Performance Analysis of Dynamic Resource Allocation with Finite Buffers in Cellular Networks

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Abstract- In this paper, we analyzed the performance of dynamic resource allocation with channel de-allocation and buffering in cellular networks. Buffers are applied for data traffic to reduce the packet loss probability while channel de-allocation is exploited to reduce the voice blocking probability. The results show that while buffering data traffic can reduce the packet loss probability, it has negative impact on the voice performance even if channel de-allocation is exploited. Although the voice blocking probability and service delay can be reduced with large slot capacity, the improvement decreases as the slot capacity increases. On the contrary, the packet loss probability increases as the slot capacity increases. In addition, the results also show that the system performance is irrelevant to the sequence of de-allocation.

I. INTRODUCTION

The provision of integrated voice/data services over wireless links requires that radio resources be allocated to users efficiently to meet the different quality of service (QoS). The bandwidth of wireless links is inherently limited and is generally much less than its wired counterpart. Thus, *resource allocation* schemes for cellular networks are exploited to utilize the channel utilization efficiently [1-4]. It is quite well known that dynamic resource allocation allows communication systems to utilize their resources more efficiently than the traditional fixed allocation schemes

Cellular networks such as General Packet Radio Service (GPRS) introduced with GSM and Universal Mobile Telecommunications System (UMTS) nowadays can provide both circuit-switched and packet-switched services [5-6]. In general, real-time applications, such as voice services, are best provided via circuit-switched service, while most data applications are more efficiently provided by packet-switched service. Both GPRS and UMTS allow multiple channels to be allocated to a user served in either circuit-switched mode or packet-switched mode to fulfill its QoS requirement. For instance, channel allocation in GPRS is flexible, where one to eight channels can be allocated to a user or one channel can be shared by several users. In UMTS Terrestrial Radio Access based on TD-CDMA (UTRA-TDD) [7], 240 resource units (15 timeslots in a frame and 16 different code sequences in each timeslots) can be dynamically distributed among users.

Ni and Haggman showed that employing the multi-slot service in GPRS will result in higher blocking probability and longer delay than using the single-slot service, and these effects can be alleviated by implementing the resource allocation scheme with flexible, or dynamic, multi-slot service [8]. Thus, the design of effective and dynamic bandwidth allocation to satisfy different service demands is important in wireless networks. Several bandwidth allocation schemes [9-10] have been proposed to improve the system performance in integrated voice/data wireless cellular networks. By adopting dynamic resource allocation with possible channel de-allocation, both the blocking probability of voice calls and the wastage probability of radio resource can be effectively reduced. However, none of the above studies considered channel de-allocation mechanism in their analyses.

The analysis and comparison of the performance of dynamic resource allocation with/without channel de-allocation in GSM/GPRS networks can be found in a previous work [11]. In this paper, we will focus on the performance analysis of the dynamic resource allocation with finite buffers. Buffers are applied for data traffic to reduce the packet loss probability while channel de-allocation is exploited to reduce the voice blocking probability. Our goal is to understand the impact of channel de-allocation and buffering on the performance of integrated voice/data service in cellular networks.

II. RESOURCE ALLOCATION

The complete sharing strategy [12] is adopted that the radio resources are completely shared by voice calls and data users. No guard channels are reserved for either voice or data service. Buffers are exploited to queue data packets which find no channels available upon arrivals.

For data traffic, dynamic resource allocation is applied. To a data request of n channels, the network allocates at most n channels. Assume there are N available channels in the system upon a data request arrival. If $N \geq n$, n channels are allocated to the request. If $0 < N < n$, N channels are allocated to the request. If $N = 0$, the request is queued in the buffer or blocked by the system depending on if there are buffers available. Whenever there are service completions, the queued data packets are allocated with available channels, and are served using the first come first served (FCFS) discipline. Throughout the paper, "slot" and "channel" are used to have the same meaning.

