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Channel Allocation for GPRS with Buffering Mechanisms

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Abstract. General Packet Radio Service (GPRS) provides mobile users end-to-end packet-switched services by sharing the radio channels with voice and circuit-switched services. In such a system, radio resource allocation for circuit-switched and packet-switched services is an important issue, which may affect the QoS for both services significantly. In this paper, we propose two algorithms: Dynamic Resource Allocation with Voice and Packet queues (DRAVP) and Dynamic Resource Allocation with Packet and Voice queues (DRAPV) for channel allocation of the voice calls and packets. We propose analytic and simulation models to investigate the performance of DRAVP and DRAPV in terms of voice call incompletion probability, packet dropping probability, average voice call waiting time, and average packet waiting time. Our study indicates that the buffering mechanism for GPRS packets significantly increase the acceptance rate of GPRS packets at the cost of slightly degrading the performance of voice calls.

Keywords: GPRS, GSM, buffering mechanism, dynamic channel allocation

1. Introduction

General Packet Radio Service (GPRS) [6,7] is an end-to-end packet-switched protocol to provide mobile users applications such as the *World Wide Web* (WWW), where users spend most of time reading information, and the bursty data are transferred through the link only when necessary. GPRS is considered as a bearer service for mobile networks (e.g., GSM [14], IS-136 [9], or UMTS [2]), which greatly improves and simplifies the wireless access to packet data networks (e.g., the Internet or X.25). Most cellular operators reuse the existing GSM infrastructure to provide the GPRS service. 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 and short message services), users of GPRS benefit from shorter access times and higher data rates.

Figure 1 illustrates the GPRS/GSM architecture. In the architecture, the *Base Station System* (BSS) consists of one *Base Station Controller* (BSC) and several *Base Transceiver Stations* (BTSs). The BSC is connected to the *Serving GPRS Support Node* (SGSN) and *Mobile Switching Center* (MSC) for the provisions of packet-switched (i.e., IP) and circuit-switched (i.e., PSTN) services, respectively. The *Mobile Station* (MS) communicates with a BTS through the radio interface Um [8] based on the TDMA technology, where the radio coverage of a BTS is referred to as *cell*. The SGSN is responsible for delivery the packets to the MS, and the *Gateway GPRS Support Node* (GGSN) acts as a gateway between GPRS and the external data networks. The existing GSM network nodes including BSS, *Mobile Switching Center/Visitor Location Register* (MSC/VLR), and *Home Location Register* (HLR) are upgraded to accommodate GPRS.

The GPRS air interface [7] has been implemented for communication between the MS and BSS, which shares the physical channels with the voice calls and circuit-switched services. The operator may dynamically allocate the physical channels for both voice calls and packet usage. The physical channel dedicated to packet data traffic is called a Packet Data Channel (PDCH). Three types of packet data logical channels are defined in GPRS: *Packet Data Traffic Channel* (PDTCH), *Packet Common Control Channel* (PCCCH) and *Packet Dedicated Control Channel* (PDCCH). These different types of logical channels can camp on the same PDCH. The PDTCH, PCCCH and PDCCH are used for user packet data transfer, the GPRS common control signaling delivery, and the dedicated control signaling delivery for an MS, respectively. Allocation of channels for a GPRS user is flexible where one to eight channels can be allocated to a user, or one channel can be shared by several users. To initiate the uplink packet transfer, the MS executes the following steps.

Step 1. An MS negotiates with the network for the radio resource via PCCCH or PDCCH.

Step 2. According the agreed resource assignment from the network, the MS starts to transmit packets to the network.

Step 3. During the packet transmission, if the MS requires more PDTCHs, it can specify the request through an assigned uplink radio block.

Step 4. The network and the MS then exchange resource reassignment messages through the PDCCHs to re-allocate the resources for uplink transmission. The MS continues to transmit packets.

Step 5. When the MS completes the transmission, the MS and network exchange the final data block indication and the final data block acknowledgement.

The downlink packet transfer is similar to the uplink packet transfer, and is not described here. Details of the packet transfer procedure can be found in [8]. Note that in this procedure, the amount of radio resource (i.e., number of PDCHs) for a packet request will be recorded in the QoS profile of the user at the SGSN. In resource assignment (step 1) and re-assignment (step 4), the BSS may “dynamically” or

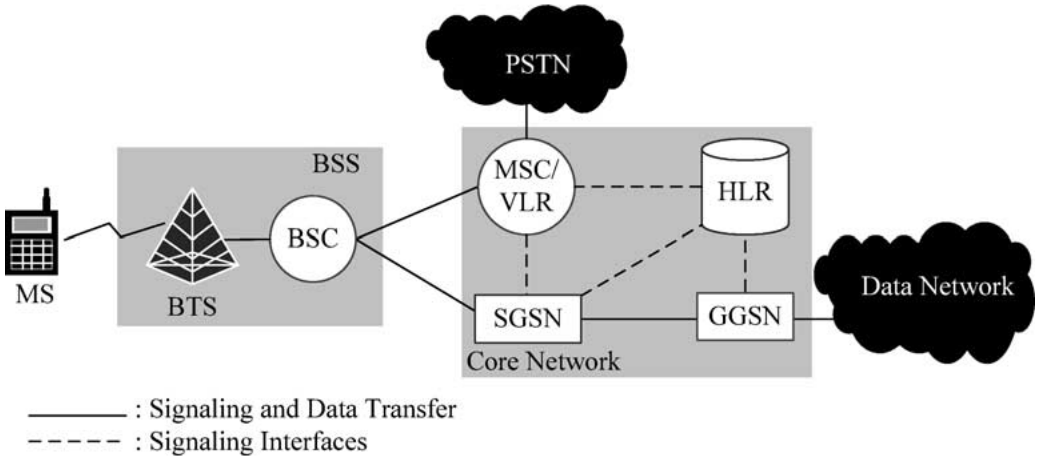


Figure 1. The GPRS/GSM architecture.

"statically" allocate radio channels to the MS. In static channel allocation, the requested amount of PDCHs is allocated for the packet request. On the other hand, in dynamic channel allocation, the BSS allocates partial amount of PDCHs for the packet request. If no radio channel is available when step 1 is executed, the packet request is buffered in the MS (for uplink packet transfer) or BSS (for downlink packet transfer) [1].

Since the GPRS packet service shares the radio channels with the GSM voice service, how to efficiently allocate radio channels for both GSM voice calls and GPRS packet requests is an important issue, which may affect the QoS for both GSM voice and GPRS packet services significantly. In [12], we proposed four channel allocation algorithms for the GPRS packets and GSM voice calls. This study indicates that the dynamic allocation for packet transmission and waiting queue for voice calls (new calls or handoff calls) significantly improve the performance of the network. However, the buffering mechanism for GPRS packets is not addressed in [12]. In this paper, we propose two channel allocation algorithms: Dynamic Resource Allocation with Voice and Packet queues (DRAVP) and Dynamic Resource Allocation with Packet and Voice queues (DRAPV) for scheduling of the radio channels for GPRS packets and GSM voice calls, where a voice queue (VQ) and packet queue (PQ) are used to buffer the voice calls and packet requests that are not served immediately. In DRAVP, the buffered voice calls have higher priority over the buffered packets. In DRAPV, the buffered packets have higher priority to be served than the buffered voice calls. The analytic models and simulation experiments are used to investigate the performance of the proposed algorithms. Our study indicates that the buffering mechanism for GPRS packet requests significantly reduces the packet dropping probability by affecting the performance of the voice calls slightly.

