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Buffer Management in Discrete Time Multiclass Models with Applications to High Speed Switching

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Abstract

In this paper, five different buffer management systems are proposed that differ in terms of different buffer allocation and service disciplines. Average loss rate is used as a performance measure, and results show that the system performance can be improved by using a buffer sharing mechanism. The results also show that the degree of superiority of the sharing mechanism will depend on the load condition. Analytic, iterative, and simulation methods are used to show how to solve specific systems.

1. Introduction

Broadband integrated networks are the trend of future telecommunication environment. These networks will carry a variety of traffic such as voice, video data and images. The availability of high speed transmission, switching and signal processing technologies will offer access rates in bit rates of hundreds of Mbit/s. Asynchronous Transfer Mode (ATM) has been accepted by CCITT as a basis for the future Broadband Integrated Services Digital Network [1].

Since the B-ISDN is designed to support many traffic types, it must be able to meet different quality of service (QOS) requirements for the variety of traffic. One of the requirements is cell loss rate which usually has to be kept at no more than 10^{-8}. CCITT has reserved one bit in the ATM cell header for the explicit marking of cell loss priority [1]. In an ATM-based B-ISDN the ene-to-end cell loss is caused mainly from the cell loss at the policing function and from buffer overflow. The use of optical fiber can minimize the cell loss caused by uncorrectable bit errors. In order to meet the diverse QOS loss requirements, the buffer access control and policing control have to be carefully designed. Several papers have been devoted to this subject. For example, [2] studies a continuous time tandem queueing system minimizing the average loss rate by changing the buffer allocation and service discipline. Different space priority mechanisms are also discussed in [3] and [4] for continuous and discrete queueing, respectively. In [5] it is shown that by partitioning the buffering capacity appropriately the loss probability due to overflow can be controlled.

In this paper, a number of choices for buffer allocation and service discipline are proposed. The proposed models are the same as those in an earlier paper [6]. However, this paper will deal with discrete time models while the previous work studied continuous time models. Performance results for the average loss rate will show the superiority of buffer sharing.

This paper is organized as follows. In section 2, the different buffer management systems are presented and analyzed. Numerical results are described in section 3. Section 3 presents a comparison of results and a brief discussion of hardware implementation complexity. The conclusion appears in section 4.

2. System Models and Analysis

A discrete time queueing system model with a buffer capacity of N-2 and two servers is studied in this paper. Thus the entire queueing system can hold N customers. Two priority classes of traffic will be used to distinguish the incoming packets to the system. Naturally this work could be generalized to more than two classes of traffic. In the queueing policies that follow a distinction will thus be made between the two generic classes of traffic though they will be treated identically. Our goal in this paper is to study the role of buffer management strategies rather than priority disciplines per se.

The two classes of arrival processes are assumed to be of the Bernoulli type with probabilities of arrival p_1 and p_2 in a time slot. They are independent of one another. The service time for each of the two servers is also assumed to be geometrically distributed with probabilities of service s_1 and s_2 in a slot. In each time slot for each class of packets at most one packet can arrive and each server can transmit at most one packet in a slot according to their respective geometrical distribution probabilities. However, a packet can not enter and leave the queue within the same time slot due to the need for synchronization time. The so-called virtual cut-through [7] will not be considered in this paper. The arrival and departure will occur at the boundary of each time slot. Arrivals occur in the beginning of a time slot and departures will occur only at the end of a time slot. In the following study s_1 will be set to equal to s_2 and equal to 0.9. Thus the service discipline is close to being deterministic and the effect of various arrival probabilities can be examined.

2.1 Partitioning Fixed Buffer Assignment (PFBA) Strategy:

A queueing system using the PFBA strategy is developed by *completely partitioning* the original queue into two independent queueing systems with the total number of buffers fixed. A queueing system using the PFBA strategy is shown in Figure 1. Each incoming packet will be sent to its respective queue on basis of its class information.

A single queue of a queueing system using the PFBA strategy with total buffer capacity N will have a state transition diagram as shown in Figure 2. As in [8], the state transition

N will have a state transition diagram as shown in Figure 2. As in [8], the state transition diagram belongs to type A structure which can be decomposed into solvable subsets. Recursive equations can be written for the equilibrium probabilities [9]. The blocking probability can be easily shown to be:

$$\begin{aligned} P_{blocking} &= \frac{p(1-s)(\rho-1)}{\rho^{N-1}s(1-s)(\rho-1)+\rho^{N-1}s-s+p(1-s)(\rho-1)} \quad (1) \\ \text{where } \rho &= \frac{(1-p)s}{p(1-s)} \quad . \end{aligned}$$

The average loss rate for the queueing system utilizing the PFBA strategy will become:

$$P_{average}(loss) = \frac{p_1}{p_1+p_2}P_{blocking}(class1) + \frac{p_2}{p_1+p_2}P_{blocking}(class2) \quad (2)$$

The minimal value of average loss rate and the optimal partition can be found through exhaustive searching by computer.

2.2 Partitioning Fixed Buffer Assignment in Proportion to Arrival Rate (PFBA+PAR) Strategy:

A queueing system utilizing the PFBA+PAR strategy is similar to the above system but the partitioning policy is different. To simplify the buffer assignment policy the partitioned size of the buffer capacity will be decided by the following equation:

$$N_1 = Nearest\ integer\ to \left(\frac{p_1}{p_1+p_2}N\right)$$

A similar allocation holds for N_2.

$$N_2 = Nearest\ integer\ to \left(\frac{p_2}{p_1+p_2}N\right)$$

The blocking probability is the same as equation (1) and the average loss rate is the same as equation (2).

