# Using Priority, Buffering, Threshold Control, and Reservation Techniques to Improve Channel-Allocation Schemes for the GPRS System

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***Abstract*—Taking a comprehensive approach, we investigate effects on the channel allocation for the general packet radio service (GPRS) system caused by priority strategy, buffering, threshold control on the buffer, and channel reservation. Moreover, four new dynamic channel-allocation schemes based on various combinations of these techniques are proposed and analyzed using the Markov chain approach. Analytical results obtained include blocking/forced-termination/dropping probabilities, cost-function definition based on the above metrics, and (mean) delay times. Through numerical examples, we demonstrate that: 1) priority and threshold control are efficient strategies to differentiate the quality of service (QoS) between a new voice call and a handoff voice call; 2) buffering allows more admitted rates of voice calls or data packets, but increases the delay time; and 3) channel reservation may directly improve a specific service, but it degrades performance of other services much. At last, better schemes suitable for the GPRS system are suggested after a thorough comparison of system performance.**

***Index Terms*—Buffering, dynamic channel allocation, general packet radio service, priority, quality of service (QoS), reservation.**

## I. INTRODUCTION

THE successful integration of multimedia applications in wired networks has been witnessed, e.g., diverse applications on the pervasive world wide web (WWW) in the Internet. As for the counterpart in mobile communication systems, the development of supporting multimedia other than voice service in some of these systems is still in progress. We notice that short message service (SMS) [11] and high-speed circuit-switched data (HSCSD) [9] have been proposed in the global system for mobile communications (GSM) [7] to provide data service using the circuit-switched mode with data rates limited to 9.6 and 14.4 kb/s per channel, respectively. Due to low data rate and longer connection setup time (40–60 s), the packet-switched general packet radio service (GPRS) [10] was then proposed by the European Telecommunications Standards Institute (ETSI) to coexist with GSM (or IS-136 [21] to form GPRS-136 [1]). GPRS uses the more efficient packet-switching technique to shorten the access time to the order less than 1 s and has a maximum net peak data rate of 21.4 kb/s per channel using coding scheme CS-4. Currently, the evolution of this direction continues for the third-generation (3G) cellular system, e.g., universal mobile telecommunications system (UMTS) [6], [15], in which wider bandwidth and even higher data rate are expected. In this paper, we will focus on the dynamic channel-allocation issue of GPRS.

The scarce radio channels make the issue on how to efficiently make use of available channels commonly shared by different types of subscribers important in wireless communication systems. In the past, a fixed number of channels was permanently allocated at a time regardless of service types in the circuit-switched voice and data integrated communication systems, e.g., [14], [19], and [23]. However, fixed channel allocation may not suit systems with bursty data traffic, e.g., GPRS, due to the permanent and inefficient use of channels. Instead, dynamic channel-allocation schemes (CASs) are frequently employed when dealing with the corresponding issue for GPRS in which a channel may be shared by multiple data users or multiple channels may be assigned to a data user because of the flexibility of channel usage. In the literature, there are some papers concerning the GPRS system [2]–[4], [8], [16], [18], [20], [22]. Brasche and Walke [2] and Cai and Goodman [3] reviewed the functionality, system architecture, and protocol stacks of GPRS along with some simulation results. In [22], Stuckmann and Müller developed a simulation tool for the GPRS system called *GPRSim* to study the performance of both fixed and on-demand channel-allocation mechanisms. In [8], Ermel *et al.* proposed a framework for analytical performance analysis of a single GSM/GPRS cell and investigated three channel-partitioning strategies, i.e., complete partitioning, complete sharing, and partial sharing. Lindemann and Thümmler [18] determined how many channels should be allocated for GPRS data packets using the Markov-modulated Poisson process (MMPP) to model data traffic. In [16], Lin and Lin proposed two major types of resource-allocation algorithms: fixed and dynamic resource allocation with respect to the usage of channels by data users. Endowing them with a buffer to voice calls forms another two variants. The authors showed that dynamic resource allocation with buffering for voice calls performs best among the four proposed algorithms.

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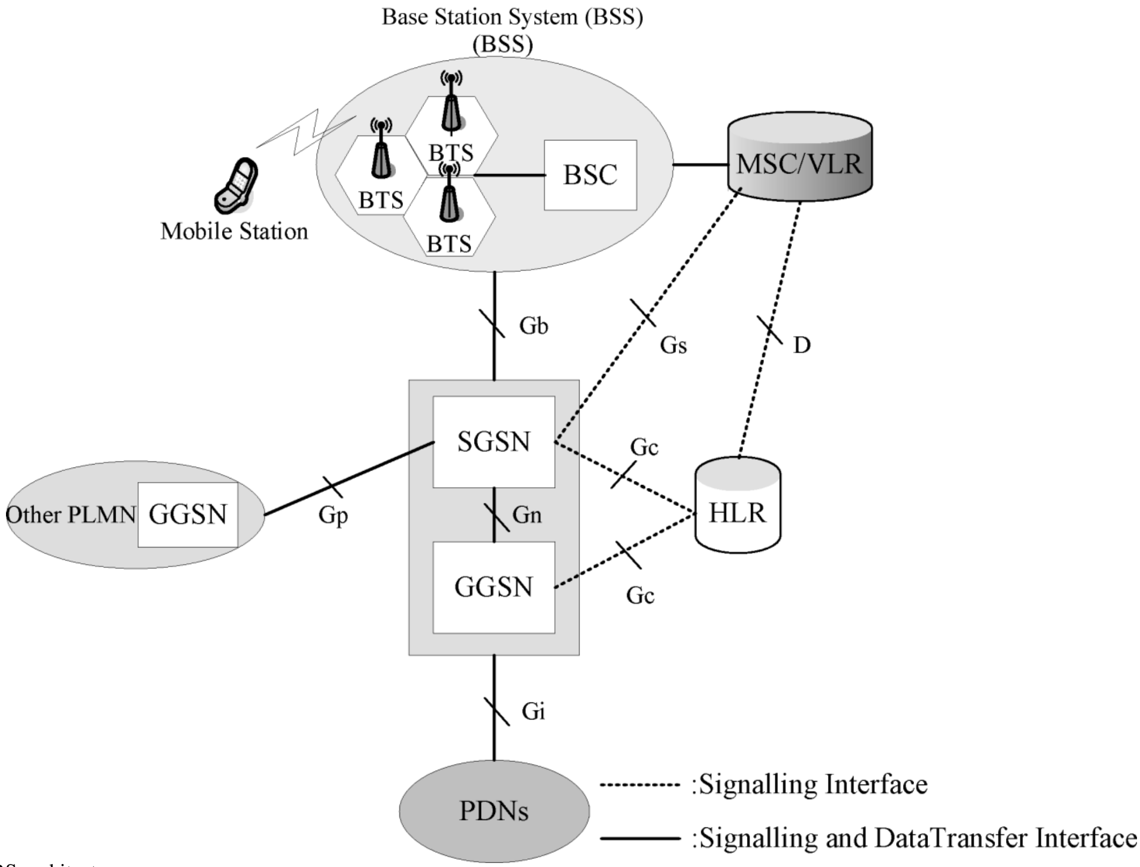


Fig. 1. GPRS architecture.

Recently, Chen *et al.* investigated the improvement caused by the de-allocation of partial allocated channels for a data user if no available channel is found upon the arrival of a GSM voice user in [4]. With an idea similar to [4], Ni and Häggman [20] allowed GSM voice calls to preempt data users if there is no available channel.

Based on dynamic channel allocation, we investigate effects of priority, channel reservation, buffering, and threshold control on the buffer and propose four dynamic CASs using these techniques. For these schemes, two types of buffers are employed: one for voice-call requests and the other for data-packet requests. If the threshold control is enabled, a threshold for the voice buffer is set to indicate the maximum number of new voice calls allowed to be queued. As for priorities, two types of priorities, i.e., priorities over different queues and priorities over different services, are employed in this paper. Finally, fixed channel reservation may be assumed for handoff voice calls. Applying the Markov chain approach, these four schemes are analyzed. Among the aforementioned papers, [16] is closest to our paper. However, our paper differs from [16] in the following aspects: 1) both voice and data buffers are used, but only the voice buffer is employed by [16]; 2) a more comprehensive approach is discussed in this paper; 3) general forms for analytical results are expressed; and 4) the cost function is proposed as an index to help system designers judge which scheme performs best.

The rest of this paper is organized as follows. In Section II, we introduce the proposed CASs after briefly reviewing the GPRS system. Section III aims at analytical performance evaluation on the proposed CASs. Then, numerical experiments to illustrate merits/defects of different CASs under various system parameters are given in Section IV. Finally, Section V concludes this paper.

## II. System Description and Channel-Allocation Schemes

Before introducing the CASs, first we briefly review the GPRS architecture for consistence and readers' convenience. In the following discussion, we assume that GPRS coexists with GSM in which there are three basic elements: mobile station (MS); base station system (BSS), which is composed of base transceiver station (BTS) communicating with MSs through the air interface and base station controller (BSC); and mobile switching center (MSC), as well as four databases, including home-location register (HLR), visitor-location register (VLR), equipment identity register (EIR), and authentication center (AUC). Here, we omit the detailed description of GSM. Readers who are interested in GSM may refer to [7] for details. For GPRS, the above corresponding elements or databases are modified. Furthermore, two additional nodes, i.e., serving GPRS support node (SGSN) responsible for packet delivery to MSs and gateway GPRS support node (GGSN) that communicates with external data networks are added into the system. In Fig. 1, the architecture of GPRS is shown diagrammatically.

Since CASs are concerned with the usage of channels, that is, the physical layer of GPRS, we now turn our attention to this part. Rather than permanently allocating channels to a data user like that in GSM due to the circuit-switched nature, multiple physical channels called packet data traffic channels (PDTCHs)

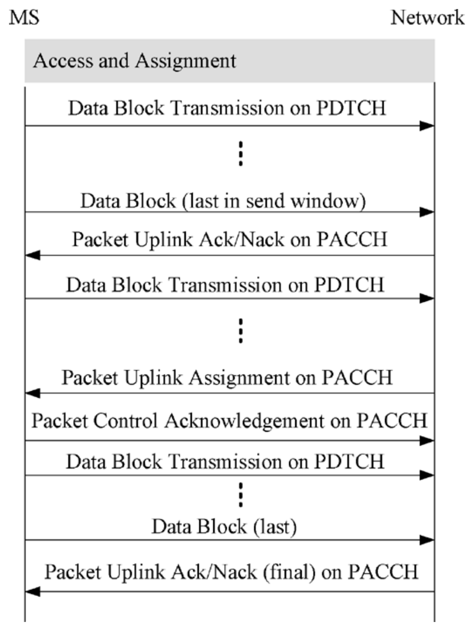


Fig. 2. Example of dynamic allocation of the uplink data transfer.

can be allocated to a data user in an on-demand manner for GPRS. Hence, several PDTCHs are allocated when requesting by a data user according as his or her current need; then, the number of channels may be increased when further requirement is set or decreased when transmission is completed. In Fig. 2, an example of dynamic channel allocation in the uplink data-transfer procedure is illustrated. The procedure is briefly described as follows. Initially, an MS requiring channels for data transfer accesses channels with other competing MS's and negotiates with the network on its requirement of channels. After that, the network makes a decision to assign channels to the MS. Then, the MS starts to transfer data blocks via the PDTCH channel. If the MS needs more channels, the network will re-assign additional channels via the packet access control channel (PACCH) to notify the MS. The MS also acknowledges via the PACCH channel. After the phase of reassignment, data block transfer continues. As for the dynamic channel allocation of the downlink data transfer procedure, it is similar to the procedure of uplink data transfer (see [12]). We note that two schemes, i.e., fixed channel allocation (FCA) and dynamic channel allocation (DCA), are allowed to allocate channels in either the assignment or reassignment phase. The former assigns exactly the requested number of channels to the MS, while the latter gives at most the requested number of channels to the MS, depending on the network situation. In this paper, we will further propose other CASs based on the concept of DCA, since it is more efficient and well performed than FCA, as suggested by [16].

In the following, we assume that the total number of channels in the channel pool shared by both GSM voice calls and GPRS data packet requests in each cell is fixed and denoted by $C$. For simplicity, we permit user mobility for GSM calls and neglect the effect caused by mobility of GPRS data users in the analytical models. To explore the effect of user mobility for data users, simulation results are given in the section of numerical results and discussions. Using the DCA, only one channel is allocated at a time to voice calls, but almost $n$ channels can be allocated at a time to a data-packet request. To have a comprehensive view of channel allocation, we will design CASs using a hybrid approach that takes most viable techniques, including priority, buffering, threshold control on the buffer, and channel reservation into consideration. Let us first examine the buffering technique. In the following schemes, two buffers are used: voice buffer for both new/originating GSM voice calls and handoff GSM voice calls and data buffer for data packet requests with size of $B_v$ and $B_d$, respectively. Typically, voice calls require more timely transmission than data packets; hence, we set $B_v < B_d$ such that voice calls may feel a higher admission rate with a little raised delay time as compared to the situation without a voice buffer. As everyone knows, a handoff voice call should possess a lower forced-termination probability in contrast to the blocking probability of a new voice call from the viewpoint of users. This implies that more handoff voice calls should be admitted. To achieve this, one may restrict the maximum allowable number of new voice calls to be queued in the voice buffer to a certain level (smaller than or equal to $B_v$) or allows handoff voice calls in the buffer to posses a higher priority than new voice calls to enter the system. The former technique is called threshold control on the buffer (the value of this level is called the threshold) and the latter is called service priority between a new voice call and a handoff voice call. Since voice calls are time sensitive and data packets are less sensitive in time, priorities over queues can be further set to assure that the priority of the voice buffer is higher than the priority of the data buffer. Finally, a portion of the channel can be (statically) reserved for handoff voice calls to reduce the forced-termination probability. The reserved channel is sometimes called *guard channel*. In the following, we use symbol $C_G$ to denote the number of reserved channels for handoff voice calls when the reservation technique is used. Fig. 3 shows an illustrative and general diagram of the hybrid approach of CASs to be addressed.

Now various CASs utilizing priority, buffering, threshold control, and channel reservation are stated as follows.