2. Dynamic channel allocation algorithms with voice and packet queues

This section describes two dynamic channel allocation algorithms DRAVP and DRAPV for both GPRS packets and GSM voice calls (either a new voice call request or a handoff voice call). Every GPRS packet request specifies the requested QoS profile for the number of channels required for transmission. At negotiation, the BSS allocates one or more channels for this packet request based on the negotiated QoS profile. In DRAVP and DRAPV, the BSS dynamically allocates the channels to a packet request based on the number of free channels in a cell. Two First-In-First-Out (FIFO) queues, VQ and PQ, are maintained in the BSS to buffer the voice call (new call or handoff call) and packet requests that are not served immediately due to that there is no free channel. When there are free channels at the cell, the requests in VQ and PQ are served based on a priority order. In GSM, the same channel assignment procedure is used for both the new voice calls and handoff voice calls. This non-prioritized scheme (i.e., VQ is used to buffer both new calls and handoff calls) is considered in this paper. In our previous study [12], the priority scheme for new call and handoff call has been addressed. Suppose that there are L free channels at a cell when a request (either a GPRS packet or GSM voice call) arrives. The details of DRAVP and DRAPV are described as follows.

Algorithm DRAVP. For a data session that requests K channels, the BSS dynamically assigns channels as follows. If $L \geqslant K$, the BSS assigns K channels to the packet request. If $0 < L < K$, then L channels are allocated to the request. If $L = 0$, this request is buffered into PQ. For a voice call request, if $L > 0$, the BSS assigns one channel to it. Otherwise (i.e., $L = 0$), the voice call request is buffered into the VQ. When free channels are available, the voice call requests in VQ are served immediately. If VQ is empty, then the BSS dynamically allocates channels to the packet requests in the PQ.

Algorithm DRAPV. This algorithm is similar to DRAVP except that the requests in the PQ have higher priority to be served than that in the VQ. That is, when free channels are available, the BSS first dynamically assigns channels to the buffered packet requests, and then to the buffered voice call requests.

3. Models for algorithms DRAVP and DRAPV

In this paper, we develop simulation models for the DRAVP and DRAPV algorithms, respectively. Analytic models are constructed to validate the simulation experiments. The simulation models follow the discrete event simulation approach in [12], and a 6 × 6 wrapped mesh cell structure is considered in our experiments. The input parameters set up and output measures evaluated in our study are listed in appendix.

In our analytic models, 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_{cv} be the voice call holding time, which is assumed to be exponentially distributed with the density function $f_{\mathrm{cv}}(t_{\mathrm{cv}}) = \mu_{\mathrm{v}} \mathrm{e}^{-\mu_{\mathrm{v}} t_{\mathrm{cv}}}$ and the mean voice call holding time $E[t_{\mathrm{cv}}] = 1/\mu_{\mathrm{v}}$. Let t_{cp} be the packet transmission times. If one channel (k channels) is (are) allocated to the packet, then the density function for the packet transmission times is $f_{\mathrm{cp}}(t_{\mathrm{cp}}) = \mu_{\mathrm{p}} \mathrm{e}^{-\mu_{\mathrm{p}} t_{\mathrm{cp}}}$ ($f_{\mathrm{cp}}(t_{\mathrm{cp}}) = k\mu_{\mathrm{p}} \mathrm{e}^{-k\mu_{\mathrm{p}} t_{\mathrm{cp}}}$) with mean $E[t_{\mathrm{cp}}] = 1/\mu_{\mathrm{p}}$ ($E[t_{\mathrm{cp}}] = 1/(k\mu_{\mathrm{p}})$). Note that in the real world, the packet inter-arrival times and packet transmission times may not be exponential distribution. By using exponential assumptions, our analytic models served for two purposes. First, exponential distribution provides the mean value analysis. Second, the analytic models are for validation of the simulation experiments that we use to investigate the performance of DRAVP and DRAPV. In the GSM/GPRS network, if an MS moves to another cell during the conversation, then the radio link to the old cell is disconnected, and a radio link to the new cell is required to continue the conversation. This process is called *handoff* [5]. If the new cell does not have any idle channel, the handoff call is *forced to terminate*. In our study, we consider the mobility of voice users but ignore the effects of mobility (handoff) on the GPRS packet transmission. This 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.

3.1. The analytic model DRAVP0

This section describes the analytic model DRAVP0, where we consider the packet traffic by ignoring voice call arrivals to a cell. We use a $(K+1)$-state Markov process to derive the packet dropping probability $P_{b_{\mathrm{p}}}$. A state $(n_{\mathrm{PQ}}, n_{\mathrm{p}_K}, n_{\mathrm{p}_{K-1}}, n_{\mathrm{p}_{K-2}}, \ldots, n_{\mathrm{p}_1})$ denotes that in a cell, n_{PQ} packet requests are buffered in the PQ, and n_{p_K} packets (each allocated K channels), $n_{\mathrm{p}_{K-1}}$ packets (each allocated $K-1$ channels), $n_{\mathrm{p}_{K-2}}$ packets (each allocated $K-2$ channels),…, and n_{p_1} packets (each allocated one channel) are being served. For the illustration purpose, we consider $K = 3$ in our discussion. Suppose that there are C channels in a cell. The maximum number of packet requests that can be buffered in the PQ is P. In this Markov process, a state is represented by (i, j, k, l) where $i = n_{\mathrm{PQ}}$, $j = n_{\mathrm{p}_3}$, $k = n_{\mathrm{p}_2}$, $l = n_{\mathrm{p}_1}$. The state space $\mathbf{S}_1$ for this Markov process is

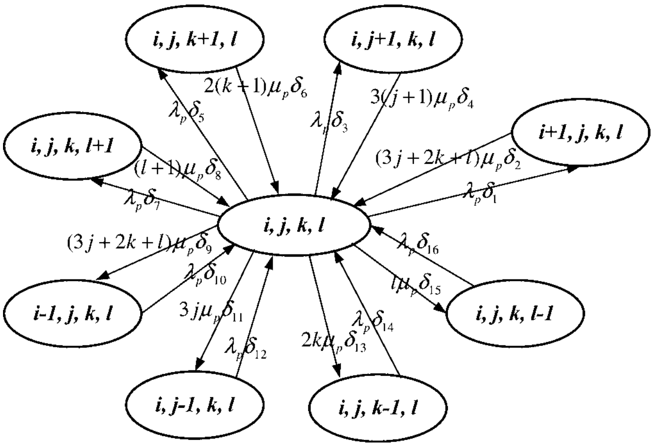


Figure 2. The state transition diagram for DRAVP0.

$$\begin{aligned}\mathbf{S}_1 = \Bigg\{&(i, j, k, l) \,\Big|\, i = 0,\ 0 \leqslant 3j + 2k + l \leqslant C,\\ &0 \leqslant j \leqslant \left\lfloor \frac{C}{3} \right\rfloor,\ 0 \leqslant k \leqslant \left\lfloor \frac{C}{2} \right\rfloor \text{ and } 0 \leqslant l \leqslant C\Bigg\}\\ \cup \Bigg\{&(i, j, k, l) \,\Big|\, 0 < i \leqslant P,\ 3j + 2k + l = C,\\ &0 \leqslant j \leqslant \left\lfloor \frac{C}{3} \right\rfloor,\ 0 \leqslant k \leqslant \left\lfloor \frac{C}{2} \right\rfloor \text{ and } 0 \leqslant l \leqslant C\Bigg\}.\end{aligned}$$

Let $\pi_{i,j,k,l}$ be the steady state probability for state (i, j, k, l), where $\pi_{i,j,k,l} = 0$ if state $(i, j, k, l) \notin \mathbf{S}_1$. For all legal states $(i, j, k, l) \in \mathbf{S}_1$, $\sum_{(i,j,k,l)\in\mathbf{S}_1} \pi_{i,j,k,l} = 1$. Figure 2 illustrates the transition diagram for this Markov process. In this figure we consider the following transitions for state $(i, j, k, l) \in \mathbf{S}_1$.