2.3 Shared Buffer with Class Based Servers (SBCBS) Strategy:

A queueing system using the SBCBS strategy will have two incoming classes of traffic sharing the same buffer. Each server serves only one preset class of traffic. In the beginning of a time slot if a server is available and there are packets which belong to its preset class, the oldest arriving packet will immediately enter the server even if there are packets of the other class in front of it. The schematic diagram of this system is shown in Figure 3.

Figure 4 illustrates an example of the state transition diagram of such system with a total buffer capacity equal to 5. In the diagram each state is specified by the number of different classes of packets in the system. Figure 5 shows the eight different sets of state transition probabilities for each state in the state transition diagram. The formula for the probabilities are presented as follows:

Set 1: State transition probabilities for the states $\{(x,y)|x>0, y>0, (x+y)<(N-1)\}$

$$\begin{aligned}
a_1 &= (1-p_1)(1-p_2)(1-s_1)(1-s_2) + (1-p_1)p_2(1-s_1)s_2 + p_1p_2s_1s_2 + p_1(1-p_2)s_1(1-s_2) \\
a_2 &= p_1p_2(1-s_1)(1-s_2) \\
a_3 &= p_1p_2(1-s_1)s_2 + p_1(1-p_2)(1-s_1)(1-s_2) \\
a_4 &= p_1(1-p_2)(1-s_1)s_2 \\
a_5 &= p_1(1-p_2)s_1s_2 + (1-p_1)(1-p_2)(1-s_1)s_2 \\
a_6 &= (1-p_1)(1-p_2)s_1s_2 \\
a_7 &= (1-p_1)p_2s_1s_2 + (1-p_1)(1-p_2)s_1(1-s_2) \\
a_8 &= (1-p_1)p_2s_1(1-s_2) \\
a_9 &= (1-p_1)p_2(1-s_1)(1-s_2) + p_1p_2s_1(1-s_2)
\end{aligned}$$

Set 2: State transition probabilities for the states $\{(x,y)|x>0, y>0, (x+y)=(N-1)\}$

$$\begin{aligned}
a_1 &= (1-p_1)(1-p_2)(1-s_1)(1-s_2) + (1-p_1)p_2(1-s_1)s_2 + p_1(1-p_2)s_1(1-s_2) \\
&\quad + \frac{1}{2}p_1p_2s_1(1-s_2) + \frac{1}{2}p_1p_2(1-s_1)s_2 \\
a_2 &= p_1(1-p_2)(1-s_1)(1-s_2) + \frac{1}{2}p_1p_2(1-s_1)(1-s_2)
\end{aligned}$$

$$
\begin{aligned}
a_3 &= p_1(1-p_2)(1-s_1)s_2 + \frac{1}{2}p_1p_2(1-s_1)s_2 \\
a_4 &= p_1(1-p_2)s_1s_2 + (1-p_1)(1-p_2)(1-s_1)s_2 + \frac{1}{2}p_1p_2s_1s_2 \\
a_5 &= (1-p_1)(1-p_2)s_1s_2 \\
a_6 &= (1-p_1)p_2s_1s_2 + (1-p_1)(1-p_2)s_1(1-s_2) + \frac{1}{2}p_1p_2s_1s_2 \\
a_7 &= (1-p_1)p_2s_1(1-s_2) + \frac{1}{2}p_1p_2s_1(1-s_2) \\
a_8 &= (1-p_1)p_2(1-s_1)(1-s_2) + \frac{1}{2}p_1p_2(1-s_1)(1-s_2)
\end{aligned}
$$

Set 3: State transition probabilities for the states $\{(x,y)|x>0, y>0, (x+y)=N\}$

$$
\begin{aligned}
a_1 &= s_1(1-s_2) \\
a_2 &= s_1s_2 \\
a_3 &= (1-s_1)s_2 \\
a_4 &= (1-s_1)(1-s_2)
\end{aligned}
$$

Set 4: State transition probabilities for the states $\{(x,y)|x=0, 0<y<(N-1)\}$

$$
\begin{aligned}
a_1 &= (1-p_1)p_2(1-s_2) \\
a_2 &= p_1p_2(1-s_2) \\
a_3 &= p_1p_2s_2 + p_1(1-p_2)(1-s_2) \\
a_4 &= p_1(1-p_2)s_2 \\
a_5 &= (1-p_1)(1-p_2)s_2 \\
a_6 &= (1-p_1)p_2s_2 + (1-p_1)(1-p_2)(1-s_2)
\end{aligned}
$$

Set 5: State transition probabilities for the states $\{(x,y)|y=0, 0<x<(N-1)\}$

$$
\begin{aligned}
a_1 &= p_1(1-p_2)(1-s_1) \\
a_2 &= p_1p_2(1-s_1) \\
a_3 &= p_1p_2s_1 + (1-p_1)p_2(1-s_1) \\
a_4 &= (1-p_1)p_2s_1
\end{aligned}
$$

$$a_5 = (1-p_1)(1-p_2)s_1$$

$$a_6 = p_1(1-p_2)s_1 + (1-p_1)(1-p_2)(1-s_1)$$

Set 6: State transition probabilities for state (0,0)

$$a_1 = (1-p_1)p_2$$

$$a_2 = p_1p_2$$

$$a_3 = p_1(1-p_2)$$

$$a_4 = (1-p_1)(1-p_2)$$

Set 7: State transition probabilities for state (0,N-1)

$$a_1 = p_1(1-s_2)$$

$$a_2 = p_1s_2$$

$$a_3 = (1-p_1)s_2$$

$$a_4 = (1-p_1)(1-s_2)$$

Set 8: State transition probabilities for state (N-1,0)

$$a_1 = p_2(1-s_1)$$

$$a_2 = p_2s_1$$

$$a_3 = (1-p_2)s_1$$

$$a_4 = (1-p_2)(1-s_1)$$

Many methods can be applied to solve the state probabilities. In this paper an iterative method is used to determine the state probabilities. After solving for the state probabilities the blocking probability for each class of packets can be represented by:

$$P_{blocking}(class1) = \sum_{x=1}^{N-1} p(x, N-x) + p(N-1,0) + \frac{1}{2}p_2 \sum_{x=1}^{N-2} p(x, N-x-1) \quad (3)$$

$$P_{blocking}(class2) = \sum_{x=1}^{N-1} p(x, N-x) + p(0,N-1) + \frac{1}{2}p_1 \sum_{x=1}^{N-2} p(x, N-x-1) \quad (4)$$

where $p(x,y)$ is the state probability for state (x,y)