Channel de-allocation is applied for voice arrivals when there are no free channels. One slot of an existing multi-slot data user is de-allocated for a voice arrival. The de-allocated

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user uses the remaining allocated channels to finish its transmission. When there are no free channels and no multi-slot users in service, the voice call request will be blocked. Channel de-allocation is not applied for data traffic since it will result in higher voice blocking probability, longer data transmission time, and lower channel utilization, with the only benefit of accommodating more data users in the system.

III. ANALYTICAL MODELS

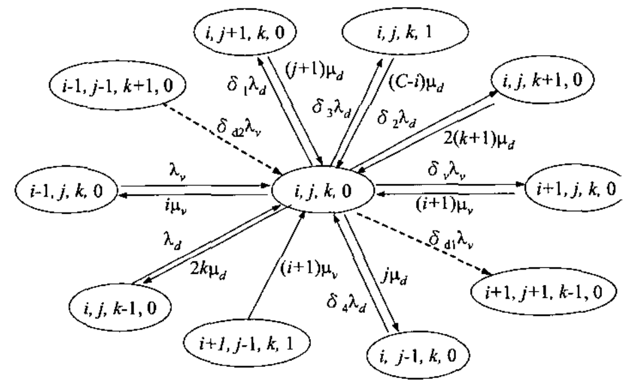
To analyze the performance of dynamic n-slot allocation with buffering for integrated voice/data services, it requires n+2 dimensions to formulate the system, *i.e.*, one dimension for voice traffic, n dimensions for data packets in service, and one dimension for data packets queued in the buffer. To simplify the analysis, we consider the case of $n = 2$, and validate the analysis by simulation experiments. For $n > 2$ the large state space makes the queueing analysis very difficult, therefore, the performance results are obtained via simulation.

The analysis focuses on a single cell in isolation and assumes that the network is symmetric and the traffic is homogenous. Let the arrivals of voice call requests form a Poisson process with a mean rate of λ_v. The service time of voice calls is assumed to be exponentially distributed with a mean of $1/\mu_v$. Fitzpatrick *et al* [13] showed that for data traffic the Poisson model, compared with both Gaussian model and aggregate On-Off model, gives the best results to agree with the measurement taken from a GSM/GPRS network. Therefore, the arrival process of data packets is assumed to be Poisson with a mean rate of λ_d. The service time of each data packet is exponentially distributed with a mean of $1/\mu_d$. The total number of channels in the system is C, and the buffer size is B.

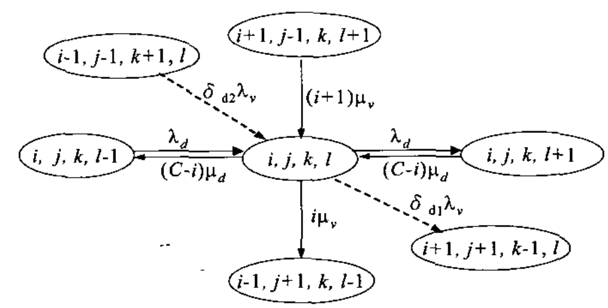
Let the state (i, j, k, l) denote that there are i voice calls, j 1-slot data users in service, k 2-slot data users in service, and l queued data packets in the system. $\pi_{i,j,k,l}$ denotes the state probability of the system in state (i, j, k, l). Fig. 1 shows the state transition diagram of the system. The case of $l > 0$ represents that there are no free channels in the system, therefore, one existing 2-slot data user will be de-allocated upon a voice arrival, and a data arrival will be queued in the buffer if there are buffer space. The dash line in the figure represents the state transition caused by de-allocating a 2-slot user upon a voice arrival. Let S be the set of feasible states,

$$\begin{aligned} S = \{(i,j,k,0) \mid & \ 0 \le i+j+2k \le C, 0 \le i \le C, \\ & 0 \le j \le C, \text{and } 0 \le k \le \lfloor C/2 \rfloor\} \\ \cup \{(i,j,k,l) \mid & \ i+j+2k = C, 0 \le i \le C, 0 \le j \le C, \\ & 0 \le k \le \lfloor C/2 \rfloor, \text{and } 1 \le l \le \text{B}\}. \end{aligned} \quad (1)$$