- $\mathrm{CAS}_1$: A voice buffer and a data buffer are employed for this scheme, but neither the priorities between these two buffers nor the service priorities among new voice calls and handoff voice calls are set. Thus, requests in both buffers are served in the first-in–first-out (FIFO) manner when channels are free. As for techniques of threshold control and channel reservation, they are not included in this scheme. Hence, this scheme is proposed for reference only. We then omit its analysis and merely provide simulation results.
- $\mathrm{CAS}_2$: Based on scheme $\mathrm{CAS}_1$, priorities over queues are set. Thus, data-packet requests receive service only when the voice buffer is empty. Obviously, this scheme improves performance of voice calls, but degrades performance of data packets.
- $\mathrm{CAS}_3$: The service priorities are activated over scheme $\mathrm{CAS}_2$ to form this scheme. Therefore, handoff voice calls have a higher priority than new voice calls to enter the system.
- $\mathrm{CAS}_4$: Further including the threshold control on the voice buffer into scheme $\mathrm{CAS}_3$, scheme $\mathrm{CAS}_4$ is obtained. In the

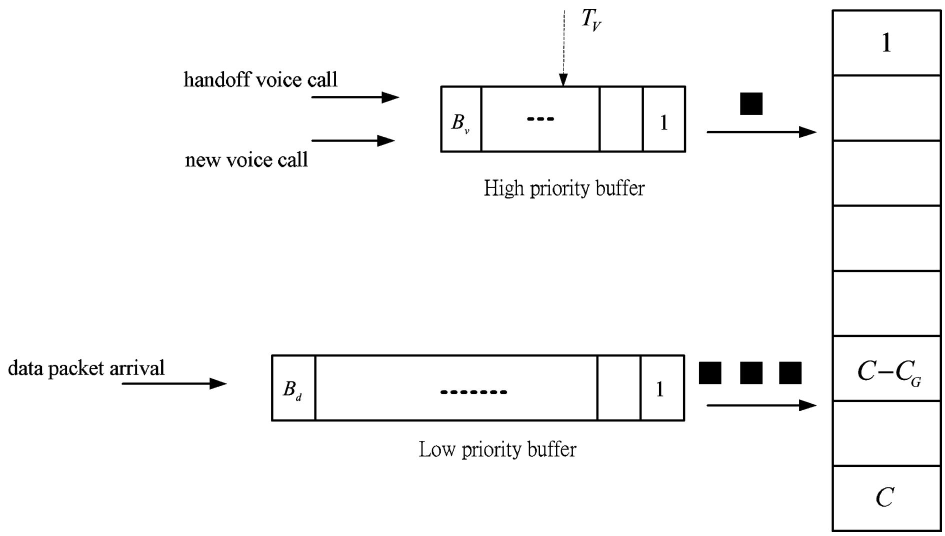


Fig. 3. System model for channel allocation.

following, $T_v$ is used to denote the value of the threshold. An arriving new voice call is no more queued once the number of the new voice calls in the buffer equals to $T_v$.

- $\mathrm{CAS}_5$: Based on scheme $\mathrm{CAS}_3$, $C_G$ channels are reserved for handoff voice calls only. Thus, $C-C_G$ available channels are shared by new voice calls, handoff voice calls, and data-packet requests. When these channels are not available, new voice calls and data-packet requests must be buffered/rejected except handoff voice calls, which are allowed to use the reserved channels.

In the literature, some papers address the issue of rate reduction or channel de-allocation, e.g., [4] in the GPRS system when a request from a voice user arrives, finding that all channels are occupied. The rate-reduction approach is to release one of channels occupied by a data user to the voice request. However, such an issue is out of the scope of this paper.

## III. Performance Analysis of CASs

Let us first describe assumptions on the system modeling. In this paper, we only consider a system with homogenous cells. Thus, an equal number of channels, same traffic patterns, and symmetric directions of handoff calls are assumed for each cell. It can then be proven that the arrival rate to a specific cell should be equal to the departure rate from that cell based on the previous assumptions. For traffic patterns in a cell, we assume that new voice calls and new data packets are generated according to Poisson processes with rates $\lambda_v$ and $\lambda_d$, respectively. As for voice call-holding time, packet-transmission time, and dwelling time of voice calls, they follow exponential distributions with means $1/\mu_v$, $1/\mu_d$, and $1/\eta$, respectively. In this paper, we take into account the effect of voice-user mobility, but ignore the effect of data-packet mobility in the analytical models. The reason is described in the previous section. Since the exponential dwelling time model for the voice calls is assumed, the handoff voice calls also form a Poisson process with rate $\lambda_h$, which can be calculated by

$$\lambda_h = \frac{\eta(1-P_{vb})}{\mu_v + \eta P_{ft}} \lambda_v \tag{1}$$

where $P_{vb}$ denotes the blocking probability of a new voice call and $P_{ft}$ represents the forced-termination probability of a handoff voice call. Readers can refer to papers such as [13] for details.

In the following, we will employ the technique of Markov chain to evaluate the four CASs, i.e., $\mathrm{CAS}_2$ to $\mathrm{CAS}_5$. The analysis of scheme $\mathrm{CAS}_1$ is not provided here for brevity, since this scheme serves as a reference scheme only. We use $S_{\mathrm{CAS}_x}$ to denote the collection of all possible states for scheme $\mathrm{CAS}_x$ ($x$ =2, 3, 4, 5), $P_{dd}$ to denote the data-packet-dropping probability, $\Lambda = \lambda_v + \lambda_h$ to represent the total voice-arrival rate, and $1/\mu = 1/(\mu_v + \eta)$ to denote the mean channel-occupation time of a voice call.

### A. Analysis of Scheme $CAS_2$

Scheme $\mathrm{CAS}_2$ employs both priority over queues and calls/requests buffering. Hence, voice calls possess a priority higher than data packets. Let $(x, y_1, \ldots, y_n, b_v, b_d)$ be a vector representing the system state, where $x$ denotes the number of voice calls in service with one allocated channel for each call; $y_i$ $(1 \le i \le n)$ denotes the numbers of data requests in service with $i$ allocated channels for each request; $b_v$ denotes the number of voice-call requests in the voice buffer; and $b_d$ denotes the number of data requests in the data buffer. Applying an iterative method shown in Appendix I, we can calculate the state probability $P_{x,y_1,\ldots,y_n,b_v,b_d}$ using the relations to be addressed in the following.

The state–space of this scheme can be expressed as

$$\begin{aligned} S_{\mathrm{CAS}_2} = \Bigg\{ &(x, y_1, \ldots, y_n, b_v, b_d) \mid 0 \le x + \sum_{i=0}^{n} i y_i \le C, \\ &0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots, \\ &0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_v \le B_v,\ 0 \le b_d \le B_d \Bigg\}. \end{aligned}$$

Summing all probabilities of states reaches

$$\sum_{(x,y_1,\ldots,y_n,b_v,b_d) \in S_{CAS_2}} P_{x,y_1,\ldots,y_n,b_v,b_d} = 1. \tag{2}$$

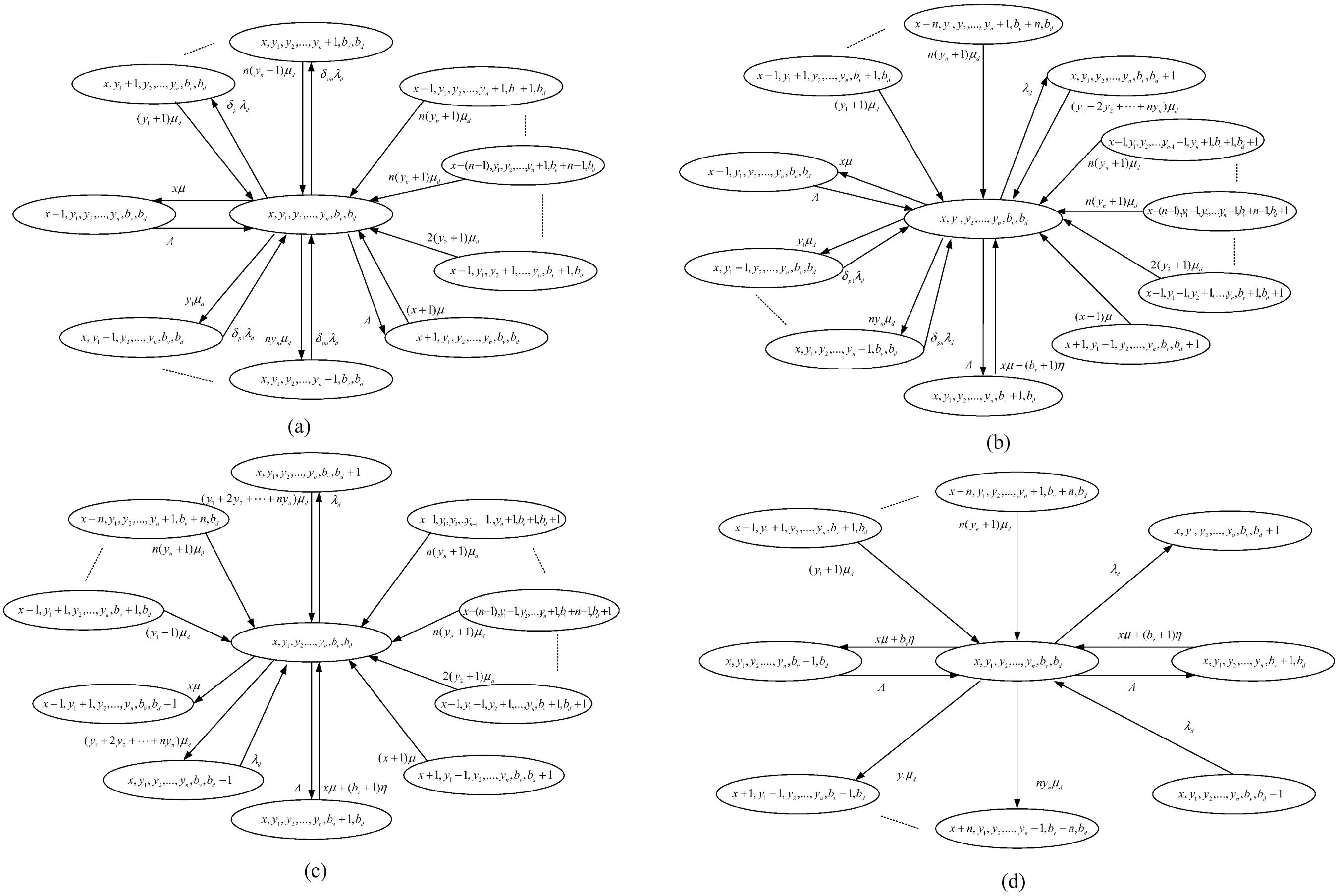

Fig. 4. State-transition diagrams for different cases of scheme $\mathrm{CAS}_2$. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

For convenience, let us define a set of indicator functions $\{\delta_{pj} \mid 1 \leq j \leq n\}$ associated with a vector $p = (x, y_1, \ldots, y_n)$ coming from the first $(n+1)$ elements of the *source/originating state* described in the following when no calls/requests are queued:

$$\delta_{pj} = \begin{cases} 1, & \text{if } x + \sum_{i=1}^{n} iy_i = C - j, \\ 0, & \text{otherwise} \end{cases} \quad \text{for } 1 \leq j \leq n-1$$

$$\delta_{pj} = \begin{cases} 1, & \text{if } x + \sum_{i=1}^{n} iy_i \leq C - n, \\ 0, & \text{otherwise} \end{cases} \quad \text{for } j = n. \tag{3}$$

Also, we define a set of vectors $\{\delta_j \mid 1 \leq j \leq n\}$ in which elements are pair-wise orthogonal and have unit length, i.e.,

$$\delta_i \delta_j = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j. \end{cases} \tag{4}$$

To eliminate any nonfeasible state (state not included in the state–space) shown in the following state-transition diagrams resulting from convenience of illustration, its state probability should be set to zero to guarantee that nonfeasible states are not taken into account in balance equations. Now let us consider the following four cases to exploit the relationship among state probabilities.

*Case 1: When* $0 \leq x + \sum_{i=1}^{n} iy_i < C$, $b_v = 0$, $b_d = 0$*:* Under such a case, both voice calls and data packets are in service for state $(x, y_1, \ldots, y_n, b_v, b_d)$ so that buffers are empty. Fig. 4(a) shows the detailed state-transition diagram. Denoting state $(x, y_1, \ldots, y_n, b_v, b_d)$ as the source state, we now briefly explain the possible transitions originating from the source state as follows: 1) a voice call arrival makes a transmission from the source state to state $(x+1, y_1, \ldots, y_n, b_v, b_d)$ with rate $\Lambda$; 2) with rate $\delta_{pj}\lambda_d$ $(1 \leq j \leq n)$, the source state will move to state $(x, y_1+\delta_1\delta_j, \ldots, y_j+\delta_j\delta_j, \ldots, y_n+\delta_n\delta_j, b_v, b_d)$; 3) the source state moves to state $(x-1, y_1, \ldots, y_n, b_v, b_d)$ with rate $x\mu$ because of call completion or handoff; 4) upon service completion of the data packet simultaneously using $j$ channels, the source state will move to state $(x, y_1-\delta_1\delta_j, \ldots, y_j-\delta_j\delta_j, \ldots, y_n-\delta_n\delta_j, b_v, b_d)$ with rate $jy_j\mu_d$. If state $(x, y_1, \ldots, y_n, b_v, b_d)$ is now denoted as the destination state, state transitions can come from the resultant states discussed before as follows: 1) state $(x+1, y_1, \ldots, y_n, b_v, b_d)$ with rate $(x+1)\mu$ due to call completion or handoff; 2) state $(x, y_1+\delta_1\delta_j, \ldots, y_j+\delta_j\delta_j, \ldots, y_n+\delta_n\delta_j, b_v, b_d)$ for $1 \leq j \leq n$ with rate $j(y_j+1)\mu_d$ due to the completion of a packet transmission using $j$ channels; 3) state $(x-1, y_1, \ldots, y_n, b_v, b_d)$ with rate $\Lambda$ due to a call arrival; and 4) state $(x, y_1-\delta_1\delta_j, \ldots, y_j-\delta_j\delta_j, \ldots, y_n-\delta_n\delta_j, b_v, b_d)$ for $1 \leq j \leq n$ with rate $\delta_{pj}\lambda_d$ because of the arrival of a packet. In addition, transitions can come from states with all busy channels, a not empty voice buffer but an empty data buffer, i.e., states $(x-l, y_1+\delta_1\delta_k, \ldots, y_k+\delta_k\delta_k, \ldots, y_n+\delta_n\delta_k, b_v+l, b_d)$ for $2 \leq k \leq n$ and $1 \leq l \leq k-1$ with rate $k(y_k+1)\mu_d$ after the data request using $k$ channels releases these $k$ channels upon its completion of transmission, which results in the service beginning of $l$ voice calls in the voice buffer. The state transition diagram in Fig. 4(a) then enables one to deduce the following balance equation:

$$\begin{aligned}\left(x\mu+\Lambda+\sum_{i=1}^{n} iy_i\mu_d+\sum_{i=1}^{n}\delta_{pi}\lambda_d\right)P_{x,y_1,\ldots,y_n,b_v,b_d} &= \Lambda P_{x-1,y_1,\ldots,y_n,b_v,b_d}+(x+1)\mu P_{x+1,y_1,\ldots,y_n,b_v,b_d}\\ &+\sum_{i=1}^{n}\delta_{pi}\lambda_d P_{x,,y_1-\delta_1\delta_i\ldots,y_i-\delta_i\delta_i,\ldots,y_n-\delta_n\delta_i,b_v,b_d}\\ &+\sum_{i=1}^{n} i(y_i+1)\mu_d P_{x,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_v,b_d}\\ &+\sum_{k=2}^{n}\sum_{l=1}^{k-1} k(y_k+1)\mu_d\\ &\times P_{x-l,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_v+l,b_d}.\end{aligned}\tag{5}$$