- If a GPRS request arrives at state $(i, j, k, l) \in \mathbf{S}_1$ where there is no free channel, and PQ is not full (i.e., $3j + 2k + l = C$ and $0 \leqslant i < P$), then this request is buffered in the PQ. Therefore the transition from states (i, j, k, l) to $(i+1, j, k, l)$ occurs only when $3j + 2k + l = C$ and $0 \leqslant i < P$. Define δ_1 as

  $$\delta_1 = \begin{cases} 1, & \text{if } 0 \leqslant i < P \text{ and } 3j + 2k + l = C,\\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

  The process moves from state (i, j, k, l) to $(i+1, j, k, l)$ with rate $\lambda_{\mathrm{p}}\delta_1$.

- If the transmission for a GPRS packet (which may be allocated three, two, or one channels) completes at state $(i+1, j, k, l) \in \mathbf{S}_1$, then one GPRS packet request in PQ will be served. Define δ_2 as

  $$\delta_2 = \begin{cases} 1, & \text{if } (i+1, j, k, l) \in \mathbf{S}_1,\\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

  Then the process moves from state $(i+1, j, k, l)$ to (i, j, k, l) with rate $(3j + 2k + l)\mu_{\mathrm{p}}\delta_2$.

- If a GPRS request arrives at state $(i, j, k, l) \in \mathbf{S}_1$, where $3j + 2k + l \leqslant C - 3$, then three channels are allocated to it. Define δ_3 as

$$\delta_3 = \begin{cases} 1, & \text{if } 3j + 2k + l \leqslant C - 3, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

  The process moves from state (i, j, k, l) to $(i, j + 1, k, l)$ with rate $\lambda_\mathrm{p}\delta_3$.

- When the transmission for a GPRS packet allocated three channels completes at state $(i, j + 1, k, l) \in \mathbf{S}_1$, and no GPRS packet requests are buffered in the PQ, three channels will be released. The process moves from state $(i, j + 1, k, l)$ to (i, j, k, l) with rate $3(j + 1)\mu_\mathrm{p}\delta_4$, where

$$\delta_4 = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j + 1, k, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

- When a GPRS request arrives at state $(i, j, k, l) \in \mathbf{S}_1$, where $3j + 2k + l = C - 2$, then this request is allocated two channels. Define δ_5 as

$$\delta_5 = \begin{cases} 1, & \text{if } 3j + 2k + l = C - 2, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

  Then the process moves from state (i, j, k, l) to $(i, j, k + 1, l)$ with rate $\lambda_\mathrm{p}\delta_5$.

- When the transmission for a GPRS packet allocated two channels completes at state $(i, j, k + 1, l)$, and no GPRS packet requests are buffered in the PQ, two channels will be released. The process moves from state $(i, j, k + 1, l)$ to (i, j, k, l) with rate $2(k + 1)\mu_\mathrm{p}\delta_6$, where

$$\delta_6 = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j, k + 1, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

- If a GPRS request arrives at state $(i, j, k, l) \in \mathbf{S}_1$, where $3j + 2k + l = C - 1$, then one channel is assigned to this request. Define δ_7 as

$$\delta_7 = \begin{cases} 1, & \text{if } 3j + 2k + l = C - 1, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

  The process moves from state (i, j, k, l) to $(i, j, k, l + 1)$ with rate $\lambda_\mathrm{p}\delta_7$.

- If the transmission for a GPRS packet allocated one channel completes at state $(i, j, k, l + 1)$, and no GPRS packet requests are buffered in the PQ, the process moves from state $(i, j, k, l + 1)$ to (i, j, k, l) with rate $\mu_\mathrm{p}\delta_8$, where

$$\delta_8 = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j, k, l + 1) \in \mathbf{S}_1, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

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 this process is:

$$\begin{aligned} &\big\{(\delta_1 + \delta_3 + \delta_5 + \delta_7)\lambda_\mathrm{p} + \big[\delta_9(3j + 2k + l) + \delta_{11}3j \\ &\quad + \delta_{13}2k + \delta_{15}l\big]\mu_\mathrm{p}\big\}\pi_{i,j,k,l} \\ &\quad = \delta_2(3j + 2k + l)\mu_\mathrm{p}\pi_{i+1,j,k,l} + \delta_4 3(j + 1)\mu_\mathrm{p}\pi_{i,j+1,k,l} \\ &\qquad + \delta_6 2(k + 1)\mu_\mathrm{p}\pi_{i,j,k+1,l} + \delta_8(l + 1)\mu_\mathrm{p}\pi_{i,j,k,l+1} \\ &\qquad + \delta_{10}\lambda_\mathrm{p}\pi_{i-1,j,k,l} + \delta_{12}\lambda_\mathrm{p}\pi_{i,j-1,k,l} \\ &\qquad + \delta_{14}\lambda_\mathrm{p}\pi_{i,j,k-1,l} + \delta_{16}\lambda_\mathrm{p}\pi_{i,j,k,l-1}, \end{aligned} \tag{9}$$

where $\delta_1, \delta_2, \delta_3, \ldots, \delta_{16}$ are obtained from (1), (2), (3), ..., (17), respectively, and

$$\delta_9 = \begin{cases} 1, & \text{if } i > 0 \text{ and } 3j + 2k + l = C, \\ 0, & \text{otherwise;} \end{cases} \tag{10}$$

$$\delta_{10} = \begin{cases} 1, & \text{if } 3j + 2k + l = C \\ & \text{and } (i - 1, j, k, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{11}$$

$$\delta_{11} = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j - 1, k, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{12}$$

$$\delta_{12} = \begin{cases} 1, & \text{if } i = 0, 3(j - 1) + k + l \leqslant C - 3 \\ & \text{and } (i, j - 1, k, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{13}$$

$$\delta_{13} = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j, k - 1, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{14}$$

$$\delta_{14} = \begin{cases} 1, & \text{if } i = 0, 3j + 2(k - 1) + l = C - 2 \\ & \text{and } (i, j, k - 1, l) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{15}$$

$$\delta_{15} = \begin{cases} 1, & \text{if } i = 0 \text{ and } (i, j, k, l - 1) \in \mathbf{S}_1, \\ 0, & \text{otherwise;} \end{cases} \tag{16}$$

$$\delta_{16} = \begin{cases} 1, & \text{if } i = 0, 3j + 2k + (l - 1) = C - 1 \\ & \text{and } (i, j, k, l - 1) \in \mathbf{S}_1, \\ 0, & \text{otherwise.} \end{cases} \tag{17}$$

When a packet request arrives at the states where the PQ is full, and there is no free channel (i.e., $i = P$ and $3j+2k+l = C$), this request will be dropped. Therefore

$$P_{b_\mathrm{p}} = \sum_{\substack{(i,j,k,l)\in\{(a,b,c,d)\,|\,a=P,\ 3b+2c+d=C, \\ (a,b,c,d)\in\mathbf{S}_1\}}} \pi_{i,j,k,l}. \tag{18}$$

From (9) and (18), the steady state probabilities $\pi_{i,j,k,l}$ and P_{b_p} can be computed by using the iterative algorithm in [13].