The average loss rate for the system using the SBCBS strategy becomes:

$$P_{average}(loss) = \frac{p_1 P_{blocking}(class1) + p_2 P_{blocking}(class2)}{p_1 + p_2} \quad (5)$$

2.4 Shared Buffer with Preemptive Priority Service(SBPPS) Strategy:

The queueing system using the SBPPS strategy has the same schematic representation as the queueing system utilizing the SBCBS strategy shown in Figure 3. It is different in the discipline for the servers. In this model, each server mainly serves its preset class of packets and can serve the other class of packets under the condition that there is no packet of its preset class in the queue. In the beginning of a time slot if a server has a packet whose class is not of the preset class for the server and one of its preset class of packets arrives to the system, then the newly arriving packet will preempt the one already in service.

Figure 6 shows the transition state diagram for a queueing system using the SBPPS strategy with total queue capacity N equal to 5. The total number of sets of state transition probabilities for each state in the state transition diagram will be 12. Among them the sets for states (0,0),(1,0),(0,1) and $\{(x, y)|x > 0, y > 0\}$ will be the same as those in the SBCBS case. The others are shown in Figure 7 and the formula for the transition probabilities are as follows:

Set 1: State transition probabilities for state (0,N)

$$a_1 = (1 - s_2)^2$$
$$a_2 = 2s_2(1 - s_2)$$
$$a_3 = s_2^2$$

Set 2: State transition probabilities for state (0,N-1)

$$a_1 = (1 - p_1)p_2(1 - s_2)^2 + \frac{1}{2}p_1 p_2(1 - s_2)^2$$
$$a_2 = p_1(1 - p_2)(1 - s_2) + \frac{1}{2}p_1 p_2(1 - s_2)$$
$$a_3 = p_1(1 - p_2)s_2 + \frac{1}{2}p_1 p_2 s_2$$

$$
\begin{aligned}
a_4 &= (1-p_1)p_2s_2^2 + 2(1-p_1)(1-p_2)s_2(1-s_2) + \frac{1}{2}p_1p_2s_2^2 \\
a_5 &= (1-p_1)(1-p_2)s_2^2 \\
a_6 &= (1-p_1)(1-p_2)(1-s_2)^2 + p_1p_2(1-s_2)s_2 + 2(1-p_1)p_2(1-s_2)s_2
\end{aligned}
$$

Set 3: State transition probabilities for states $\{(x,y)|x=0, 1<y<(N-1)\}$

$$
\begin{aligned}
a_1 &= (1-p_1)p_2(1-s_2)^2 \\
a_2 &= p_1p_2(1-s_2) \\
a_3 &= p_1p_2s_2 + p_1(1-p_2)(1-s_2) \\
a_4 &= p_1(1-p_2)s_2 \\
a_5 &= 2(1-p_1)(1-p_2)(1-s_2)s_2 + (1-p_1)p_2s_2^2 \\
a_6 &= (1-p_1)(1-p_2)s_2^2 \\
a_7 &= (1-p_1)(1-p_2)(1-s_2)^2 + 2(1-p_1)p_2(1-s_2)s_2
\end{aligned}
$$

Set 4: State transition probabilities for state (N,0)

$$
\begin{aligned}
a_1 &= (1-s_1)^2 \\
a_2 &= 2s_1(1-s_1) \\
a_3 &= s_1^2
\end{aligned}
$$

Set 5: State transition probabilities for state (N-1,0)

$$
\begin{aligned}
a_1 &= p_1(1-p_2)(1-s_1)^2 + \frac{1}{2}p_1p_2(1-s_1)^2 \\
a_2 &= (1-p_1)p_2(1-s_1) + \frac{1}{2}p_1p_2(1-s_1) \\
a_3 &= (1-p_1)p_2s_1 + \frac{1}{2}p_1p_2s_1 \\
a_4 &= p_1(1-p_2)s_1^2 + 2(1-p_1)(1-p_2)s_1(1-s_1) + \frac{1}{2}p_1p_2s_1^2 \\
a_5 &= (1-p_1)(1-p_2)s_1^2 \\
a_6 &= (1-p_1)(1-p_2)(1-s_1)^2 + p_1p_2(1-s_1)s_1 + 2p_1(1-p_2)(1-s_1)s_1
\end{aligned}
$$

Set 6: State transition probabilities for states $\{(x,y)|1<x<(N-1), y=0\}$

$$
\begin{aligned}
a_1 &= p_1(1-p_2)(1-s_1)^2 \\
a_2 &= p_1p_2(1-s_1) \\
a_3 &= p_1p_2s_1 + (1-p_1)p_2(1-s_1) \\
a_4 &= (1-p_1)p_2s_1 \\
a_5 &= 2(1-p_1)(1-p_2)(1-s_1)s_1 + p_1(1-p_2)s_1^2 \\
a_6 &= (1-p_1)(1-p_2)s_1^2 \\
a_7 &= (1-p_1)(1-p_2)(1-s_1)^2 + 2p_1(1-p_2)(1-s_1)s_1
\end{aligned}
$$