where $\lfloor x \rfloor$ is the floor function of x. An indicator function $\varphi(i, j, k, l)$ is used to indicate whether the state (i, j, k, l) is feasible or not, *i.e.*, $\varphi(i, j, k, l) = 1$ if $(i, j, k, l) \in S$. For all $(i, j, k, l) \in S$, the balance equations can be expressed in the following.



(a) $l = 0$ case



(b) $l > 0$ case

Fig. 1 The state transition diagram

$l = 0$ case:

$$\begin{aligned} &\pi_{i,j,k,0}(\delta_v\lambda_v\varphi(i+1,j,k,0)+\delta_1\lambda_d\varphi(i,j+1,k,0)+\delta_2\lambda_d\varphi(i,j,k+1,0) \\ &\quad +\delta_3\lambda_d\varphi(i,j,k,1)+i\mu_v\varphi(i-1,j,k,0)+j\mu_d\varphi(i,j-1,k,0) \\ &\quad +2k\mu_d\varphi(i,j,k-1,0)+\delta_{d1}\lambda_v\varphi(i+1,j+1,k-1,0)) \\ &=\lambda_v\pi_{i-1,j,k,0}\varphi(i-1,j,k,0)+\delta_4\lambda_d\pi_{i,j-1,k,0}\varphi(i,j-1,k,0) \\ &\quad +\lambda_d\pi_{i,j,k-1,0}\varphi(i,j,k-1,0)+(i+1)\mu_v\pi_{i+1,j,k,0}\varphi(i+1,j,k,0) \\ &\quad +(i+1)\mu_v\pi_{i+1,j-1,k,1}\varphi(i+1,j-1,k,1)+(j+1)\mu_d\pi_{i,j+1,k,0}\varphi(i,j+1,k,0) \\ &\quad +2(k+1)\mu_d\pi_{i,j,k+1,0}\varphi(i,j,k+1,0)+(C-i)\mu_d\pi_{i,j,k,1}\varphi(i,j,k,1) \\ &\quad +\delta_{d2}\lambda_v\pi_{i-1,j-1,k+1,0}\varphi(i-1,j-1,k+1,0) \end{aligned} \quad (2)$$

$l > 0$ case:

$$\begin{aligned} &\pi_{i,j,k,l}(\lambda_d\varphi(i,j,k,l+1)+i\mu_v\varphi(i-1,j+1,k,l-1) \\ &\quad +(C-i)\mu_d\varphi(i,j,k,l-1)+\delta_{d1}\lambda_v\varphi(i+1,j+1,k-1,l)) \\ &=\lambda_d\pi_{i,j,k,l-1}\varphi(i,j,k,l-1)+(C-i)\mu_d\pi_{i,j,k,l+1}\varphi(i,j,k,l+1) \\ &\quad +(i+1)\mu_v\pi_{i+1,j-1,k,l+1}\varphi(i+1,j-1,k,l+1) \\ &\quad +\delta_{d2}\lambda_v\pi_{i-1,j-1,k+1,l}\varphi(i-1,j-1,k+1,l) \end{aligned} \quad (3)$$

where

$$\delta_v = \begin{cases} 1, & \text{if } i+j+2k < C \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$\delta_1 = \begin{cases} 1, & \text{if } i+j+2k = C-1 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

$$\delta_2 = \begin{cases} 1, & \text{if } i+j+2k \le C-2 \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$\delta_3 = \begin{cases} 1, & \text{if } i+j+2k = C \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

$$\delta_4 = \begin{cases} 1, & \text{if } i+(j-1)+2k = C-1 \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

$$\delta_{d1} = \begin{cases} 1, & \text{if } i+j+2k = C, \text{and } 1 \le k \le \lfloor C/2 \rfloor \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

$$\delta_{d2} = \begin{cases} 1, & \text{if } i+j+2k = C, \text{and } 0 \le k \le \lfloor C/2 \rfloor - 1 \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