3.2. The analytic model DRAVP1

This section proposes the analytic model DRAVP1 for the DRAVP algorithm when $K = 1$ (i.e., the number of channels specified in the GPRS packet request is one). In the model, the cell residence times for a GSM voice user are assumed to have exponential distribution with mean $1/\eta_\mathrm{v}$ and Laplace transform

$$f_\mathrm{m}^*(s) = \frac{\eta_\mathrm{v}}{\eta_\mathrm{v} + s}. \tag{19}$$

We use the handoff traffic model in [13] to derive handoff traffic for the voice calls, and then obtain the voice call incompletion probability P_{nc_v} and packet data dropping probability P_{b_p} by using a Markov process. In the DRAVP algorithm, the channel assignments for the handoff voice calls and the new voice calls are not distinguishable. Thus the new voice call blocking probability $P_{b_{\rm v}}$ and the handoff call force-termination probability $P_{f_{\rm v}}$ are the same, that is,

$$P_{b_{\rm v}} = P_{f_{\rm v}}. \tag{20}$$

Let $\lambda_{\rm vh}$ be the voice handoff call arrival rate to a cell, and $P_{nc_{\rm v}}$ be the voice call incompletion probability. From [13] and (19), $\lambda_{\rm vh}$ and $P_{nc_{\rm v}}$ are expressed as

$$\lambda_{\rm vh} = \frac{\eta_{\rm v}^2(1 - P_{b_{\rm v}})\lambda_{\rm v}}{\mu_{\rm v}(\eta_{\rm v} + \mu_{\rm v}P_{b_{\rm v}})} \tag{21}$$

and

$$P_{nc_{\rm v}} = P_{b_{\rm v}} + \left[\frac{\eta_{\rm v}^2(1 - P_{b_{\rm v}})}{\mu_{\rm v}(\eta_{\rm v} + \mu_{\rm v}P_{b_{\rm v}})}\right]P_{f_{\rm v}}. \tag{22}$$

Suppose that the size of the VQ and PQ are V and P, respectively. We model this problem by a four-dimensional Markov process. A state in this process is defined as (m, n, o, p) where m is the number of the buffered voice calls, n is the number of the voice calls being served, o is the number of the buffered packets, and p is the number of the packets (each allocated one channel) being served in the cell. The state space $\mathbf{S}_2$ for this Markov process is

$$\begin{aligned} \mathbf{S}_2 = \big\{&(m, n, o, p) \mid 0 \leqslant m \leqslant V, \\ &0 \leqslant o \leqslant P \text{ and } n + p = C\big\} \\ \cup\big\{&(m, n, o, p) \mid m = 0, \\ &o = 0 \text{ and } 0 \leqslant n + p < C\big\}. \end{aligned}$$

Let $\pi^*_{m,n,o,p}$ denote the steady state probability for state (m, n, o, p), where $\pi^*_{m,n,o,p} = 0$ if state $(m, n, o, p) \notin \mathbf{S}_2$. For all legal states $(m, n, o, p) \in \mathbf{S}_2$, $\sum_{(m,n,o,p)\in\mathbf{S}_2} \pi^*_{m,n,o,p} = 1$. Let $\Lambda_{\rm v} = \lambda_{\rm v} + \lambda_{\rm vh}$ be the net new and handoff voice call arrival rate to a cell. Let $1/M_{\rm v} = 1/(\mu_{\rm v} + \eta_{\rm v})$ be the mean channel occupancy time of a voice call in a cell. The transition diagram for this process is shown in figure 3. For state $(m, n, o, p) \in \mathbf{S}_2$, we consider the state transitions for the DRAVP1 in three cases.

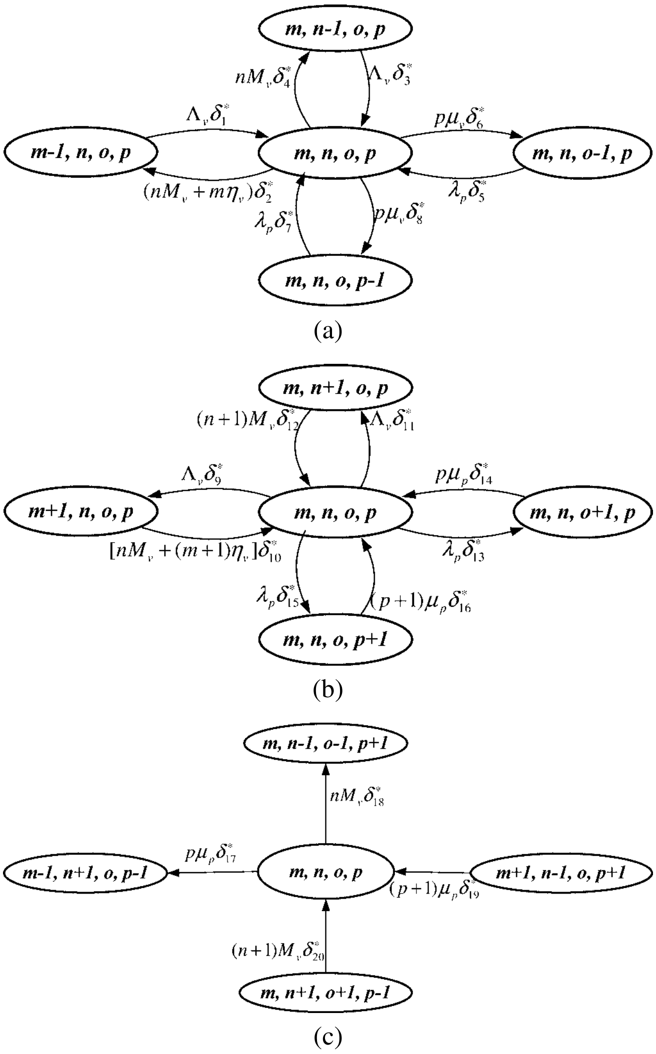
Case 1. We consider the transitions between states (m, n, o, p) and $(m - 1, n, o, p)$, $(m, n - 1, o, p)$, $(m, n, o - 1, p)$, $(m, n, o, p - 1)$.

- If a new voice call or handoff call arrives at state $(m - 1, n, o, p) \in \mathbf{S}_2$ where $n + p = C$ and $0 < m \leqslant V$, this voice call request will be queued in the VQ. Define δ_1^* as

  $$\delta_1^* = \begin{cases} 1, & \text{if } n + p = C, 0 < m \leqslant V \\ & \text{and } (m - 1, n, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{23}$$

  Then the process transits from state $(m - 1, n, o, p)$ to (m, n, o, p) with rate $\Lambda_{\rm v}\delta_1^*$.

- At state $(m, n, o, p) \in \mathbf{S}_2$ where $n + p = C$ and $0 < m \leqslant V$, one of the n voice calls being served may complete or handoff to another cell (i.e., one of them may release the channel with rate $M_{\rm v}$), and one of the m buffered voice calls may leave the cell with rate $\eta_{\rm v}$ before it is served.



(a)

(b)

(c)

Figure 3. The state transition diagram for DRAVP1. (a) Case 1. (b) Case 2. (c) Case 3.