The iterative method is used again to solve the state probabilities. The blocking probability for each class of packets becomes:

$$
P_{blocking}(class1) = \sum_{x=0}^{N} p(x, N-x) + \frac{1}{2}p_2 \sum_{x=0}^{N-1} p(x, N-x-1) \tag{6}
$$

$$
P_{blocking}(class2) = \sum_{x=0}^{N} p(x, N-x) + \frac{1}{2}p_1 \sum_{x=0}^{N-1} p(x, N-x-1) \tag{7}
$$

where $p(x,y)$ is the state probability for state (x,y)

The average loss rate for the system using the SBPPS strategy is defined as:

$$
P_{average}(loss) = \frac{p_1 P_{blocking}(class1) + p_2 P_{blocking}(class2)}{p_1 + p_2} \tag{8}
$$

2.5 SBCBS Strategy with Head of the Line Blocking (SBCBS+HOLB) :

A queueing system using the SBCBS+HOLB strategy has the same service discipline but a different buffer management policy than the SBCBS model. Each packet in the buffer will keep its position in order of arrival. If a server is free at the end boundary of a time slot, its preset class of packets can enter the server only if it is at the head of the line of the buffers. In other words, packets in the buffer can be blocked by a packet in the head of the line.

The state transition diagram for this kind of system is not very tractable. Simulation was used to find the average loss rate. Only cases where the total capacity will produce an average loss rate higher than 10^{-6} will be considered due to the difficulty of simulating rare events. The simulation was run for 10^8 time slots with the first 10^6 slots discarded due to transient phenomena.

3. Comparison of Performance Results and Discussion

The previous models can be divided into two groups according to resource arrangement. The complete buffer partitioning strategies, PFBA and PFBA+PAR, comprise the group of fixed buffer assignment queueing systems. The rest of the models belong to the group of buffer sharing queueing systems.

3.1 PFBA and PFBA+PAR strategies

As mentioned in section 2.1 the average loss rate for a queueing system using the PFBA strategy will be smallest under the complete partitioning. However it will need substantial memory to store the optimal buffer assignment for each queue.

The buffer assignment for a queueing system utilizing the PFBA+PAR strategy is easier to calculate once the system has the information about the arrival probabilities of two classes of traffic. This makes such system more practical than the system using the PFBA strategy. From the performance results shown in Figure 8 the system using the PFBA+PAR strategy can sometimes yield a value very close to the optimal (smallest) one. Moreover the system utilizing the PFBA+PAR strategy is simple to implement in conjunction with load estimation algorithms.

3.2 Buffer sharing strategies

Figure 8 also shows the performance results for the three different models of buffer sharing queueing systems. In Figure 8 the queueing system using the SBCBS+HOLB strategy always has the worst average loss rate compared to the other two buffer sharing system. This is due to the limitation that packets at the head of the line will cause blocking in this system or the so-called head-of-line blocking problem.

For the SBPPS and SBCBS strategies it is natural that a system using the SBPPS strategy should produce a better result since it makes fuller use of the servers. From Figure 8 the performances for both systems are very close under the condition that the two traffic loads are in balance. The queueing system using the SBPPS strategy becomes superior in the sense of average loss rate when the traffic loads become more unbalanced.

The reason for this is that when the loads of both classes of packets become more unbalanced, one of the classes of packets will exist in the buffer more frequently. In a buffer management system using the SBPPS strategy, the packets of the heavy traffic class can utilize both servers more fully while the queueing system using the SBCBS strategy can only utilize one server for one class packets. For a balanced load, both classes of packets will exist in the buffer with equal chance and this means that the system using the SBPPS strategy does not have much chance to utilize both servers for any one class of packets. Thus the average loss rate when using SBCBS and SBPPS strategies should be very close and this can be seen in Figure 9.

For the queueing systems using the SBCBS and SBCBS+HOLB strategies the performance of the system using the SBCBS strategy should be better than that of the latter one under any load condition. From Figure 8 the performance of the system using the SBCBS strategy will approach to that of the system using the SBCBS+HOLB strategy when the load becomes unbalanced. This is because under a serious unbalanced load one of the class of packets will seldom be inside the buffer and the head-of-line blocking phenomena in the queueing system using SBCBS+HOLB strategy will seldom occur and this will make the system behave like a system using the SBCBS strategy.

From Figure 8.4 the performance of one of the buffer sharing queueing systems, the system using the SBCBS+HOLB strategy, does not have a better performance compared to the complete partitioning queueing system using the PFBA strategy under unbalanced loads. This is because when the load is unbalanced the effect of head-of-line blocking will degrade the performance of a system using the SBCBS+HOLB strategy.

Figure 9 shows the performance of the five queueing systems under the same traffic loads for both classes of packets. When the loads become heavier the performance results of the buffer sharing queueing systems will approach the result of complete buffer partitioning system. The exception is the queueing system using the SBCBS+HOLB strategy, whose performance degrades. The influence of the head-of -line blocking becomes more dominant under heavy load.

In summary, the performance of a queueing system using the SBPPS strategy will be superior to those of other queueing systems when the load becomes more unbalanced. The more unbalanced the load is, the less superior the queueing systems using the SBCBS and SBCBS+HOLB strategies are compared to a PFBA queueing system. For loads in balance, if the loads become heavier the buffer sharing queueing systems will not be much superior to those with a fixed buffer assignment. The system using the SBCBS+HOLB strategy will have an inferior performance to that of a system using the PFBA strategy since the head-of-line blocking problem will be more serious when the loads become heavier.