*Case 2: When $x+\sum_{i=1}^{n} iy_i=C$, $b_v=0$, $b_d=0$:* The detailed state-transition diagram for this case is shown in Fig. 4(b). We now explain it as follows. Originating from state $(x,y_1,\ldots,y_n,b_v,b_d)$, it will move to state $(x,y_1,\ldots,y_n,b_v+1,b_d)$ with rate $\Lambda$ upon the arrival of a voice call; it will move to state $(x,y_1,\ldots,y_n,b_v,b_d+1)$ with rate $\lambda_d$ if a data packet arrives, will move to state $(x-1,y_1,\ldots,y_n,b_v,b_d)$ with rate $x\mu$ if a voice call is completed or moves to an adjacent cell, and will move to state $(x,y_1-\delta_1\delta_j,\ldots,y_j-\delta_j\delta_j,\ldots,y_n-\delta_n\delta_j,b_v,b_d)$ with rate $jy_j\mu_d$ if a data-packet request using $j$ channels is completed. As for states that will move to destination state of $(x,y_1,\ldots,y_n,b_v,b_d)$, they are state $(x,y_1,\ldots,y_n,b_v+1,b_d)$ with rate $x\mu+(b_v+1)\eta$ because of completion/handoff of a voice call or moving to an adjacent cell of a call request in the voice buffer before getting service, state $(x,y_1,\ldots,y_n,b_v,b_d+1)$ with rate $\sum_{i=1}^{n} iy_i\mu_d$ for the completion of data-packet requests, state $(x,y_1-\delta_1\delta_j,\ldots,y_j-\delta_j\delta_j,\ldots,y_1-\delta_n\delta_j,b_v,b_d)$ with rate $\delta_{pj}\lambda_d$ due to the arrival of a packet, state $(x-j,y_1+\delta_1\delta_j,\ldots,y_j+\delta_j\delta_j,y_1+\delta_n\delta_j,b_v+j,b_d)$ for $1\le j\le n$ with rate $j(y_j+1)\mu_d$ because $j$ occupied channels by a data-packet request have been released on its service completion and $j$ voice-call requests in the voice buffer take these channels immediately, state

$$\begin{aligned}(x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k\\ +\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_v+l,b_d+1)\end{aligned}$$

for $2\le k\le n$ and $1\le l\le k-1$ with rate $k(y_k+1)\mu_d$ since $k$ occupied channels by a data-packet request have been released and $k-1$ voice-call requests in the voice buffer and one data-packet request in the data-packet buffer that is assigned one channel get their service immediately and state $(x+1,y_1-1,\ldots,y_n,b_v,b_d+1)$ with rate $(x+1)\mu$ since the completion of a call allows the data-packet request in the data queue to enter the

$$\begin{aligned}\left(x\mu+\Lambda+\sum_{i=1}^{n} iy_i\mu_d+\lambda_d\right)P_{x,y_1,\ldots,y_n,b_v,b_d} &= \Lambda P_{x-1,y_1,\ldots,y_n,b_v,b_d}+[x\mu+(b_v+1)\eta]P_{x,y_1,\ldots,y_n,b_v+1,b_d}\\ &+(x+1)\mu P_{x+1,y_1-1,\ldots,y_n,b_v,b_d+1}+\sum_{i=1}^{n}\delta_{pi}\lambda_d P_{x,,y_1-\delta_1\delta_i\ldots,y_i-\delta_i\delta_i,\ldots,y_n-\delta_n\delta_i,b_v,b_d}\\ &+\sum_{i=1}^{n} iy_i\mu_d P_{x,y_1,\ldots,y_n,b_v,b_d+1}+\sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_v+i,b_d}\\ &+\sum_{k=2}^{n}\sum_{l=1}^{k-1} k(y_k+1)\mu_d P_{x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_v+l,b_d+1}.\end{aligned}\tag{6}$$

$$\begin{aligned}\left(x\mu+\Lambda+\sum_{i=1}^{n} iy_i\mu_d+\lambda_d\right)P_{x,y_1,\ldots,y_n,b_v,b_d} &= \lambda_d P_{x,y_1,\ldots,y_n,b_v,b_d-1}+[x\mu+(b_v+1)\eta]P_{x,y_1,\ldots,y_n,b_v+1,b_d}+(x+1)\mu P_{x+1,y_1-1,\ldots,y_n,b_v,b_d+1}\\ &+\sum_{i=1}^{n} iy_i\mu_d P_{x,y_1,\ldots,y_n,b_v,b_d+1}+\sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_v+i,b_d}\\ &+\sum_{k=2}^{n}\sum_{l=1}^{k-1} k(y_k+1)\mu_d P_{x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_v+l,b_d+1}.\end{aligned}\tag{7}$$

system. Thus, the balance equation is obtained in (6), as shown at the bottom of the previous page.

*Case 3: When $x + \sum_{i=1}^{n} iy_i = C$, $b_v = 0$, $1 \le b_d \le B_d$:* Most descriptions of state transitions shown in Fig. 4(c) of this case can be rendered from Case 2, except state $(x, y_1, \ldots, y_n, b_v, b_d)$ moving to state $(x-1, y_1+1, \ldots, y_n, b_v, b_d-1)$ and to state $(x, y_1, \ldots, y_n, b_v, b_d-1)$ with rate $x\mu$ and rate $\sum_{i=1}^{n} iy_i\mu_d$, respectively, as well as state $(x, y_1, \ldots, y_n, b_v, b_d-1)$ moving to state $(x, y_1, \ldots, y_n, b_v, b_d)$ with $\lambda_d$. Therefore, the balance equation can be expressed in (7), as shown at the bottom of the previous page.

*Case 4: When $x + \sum_{i=1}^{n} iy_i = C$, $1 \le b_v \le B_v$, $1 \le b_d \le B_d$:* The state-transition diagram for this case is shown in Fig. 4(d) and we omit its detailed description for brevity. Using Fig. 4(d) leads to the following balance equation:

$$\begin{aligned}\left(x\mu + b_v\eta + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) &P_{x,y_1,\ldots,y_n,b_v,b_d}\\ &= \Lambda P_{x,y_1,\ldots,y_n,b_v-1,b_d} + \lambda_d P_{x,y_1,\ldots,y_n,b_v,b_d-1}\\ &\quad + [x\mu + (b_v+1)\eta] P_{x,y_1,\ldots,y_n,b_v+1,b_d}\\ &\quad + \sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_v+i,b_d}.\end{aligned} \tag{8}$$

State probabilities obtained via solving the balance equations shown previously enable us to get the blocking probability of a new voice call, forced-termination probability of a handoff voice call, and data-packet-dropping probability. Further considering *full blocking probabilities* $P_{vbf}$ for the new voice call and $P_{ftf}$ for the handoff voice call, which result from lack of buffer space (in the following, full blocking probabilities are obtained by summing all possible probabilities when no available room can be offered for the voice buffer) and *timeout blocking probabilities* $P_{vbt}$ for the new voice call and $P_{ftt}$ for the handoff voice call when a request is allowed to be queued in the voice buffer, but fails to get a channel during its stay at the current cell while waiting for service in the queue (note that timeout blocking probabilities are ratios of the leaving rate of requests in queue and the admitted rate into the cell), the blocking probability of a new voice call $P_{vb}$, and forced-termination probability of a handoff voice call $P_{ft}$ can be calculated using the relations

$$P_{vb} = P_{vbf} + (1 - P_{vbf})P_{vbt} \tag{9}$$

$$P_{ft} = P_{ftf} + (1 - P_{ftf})P_{ftt} \tag{10}$$

where

$$P_{vbf} = P_{ftf} = \sum_{(x,y_1,\ldots,y_n,b_v,b_d)\in G_1} P_{x,y_1,\ldots,y_n,b_v,b_d} \tag{11}$$

$$P_{vbt} = P_{ftt} = \frac{\sum_{(x,y_1,\ldots,y_n,b_v,b_d)\in G_2} b_v\eta P_{x,y_1,\ldots,y_n,b_v,b_d}}{\Lambda(1 - P_{vbf})} \tag{12}$$

---

$$\begin{aligned}\left(x\mu + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \sum_{i=1}^{n} \delta_{pi}\lambda_d\right) &P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}\\ &= \Lambda P_{x-1,y_1,\ldots,y_n,b_n,b_h,b_d} + (x+1)\mu P_{x+1,y_1,\ldots,y_n,b_n,b_h,b_d}\\ &\quad + \sum_{i=1}^{n} \delta_{pi}\lambda_d P_{x,,y_1-\delta_1\delta_i\ldots,y_i-\delta_i\delta_i,\ldots,y_n-\delta_n\delta_i,b_n,b_h,b_d} + \sum_{i=1}^{n} i(y_i+1)\mu_d P_{x,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n,b_h,b_d}\\ &\quad + \sum_{k=2}^{n}\sum_{l=1}^{k-1}\sum_{s=0}^{l} k(y_k+1)\mu_d P_{x-l,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+s,b_h+l-s,b_d}.\end{aligned} \tag{15}$$

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$$\left(x\mu + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{16}$$

$$\begin{aligned}&= \Lambda P_{x-1,y_1,\ldots,y_n,b_n,b_h,b_d} + [x\mu + (b_n+1)\eta] P_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} + (x+1)\mu P_{x+1,y_1-1,\ldots,y_n,b_n,b_h,b_d+1}\\ &\quad + \sum_{i=1}^{n} \delta_{pi}\lambda_d P_{x,,y_1-\delta_1\delta_i\ldots,y_i-\delta_i\delta_i,\ldots,y_n-\delta_n\delta_i,b_n,b_h,b_d} + [x\mu + (b_h+1)\eta] P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d}\\ &\quad + \sum_{i=1}^{n} iy_i\mu_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d+1} + \sum_{k=1}^{n}\sum_{l=0}^{k} k(y_k+1)\mu_d P_{x-k,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+l,b_h+k-l,b_d}\\ &\quad + \sum_{k=2}^{n}\sum_{l=1}^{k-1}\sum_{s=0}^{l} k(y_k+1)\mu_d P_{x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+s,b_h+l-s,b_d+1}.\end{aligned} \tag{17}$$

$$G_1 = \Bigg\{ (x, y_1, \ldots, y_n, b_v, b_d) \mid x + \sum_{i=0}^{n} i y_i = C, 0 \le x \le C$$
$$0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor$$
$$b_v = B_v, \text{ and } 0 \le b_d \le B_d \Bigg\}$$

$$G_2 = \Bigg\{ (x, y_1, \ldots, y_n, b_v, b_d) \mid x + \sum_{i=0}^{n} i y_i = C, 0 \le x \le C$$
$$0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor \ldots, 0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor,$$
$$0 \le b_v \le B_v,$$
$$0 \le b_d \le B_d \Bigg\}.$$

As for the data-packet-dropping probability $P_{dd}$ resulting from overflow of the data buffer, it can be expressed as

$$P_{dd} = \sum_{(x,y_1,\ldots,y_n,b_v,b_d) \in G_3} P_{x,y_1,\ldots,y_n,b_v,b_d} \tag{13}$$

where

$$G_3 = \Bigg\{ (x, y_1, \ldots, y_n, b_v, b_d) \mid x + \sum_{i=0}^{n} i y_i = C, 0 \le x \le C$$
$$0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor$$
$$0 \le b_v \le B_v, \text{ and } b_d = B_d \Bigg\}.$$

### B. Analysis of Scheme $CAS_3$

To analyze scheme $\text{CAS}_3$, we need to differentiate the number of new voice-call requests in queue $b_n$ and the number of handoff voice-call requests in queue $b_h$. Thus, the state vector to be employed becomes $(x, y_1, \ldots, y_n, b_n, b_h, b_d)$ with the state–space

$$S_{\text{CAS}_3} = \Bigg\{ (x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid 0 \le x + \sum_{i=0}^{n} i y_i \le C$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le B_v, 0 \le b_h \le B_v$$
$$0 \le b_d \le B_d \Bigg\}. \tag{14}$$

Following a philosophy similar to that used by scheme $\text{CAS}_2$, state probabilities $P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}$ can be obtained from balance equations of the following six cases diagrammatically illustrated in Fig. 5.

*Case 1: When* $0 \le x + \sum_{i=1}^{n} i y_i < C$, $b_n = 0$, $b_h = 0$, $b_d = 0$*:* See (15) at the bottom of the previous page.

*Case 2: When* $x + \sum_{i=1}^{n} i y_i = C$, $b_n = 0$, $b_h = 0$, $b_d = 0$*:* See (16)–(17) at the bottom of the previous page.

*Case 3: When* $x + \sum_{i=1}^{n} i y_i = C$, $bn = 0$, $b_h = 0$, $0 \le b_d \le B_d$*:* See (18) at the bottom of the page.

*Case 4: When* $x + \sum_{i=1}^{n} i y_i = C$, $b_n = 0$, $1 \le b_h \le B_v$, $0 \le b_d \le B_d$*:* See (19) at the bottom of the page.