The last term on both sides of (2) is attributed to channel de-allocation caused by voice arrivals. δ_v, δ_1 (or δ_4), and δ_2 are the conditions of transition caused by voice call arrivals, data arrivals using 1 slot, and data arrivals using 2 slots, respectively. δ_3 is the condition of transition caused by data arrivals when there are no free channels. δ_{d1} and δ_{d2} are the conditions for channel de-allocation upon voice arrivals. Applying the constraint $\sum_S \pi_{i,j,k,l} = 1$ to the set of balance equations, we can obtain the steady-state probability $\pi_{i,j,k,l}$ to evaluate the voice blocking probability, packet loss probability of data users, the mean service delay of data packets, and probability of de-allocation.

A voice call arrival will be blocked when there are no free channels and no 2-slot data users in the system. Thus, the blocking probability of voice calls, P_{vb}, can be expressed as

$$P_{vb} = \sum_{l=0}^{B} \sum_{i+j=C} \pi_{i,j,0,l} \tag{11}$$

The packet loss probability of data users, P_{gb}, can be obtained

$$P_{gb} = \sum_{i+j+2k=C} \pi_{i,j,k,B} \,. \tag{12}$$

The mean service delay of data packets, W, is

$$W = \frac{1}{\lambda_d (1 - P_{gb})} \cdot \sum_S (j+k+l) \cdot \pi_{i,j,k,l} \,. \tag{13}$$

The probability of data packets being de-allocated, $P_{de\text{-}alloc}$, is

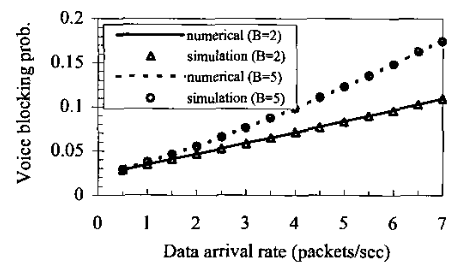
$$P_{de\text{-}alloc} = \frac{\lambda_v}{\lambda_d (1 - P_{gb})} \cdot \sum_{l=0}^{B} \sum_{\substack{i+j+2k=C \\ \& \, k \ge 1}} \pi_{i,j,k,l} \tag{14}$$

IV. Numerical And Simulation Results

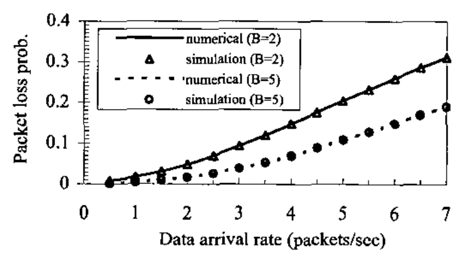
A. Validation of Analysis

To validate the numerical results, simulation experiments are conducted. We will consider the GPRS environment because it supports both circuit-switched and packet-switched services and it also supports channel de-allocation. The total number of channels in a cell is set to be 32. The mean arrival rate of voice calls is taken to be 0.1977 calls/sec, and the mean service time of voice calls is 120 seconds. The voice traffic load is chosen to be 23.72 Erlang corresponding to a 2% blocking probability for 32 channels. The mean arrival rate of data packets is a system parameter and is chosen to be in the range of 0.5 to 7 packets/sec. The mean service time of data packets is taken to be 2 seconds if one channel is allocated. The buffer size ranges from 1 to 5.