Although the queueing system using the SBCBS+HOLB strategy does not have the best performance result, it involves a simpler buffering mechanism and service discipline than the other buffer sharing systems. By way of contrast, the queueing system using the SBPPS strategy will need a more complex buffer management system and more registers to temporarily store the packet which suffers an interruption of service. There is thus a compromise between performance and hardware complexity.

4. Conclusion

On the basis of different buffer management policies and service disciplines, five different queueing systems are proposed and studied in this paper. Various methods which are analytical, numerical or simulative are also provided for analyzing the queueing systems. It was found that the system performance can be improved through buffer sharing. When using the buffer sharing strategy the head-of-line blocking will degrade the performance for a nonpreemptive system under the unbalanced loads or balanced heavy loads. The queueing system using the SBPPS strategy has the best performance under any load condition .

References

[1] "Broadband aspects of ISDN-B-ISDN ATM functional characteristics. ATM layer specification for B-ISDN and B-ISDN ATM adaptation layer functional description/specification," CCITT Draft Recommendations I.150, and I.361-I.363. Geneva. Switzerland, Feb. 1990.

[2] P. J. Courtois and G. Scheys, "Minimization of the Total Loss Rate for Two Finite Queues in Series," *IEEE Transactions on Communications,* Vol. 39, No 11, Nov. 1991, pp. 1651-1661.

[3] Hans Kroner, "Comparative Performance Study of Space Priority Mechanisms for ATM Networks," *Proceedings of the INFOCOM'90*, San Francisco, 1990, pp. 1136-1143.

[4] Y. M. Lin and John A. Silvester, "Priority Queueing Strategies and Buffer Allocation Protocols for Traffic Control at an ATM Integrated Broadband Switching System," *IEEE Journal on Selected Areas in Communication*, Vol. 9 , No. 9, Dec. 1991, pp.1524-1536.

[5] David X. Chen and Jon W. Mark, "Delay and Loss Control of An Output Buffered Fast Packet Switch Supporting Integrated Services," *ICC'92*, Chicago, 1992, pp.985-989.

[6] J.-W. Jeng and T. G. Robertazzi, "Evaluation of Continuous-Time Priority Queueing System under Different Buffering Strategies with Applications to High Speed Switching," SUNY at Stony Brook College of Engïneering and Applied Science Tech. Rep. 628, June 19, 1992.

[7] P. Kermani and L. Kleinrock, "Virtual cut-through: A new computer communication switching technique," *Computer Networks*, Vol. 3, 1979, pp. 267-286.

[8] T. G. Robertazzi, "Computer Networks and System: Queueing theory and Performance Evaluation," Springer-Verlag 1990, pp. 139-143.

[9] H. Y. Huang and T. G. Robertazzi, "Recursive Solution for Discrete Time Queues with Applications to High Speed Switching Fabrics," *Proceedings of the 1992 Conference on Information Sciences Systems,* Princeton, N. J., March 1992.