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$$\begin{aligned}
&\left( x\mu + \Lambda + \sum_{i=1}^{n} i y_i \mu_d + \lambda_d \right) P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\
&\quad = [x\mu + (b_n+1)\eta] P_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} + [x\mu + (b_h+1)\eta] P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d} \\
&\qquad + \lambda_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} + \sum_{i=1}^{n} i y_i \mu_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d+1} + (x+1)\mu P_{x+1,y_1-1,\ldots,y_n,b_n,b_h,b_d+1} \\
&\qquad + \sum_{k=1}^{n} \sum_{l=0}^{k} k(y_k+1)\mu_d P_{x-k,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+l,b_h+k-l,b_d} \\
&\qquad + \sum_{k=2}^{n} \sum_{l=1}^{k-1} \sum_{s=0}^{l} k(y_k+1)\mu_d P_{x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+s,b_h+l-s,b_d+1}.
\end{aligned} \tag{18}$$

---

$$\begin{aligned}
&\left( x\mu + b_h\eta + \Lambda + \sum_{i=1}^{n} i y_i \mu_d + \lambda_d \right) P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\
&\quad = \lambda_h P_{x,y_1,\ldots,y_n,b_n,b_h-1,b_d} + \lambda_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} + [x\mu + (b_h+1)\eta] P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d} \\
&\qquad + (b_n+1)\eta P_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} + \sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n,b_h+i,b_d}.
\end{aligned} \tag{19}$$

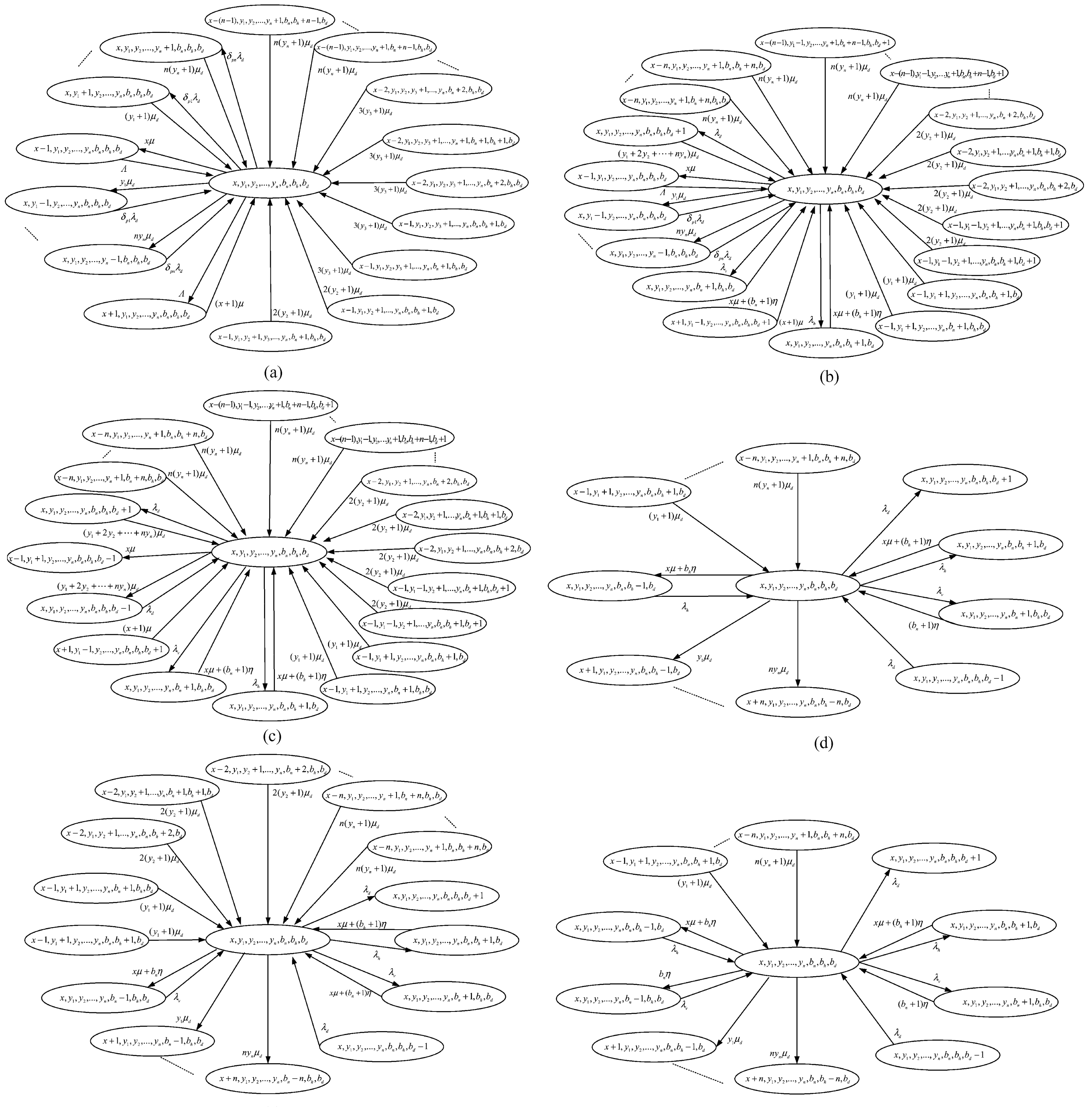

Fig. 5. State-transition diagrams for different cases of scheme $\mathrm{CAS}_3$. (a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4. (e) Case 5. (f) Case 6.

*Case 5: When $x + \sum_{i=1}^{n} iy_i = C$, $1 \le b_n \le B_v$, $b_h = 0$, $0 \le b_d \le B_d$:* See (20) at the bottom of the next page.

*Case 6: When $x + \sum_{i=1}^{n} iy_i = C$, $1 \le b_n \le B_v$, $1 \le b_h \le B_v$, $0 \le b_d \le B_d$:* See (21) at the bottom of the next page. Then, the blocking probability of a new voice call and forced-termination probability of a handoff voice call can be calculated using (9) and (10) with $P_{vbf}$, $P_{ftf}$, $P_{vbt}$, and $P_{ftt}$ expressed as

$$P_{vbf} = P_{ftf} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_4} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{22}$$

where

$$\begin{aligned} G_4 = \Bigg\{ &(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C \\ &0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots, \\ &0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le B_v, 0 \le b_h \le B_v \\ &b_n + b_h = B_v, \text{ and } 0 \le b_d \le B_d \Bigg\}, \end{aligned}$$

$$P_{vbt} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_5} b_n \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_v(1-P_{vbf})} \tag{23}$$

$$P_{ftt} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_5} b_h \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_h(1-P_{ftf})} \tag{24}$$

where

$$G_5 = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x+\sum_{i=0}^{n} iy_i = C \right.$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le B_v, 0 \le b_h \le B_v$$
$$\left. 0 \le b_d \le B_d \right\}.$$

The data-packet-dropping probability $P_{dd}$ is expressed as

$$P_{dd} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_6} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{25}$$

where

$$G_6 = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x+\sum_{i=0}^{n} iy_i = C \right.$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le B_v, 0 \le b_h \le B_v$$

and

$$\left. b_d = B_d \right\}.$$

### C. Analysis of Scheme CAS$_4$

We use the state vector employed by scheme CAS$_3$ to analyze scheme CAS$_4$, which applies threshold control method to the voice buffer with at most $T_v$ allowable new voice-call requests in the queue. Thus, the state–space for this scheme is shown as

$$S_{\mathrm{CAS}_4} = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid 0 \le x+\sum_{i=0}^{n} iy_i \le C \right.$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le T_v, 0 \le b_h \le B_v$$

and

$$\left. 0 \le b_d \le B_d \right\}. \tag{26}$$

Fig. 6 illustrates the specific state-transition diagram for scheme CAS$_4$ when $x+\sum_{i=1}^{n} iy_i = C$, $b_n = T_v$, $1 < b_h \le B_v$, and $1 < b_d \le B_d$. From Fig. 6, one can easily derive the balance equation given in Appendix II. As for other situations, balance equations are omitted for compactness, but they can be obtained in the analogous manner done for scheme CAS$_3$. Again, we can obtain the blocking probability of a new voice call and forced-termination probability of a handoff voice call via (9) and (10) using the following forms of full and timeout blocking probabilities:

$$P_{vbf} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_7} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} + \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_8} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{27}$$

---

$$\begin{aligned}
&\left(x\mu + b_n\eta + \Lambda + \sum_{i=1}^{n} y_i\mu_d + \lambda_d\right) P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\
&\quad = \lambda_v P_{x,y_1,\ldots,y_n,b_n-1,b_h,b_d} + \lambda_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} \\
&\qquad + [x\mu + (b_n+1)\eta] P_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} + [x\mu + (b_h+1)\eta] P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d} \\
&\qquad + \sum_{k=1}^{n}\sum_{l=0}^{k} k(y_k+1)\mu_d P_{x-k,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+l,b_h+k-l,b_d}.
\end{aligned} \tag{20}$$

---

$$\begin{aligned}
&\left[x\mu + (b_h+b_n)\eta + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right] P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\
&\quad = \lambda_v P_{x,y_1,\ldots,y_n,b_n-1,b_h,b_d} + \lambda_h P_{x,y_1,\ldots,y_n,b_n,b_h-1,b_d} + (b_n+1)\eta P_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} + \lambda_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} \\
&\qquad + [x\mu + (b_h+1)\eta] P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d} + \sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n,b_h+i,b_d}.
\end{aligned} \tag{21}$$

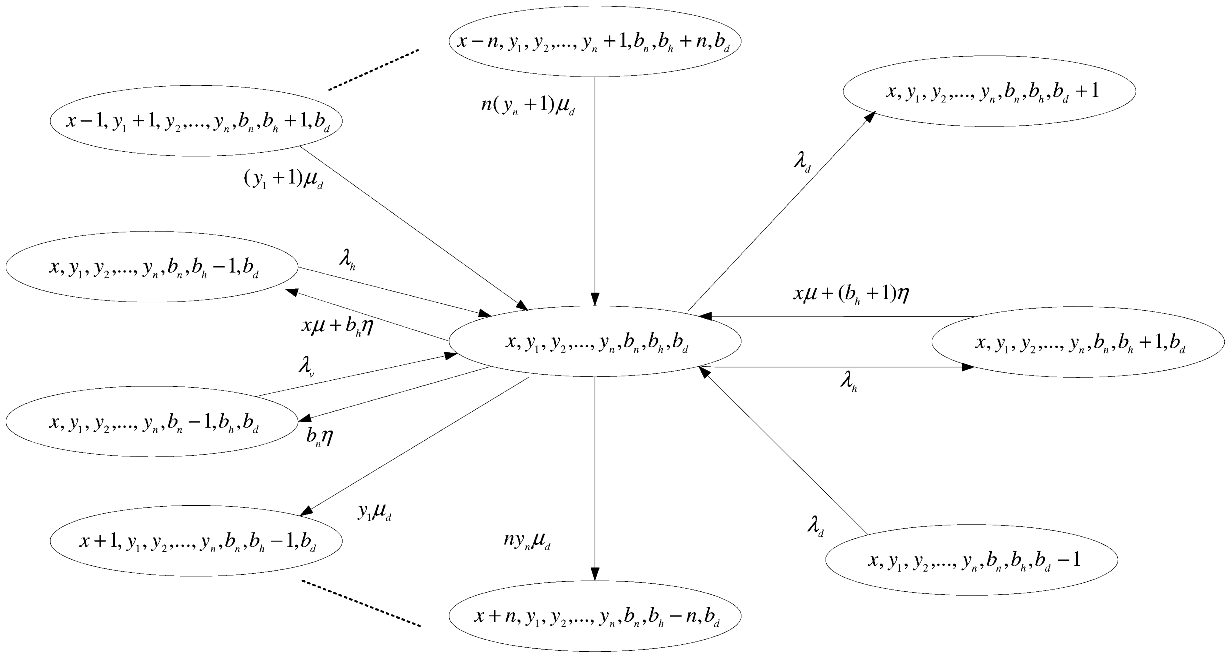


Fig. 6. State-transition diagram for scheme CAS$_4$ when $x + \sum_{i=1}^{n} iy_i = C$, $b_n = T_v$, $1 \le b_h \le B_v - T_v$, and $1 \le b_d \le B_d$.

where

$$G_7 = \Big\{(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C, 0 \le x \le C$$
$$0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor$$
$$b_n = T_v, 0 \le b_h < B_v - T_v,$$
$$0 \le b_d \le B_d\Big\},$$

$$G_8 = \Big\{(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n < T_v, 0 \le b_h \le B_v$$
$$b_n + b_h = B_v,$$
$$0 \le b_d \le B_d\Big\}$$

$$P_{ftf} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_9} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{28}$$

where

$$G_9 = \Big\{(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le T_v, 0 \le b_h \le B_v$$
$$b_n + b_h = B_v$$
$$0 \le b_d \le B_d\Big\}$$

$$P_{vbt} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{10}} b_n \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_v(1-P_{vbf})} \tag{29}$$

$$P_{ftt} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{11}} b_h \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_h(1-P_{ftf})} \tag{30}$$

where

$$G_{10} = \Big\{(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le T_v, 0 \le b_h \le B_v - T_v$$
$$0 \le b_d \le B_d\Big\}$$

$$G_{11} = \Big\{(x, y_1, \ldots, y_n, b_n, b_h, b_d) \mid x + \sum_{i=0}^{n} iy_i = C$$
$$0 \le x \le C, 0 \le y_1 \le C, 0 \le y_2 \le \left\lfloor \frac{C}{2} \right\rfloor, \ldots,$$
$$0 \le y_n \le \left\lfloor \frac{C}{n} \right\rfloor, 0 \le b_n \le T_v, 0 \le b_h \le B_v$$
$$0 \le b_d \le B_d\Big\}.$$

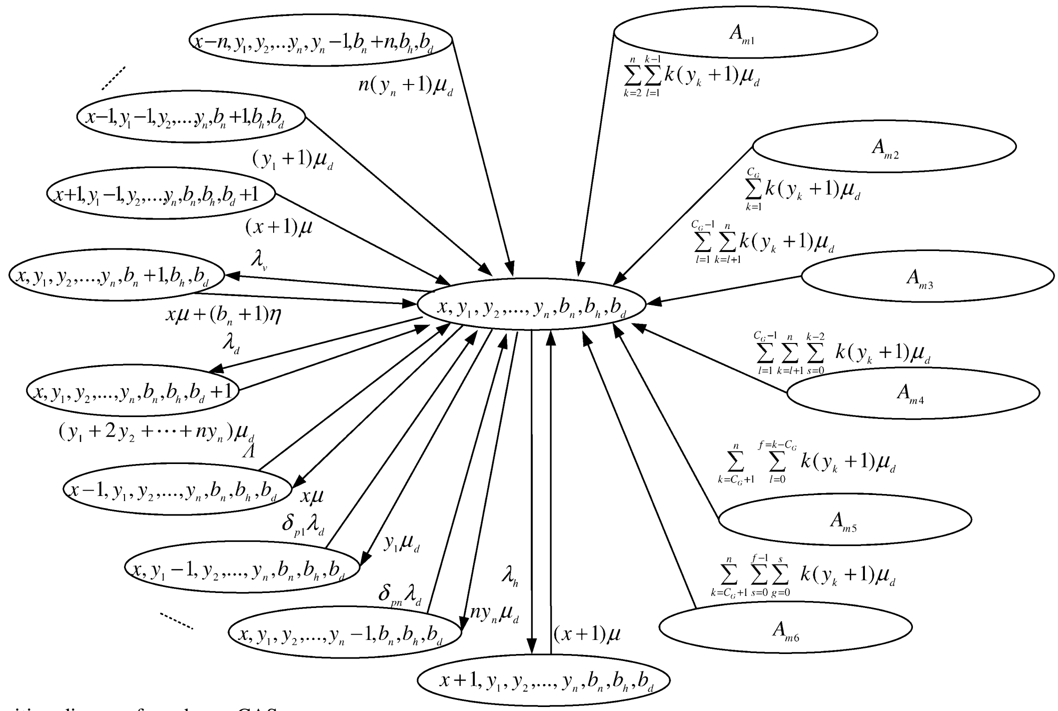


Fig. 7. State-transition diagram for scheme $\mathrm{CAS}_5$.