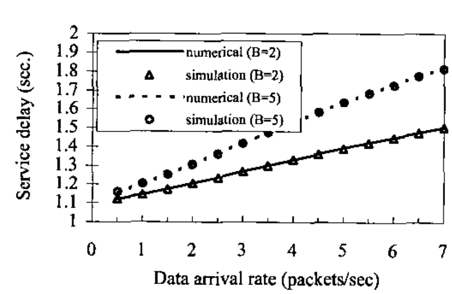
Fig. 2 shows the performance comparisons of numerical results and simulation results for a buffer of sizes 2 and 5. It can be seen that numerical results match very well with simulation results for all performance metrics. Therefore, we can use the results obtained from simulations to investigate the impact of dynamic n-slot (n>2) allocation in the next subsection.



(a) Voice blocking probability



(b) Data packet loss probability



(c) Service delay of data packet

Fig. 2 Performance comparisons of numerical results and simulation results.

Fig. 3 plots the system performance for different buffer sizes as a function of data arrival rate. From Fig. 3(a), it is clear that buffering data traffic has negative impact on the voice performance even channel de-allocation is exploited. It is worth noting that at high data load, voice blocking probability is still below 5% for B=0 due to the contribution of channel de-allocation.

On the contrary, the packet loss probability decreases as the buffer size increases as shown in Fig. 3(b). In addition, the service delay increases with data traffic load and buffer size as shown in Fig. 3(c).

Fig. 3(d) shows the probability of de-allocation for different buffer sizes. At low data traffic load, most data users are allocated with multiple channels, therefore, the probability of de-allocation increases with increasing traffic load. However, as the load further increases, data users will be mostly allocated with single channel and more data users will be admitted into the system when buffer size is large, the probability of de-allocation will decrease with increasing traffic load. This fact will be more evident in Fig. 4 which plots the probability of de-allocation under high data traffic load.

B. The effect of slot capacity

In this work, the slot capacity means that the maximum number of channels that can be allocated to a data user to transfer its packets. In GPRS, at most 8 channels can be dedicated to a data user, therefore, the maximum slot capacity is 8. For slot capacity greater than 2, when there are no channels available upon voice arrivals, the data users that are allocated with most channels will be de-allocated first. Fig. 5 shows the system performance for different slot capacity and buffer sizes at a data packet arrival rate of 7 packets/sec.

As can be seen in Fig. 5(a), the voice blocking probability decreases with increasing slot capacity. It is worth noting that the voice blocking probability can be significantly reduced when the slot capacity increases from one to two. As the slot capacity further increases, the voice blocking probability is almost independent of the number of slot capacity. The reason is that the increment of de-allocation probability is large when the slot capacity increases from one to two, and then the increment becomes less as the slot capacity further increases as can be seen in Fig. 5(d). The impact of multi-slot allocation on voice blocking probability in this work is quite different from that in the work of [9] which says that if many channels are allocated to a packet transmission, voice blocking probability will increase. The main reason is that the channel de-allocation was not considered in their work.

On the contrary, the packet loss probability increases with increasing slot capacity as shown in Fig. 5(b). This is because data users allocated with more channels will use up channels more quickly, thus the forthcoming data packets will have less chance to obtain services and be dropped when buffer overflows.

Although higher slot capacity causes larger packet loss probability, the service delay of data packet decreases as shown in Fig. 5(c). However, the decrement in delay decreases with increasing slot capacity, especially for large buffer size. When the buffer size is large, the service delay is mainly contributed by queueing delay instead of transmission