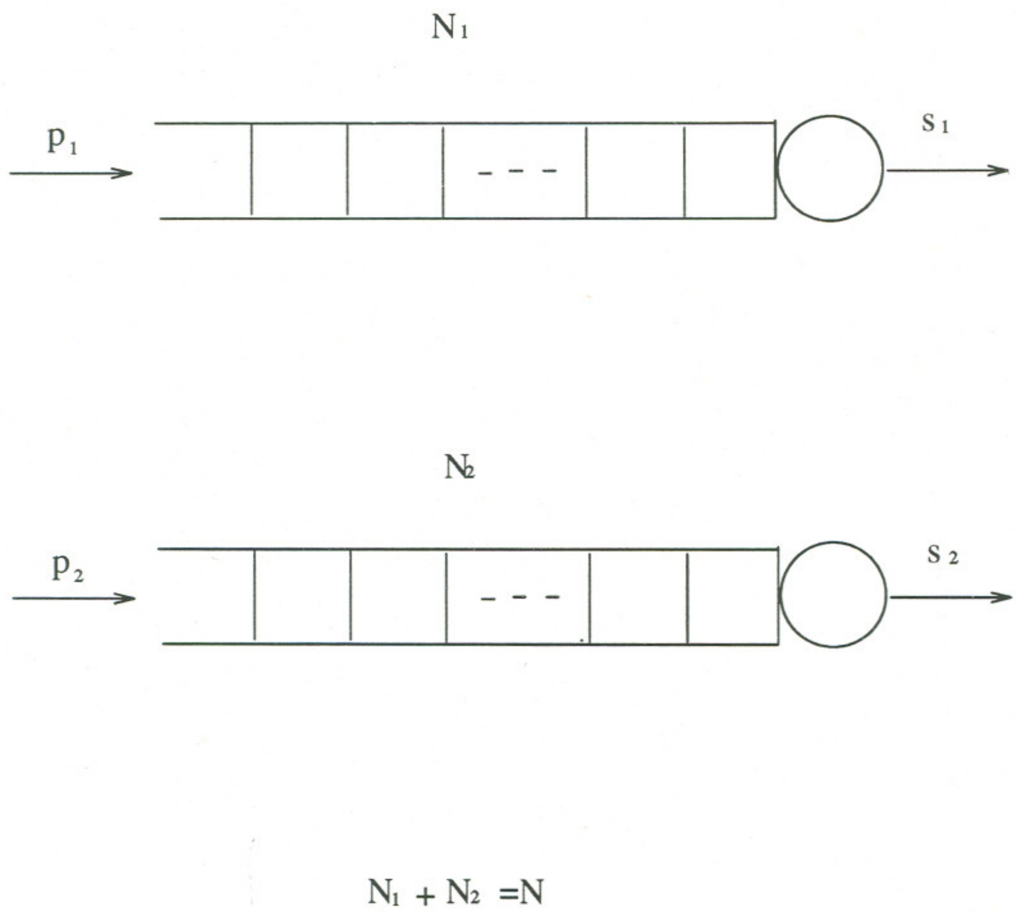

Figure 1. Queueing system using the PFBA strategy

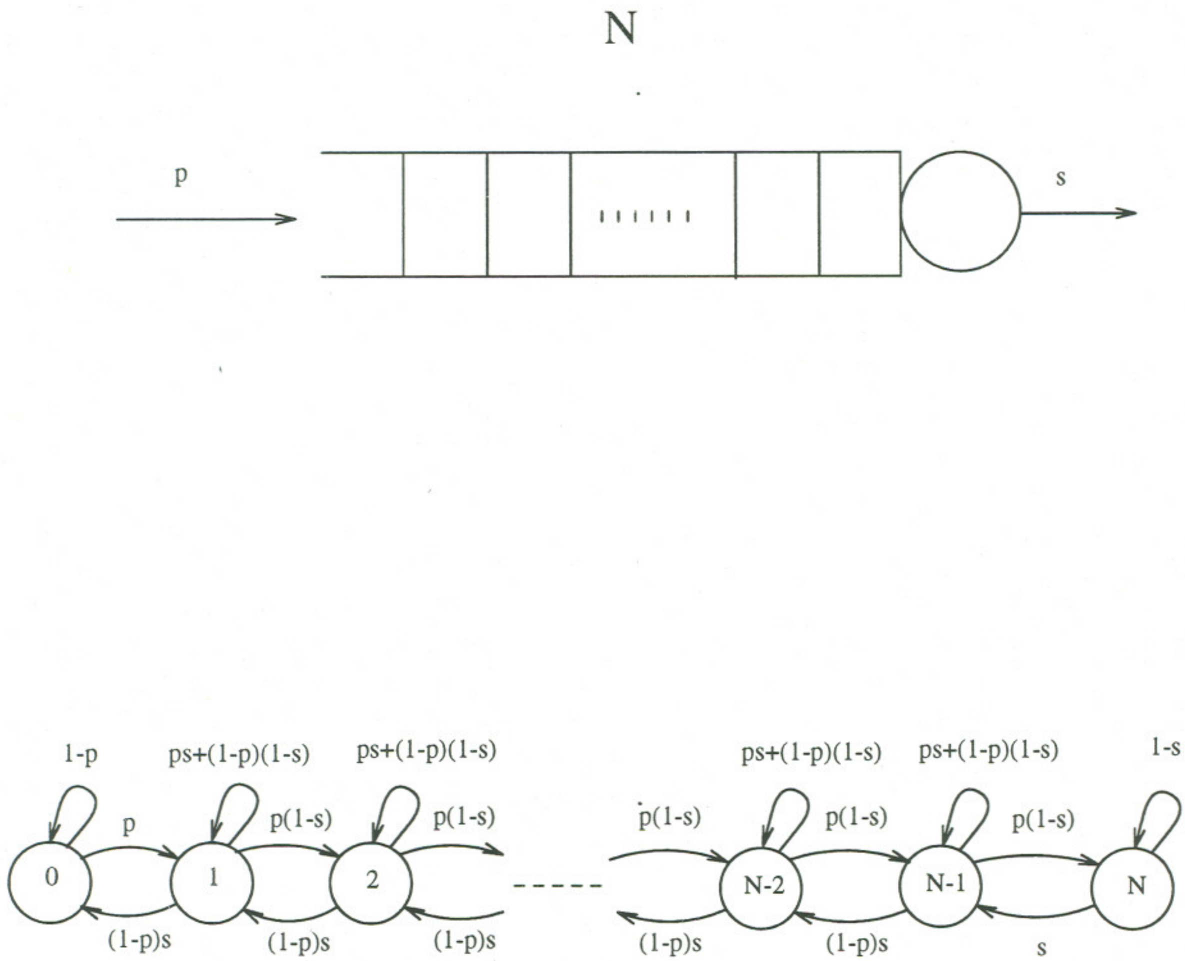

Figure 2 State transition diagram for a single queue system with total buffer capacity equals to N