Finally, the data-packet-dropping probability $P_{dd}$ is shown as

$$P_{dd} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{12}} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{31}$$

where

$$G_{12} = \Bigg\{(x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x+\sum_{i=0}^{n} iy_i = C \\ 0\le x\le C, 0\le y_1\le C, 0\le y_2\le \left\lfloor \frac{C}{2}\right\rfloor,\ldots, \\ 0\le y_n\le \left\lfloor\frac{C}{n}\right\rfloor, 0\le b_n\le T_v, 0\le b_h\le B_v \\ b_d = B_d\Bigg\}.$$

## D. Analysis of Scheme $CAS_5$

At last, let us consider scheme $\mathrm{CAS}_5$ utilizing both priority and channel-reservation techniques. To analyze this scheme, state vectors for scheme $\mathrm{CAS}_3$ are used again. As for the state–space of this scheme, it is shown as

$$S_{\mathrm{CAS}_5} = \Bigg\{(x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid 0\le x+\sum_{i=0}^{n} iy_i \le C \\ 0\le x\le C, 0\le y_1\le C-C_G \\ 0\le y_2\le\left\lfloor\frac{C-C_G}{2}\right\rfloor,\ldots,0\le y_n\le\left\lfloor\frac{C-C_G}{n}\right\rfloor \\ 0\le b_n\le B_v, 0\le b_h\le B_v \\ 0\le b_d\le B_d\Bigg\}. \tag{32}$$

When deriving balance equations, three specific situations must be considered: $0 \le x+\sum_{i=0}^{n} iy_i < C-C_G$, $C-C_G \le x+\sum_{i=0}^{n} iy_i < C$, and $x+\sum_{i=0}^{n} iy_i = C$. We show balance equations for the second situation in Appendix III using the state-transition diagram in Fig. 7, but omit balance equations for the other two situations for compactness, since they can be derived in a similar manner as used by scheme $\mathrm{CAS}_3$. The blocking probability of a new voice call still requires the full and timeout blocking probabilities, but they must be calculated for two cases: $C-C_G \le x+\sum_{i=0}^{n} iy_i < C$ and $x+\sum_{i=0}^{n} iy_i = C$. As for the full blocking probability for the new voice call when $C-C_G\le x+\sum_{i=0}^{n} iy_i < C$, i.e., $P_{vbf1}$, and the full blocking probability for the new voice call when $x+\sum_{i=0}^{n} iy_i = C$, i.e., $P_{vbf2}$, they have the following forms:

$$P_{vbf1} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{13}} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{33}$$

$$P_{vbf2} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{13'}} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \tag{34}$$

where

$$G_{13} = \Bigg\{(x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid C-C_G\le x+\sum_{i=0}^{n} iy_i < \\ C, 0\le x\le C, 0\le y_1\le C-C_G, 0\le y_2\le \\ \left\lfloor\frac{C-C_G}{2}\right\rfloor,\ldots,0\le y_n\le\left\lfloor\frac{C-C_G}{n}\right\rfloor, b_n = B_v \\ b_h = 0 \\ 0\le b_d\le B_d\Bigg\}$$

$$G_{13'} = \Bigg\{(x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x+\sum_{i=0}^{n} iy_i = C \\ 0\le x\le C, 0\le y_1\le C-C_G, 0\le y_2\le \\ \left\lfloor\frac{C-C_G}{2}\right\rfloor,\ldots,0\le y_n\le\left\lfloor\frac{C-C_G}{n}\right\rfloor, 0\le b_n\le$$

$$B_v, 0 \le b_h \le B_v, b_n + b_h = B_v$$
$$\left. 0 \le b_d \le B_d \right\}.$$

The timeout probabilities for the new voice call corresponding to $P_{vbt1}$ and $P_{vbt2}$ can be expressed as

$$P_{vbt1} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{14}} b_n \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_v(1-P_{vbf1})} \quad (35)$$

$$P_{vbt2} = \frac{\sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{14'}} b_n \eta P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}}{\lambda_v(1-P_{vbf2})} \quad (36)$$

where

$$G_{14} = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid C - C_G \le x + \sum_{i=0}^{n} i y_i < C, 0 \le x \le C, 0 \le y_1 \le C - C_G, 0 \le y_2 \le \left\lfloor \frac{C-C_G}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C-C_G}{n} \right\rfloor, 0 \le b_n \le B_v, b_h = 0 \quad 0 \le b_d \le B_d \right\}$$

$$G_{14'} = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x + \sum_{i=0}^{n} i y_i = C \quad 0 \le x \le C, 0 \le y_1 \le C - C_G, 0 \le y_2 \le \left\lfloor \frac{C-C_G}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C-C_G}{n} \right\rfloor, 0 \le b_n \le B_v, 0 \le b_h \le B_v \quad 0 \le b_d \le B_d \right\}.$$

Therefore, the blocking probability of a new voice call is obtained as

$$P_{vb} = P_{vbf1} + (1-P_{vbf1})P_{vbt1} + P_{vbf2} + (1-P_{vbf2})P_{vbt2}. \quad (37)$$

The full and timeout blocking probabilities for the handoff voice call can be calculated using (22) and (24), respectively, with proper limitation on variables $y_i$ $(1 \le i \le n)$. Thus, the forced-termination probability of a handoff voice call can be obtained using (10). As for the data-packet-dropping probability, it can be expressed as

$$P_{dd} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{15}} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} + \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_{15'}} P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \quad (38)$$

where

$$G_{15} = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid C - C_G \le x + \sum_{i=0}^{n} i y_i < C, 0 \le x \le C, 0 \le y_1 \le C - C_G, 0 \le y_2 \le \left\lfloor \frac{C-C_G}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C-C_G}{n} \right\rfloor \quad 0 \le b_n \le B_v, b_h = 0 \quad b_d = B_d \right\}$$

$$G_{15'} = \left\{ (x,y_1,\ldots,y_n,b_n,b_h,b_d) \mid x + \sum_{i=0}^{n} i y_i = C \quad 0 \le x \le C, 0 \le y_1 \le C - C_G, 0 \le y_2 \le \left\lfloor \frac{C-C_G}{2} \right\rfloor, \ldots, 0 \le y_n \le \left\lfloor \frac{C-C_G}{n} \right\rfloor \quad 0 \le b_n \le B_v, 0 \le b_h \le B_v \quad b_d = B_d \right\}.$$

### E. Analysis of Delay Times

Now let us derive delay times for voice calls and data packets using Little's formula, which relates delay times to average queue lengths. From results in Sections III-A–III-D, we can easily obtain the average queue length for new voice calls $L_{nv}$, average queue length for handoff voice calls $L_{hv}$, and average queue length for data packets $L_d$ as

$$L_{nv} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_v} b_n P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \quad (39)$$

$$L_{hv} = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_v} b_h P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \quad (40)$$

$$L_d = \sum_{(x,y_1,\ldots,y_n,b_n,b_h,b_d)\in G_d} b_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \quad (41)$$

where $G_v = G_2$ for scheme $\mathrm{CAS}_2$, $G_5$ for scheme $\mathrm{CAS}_3$, $G_{10} \cup G_{11}$ for scheme $\mathrm{CAS}_4$, $G_{14} \cup G_{14'}$ for scheme $\mathrm{CAS}_5$ and $G_d = G_3$ for scheme $\mathrm{CAS}_2$, $G_6$ for scheme $\mathrm{CAS}_3$, $G_{12}$ for scheme $\mathrm{CAS}_4$, and $G_{15}$ for scheme $\mathrm{CAS}_5$. Thus, from (39)–(41) as well as Little's formula, the delay time for new voice calls $W_{nv}$, delay time for handoff voice calls $W_{hv}$, and delay time for data packets $W_d$ can be calculated using the relations

$$W_{nv} = \frac{L_{nv}}{\lambda_v(1-P_{vbf})} \quad (42)$$

$$W_{hv} = \frac{L_{hv}}{\lambda_h(1-P_{ftf})} \quad (43)$$

$$W_d = \frac{L_d}{\lambda_d(1-P_{dd})}. \quad (44)$$

## IV. Numerical Results and Discussions

Through numerical examples done by simulation and analysis, we examine the performance exhibited by different schemes under various parameters in this section. The performance metrics include blocking probability of a new voice call $P_{vb}$, forced-termination probability of a handoff voice call $P_{ft}$, data-packet-dropping probability $P_{dd}$, and delay times ($W_{nv}$ for new voice calls, $W_{hv}$ for handoff voice calls, and $W_d$ for data packets). Moreover, we propose another measure called cost function, to be defined later, to provide system designers on how to select a better CAS to satisfy users' quality-of-service (QoS) requirements. To distinguish between results obtained by simulation from analytical results, we use dots to indicate simulation results and lines to represent analytical results. Now let us begin by first describing the experimental arrangement in the following.

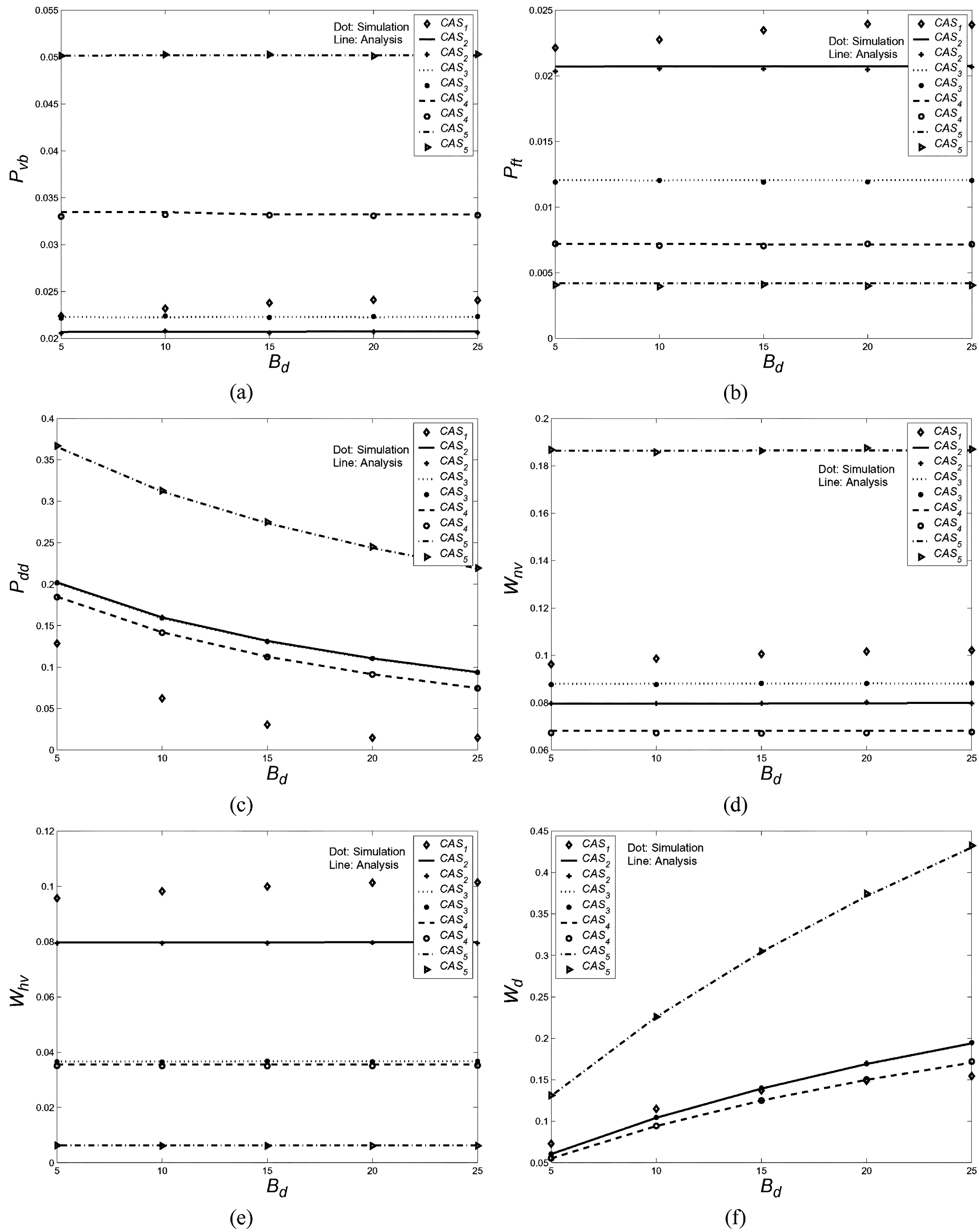


Fig. 8. Effect of data-packet buffering under $\lambda_v = 5\mu_v$, $\eta = 0.2\mu_v$, $T_v = 4$, and $C_G = 1$. (a) Blocking probability. (b) Forced-termination probability. (c) Data-packet-dropping probability. (d) Delays for new voice calls. (e) Delays for handoff voice calls. (f) Delays for data packets.