  Therefore the process moves from state (m, n, o, p) to $(m - 1, n, o, p)$ with rate $(nM_{\rm v} + m\eta_{\rm v})\delta_2^*$ where

  $$\delta_2^* = \begin{cases} 1, & \text{if } n + p = C \\ & \text{and } (m - 1, n, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{24}$$

- When a new voice call or handoff call arrives at state $(m, n - 1, o, p) \in \mathbf{S}_2$ where $n + p - 1 < C$, one channel is allocated to this voice call request. Define δ_3^* as

  $$\delta_3^* = \begin{cases} 1, & \text{if } n + p - 1 < C \\ & \text{and } (m, n - 1, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{25}$$

  The process moves from state $(m, n - 1, o, p)$ to (m, n, o, p) with rate $\Lambda_{\rm v}\delta_3^*$.

- A served voice call releases the channel at state $(m, n, o, p) \in \mathbf{S}_2$ where $m = 0$ and $o = 0$ (i.e., no voice call or packet requests are buffered in the VQ or PQ). Define δ_4^* as

$$\delta_4^* = \begin{cases} 1, & \text{if } m = 0, o = 0 \\ & \text{and } (m, n-1, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{26}$$

The process moves from state (m, n, o, p) to $(m, n-1, o, p)$ with rate $nM_v\delta_4^*$.

- When a GPRS packet request arrives at state $(m, n, o-1, p) \in \mathbf{S}_2$ where $n + p = C$, the packet request is buffered into PQ. The process moves from $(m, n, o-1, p)$ to (m, n, o, p) with rate $\lambda_p\delta_5^*$ where

$$\delta_5^* = \begin{cases} 1, & \text{if } n + p = C \\ & \text{and } (m, n, o-1, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{27}$$

- If the transmission for a GPRS packet completes at state $(m, n, o, p) \in \mathbf{S}_2$ where $p \geqslant 1, m = 0$, and $0 < o \leqslant P$, one buffered GPRS packet request will be served. Define δ_6^* as

$$\delta_6^* = \begin{cases} 1, & \text{if } m = 0, 0 < o \leqslant P, p \geqslant 1 \\ & \text{and } (m, n, o-1, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{28}$$

The process moves from state (m, n, o, p) to $(m, n, o-1, p)$ with rate $p\mu_p\delta_6^*$.

- If a GPRS packet request arrives at state $(m, n, o, p-1) \in \mathbf{S}_2$ where $n + p - 1 < C$, then this request is allocated one channel. Define δ_7^* as

$$\delta_7^* = \begin{cases} 1, & \text{if } n + p - 1 < C \\ & \text{and } (m, n, o, p-1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{29}$$

The process moves from state $(m, n, o, p-1)$ to (m, n, o, p) with rate $\lambda_p\delta_7^*$.

- When the transmission of a GPRS packet completes at state (m, n, o, p) where $m = 0$, $o = 0$, one channel is released, and the process moves from state (m, n, o, p) to $(m, n, o, p-1)$ with rate $p\mu_p\delta_8^*$ where

$$\delta_8^* = \begin{cases} 1, & \text{if } m = 0, o = 0 \\ & \text{and } (m, n, o, p-1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

Case 2. In this case, we consider the transitions between states (m, n, o, p) and $(m+1, n, o, p)$, $(m, n+1, o, p)$, $(m, n, o, p+1)$, which are similar to that between (m, n, o, p) and $(m-1, n, o, p)$, $(m, n-1, o, p)$, $(m, n, o-1, p)$, $(m, n, o, p-1)$, and

$$\delta_9^* = \begin{cases} 1, & \text{if } n + p < C \\ & \text{and } (m+1, n, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{31}$$

$$\delta_{10}^* = \begin{cases} 1, & \text{if } n + p = C \\ & \text{and } (m+1, n, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{32}$$

$$\delta_{11}^* = \begin{cases} 1, & \text{if } n + p < C \\ & \text{and } (m, n+1, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{33}$$

$$\delta_{12}^* = \begin{cases} 1, & \text{if } m = 0, o = 0 \\ & \text{and } (m, n+1, o, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{34}$$

$$\delta_{13}^* = \begin{cases} 1, & \text{if } n + p = C \\ & \text{and } (m, n, o+1, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{35}$$

$$\delta_{14}^* = \begin{cases} 1, & \text{if } m = 0 \\ & \text{and } (m, n, o+1, p) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{36}$$

$$\delta_{15}^* = \begin{cases} 1, & \text{if } n + p < C \\ & \text{and } (m, n, o, p+1) \in \mathbf{S}_2, \\ 0, & \text{otherwise;} \end{cases} \tag{37}$$

$$\delta_{16}^* = \begin{cases} 1, & \text{if } n + p = C \\ & \text{and } (m, n, o, p+1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{38}$$

Case 3. This case considers the transitions between state (m, n, o, p) and $(m-1, n+1, o, p-1)$, $(m, n-1, o-1, p+1)$, $(m+1, n-1, o, p+1)$, $(m, n+1, o+1, p-1)$.

- If the transmission for the GPRS packet completes at state $(m, n, o, p) \in \mathbf{S}_2$ where $m > 0$, then the released channel will be allocated to one buffered voice call request. The process moves from state (m, n, o, p) to $(m-1, n+1, o, p-1)$ with rate $p\mu_p\delta_{17}^*$ where

$$\delta_{17}^* = \begin{cases} 1, & \text{if } m > 0 \\ & \text{and } (m-1, n+1, o, p-1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{39}$$

- If a served voice call either completes or hands off to another cell at state $(m, n, o, p) \in \mathbf{S}_2$ where $m = 0$ and $o > 0$, then one buffered GPRS packet request will be allocated one channel. Thus the process moves from state (m, n, o, p) to $(m, n-1, o-1, p+1)$ with rate $nM_v\delta_{18}^*$ where

$$\delta_{18}^* = \begin{cases} 1, & \text{if } m = 0, o > 0 \\ & \text{and } (m, n-1, o-1, p+1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{40}$$

- When the transmission for a GPRS packet completes at state $(m+1, n-1, o, p+1) \in \mathbf{S}_2$, the BSS will allocate one channel to one buffered voice call. Define δ_{19}^* as

$$\delta_{19}^* = \begin{cases} 1, & \text{if } (m+1, n-1, o, p+1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{41}$$

The process moves from state $(m+1, n-1, o, p+1)$ to (m, n, o, p) with rate $(p+1)\mu_p\delta_{19}^*$.

- When a served voice call either completes or hands off to another cell at state $(m, n+1, o+1, p-1) \in \mathbf{S}_2$ where

$m = 0$, then the released channel will be allocated to one buffered packet request. Define δ_{20}^* as

$$\delta_{20}^* = \begin{cases} 1, & \text{if } m = 0 \\ & \text{and } (m, n+1, o+1, p-1) \in \mathbf{S}_2, \\ 0, & \text{otherwise.} \end{cases} \tag{42}$$

The process moves from state $(m, n+1, o+1, p-1)$ to (m, n, o, p) with rate $(n+1)M_\mathrm{v}\delta_{20}^*$.