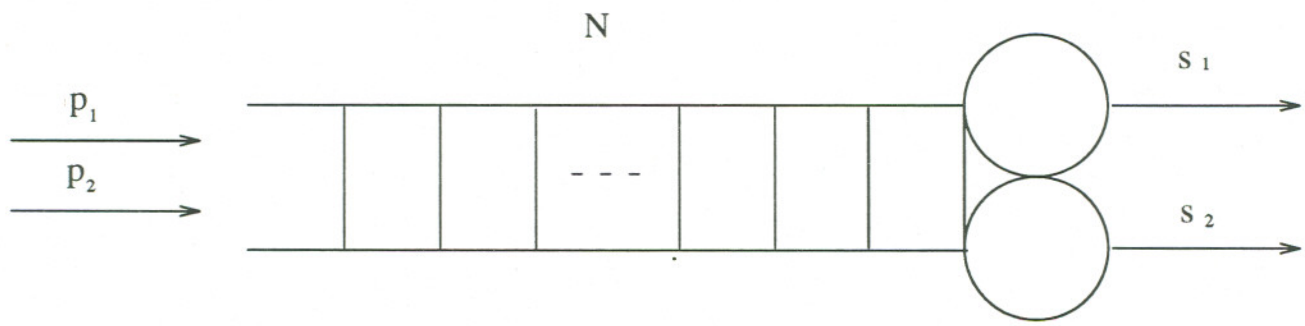

Figure 3. Queueing system using the SBCBS strategy

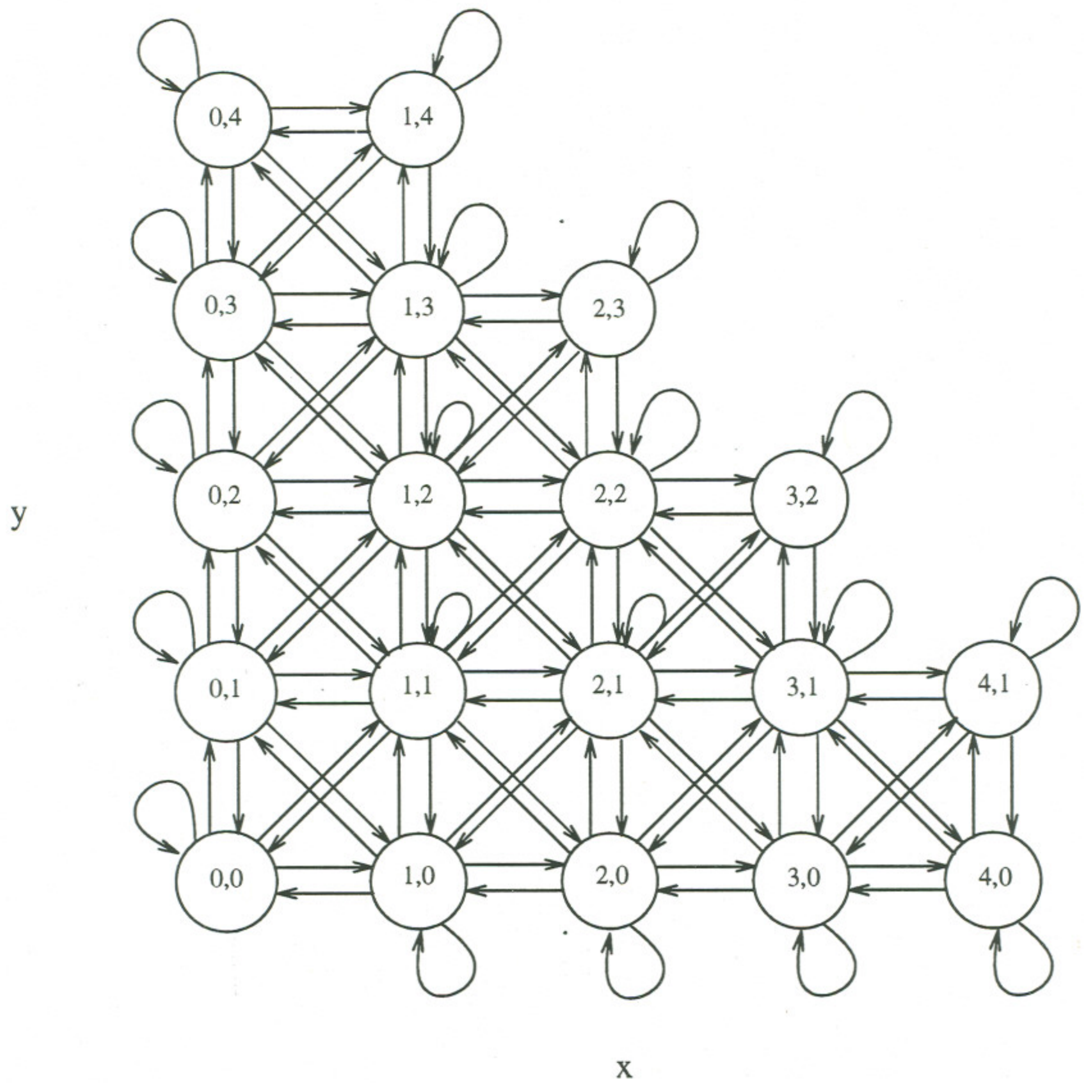

Figure 4 State transition diagram for a queueing system using the SBCBS strategy with N=5

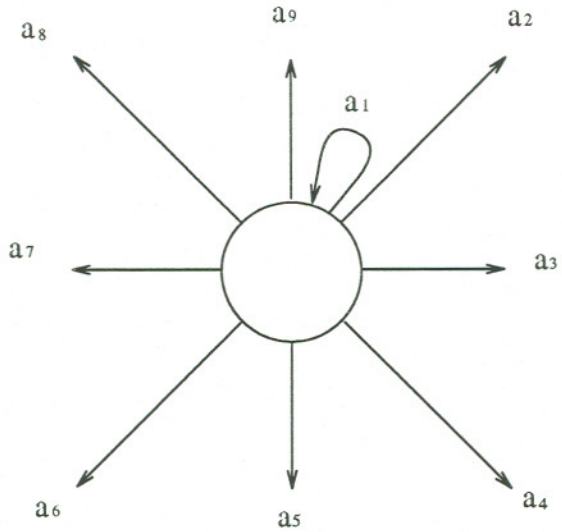

Figure 5.1 State transition probabilities for the states
$\{(x,y)|x>0,y>0,(x+y)<(N-1)\}$