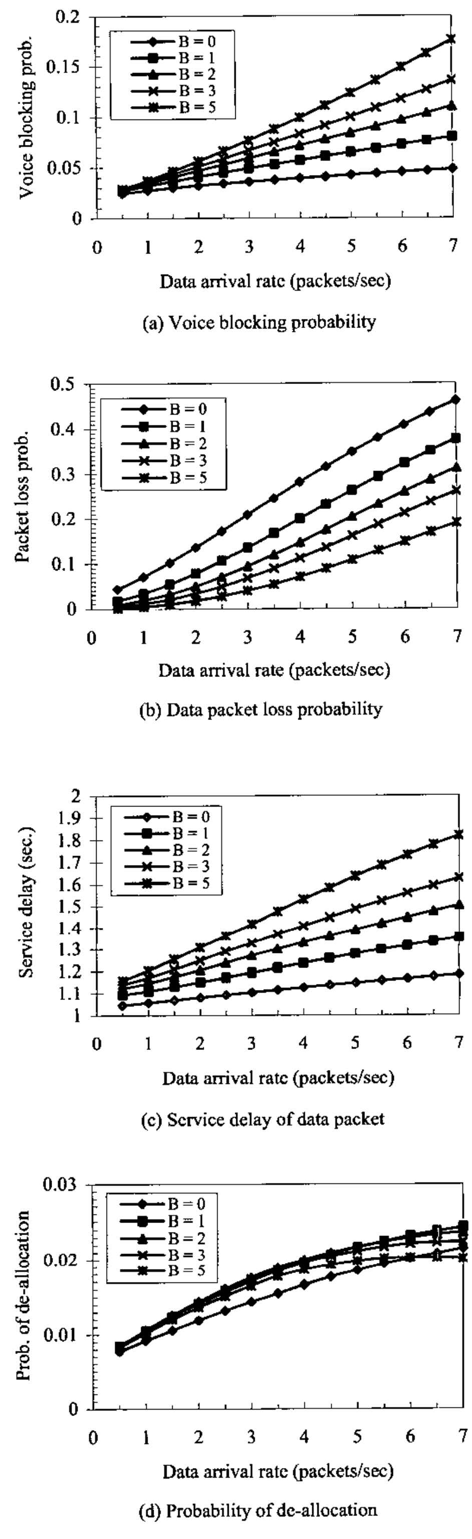


Fig. 3 System performance versus buffer size

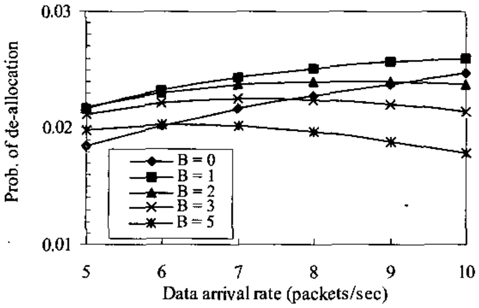


Fig. 4 Probability of de-allocation under high data traffic load

delay, thus, large slot capacity will have little impact on service delay.

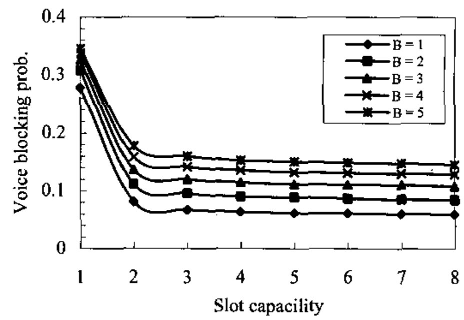
C. The effect of de-allocation sequence

To further investigate the effect of channel de-allocation, two different de-allocation strategies are considered. When there are no free channels upon a voice arrival: (i) the data user allocated with the most channels is de-allocated first, and (ii) random selection. Fig. 6 shows the performance comparisons of different de-allocation strategies for a slot capacity of 8 and a buffer size of 2. It is clear that the voice blocking probability, packet loss probability and mean service delay are almost the same in despite of the strategy as shown in Figs. 6(a)-6(c). The reason is that the probability of de-allocation of these two strategies is almost the same as can be seen in Fig. 6(d). In addition, the results for different slot capacities and buffer sizes have similar characteristics, and are not shown here.