## A. Simulation Arrangement

The cellular system model simulated is $6 \times 6$ mesh homogeneous cells in which each user moves to any adjacent cell in a uniform manner, i.e., probabilities of a user moving to adjacent cells are equal. We assume that new voice calls and data requests arrive according to Poisson processes with rates $\lambda_v$ and $\lambda_d$, respectively, if there is no explicit redefinition. As for the new/handoff voice call-holding time, data-packet-transmission time, voice-user cell-dwelling time, and packet-dwelling time (the data users are assumed to be static in the analytical models for simplicity), they follow exponential distributions with means $1/\mu_v$, $1/\mu_d$, $1/\eta$, and $1/\eta_d$, respectively. If it is not explicitly

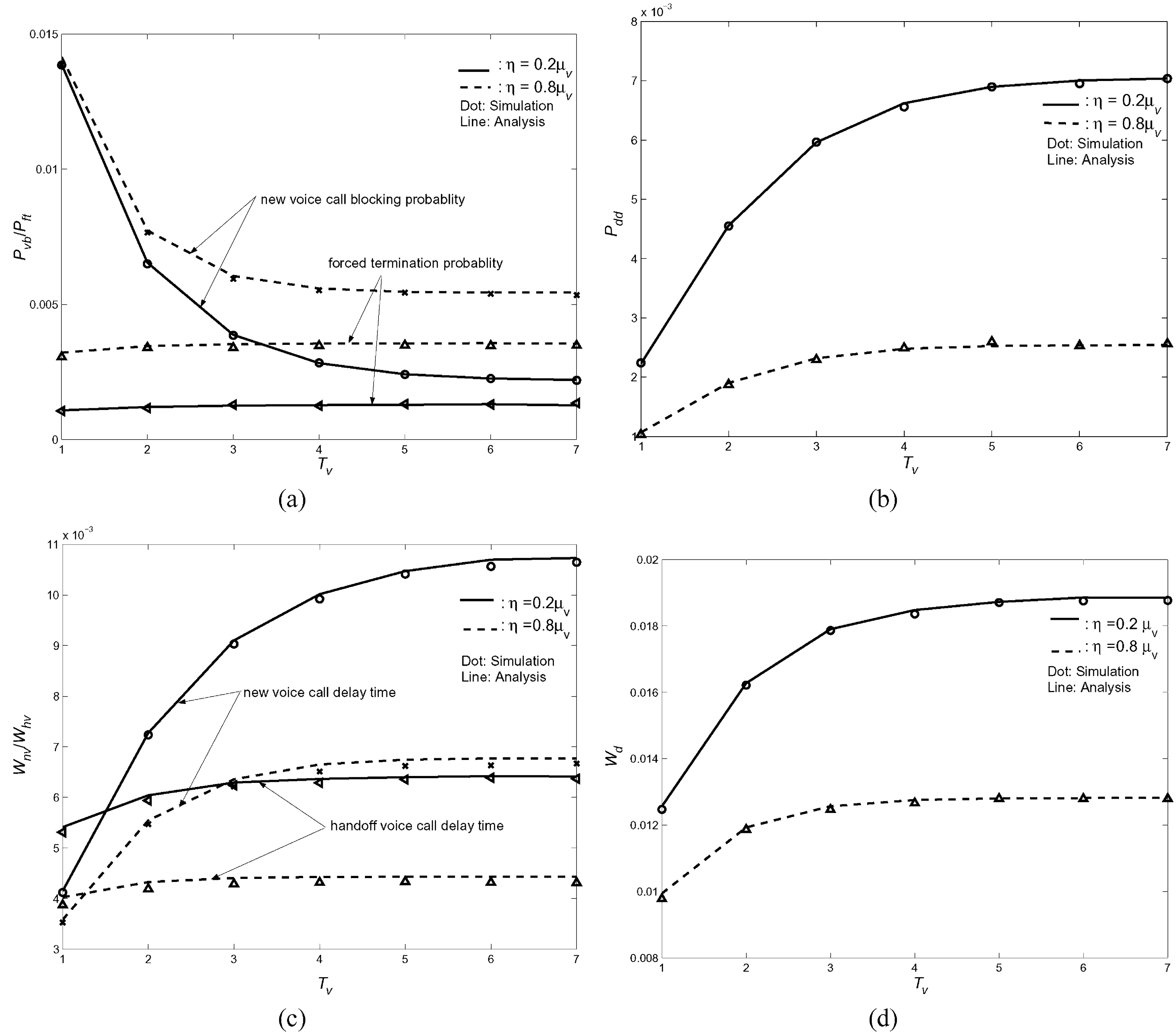


Fig. 9. Effect of threshold control on the voice buffer (for scheme $\text{CAS}_4$) under $\lambda_v = 3.2\mu_v$ and $B_d = 21$ with two mobility rates. (a) Blocking and forced-termination probabilities. (b) Data-packet-dropping probability. (c) Delays for voice calls. (d) Delays for data packets.

mentioned, the following parameters for each cell are used: number of available channels (slots) $C = 7$ (due to the fact that GSM/GPRS has eight time slots in which seven time slots are used for data transmission and one time slot is utilized for signaling), voice buffer size $B_v = 7$, maximum assignable number of channels for a data request $n = 3$, $\mu_v = 1$, $\mu_d = 100\mu_v$, and $\lambda_d = 25\mu_v$.

## *B. Performance and Discussions*

*1) Effects of Data Buffering:* Shown in Fig. 8(a) and (b) (under $\lambda_v = 5\mu_v$, $\eta = 0.2\mu_v$, $T_v = 4$, and $C_G = 1$) is the effect of data buffer size to the blocking probability of a new voice call and forced-termination probability of a handoff voice call. When the size of the data buffer increases, we note that all schemes except $\text{CAS}_1$ are insensitive, since the priority of the voice buffer is higher than that of the data buffer. Further comparing scheme $\text{CAS}_3$ with scheme $\text{CAS}_2$, using these two figures illustrates that scheme $\text{CAS}_3$ increases a bit (approximately 7.6%) on the blocking probability of a new voice call while it decreases greatly (about 41.8%) on the forced-termination probability of a handoff voice call than scheme $\text{CAS}_2$. Therefore, we propose other schemes, i.e., schemes $\text{CAS}_4$ and $\text{CAS}_5$, based on $\text{CAS}_3$ to seek a better scheme to satisfy users' QoS requirements. Fig. 8(c) demonstrates that the effect of data-buffer size to the data-packet-dropping probability. From this figure, the data-packet-dropping probability is clearly improved by a larger buffer. We note that: 1) scheme $\text{CAS}_1$ performs best on the data-packet-dropping probability, because data-packet requests are allowed to compete channel resource with voice calls, while it makes the blocking probability of a new voice call and forced-termination probability of a handoff voice call increase; 2) the results for schemes $\text{CAS}_2$ and $\text{CAS}_3$ are the same due

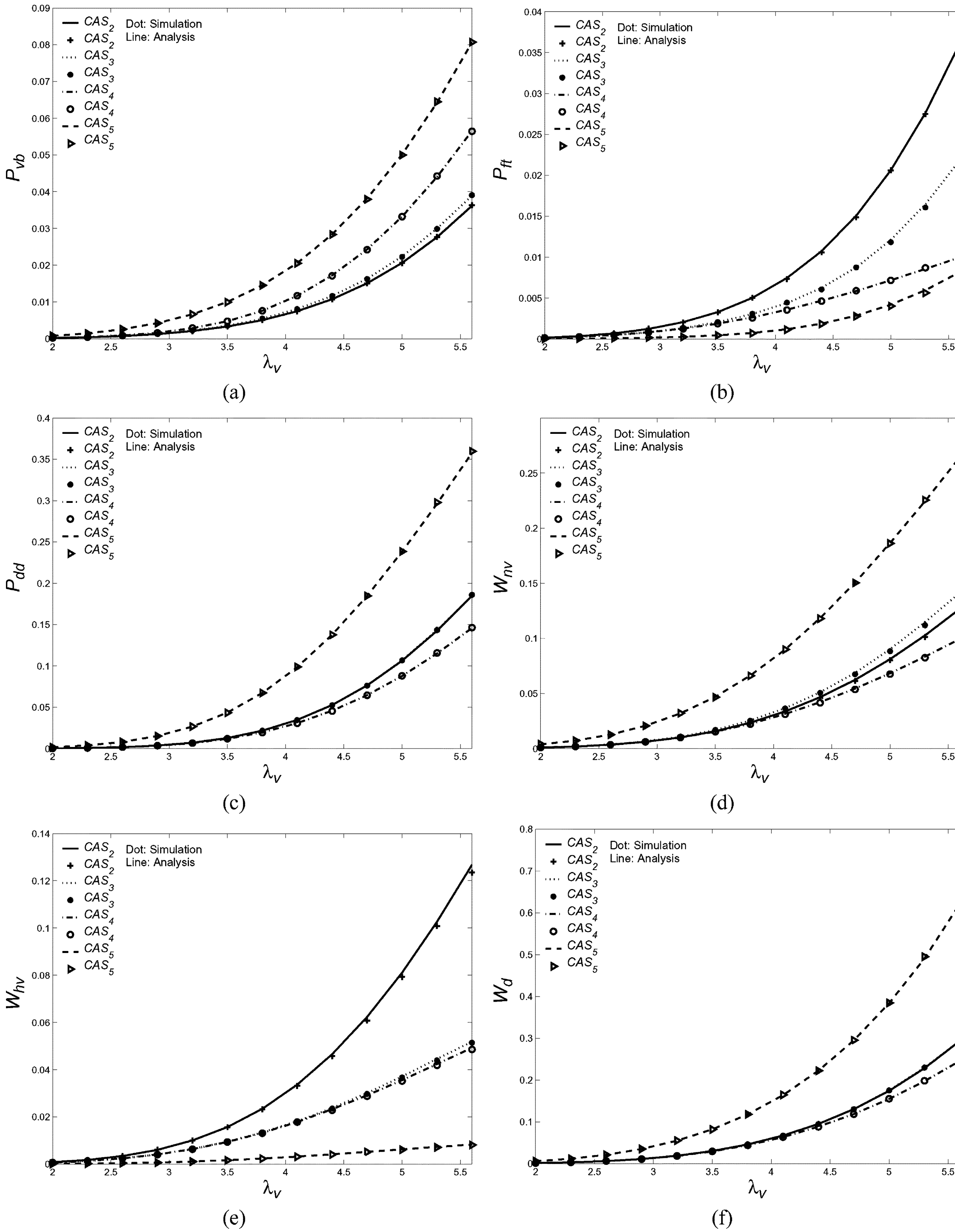


Fig. 10. Schemes comparison for various arrival rates of the new voice call under $\eta = 0.2\mu_v, T_v = 4, C_G = 1$, and $B_d = 21$. (a) Blocking probability. (b) Forced-termination probability. (c) Data-packet-dropping probability. (d) Delays for new voice calls. (e) Delays for handoff voice calls. (f) Delays for data packets.

to the fact that whether or not priority setting is activated for new and handoff voice calls does not affect data packets to get the system resource; 3) scheme $CAS_4$ can improve a bit data-packet-dropping probability than scheme $CAS_2$ (or $CAS_3$) since the rate of new voice calls is throttled (thus, they allow more data packets to enter the system); and 4) as for scheme $CAS_5$, channel reservation for the handoff voice call makes data packets have fewer chances of getting the system resource. As for the effect on delay times of new/handoff voice calls as well as data packets caused by data buffering, it is shown in Fig. 8(d)–(f). The trend shown by Fig. 8(d) and (e) is similar to that shown by Fig. 8(a) and (b). In Fig. 8(f), delay times under

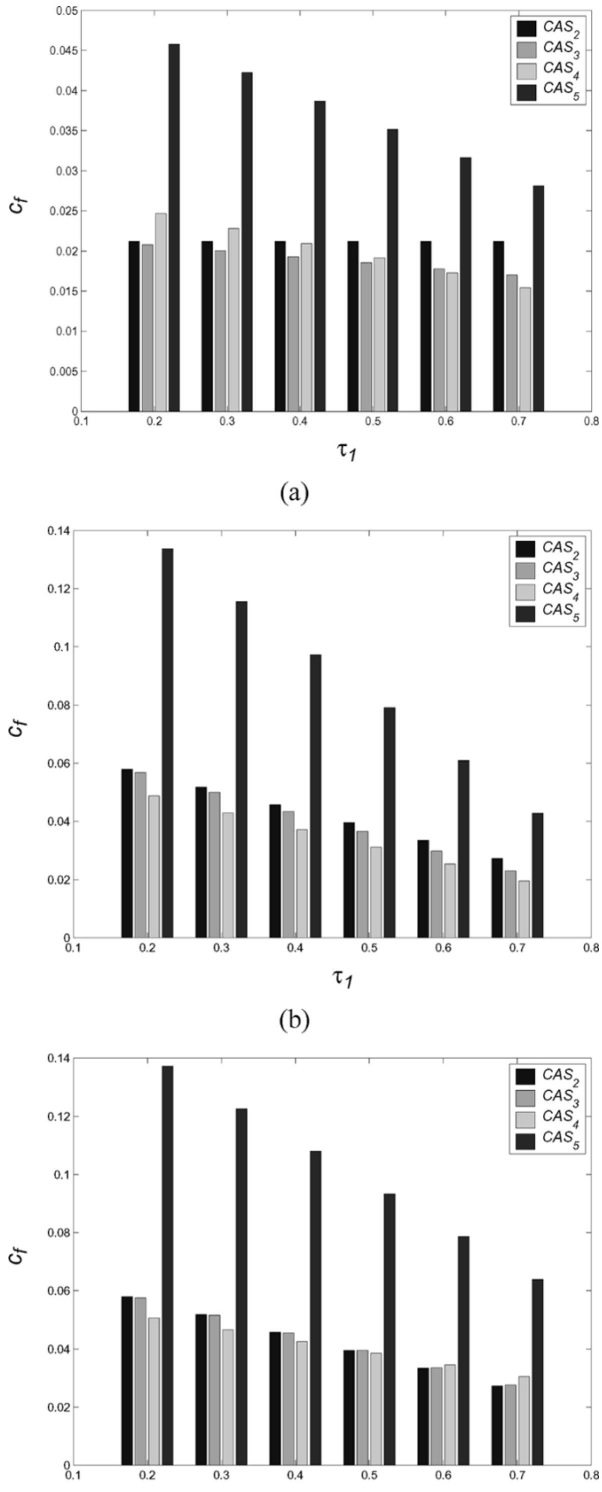


Fig. 11. Cost comparisons for various weighting factors under $\lambda_v = 5\mu_v$, $\eta = 0.2\mu_v$, $T_v = 4$, $C_G = 1$, and $B_d = 21$ with (a) $\tau_3 = 0.1$, (b) $\tau_2 = 0.1$, and (c) $\tau_1 = 0.1$.

different schemes for data packets rise when the data-buffer size increases with the worst one caused by scheme $\text{CAS}_5$. Based on the previous observations, we can reach the following conclusions.

TABLE I
FORCED-TERMINATION PROBABILITY $P_{ft}$ VERSUS THRESHOLD VALUE $T_v$ WITH TWO MOBILITY RATES $\eta = 0.2\mu_v$ AND $\eta = 0.8\mu_v$ UNDER $\lambda_v = 3.2\mu_v$ AND $B_d = 21$

| $T_v$ | $P_{ft}(\eta = 0.2\mu_v)$ | $P_{ft}(\eta = 0.8\mu_v)$ |
|---|---|---|
| 1 | 0.001079 | 0.003212 |
| 2 | 0.001206 | 0.003458 |
| 3 | 0.001254 | 0.003525 |
| 4 | 0.001274 | 0.003549 |
| 5 | 0.001288 | 0.003559 |
| 6 | 0.001309 | 0.003564 |
| 7 | 0.001337 | 0.003566 |

1) Although a larger data buffer improves the data-packet-dropping probability, it makes the delay time of data requests increase accordingly; thus, it is a tradeoff.
2) QoS of voice service is not affected, except for scheme $\text{CAS}_1$, by the increase of the data-buffer size due to the fact that a higher priority for voice service than that of data service is set.
3) Taking the improvement of both forced-termination and data-dropping probabilities as well as delays into account, scheme $\text{CAS}_4$ seems to be a better choice with the raised blocking probability of a new voice call, despite the best performance on the forced-termination probability of a handoff voice call that is exhibited by scheme $\text{CAS}_5$, which causes poor performance on other performance metrics.