The balance equations for this Markov process are expressed as

$$\begin{aligned} &\big[\big(\delta_2^* + \delta_4^* + \delta_{18}^*\big)nM_\mathrm{v} + \big(\delta_9^* + \delta_{11}^*\big)\Lambda_\mathrm{v} + \delta_2^* m\eta_\mathrm{v} \\ &\quad + \big(\delta_6^* + \delta_8^* + \delta_{17}^*\big)p\mu_\mathrm{p} + \big(\delta_{13}^* + \delta_{15}^*\big)\lambda_\mathrm{p}\big]\pi_{m,n,o,p}^* \\ &= \delta_1^*\Lambda_\mathrm{v}\pi_{m-1,n,o,p}^* + \delta_3^*\Lambda_\mathrm{v}\pi_{m,n-1,o,p}^* \\ &\quad + \delta_5^*\lambda_\mathrm{p}\pi_{m,n,o-1,p}^* + \delta_7^*\lambda_\mathrm{p}\pi_{m,n,o,p-1}^* \\ &\quad + \delta_{10}^*\big[nM_\mathrm{v} + (m+1)\eta_\mathrm{v}\big]\pi_{m+1,n,o,p}^* \\ &\quad + \delta_{12}^*(n+1)M_\mathrm{v}\pi_{m,n+1,o,p}^* + \delta_{14}^* p\mu_\mathrm{p}\pi_{m,n,o+1,p}^* \\ &\quad + \delta_{16}^*(p+1)\mu_\mathrm{p}\pi_{m,n,o,p+1}^* \\ &\quad + \delta_{19}^*(p+1)\mu_\mathrm{p}\pi_{m+1,n-1,o,p+1}^* \\ &\quad + \delta_{20}^*(n+1)M_\mathrm{v}\pi_{m,n+1,o+1,p-1}^*, \end{aligned} \tag{43}$$

where $\delta_1^*, \delta_2^*, \delta_3^*, \ldots, \delta_{20}^*$ are defined in (23), (24), (25), …, (42), respectively. We derive P_{b_v} and P_{b_p} as follows. A new voice call is blocked if one of the following two events occurs:

(E1) When the voice call arrives at the cell, there are no free channels, and the VQ is full (i.e., $n + p = C$ and $m = V$). Then

$$\Pr\big[(\text{E1}) \text{ occurs}\big] = \sum_{\substack{(m,n,o,p)\in\{(a,b,c,d)\,|\,a=V,\ 0\leqslant c\leqslant P \\ b+d=C,\ (a,b,c,d)\in\mathbf{S}_2\}}} \pi_{m,n,o,p}^*; \tag{44}$$

(E2) The voice call in the VQ leaves the cell before it is served. From [12], Pr[(E2) occurs] is expressed as

$$\begin{aligned} &\Pr\big[(\text{E2}) \text{ occurs}\big] \\ &= \sum_{\substack{(m,n,o,p)\in\{(a,b,c,d)\,|\,0\leqslant a\leqslant V,\ 0\leqslant c\leqslant P, \\ b+d=C,\ (a,b,c,d)\in\mathbf{S}_2\}}} \frac{(m+1)\eta_\mathrm{v}\pi_{m,n,o,p}^*}{nM_\mathrm{v} + p\mu_\mathrm{p} + (m+1)\eta_\mathrm{v}}. \end{aligned} \tag{45}$$

P_{b_v} can be obtained by summation of (44) and (45). For a packet arrival to a cell, if no free channel is available, and the PQ is full (i.e., $n + p = C$ and $o = P$), then this packet is dropped. The P_{b_p} can be expressed as

$$P_{b_\mathrm{p}} = \sum_{\substack{(m,n,o,p)\in\{(a,b,c,d)\,|\,0\leqslant a\leqslant V,\ c=P, \\ b+d=C,\ (a,b,c,d)\in\mathbf{S}_2\}}} \pi_{m,n,o,p}^*. \tag{46}$$

With (20)–(22), (44), (45), (43), and (46), we use the iterative algorithm in [13] to compute λ_vh, $\pi_{m,n,o,p}^*$, P_{nc_v} and P_{b_p}.

Table 1
Comparison of the analytic data of DRAVP0 and the simulation results for DRAVP ($\mu_\mathrm{p} = 10\mu_\mathrm{v}$, $C = 7$).

	λ_p (units: μ_v)	Analytic	Simulation	Error
P_{b_p} $(P = 3)$	50	6.1752%	6.1922%	0.2745%
P_{b_p} $(P = 3)$	100	34.4477%	34.4666%	$5.5 \cdot 10^{-4}$
P_{b_p} $(P = 7)$	50	1.44271%	1.4948%	3.5%
P_{b_p} $(P = 7)$	100	30.9598%	30.8461%	0.37%

Table 2
Comparison of the analytic data of DRAVP1 and the simulation results for DRAVP ($\lambda_\mathrm{v} = 4\mu_\mathrm{v}$, $\mu_\mathrm{p} = 100\mu_\mathrm{v}$, $\eta_\mathrm{v} = 0.2\mu_\mathrm{v}$, $C = 7$, $V = 4$, $P = 3$, $K = 1$).

	λ_p (units: μ_v)	Analytic	Simulation	Error
P_{nc_v}	25	1.23487%	1.203%	2.6%
P_{b_p}	25	8.85648%	8.74934%	1.21%
P_{nc_v}	50	1.24146%	1.2359%	0.45%
P_{b_p}	50	10.8194%	10.8606%	0.38%
P_{nc_v}	75	1.24792%	1.2343%	1.1%
P_{b_p}	75	12.3118%	12.3931%	0.66%

3.3. Simulation validation

We have developed a simulation model for the DRAVP algorithm, which is similar to that in [12]. The analytic models and the simulation experiments are validated against to each other in two parts.

Part 1. Validation of the dynamic channel allocation and buffering mechanism for GPRS packet data. In this part, we consider the packet traffic by ignoring voice call arrivals. Table 1 lists the P_{b_p} values for the simulation experiments and the analytic data of the analytic model DRAVP0. The details of the parameter setup in this table will be described in the following section. In this table, the errors between the simulation experiments and analytic data are within 1% in most cases and are always less than 4%.

Part 2. Validation for the case when $K = 1$. In this part, we consider a special case for DRAVP when $K = 1$. We list the P_{nc_v} and P_{b_p} values of the simulation experiments and the analytic results of the analytic model DRAVP1 in table 2, which indicates that the errors are within 2% in all cases.

For DRAVP, the analytic results and simulation experiments are also consistent, and the results will not be presented.

4. Performance evaluation

Base on the analytic and simulation models developed in the previous section, we investigate the performance of the channel allocation algorithms DRAVP and DRAPV. In this section, the input parameters λ_v, λ_p, η_v and μ_p are normalized by μ_v. For example, if the expected voice call holding time is $1/\mu_\mathrm{v} = 3$ minutes, then $\lambda_\mathrm{v} = \mu_\mathrm{v}$ means that the expected

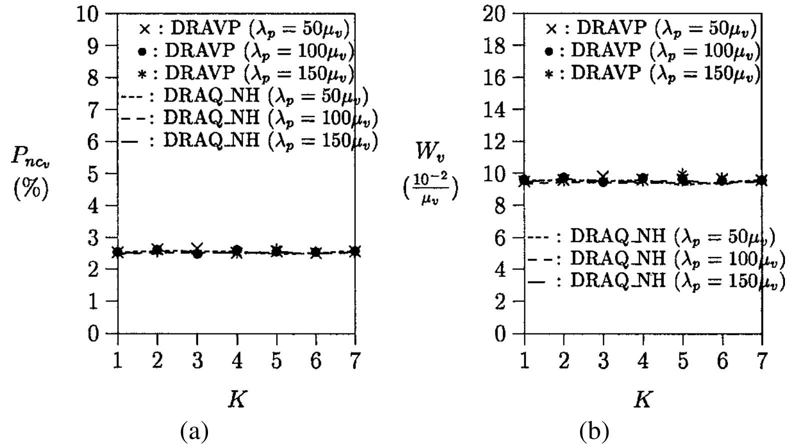


Figure 4. Effects of the PQ on the voice calls ($\lambda_v = 5\mu_v$, $\eta_v = 0.2\mu_v$, $\mu_p = 100\mu_v$, $C = 7$, $P = 7$, $V = 7$). (a) P_{nc_v}. (b) W_v.