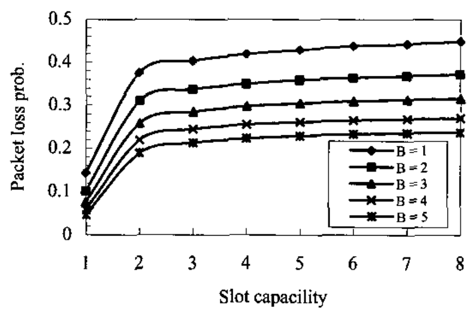
V. CONCLUSIONS

This paper investigated the dynamic resource allocation strategy with channel de-allocation and buffering in cellular networks with integrated voice/data services. Using the analytical model, the system performance in terms of voice blocking probability, packet loss probability, mean service delay of data packets and probability of de-allocation can be efficiently obtained. The results are validated by simulation experiments.

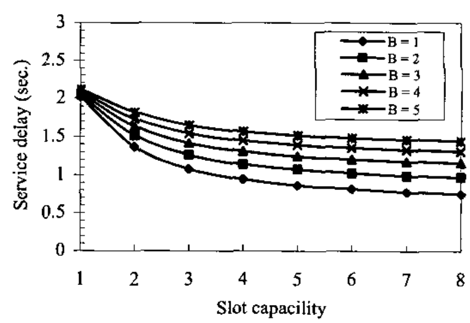
The results show that while buffering data traffic can reduce the packet loss probability, it has negative impact on voice performance even if channel de-allocation is exploited. With channel de-allocation, the voice blocking probability can be significantly reduced when the slot capacity increases from one to two. As the slot capacity increases, the voice blocking probability is almost independent of the number of slot capacity. Although the service delay can be reduced with large slot capacity, the improvement decreases as the slot capacity increases. On the contrary, the packet loss probability increases as the slot capacity increases. The operator should thus think deliberately if he/she would provide quick data transmission service at the expense of high packet loss probability and little improvement on voice blocking. To our opinion, the slot capacity ranging from 2 to



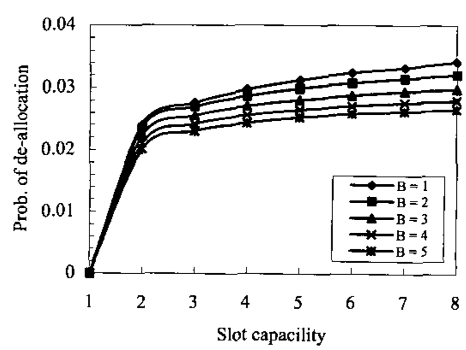
(a) Voicc blocking probability



(b) Data packet loss probability



(c) Service delay of data packet

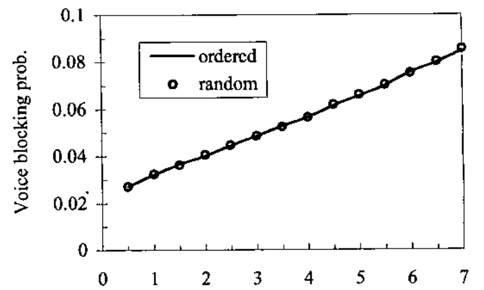


(d) Probability of de-allocation

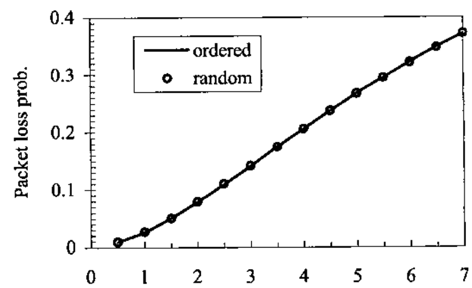
Fig. 5 System performance for different slot capacity

4 will be a good choice. In addition, the results also show that the system performance is irrelevant to the de-allocation sequence.

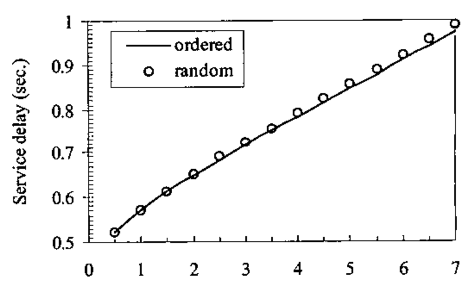
Although we focus on the performance of GPRS networks, the analysis developed in this work can also be applied to the next generation cellular communication systems, such as TD-CDMA, which use codes as the radio resources.