*2) Effect of Threshold Control:* The objective of threshold control is to limit the number of new voice-call requests in the voice buffer, thus giving more buffer space to handoff voice calls. Setting $\lambda_v = 3.2\mu_v$ and $B_d = 21$, we see that threshold control affects little to new and handoff voice calls when $T_v > 4$ for both low ($\eta = 0.2\mu_v$) and high ($\eta = 0.8\mu_v$) mobility rates in Fig. 9(a). However, the blocking probability of a new voice call increases and the forced-termination probability of a handoff call decreases when $T_v$ decreases (see Table I for details on the forced-termination probability) starting from $T_v = 4$ due to less voice buffer space for new voice-call requests. We also note from this figure that both blocking and forced-termination probabilities are raised when the mobility rate is high under a fixed value of the new voice-call arrival rate $\lambda_v$, because more handoff voice calls are generated. Shown in Fig. 9(b) is the effect on the data-packet-dropping probability by threshold value $T_v$. The data-packet-dropping probability decreases as $T_v$ goes down, because data-packet requests also benefit due to the decrease of new voice-call requests. This phenomenon is magnified when the mobility rate is low, since data packets then share more benefit due to fewer handoff calls. From this figure, we also observed that a higher mobility rate causes the channel-occupancy time to be shorter than a lower mobility rate, i.e., the service/handoff rate is higher for voice-call requests; hence, data packets incur lower dropping probabilities when the mobility rate is high, as shown in Fig. 9(b). Based on the same reasoning, one can easily understand the phenomena exhibited by Fig. 9(d) for the delay time of data packets. Since the service/handoff rate is higher for a larger mobility rate, thus delay times for new and handoff voice calls with $\eta = 0.8\mu_v$ are smaller than those with $\eta = 0.2\mu_v$, as shown in Fig. 9(c). When $T_v$ increases (i.e., more

TABLE II
EFFECTS OF THE PARETO DISTRIBUTION TO MODEL PACKET INTERARRIVAL TIME AND SERVICE TIME FOR SCHEME $CAS_3$ WITH TWO PACKET-ARRIVAL RATES $\lambda_p = 10\mu_v$ AND $\lambda_p = 25\mu_v$ UNDER $\lambda_v = 4\mu_v$, $\mu_p = 100\mu_v$, $\eta = 0.2\mu_v$, $n = 3$, $\alpha = 1.2$, AND $B_d = 21$

| | (Arrival, Service) | $P_{vb}$ | $P_{ft}$ | $P_d$ | $W_n$ | $W_h$ | $W_d$ |
|---|---|---|---|---|---|---|---|
| $\lambda_p = 10\mu_v$ | 1. (exp., exp.) | 0.007053 | 0.003838 | 0.006432 | 0.031947 | 0.016213 | 0.070848 |
| | 2. (Pareto, exp.) | 0.007032 | 0.003866 | 0.017476 | 0.031929 | 0.016124 | 0.065955 |
| | 3. (exp., Pareto) | 0.007517 | 0.004105 | 0.006911 | 0.033873 | 0.016808 | 0.067820 |
| $\lambda_p = 25\mu_v$ | 1. (exp., exp.) | 0.007064 | 0.003882 | 0.029593 | 0.032324 | 0.016331 | 0.059324 |
| | 2. (Pareto, exp.) | 0.007052 | 0.003834 | 0.047849 | 0.032284 | 0.016430 | 0.051551 |
| | 3. (exp., Pareto) | 0.008288 | 0.004581 | 0.031291 | 0.036861 | 0.018233 | 0.056300 |

new voice rate or more total rate of voice calls is admitted), delay times for both new and handoff voice calls increase, too. One point that deserves mention is that there is a crossing for delays times of new and handoff voice calls when $T_v$ increases from 1 to 2. This can be explained as follows. Since the new voice rate admitted is far less than the handoff voice rate when $T_v = 1$, the delay time for new voice calls is smaller than that for handoff voice calls. However, the situation changes dramatically when $T_v = 2$. The delay time for new voice calls is raised quickly due to much more admitted new voice rate. Based on these observations, we know that threshold control improves the forced-termination probability of a handoff voice call and data-packet-dropping probability with degradation of the blocking probability of a new voice call. It also improves delay times for voice calls and data packets. From the viewpoint of users, the forced-termination probability of a handoff call should be kept smaller than the blocking probability of a new voice call, since the abrupt termination for an ongoing call makes one feel uncomfortable. Thus, the technique of threshold control may be a good method to achieve this goal.

*3) Performance Comparison for Different Schemes:* Fig. 10 shows the performance comparison for schemes $CAS_2$–$CAS_5$ under $\eta = 0.2\mu_v$, $T_v = 4$, $C_G = 1$, and $B_d = 21$ with various arrival rates of the new voice call $\lambda_v$ and the omission of scheme $CAS_1$, which serves as a reference scheme only. It is clear that the blocking probability of a new voice call, forced-termination probability of a handoff call, data-packet-dropping probability, and delay times increase as the arrival rate of the new voice call goes up, as shown in Fig. 10. Since scheme $CAS_3$ is based on scheme $CAS_2$ with the activation of service priorities between new voice calls and handoff voice calls, scheme $CAS_4$ modifies scheme $CAS_3$ by employing threshold control and scheme $CAS_5$ is a modified scheme of $CAS_3$ with a portion of channels reserved for handoff voice calls; thus, we can easily conclude that, from the best to the worst, schemes on the blocking probability of a new voice call are $CAS_2$, $CAS_3$, $CAS_4$, and $CAS_5$, as shown in Fig. 10(a), while the result is revere for the forced-termination probability of a handoff voice call, as shown in Fig. 10(b). Because the priority for the voice queue is higher than that of the data queue, the data-packet-dropping probability is the same for schemes $CAS_2$ and $CAS_3$ even if the service priorities are activated for new and handoff voice calls. As aforementioned, data packets benefit from threshold control of $CAS_4$ while they have fewer available channels in scheme $CAS_5$, since scheme $CAS_5$ reserves some channels for handoff voice calls. Thus, the resultant data-packet-dropping probabilities for different schemes from the smallest to the largest are $CAS_4$, $CAS_2$ (and $CAS_3$), $CAS_5$, as shown in Fig. 10(c). Comparison of delay times is shown in Fig. 10(d)–(f). We observe that delay times for handoff voice calls and delay times for data packets performed by different schemes are similar to the trend of the forced-termination probability of a handoff voice call and the trend of the data-packet-dropping probability, respectively. However, for delay times of new voice calls, the trend of different schemes is similar to that of the blocking probability of a new voice call, except that scheme $CAS_4$ rather than scheme $CAS_2$ incurs the smallest delay, since the arrival rate of new voice calls is throttled. From Fig. 10, we can show that: 1) although scheme $CAS_5$ makes the smallest forced-termination probability and delay time for the handoff voice call, it performs worst otherwise and 2) besides scheme $CAS_5$, scheme $CAS_4$ performs best in all respects except for the degradation of the new voice-call-blocking probability. From the above discussions, we suggest that scheme $CAS_4$ is used in the GPRS system.

TABLE III
PERFORMANCE OF TWO DATA CLASSES (TYPE I: $n = 4$, $\lambda_p = 150\mu_v$ AND TYPE II: $n = 2$, $\lambda_p = 30\mu_v$) FOR SCHEME $CAS_3$ UNDER $\lambda_v = 4\mu_v$, $\eta = 0.2\mu_v$, $\mu_p = 100\mu_v$, $B_d = 21$

| Data class | $P_d$ | $W_d$ | $n_a$ |
|---|---|---|---|
| Type I | 0.145373 | 0.036776 | 2.539512 |
| Type II | 0.145393 | 0.036772 | 1.695892 |

*4) Effects of Different Traffic Models and Multiple Data Classes:* We also arrange numerical experiments here to have insights into effects of traffic models and data classes. In the past, exponential (exp.) distributions are frequently employed to model interarrival times of calls for its simplicity, but exponential distributions may not be appropriate in modeling data traffic. Instead, the Pareto distribution, which is one of popular heavy-tailed distributions in the literature, can be used to close capture the nature of data traffic [5], [17]. The probability density function of Pareto has the form

$$f(t) = \frac{\alpha\beta^{\alpha}}{t^{\alpha+1}}, t > \alpha$$

with mean $\alpha\beta/(\alpha - 1)$, where $\alpha > 0$ is called the shape parameter and $\beta > 0$ is called the scale parameter. Using Pareto or exponential to model packet interarrival or service times, we obtain performance for scheme $CAS_3$, shown in Table II. Obviously, using Pareto to model data traffic results in a larger packet-dropping probability but smaller data delay time (since less data rate is admitted) without changing performance of voice calls. If the data service time is modeled by Pareto, performance of both voice calls and data packets is affected. Next, let us consider multiple data classes in the system, such as electronic mail (e-mail), web browsing etc., with different QoS requirements. Shown in Table III is performance of two data

TABLE IV
EFFECT WHEN DATA-USER MOBILITY IS INCORPORATED INTO SCHEME $CAS_3$ UNDER $\lambda_v = 3.2\mu_v, \lambda_p = 25\mu_v, \mu_p = 100\mu_v, \eta = 0.2\mu_v, n = 3$, AND $B_d = 21$

| $\eta_d$ | $P_{vb}$ | $P_{ft}$ | $P_d$ | $W_n$ | $W_h$ | $W_d$ |
|---|---|---|---|---|---|---|
| 0 | 0.002194 | 0.001326 | 0.007106 | 0.010784 | 0.006425 | 0.018910 |
| $0.01\mu_v$ | 0.002202 | 0.001371 | 0.007177 | 0.010698 | 0.006325 | 0.018731 |
| $0.5\mu_v$ | 0.002212 | 0.001354 | 0.012471 | 0.010723 | 0.006370 | 0.015887 |

TABLE V
EFFECT AND ILLUSTRATION OF COMPUTATION FEASIBILITY FOR CHANNEL RESERVATION UNDER $\lambda_v = 3.2\mu_v$, $\lambda_p = 25\mu_v$, $\mu_p = 100\mu_v$, $\eta = 0.2\mu_v$, $n = 3$, AND $B_d = 21$

| | | $P_{vb}$ | $P_{ft}$ | $P_d$ | $W_n$ | $W_h$ | $W_d$ |
|---|---|---|---|---|---|---|---|
| $C_G = 1$ | analysis | 0.006631 | 0.000269 | 0.026626 | 0.031933 | 0.001103 | 0.055027 |
| | simulation | 0.006642 | 0.000259 | 0.026641 | 0.032061 | 0.001082 | 0.055120 |
| | error (% ) | 0.16 | 3.72 | 0.06 | 0.40 | 1.90 | 0.17 |
| $C_G = 2$ | analysis | 0.019845 | 0.000071 | 0.091633 | 0.092427 | 0.000188 | 0.153873 |
| | simulation | 0.019743 | 0.000073 | 0.091278 | 0.091895 | 0.000184 | 0.153575 |
| | error (% ) | 0.51 | 1.91 | 0.39 | 0.58 | 2.49 | 0.19 |

classes, i.e., Type I: $n = 4$, $\lambda_p = 150\mu_v$ and Type II: $n = 2$, $\lambda_p = 30\mu_v$ in scheme $CAS_3$. Due to the higher priority of voice calls over data packets, blocking and forced-termination probabilities of new and handoff voice calls are not affected if the total data rate is kept the same. These results are then omitted in this table. Since no further priority is set between these two data classes, dropping probabilities and delay times of these two data classes are comparable but $n_a$, which is the average number of channels used by a data packet, for Type I data is larger than $n_a$ of Type II data, since the rate of Type I data is larger than that of Type II data. Of course, extra mechanisms can be used to differentiate QoS received by different data classes. But this issue is out of the scope of this paper.

*5) Effect of Data-User Mobility and Computation Illustration on Channel Reservation:* Let us now investigate the effect of data-user mobility. Varying $\eta_d$ among $0, 0.01\mu_v$ and $0.5\mu_v$, we get performance of the system using scheme $CAS_3$, listed in Table IV. We observed that the performance of voice calls is not sensitive to the variation of $\eta_d$, because voice calls have higher precedence over data packets. However, data-packet-dropping probabilities (delay times) increase (decrease) as $\eta_d$ increases, i.e., residence time decreases. As for Table V, it shows performance measures for scheme $CAS_5$ under $C_G = 1$ and $C_G = 2$ to illustrate the feasibility of computation for different values of $C_G$. This table demonstrates that simulation and analytical results match well.

### C. Cost Comparisons Among Different Schemes

In this paper, we introduce a metric called cost function $c_f$, defined by

$$c_f = \tau_1 P_{ft} + \tau_2 P_{vb} + \tau_3 P_{dd} \tag{45}$$

where $\tau_1$, $\tau_2$, and $\tau_3$ are weighting factors ($\tau_1+\tau_2+\tau_3 = 1$) that can be treated as indexes regarding the importance of different QoSs and fall within [0, 1]. According to the cost function, a scheme with a lower cost then performs better. In Fig. 11, we show costs for different schemes under $\lambda_v = 5\mu_v$, $\eta = 0.2\mu_v$ (lower mobility rate), $T_v = 4$, $C_G = 1$, $B_d = 21$, and three different situations: 1) fixed $\tau_3$ $(= 0.1)$ and various $\tau_1$ and $\tau_2$; 2) fixed $\tau_2$ $(= 0.1)$ and various $\tau_1$ and $\tau_3$; and 3) fixed $\tau_1$ $(= 0.1)$ and various $\tau_2$ and $\tau_3$. Since similar results for higher mobility rate, say $\eta = 0.8\mu_v$, have been observed, but are omitted here for brevity. Keeping the importance of data packets low ($\tau_3 = 0.1$), we notice that scheme $CAS_3$ performs best when $\tau_1$ is not greater than 0.5; otherwise, scheme $CAS_4$ performs best from Fig. 11(a). If cost functions are dominated by the forced-termination probability of handoff voice calls and data-packet-dropping probability ($\tau_2 = 0.1$), scheme $CAS_4$ has the lowest cost regardless of $\tau_1$ and $\tau_3$, as shown in Fig. 11(b). When $\tau_2$ falls within [0.2, 0.5] and $\tau_1 = 0.1$, scheme $CAS_4$ performs best; otherwise, scheme $CAS_2$ performs best, as shown in Fig. 11(c) (because scheme $CAS_2$ takes good care of the data-packet-dropping probability than other schemes). Therefore, one can easily find which scheme (here it is scheme $CAS_4$ or scheme $CAS_3$) performs best using the cost function during the design stage.