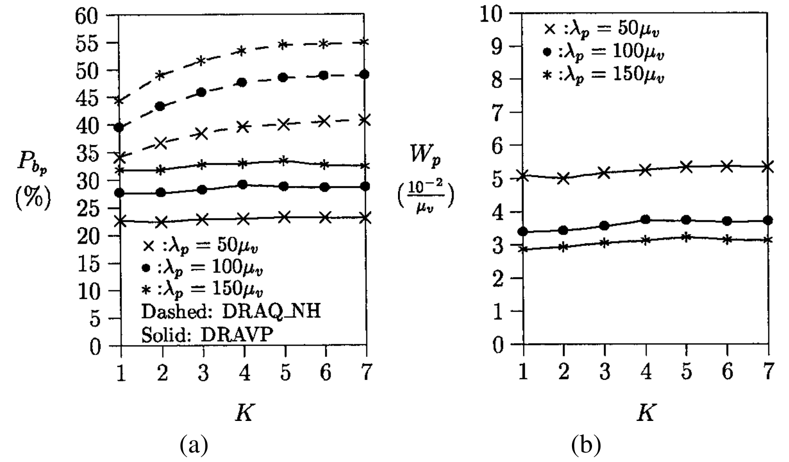


Figure 5. Effects of the PQ on the packets ($\lambda_v = 5\mu_v$, $\eta_v = 0.2\mu_v$, $\mu_p = 100\mu_v$, $C = 7$, $P = 7$, $V = 7$). (a) P_{b_p}. (b) W_p (DRAVP only).

voice call inter-arrival time at a cell is 3 minutes. Our experiments consider one frequency carrier (or 7 channels) per cell, that is, $C = 7$. Similar results are observed for various C values and will not be presented in this paper.

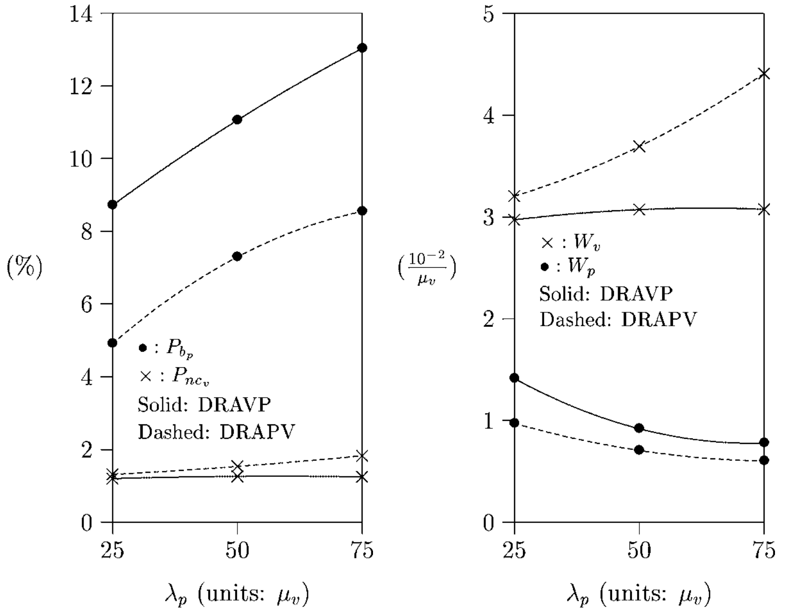
4.1. Effects of the packet queue PQ

In [12], we studied the performance for DRAQ_NH where the BSS only maintains the VQ for the voice calls but no PQ exists for the packet data. The results in [12] showed that DRAQ_NH effectively increases the packet acceptance rate, and its queuing mechanism for voice calls significantly reduces the voice call incompletion probability. In this paper, DRAVP is compared with DRAQ_NH to investigate how the buffering mechanism for the packets in DRAVP affects the performance for both voice calls and packets. Note that DRAVP is the same as DRAQ_NH, except that a PQ exists for the packets, and the requests in the VQ have higher priority over that in the PQ.

Effects of the PQ on voice calls. Figure 4 shows P_{nc_v} and W_v values against λ_p and K for DRAVP and DRAQ_NH, where $\lambda_v = 5\mu_v$, $\mu_p = 100\mu_v$, $\eta_v = 0.2\mu_v$, $C = 7$, $V = 7$, and $P = 7$. Figure 4 indicates that when K and λ_p increases, P_{nc_v} and W_v values for DRAVP and DRAQ_NH are almost identical, which is due to the fact that both algorithms give higher priority to the buffered voice calls. Therefore the introduction of the PQ in DRAVP does not affect the performance of voice calls (i.e., P_{nc_v} and W_v).

Effects of the PQ on the packet dropping probability (P_{b_p}). Figure 5(a) shows P_{b_p} and W_p values against λ_p and K for DRAVP and DRAQ_NH, where the input parameter setup is the same as that in figure 4. We observe that DRAVP outperforms DRAQ_NH in terms of the packet dropping probability P_{b_p}, which impliess that the buffering mechanism for packet requests significantly reduces the packet dropping probability. Furthermore, we observe that in DRAVP, P_{b_p} is not affected by the change of K. On the other hand, in DRAQ_NH, P_{b_p} is an increasing function of K. When K increases, the packet requests become more bursty. It is more likely that these packet requests find no available channels and are therefore dropped. In DRAVP, for the packet requests that cannot be served immediately, they can be buffered in the PQ, and have the second chance of being served.

Effects of the PQ on the buffered packet request waiting time (W_p). Figure 5(b) plots W_p as functions of K and λ_p. The



(a) (b)

Figure 6. The comparison between DRAVP and DRAPV ($\lambda_v = 4\mu_v$, $\mu_p = 100\mu_v$, $\eta_v = 0.2\mu_v$, $K = 4$, $C = 7$, $V = 4$, $P = 3$). (a) P_{nc_v} and P_{b_p}. (b) W_v and W_p.

figure shows an abnormal phenomenon that W_p decreases as λ_p increases. In this figure, $\mu_p = 100\mu_v$, $\lambda_v = 5\mu_v$, and $\lambda_p \geqslant 50\mu_p$, which implies that during the packet transmission period t_{cp}:

(P.1) voice calls are not likely to arrive (only average $\lambda_v \cdot E[t_{cp}] = \lambda_v/\mu_p = 0.05$ voice calls arrive); but

(P.2) instead, packet requests are likely to arrive at the cell (average $\lambda_p E[t_{cp}] = \lambda_p/\mu_p \geqslant 0.5$ packets arrive).

As λ_p increases, (P.2) is more likely to occur. If there are channels released by the voice calls during the transmission of packets, these channels are more likely to be occupied by packets as λ_p becomes larger. Therefore, more channels serve for packets, and the buffered packet requests spend shorter waiting times in the PQ.