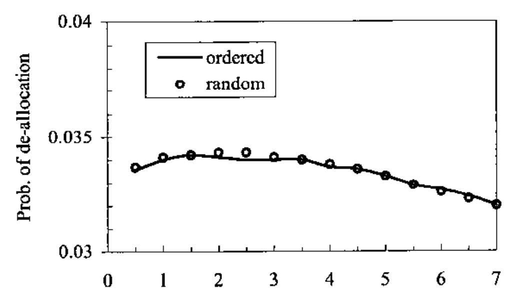
(a) Voice blocking probability



(b) Data packet loss probability



(c) Service delay of data packet



(d) Probability of de-allocation

Fig. 6 Performance comparisons of different de-allocation sequence

REFERENCES

[1] L. Chen, U. Yoshida, H. Murata, and S. Hirose, "Dynamic timeslot allocation algorithms suitable for asymmetric traffic in multimedia TDMA/TDD cellular radio," *Proceeding of VTC 1998 IEEE*, vol. 2, pp. 1424 -1428, Ottawa, Canada, May. 1998.

[2] C. Mihailescu, X. Lagrange, and Ph. Godlewski, "Performance evaluation of a dynamic resource allocation algorithm for UMTS-TDD systems," *Proceeding of VTC 2000-Spring IEEE*, vol. 3, pp. 2339 - 2342, Tokyo, Japan, May. 2000.

[3] M. Cheung and J. W. Mark, "Resource allocation in wireless networks based on joint packet/call levels QoS constraints," *Proceeding of GLOBECOM'00 IEEE*, vol. 1, pp. 271 -275, San Francisco, CA , USA, Nov. 2000.

[4] J. B. Kim, M. L. Honig, and S. Jordan, "Dynamic resource allocation for integrated voice and data traffic in DS-CDMA," *Proceeding of VTC 2001 IEEE*, Vol. 1, pp. 42-46, Atlantic City, USA, Oct. 2001.

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

[6] "Selection procedure for the choice of radio transmission technologies of the Universal Mobile Telecommunication System UMTS (UMTS 30.03)", ETSL TR 101 112, Apr. 1998.

[7] "TS 25.22x – Physical Layer, General Description (TDD). Technical report", 3rd Generation Partnership Project, 3GPP, Oct. 1999.

[8] S. Ni and S. G. Haggman, "GPRS performance estimation in GSM circuit switched services and GPRS shared resource systems," *Proceedings of IEEE WCNC'99*, vol. 3, pp. 1417-1421, New Orleans, USA, Sep. 1999.

[9] P. Lin and Y. B. Lin, "Channel allocation for GPRS," *IEEE Transactions on Vehicular Technology*, Vol. 50, No. 2, pp. 375-387, March 2001.

[10] H. H. Liu, J. L. C. Wu and W. C. Hsieh, "Delay analysis of integrated voice and data service for GPRS," *IEEE Communications Letters*, Vol. 6, No. 8, pp. 319-321, Aug. 2002.

[11] 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 Communications Letters*, Vol. 7, No. 1, pp. 10-12, Jan. 2003.

[12] M. Ermel, K. Begain, T. Muller, J. Schuler, and M. Schweigel, "Analytical comparison of different GPRS introduction strategies," *Proc. 3rd ACM Int. Workshop on Modeling Analysis and Simulation of Wireless and Mobile Systems*, pp. 3-10, Boston, USA, Aug. 2000.

[13] P. Fitzpatrick, M. Ivanovich and J. Yin, "Models for pre-emption of packet data by voice in slotted cellular radio networks," *Proceeding of GLOBECOM 2002 IEEE*, Taipei, Taiwan, Nov. 2002.