## V. CONCLUSION

Through proposing and analyzing four new CASs using priority, buffering, threshold control, and channel-reservation techniques for the GPRS system, we examine and compare the performance of different schemes accompanying with a cost function to facilitate system designers to select the best scheme. The observations from numerical examples enable us to conclude the following.

1) Buffering for both voice calls and data packets reduces blocking probability, forced-termination probability, and dropping probability, but increases delay times. Thus, one should set a smaller buffer for delay-sensitive voice calls and a larger buffer for nondelay-sensitive data packets.
2) Although channel reservation greatly improves the forced-termination probability and delay time of a handoff voice call, it degrades much the performance of new voice calls and data packets, too.
3) Threshold control on the voice buffer can effectively differentiate the blocking and forced-termination probabilities. Moreover, it improves the performance for both handoff voice calls and data packets.
4) Finally, we suggest schemes $CAS_3$ and $CAS_4$, which employ techniques of priorities over buffers, service priority buffering for both voice calls as well as data packets, and threshold control on the voice buffer to be used in the GPRS system through the comprehensive performance comparison and the cost function.

## APPENDIX I
## ITERATIVE CALCULATION FOR STATE PROBABILITIES

We must know state probabilities before calculating the blocking probability of a new voice call, forced-termination probability of a handoff voice call, and data-packet-dropping probability. Thus, an iterative procedure for calculating state probabilities employing balance equations is shown as follows.

Step 1) Initially, set $\lambda_h = \lambda_h^{\mathrm{Ini}}$ and other system parameters, where $\lambda_h^{\mathrm{Ini}}$ is a preselected initial value.

Step 2) First, obtain $P_{x,y_1,\ldots,y_n,b_v,b_d}$ (or $P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}$) using corresponding balance equations by setting $P_{0,0,\ldots,0,0,0} = 1$. Then, normalize $P_{x,y_1,\ldots,y_n,b_v,b_d}$ (or $P_{x,y_1,\ldots,y_n,b_n,b_h,b_d}$) to have the total probability of 1.

Step 3) Compute $P_{vb}$ and $P_{ft}$ using proper equations.

Step 4) Compute $\lambda_h^{\mathrm{new}}$ using (1). If $|\lambda_h^{\mathrm{new}} - \lambda_h| > \varepsilon$ (a predefined stoppage parameter, say, $\varepsilon = 10^{-8}$), then go to Step 2 with $\lambda_h = \lambda_h^{\mathrm{new}}$; otherwise, go to Step 5.

Step 5) Output state probabilities (for calculation of $P_{vb}$, $P_{ft}$, and $P_{dd}$, etc.).

## APPENDIX II
## BALANCE EQUATION OF SCHEME CAS$_4$

The following equation given is under the condition of $x + \sum_{i=1}^{n} iy_i = C$, $b_n = T_v$, $1 < b_h \leq B_v$, $1 < b_d \leq B_d$ (see Fig. 6): see (46) at the bottom of the page.

## APPENDIX III
## BALANCE EQUATIONS OF SCHEME CAS$_5$

The state-transition diagram for scheme CAS$_5$ when $x + \sum_{i=0}^{n} iy_i = C - C_G$ is shown in Fig. 7. Further splitting $x + \sum_{i=0}^{n} iy_i = C - C_G$ into three different cases, we have balance equations shown as follows with the aid of superscripts $^{[C-C_G]}$ and $^{[C-C_G+l]}$, etc., used to explicitly denote the number of occupied channels at that state. Note that the function $\delta_{pj}$ for this scheme should be slightly changed by replacing $C$ in (3) with $C - C_G$, since $C_G$ channels are reserved for handoff voice calls.

*Case 1: When* $x + \sum_{i=1}^{n} iy_i = C - C_G$, $b_n = 0$, $b_h = 0$, $b_d = 0$:

$$\left(x\mu + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) P^{[C-G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d} = \Lambda P_{x-1,y_1,\ldots,y_n,b_n,b_h,b_d} + A_m \sum_{i=1}^{n} \delta_{pi}\lambda_d P_{x,y_1-\delta_1\delta_i,\ldots,y_i-\delta_i\delta_i,\ldots,y_n-\delta_n\delta_i,b_n,b_h,b_d} \quad (47)$$

where

$$\begin{aligned} A_m = &\sum_{i=1}^{n} i(y_i+1)\mu_d \\ &\times P^{[C-C_G]}_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n+i,b_h,b_d} \\ &+ [x\mu + (b_n+1)]P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} \\ &+ (x+1)\mu P^{[C-G]}_{x+1,y_1-1,\ldots,y_n,b_n,b_h,b_d+1} \\ &+ (x+1)\mu P_{x+1,y_1,\ldots,y_n,b_n,b_h,b_d} \\ &+ \sum_{i=1}^{n} iy_i\mu_d P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d+1} \\ &+ \sum_{k=2}^{n}\sum_{l=1}^{k-1} k(y_k+1)\mu_d A_{m1} + \sum_{k=1}^{C_G} k(y_k+1)\mu_d A_{m2} \\ &+ \sum_{l=1}^{C_G-1}\sum_{k=l+1}^{n} k(y_k+1)\mu_d\left[A_{m3} + \sum_{s=0}^{k-2} A_{m4}\right] \\ &+ \sum_{k=C_G+1}^{n} k(y_k+1)\mu_d\left[\sum_{l=0}^{f=k-C_G} A_{m5} + \sum_{s=0}^{f-1}\sum_{g=0}^{s} A_{m6}\right] \end{aligned}$$

and shown in the equation at the top of the next page.

*Case 2: When* $x + \sum_{i=1}^{n} iy_i = C - C_G$, $b_n = 0$, $b_h = 0$, $1 \leq b_d \leq B_d$:

$$\left(x\mu + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d} = \lambda_d P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} + A_m. \quad (48)$$

*Case 3: When* $x + \sum_{i=1}^{n} iy_i = C - C_G$, $1 \leq b_n \leq B_v$, $b_h = 0$, $1 \leq b_d \leq B_d$:

$$\begin{aligned} &\left(x\mu + b_n\eta + \Lambda + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\ &= \lambda_v P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n-1,b_h,b_d} + \lambda_d P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} \\ &\quad + [x\mu + (b_n+1)]P^{[C-C_G]}_{x,y_1,\ldots,y_n,b_n+1,b_h,b_d} \\ &\quad + \sum_{k=1}^{C_G} k(y_k+1)\mu_d A_{m1} + (x+1)\mu P_{x+1,y_1,\ldots,y_n,b_n,b_h,b_d} \\ &\quad + \sum_{l=1}^{C_G-1}\sum_{k=l+1}^{n} k(y_k+1)\mu_d A_{m3} \\ &\quad + \sum_{k=C_G+1}^{n}\sum_{l=0}^{f=k-C_G} k(y_k+1)\mu_d A_{m5} \\ &\quad + \sum_{i=1}^{n} i(y_i+1)\mu_d \\ &\quad \times P^{[C-C_G]}_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n+i,b_h,b_d}. \end{aligned} \quad (49)$$

$$\begin{aligned} &\left(x\mu + b_h\eta + b_n\eta + \lambda_h + \sum_{i=1}^{n} iy_i\mu_d + \lambda_d\right) P_{x,y_1,\ldots,y_n,b_n,b_h,b_d} \\ &= \lambda_v P_{x,y_1,\ldots,y_n,b_n-1,b_h,b_d} + \lambda_h P_{x,y_1,\ldots,y_n,b_n,b_h-1,b_d} + [x\mu + (b_h+1)\eta]P_{x,y_1,\ldots,y_n,b_n,b_h+1,b_d} \\ &\quad + \lambda_d P_{x,y_1,\ldots,y_n,b_n,b_h,b_d-1} + \sum_{i=1}^{n} i(y_i+1)\mu_d P_{x-i,y_1+\delta_1\delta_i,\ldots,y_i+\delta_i\delta_i,\ldots,y_n+\delta_n\delta_i,b_n,b_h+i,b_d}. \end{aligned} \quad (46)$$

$$A_{m1} = P^{[C-C_G]}_{x-l,y_1-\delta_1\delta_{k-l},\ldots,y_{k-l}-\delta_{k-l}\delta_{k-l},y_{k-l+1},\ldots,y_{k-1},y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+l,b_h,b_d+1}$$
$$A_{m2} = P^{[C-C_G+k]}_{x,y_1+\delta_1\delta_k,\ldots,y_n+\delta_n\delta_k,b_n,b_h,b_d}$$
$$A_{m3} = P^{[C-C_G+l]}_{x-k-1,y_1+\delta_1\delta_k,\ldots,y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k,b_n+k-1,b_h,b_d} \ (C_G > 1)$$
$$A_{m4} = P^{[C-C_G+l]}_{x-s,y_1-\delta_i\delta_{k-1-s},\ldots,y_{k-1}-\delta_{k-1}\delta_{k-1-s},y_k+\delta_k\delta_k+\cdots+y_n+\delta_n\delta_k,b_n+s,b_h.b_d+1} \ (C_G > 1)$$
$$A_{m5} = P^{[C]}_{x-f,y_1-\delta_1\delta_k,\ldots,y_n-\delta_n\delta_k,b_n+l,b_h+f-l,b_d}$$
$$A_{m6} = P^{[C]}_{x-s,y_1-\delta_1\delta_{f-s},\ldots,y_{k-1}-\delta_{k-1}\delta_{f-s}+y_k+\delta_k\delta_k,\ldots,y_n+\delta_n\delta_k+b_n+g,b_h+s-g,b_d+1}.$$

As for the other situation, i.e., $C_G < x + \sum_{i=0}^{n} iy_i < C$, it can be obtained in an analogous manner. For the sake of compactness, we leave this part to readers.

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## References

[1] K. Balachandran, R. Ejzak, S. Nanda, S. Vitebskiy, and S. Seth, "GPRS-136: High-rate packet data service for North American TDMA digital cellular systems," *IEEE Pers. Commun.*, vol. 6, no. 3, pp. 34–47, Jun. 1999.

[2] G. Brasche and B. Walke, "Concept, service, and protocols of the new GSM phase2+ general packet racket radio service," *IEEE Commun. Mag.*, vol. 35, no. 10, pp. 94–104, Oct. 1997.

[3] J. Cai and D. J. Goodman, "General packet radio service in GSM," *IEEE Commun. Mag.*, vol. 35, no. 8, pp. 122–131, Aug. 1997.

[4] W. Y. Chen, J. L. C. Wu, and L. L. Lu, "Performance comparisons of dynamic resource allocation with/without channel de-allocation in GSM/GPRS networks," *IEEE Commun. Lett.*, vol. 7, no. 1, pp. 10–12, Jan. 2003.

[5] M. Cheng and L. F. Chang, "Wireless dynamic channel assignment performance under packet data traffic," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 7, pp. 1257–1269, Jul. 1999.

[6] E. Dahlman, B. Gudmundson, M. Nilsson, and J. Skold, "UMTS/IMT-2000 based on wide-band CDMA," *IEEE Commun. Mag.*, vol. 36, no. 9, pp. 70–80, Sep. 1998.

[7] J. Eberspacher, H. J. Vogel, and C. Bettstetter, *GSM – Switching, Services, and Protocols*. New York: Wiley, 2001.

[8] M. Ermel, T. Müller, J. Schüler, M. Schweigel, and K. Begain, "Performance of GSM networks with general packet radio services," *Perform. Eval.*, vol. 48, no. 1–4, pp. 285–310, May 2002.

[9] "Digital cellular telecommunications system (Phase 2+): High speed circuit switched data (HSCSD); Stage 2 (GSM 03.34 ver. 7.0.0 Release 1998)," ETSI, ETSI/TC, Tech. Rep. Rec. GSM 03.34, 1999.

[10] "Digital cellular telecommunications system (Phase 2+): General packet radio service (GPRS); Service description; Stage 2 (3GPP TS 03.60 ver. 7.7.0 Release 1998)," ETSI, ETSI/TC, Tech. Rep. Rec. 3GPP 03.60, 2002.

[11] "Digital cellular telecommunications system (Phase 2+): Technical realization of short message service (SMS) (3GPP TS 23.040 ver. 5.5.1 Release 5)," ETSI, ETSI/TC, Tech. Rep. Rec. 3GPP 23.040, 2002.

[12] "Digital cellular telecommunications system (Phase 2+): General packet radio service (GPRS); Overall description of the GPRS radio interface; Stage 2 (GSM 03.64 ver. 7.0.0 Release 1999)," ETSI, ETSI/TC, Tech. Rep. Rec. GSM 03.64, 1999.

[13] Y. Fang, I. Chlamtac, and Y. B. Lin, "Channel occupancy times and handoff rate for mobile computing and PCS networks," *IEEE Trans. Comput.*, vol. 47, no. 6, pp. 679–692, Jun. 1998.

[14] Y. Hwang, Y. Han, and Y. Kim, "Performance analysis of mixed voice/data service in a microcell-based PCS network," *IEICE Trans. Fundamentals*, vol. E81-A, no. 6, pp. 1136–1144, 1998.

[15] H. Kaaranen, A. Ahtiainen, L. Laitinen, S. Naghian, and V. Niemi, *UMTS Networks: Architecture, Mobility, and Services*. New York: Wiley, 2001.

[16] P. Lin and Y. B. Lin, "Channel allocation for GPRS," *IEEE Trans. Veh. Technol.*, vol. 50, no. 2, pp. 375–387, Mar. 2001.

[17] P. Lin, "Channel allocation for GPRS with buffering mechanisms," *Wireless Networks*, pp. 431–441, 2003.

[18] C. Lindemann and A. Thümmler, "Performance analysis of general packet radio service," *Comp. Networks*, vol. 41, no. 1, pp. 1–17, 2003.

[19] K. Mitchell and K. Sohraby, "An analysis of the effects of mobility on bandwidth allocation strategies in multi-class cellular wireless networks," in *Proc. IEEE INFOCOM'01*, 2001, pp. 1005–1011.

[20] S. Ni and S. G. Häggman, "GPRS performance estimation in GSM circuit switched services and GPRS shared resource systems," in *Proc. IEEE WCNC'99*, 1999, pp. 1417–1421.

[21] N. R. Sollenberger, N. Seshadri, and R. Cox, "The evolution of IS-136 TDMA for third-generation wireless services," *IEEE Pers. Commun.*, vol. 6, no. 3, pp. 8–18, Jun. 1999.

[22] P. Stuckmann and F. Müller, "GPRS radio network capacity and quality of service using fixed and on-demand channel allocation techniques," in *Proc. IEEE VTC'00*, 2000, pp. 440–444.

[23] J. Wang, Q. A. Zeng, and D. P. Agrawal, "Performance analysis of preemptive handoff scheme for integrated wireless mobile networks," in *Proc. IEEE GLOBECOM'01*, 2001, pp. 3277–3281.

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