4.2. Comparison for the DRAVP and DRAPV algorithms

Figure 6 plots P_{nc_v}, P_{b_p}, W_v, and W_p as functions of λ_p for DRAVP and DRAPV. In this figure, we set $\lambda_v = 4\mu_v$, $\mu_p = 100\mu_v$, $\eta_v = 0.2\mu_v$, $K = 4$, $C = 7$, $V = 4$, and $P = 3$. For various input parameter setups, we observe the same results that will not be presented in this paper. This figure shows that DRAVP outperforms DRAPV in terms of the P_{nc_v} and W_v performance, and DRAPV outperforms DRAVP in terms of the P_{b_p} and W_p performance (due to the different priority order of the buffered packets and voice calls). When λ_p is small, the improvements of P_{nc_v} and W_v for DRAVP over DRAPV are insignificant. As λ_p increases, the improvements become significant, which implies that with small λ_p, DRAPV is suitable for channel allocation. When λ_p becomes large, to maintain both QoS for voice and packet data users, DRAVP is the better choice.

4.3. Effects of the variance of voice user cell residence times

We assume that the cell residence times are gamma distribution with mean $1/\eta_v$ and variance v_v. The gamma distribution was adopted to model the mobile user movement in many studies [4,10,11]. Figure 7 plots P_{nc_v}, P_{b_p}, W_v and W_p as functions of v_v for DRAVP, where the input parameter setup is the same as that in figure 6. The distributions for other input parameters are exponential. This figure indicates that:

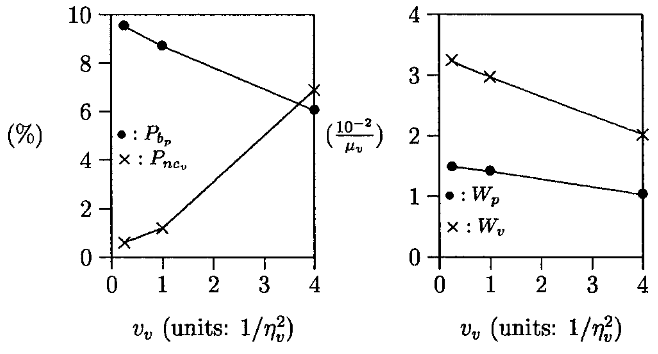
- P_{nc_v} is an increasing function of v_v.
- P_{b_p}, W_v, and W_p decreases as v_v increases.

The above results indicate that with a larger v_v, more short cell residence times for voice users are observed. Thus the voice calls are more likely to handoff to another cell, and voice handoff traffic becomes more bursty. Consequently, voice calls become less likely to be completed. On the other hand, packets have better chance to be accepted in this case. Furthermore, shorter cell residence times lead shorter voice call channel occupancy times, and both buffered voice call requests and packets spend less time waiting in the queue.

4.4. Effects of Pareto packet inter arrival/transmission times

The Pareto distribution is widely used to approximate the WWW packet traffic very well [3]. In this paper, we investigate the effects of Pareto distribution. Assume that the packet inter-arrival times and transmission times are Pareto distribution with two parameters β and l, where β describes the "heaviness" of the tail of the distribution. The Pareto density function is $f_P(t) = (\beta/l)(l/t)^{\beta+1}$ and the expected value is

$$E[t] = \left(\frac{\beta}{\beta - 1}\right)l. \tag{47}$$



(a) (b)

Figure 7. Effects of the variance of voice user cell residence times ($\lambda_v = 4\mu_v$, $\lambda_p = 25\mu_v$, $\mu_p = 100\mu_v$, $K = 4$, $C = 7$, $V = 4$, $P = 3$). (a) P_{nc_v} and P_{b_p}. (b) W_v and W_p.

Table 3
Effects of Pareto packet inter-arrival and transmission times on DRAVP ($\beta = 1.2$, $\lambda_v = 4\mu_v$, $\lambda_p = 25\mu_p$, $\mu_p = 100\mu_v$, $\nu_v = 0$, $K = 4$, $C = 7$, $V = 4$, $P = 3$).

(Arrival, transmission)	P_{nc_v} (%)	P_{b_p} (%)	W_v ($10^{-2}/\mu_v$)	W_p ($10^{-2}/\mu_v$)
1. (exp., exp.)	1.2017	8.717	2.97251	1.41129
2. (Pareto, exp.)	1.2363	10.1734	3.06845	1.00832
3. (exp., Pareto)	1.4201	9.70191	3.38182	1.5528

If β is between 1 and 2, then the variance for the distribution becomes infinity. Once a suitable value for β is selected to describe the traffic characteristics, then l is determined by the mean of the distribution. We select $\beta = 1.2$ for packet inter-arrival times and transmission times as in [3]. By substituting β into (47), we obtain $l = 1/(6\lambda_p)$ for packet inter-arrival times and $l = 1/(6\mu_p)$ ($l = 1/(6k\mu_p)$) for transmission times if one channel (k channels) allocated to the packet. Table 3 compares P_{nc_v}, P_{b_p}, W_v, and W_p for DRAVP in three scenarios:

Scenario 1. Both packet inter-arrival and transmission times have exponential distributions.

Scenario 2. Packet inter-arrival times have Pareto distribution, and packet transmission times have exponential distribution.

Scenario 3. Packet inter-arrival times have exponential distribution, and packet transmission times have Pareto distribution.

The table indicates that in most cases, the three scenarios show similar performance (i.e., P_{nc_v}, P_{b_p}, W_v, and W_p). The exponential packet inter-arrival and transmission times can provide performance trend in the real world.

5. Conclusion

In this paper, we proposed analytic and simulation models to investigate the impact of the buffering mechanism on the GPRS/GSM performance. We considered two channel allocation algorithms DRAVP and DRAPV where the voice queue and packet queue are used to buffer the GPRS packet and GSM voice call requests, respectively. In DRAVP, the buffered voice calls have higher priority to be served than the buffered packets. On the other hand, in DRAVP, the buffered packets have higher priority over the buffered calls. Our study indicated that the buffering mechanism for the GPRS packets effectively increases the GPRS packet acceptance rate at the cost of slightly degrading the performance of GSM voice calls. Furthermore, our study indicated that when the packet arrival rate is small, DRAPV is suitable for channel allocation. When the packet arrival rate becomes large, to maintain QoS of both GSM voice calls and GPRS packet services, DRAPV is the better choice.

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Appendix. Input parameters and output measures

The output measures evaluated in our study include:

- P_{b_p}: the GPRS packet dropping probability.
- P_{nc_v}: the GSM 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 handoff call attempt).
- W_p: the average GPRS packet waiting time.
- W_v: the average GSM voice call waiting time.

The input parameters set up in our study are:

- β: the parameter to describe the heaviness of Pareto packet inter-arrival (transmission) times.
- λ_p: the GPRS packet request arrival rate to a cell.
- λ_v: the GSM voice call arrival rate to a cell.
- μ_p ($k\mu_p$): the transmission rate when a single channel (k channels) is (are) used to deliver a GPRS packet request.
- $1/\mu_v$: the mean of GSM voice call holding times.
- $1/\eta_v$: the mean of cell residence times of a GSM voice user.
- v_v: the variance of the Gamma GSM voice user cell residence times.
- C: the total number of channels in a cell.
- K: the number of channels specified in a GPRS packet request.
- P: the maximum number of packet requests that could be buffered in the PQ.
- Q: the maximum number of GSM voice call requests that could be buffered in the VQ.

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