service at the cost of decreasing packet/voice call acceptance rates.

In terms of GPRS data performance, this paper studied the packet dropping effect, that is, performance of radio resource allocation at GPRS MAC layer. Our study can be extended to investigate the management of GPRS session at higher layer protocols (i.e., session management layer and TCP), where certain average bandwidth may be guaranteed for GPRS data transmission.

ACKNOWLEDGMENT

The authors would like to thank the three anonymous reviewers who provided valuable comments to improve the quality of this paper.

REFERENCES

[1] I. Chlamtac, Y. Fang, and H. Zeng, "Call blocking analysis for PCS networks under general cell residence time," in *Proc. IEEE WCNC* New Orleans, LA, Sept. 1999.

[2] "Digital cellular telecommunications system (Phase 2+); Technical realization of the Short Message Service (SMS); Point-to-Point (PP) (GSM 03.40 version 7.2.0)," ETSI SMG, Tech. Rep. Rec. GSM 03.40, 1999.

[3] "Digital cellular telecommunications system (Phase 2+); Handover procedures (GSM 03.09 version 5.1.0)," ETSI/TC, Tech. Rep. Rec. GSM 03.09, 1997.

[4] "Digital cellular telecommunications system (Phase 2+); High speed circuit switched data (HSCSD); Stage 2 (GSM 03.34) ," ETSI/TC, Tech. Rep. Rec. GSM 03.34, 1997.

[5] "Digital cellular telecommunications system (Phase 2+); General Packet Radio Service (GPRS); Overall description of the GPRS radio interface; Stage 2 (GSM 03.64 version 7.0.0 release 1999) ," ETSI/TC, Tech. Rep. Rec. GSM 03.64, 1999.

[6] "Digital cellular telecommunications system (Phase 2+); General Packet Radio Service (GPRS); Service description; Stage 1 (GSM 02.60 version 7.2.0 release 1999) ," ETSI/TC, Tech. Rep. Rec. GSM 02.60, 1999.

[7] "Digital cellular telecommunications system (Phase 2+); General Packet Radio Service (GPRS); Service description; Stage 2 (GSM 03.60 version 7.0.0 release 1999)," ETSI/TC, Tech. Rep. Rec. GSM 03.60, 1999.

[8] S. Faccin, L. Hsu, R. Koodli, K. Le, and R. Purnadi, "GPRS and IS-136 integration for flexible network and services evolution," *IEEE Personal Commun.*, vol. 6, no. 3, pp. 48–54, 1999.

[9] Y. Fang and I. Chlamtac, "Teletraffic analysis and mobility modeling for PCS networks," *IEEE Trans. Commun.*, vol. 47, July 1999.

[10] F. P. Kelly, "Loss networks," *The Ann. Appl. Prob.*, vol. 1, no. 3, pp. 319–378, 1991.

[11] W.-R. Lai and Y.-B. Lin, "Resource planning for wireless PBX systems," *Int. J. Wireless Inform. Networks*, vol. 5, no. 4, pp. 351–357, 1998.

[12] Y.-B Lin, "Performance Modeling for Mobile Telephone Networks," *IEEE Network Mag.*, vol. 11, pp. 63–68, Nov./Dec. 1997.

[13] Y.-B. Lin and I. Chlamtac, *Mobile Network Protocols and Services*. New York: Wiley, 2000.

[14] W.-Z. Yang, M.-F. Chang, and Y.-B. Lin, "Priority call service for PCS networks," *SCS Trans. (Special Issue on Wireless Networks)*, vol. 16, no. 3, 1999.

[15] S. Zachary, "On blocking in loss networks," *Adv. Appl. Prob.*, vol. 23, pp. 355–372, 1991.

Phone Lin received his B.S.C.S.I.E. degree from National Chiao Tung University, Taiwan, R.O.C., in 1996, where he is currently pursuing the Ph.D. degree in the Department of Computer Science and Information Engineering.

His current research interests include personal communications services, mobile computing, and performance modeling.

Yi-Bing Lin (SM'98) received the B.S.E.E. degree from National Cheng Kung University, Taiwan, R.O.C., in 1983 and the Ph.D. degree in computer science from the University of Washington, Seattle, in 1990.

From 1990 to 1995, he was with the Applied Research Area at Bell Communications Research (Bellcore), Morristown, NJ. In 1995, he became a Professor in the Department of Computer Science and Information Engineering (CSIE), National Chiao Tung University (NCTU). In 1996, he became Deputy Director of the Microelectronics and Information Systems Research Center, NCTU. During 1997–1999, he became Chairman of CSIE, NCTU. He is an editor of *Computer Networks*, an area editor of *ACM Mobile Computing and Communication Review*, a columnist of *ACM Simulation Digest*, an editor of *International Journal of Communications Systems*, an editor of *ACM/Baltzer Wireless Networks*, an editor of *Computer Simulation Modeling and Analysis*, an editor of *Journal of Information Science and Engineering*. He was Guest Editor for the *ACM/Baltzer MONET Special Issue on Personal Communications*. He is the coauthor of the book *Wireless and Mobile Network Architecture* (New York: Wiley). His current research interests include design and analysis of personal communications services network, mobile computing, distributed simulation, and performance modeling.

Dr. Lin is an Associate Editor of *IEEE Network*, an editor of IEEE JOURNAL OF SELECTED AREAS OF COMMUNICATION: *Wireless Series*, and an editor of *IEEE Personal Communications Magazine*. He was a Guest Editor for IEEE TRANSACTIONS ON COMPUTERS *Special Issue on Mobile Computing*, and a Guest Editor for *IEEE Communications Magazine Special Issue on Active, Programmable, and Mobile Code Networking*. He was Program Chair for the *8th Workshop on Distributed and Parallel Simulation*, General Chair for the *9th Workshop on Distributed and Parallel Simulation*, and Program Chair for the *2nd International Mobile Computing Conference*. He received 1998 and 2000 Outstanding Research Awards from National Science Council, R.O.C. and 1998 Outstanding Youth Electrical Engineer Award from CIEE, R.O.C. He is an Adjunct Research Fellow of Academia Sinica.