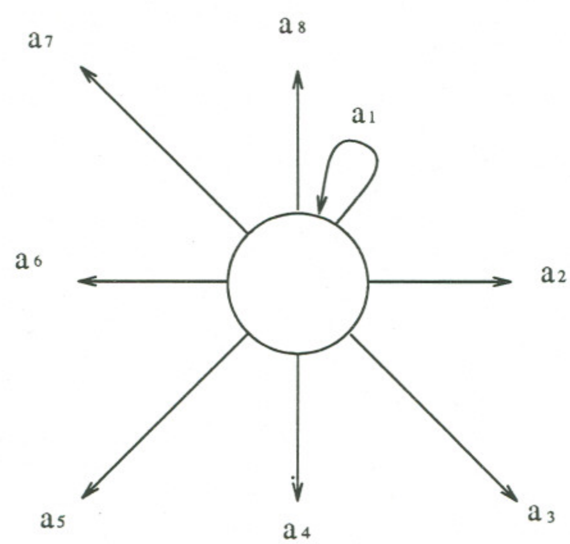

Figure 5.2 State transition probabilities for the states
$\{(x,y)|x>0,y>0,(x+y)=(N-1)\}$

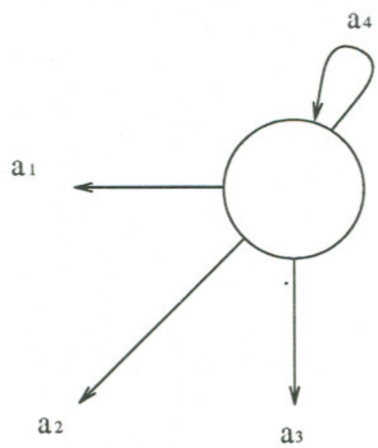

Figure 5.3 State transition probabilities for the states
{(x,y)|x>0,y>0,(x+y)=N}

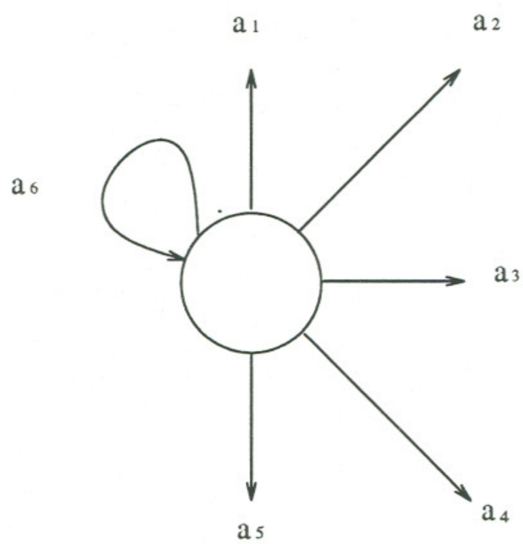

Figure 5.4 State transition probabilities for the states
{(x,y)|x=0,0<y<(N-1)}

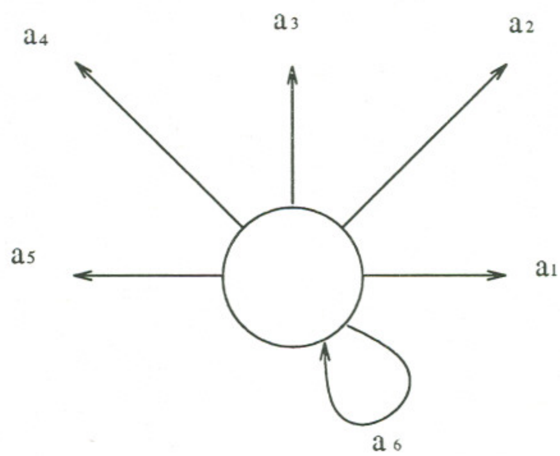

Figure 5.5 State transition probabilities for the states
{(x,y)|y=0,0<x<(N-1)}

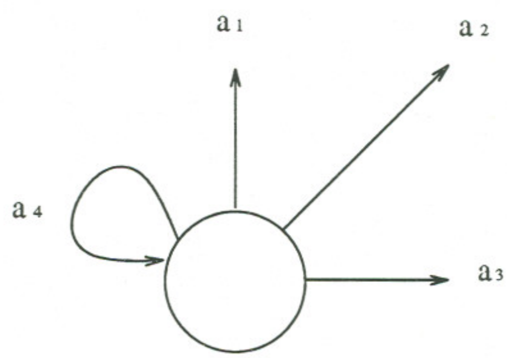

Figure 5.6 State transition probabilities for state (0,0)

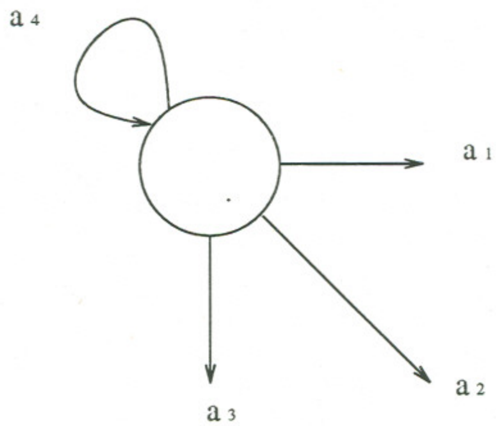

Figure 5.7 State transition probabilities for state (0,N-1)

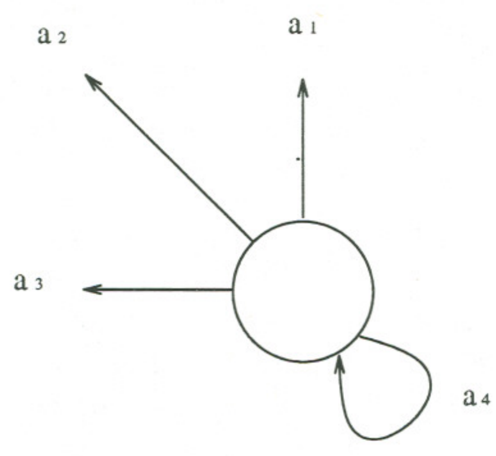

Figure 5.8 State transition probabilities for state (N-1,0)

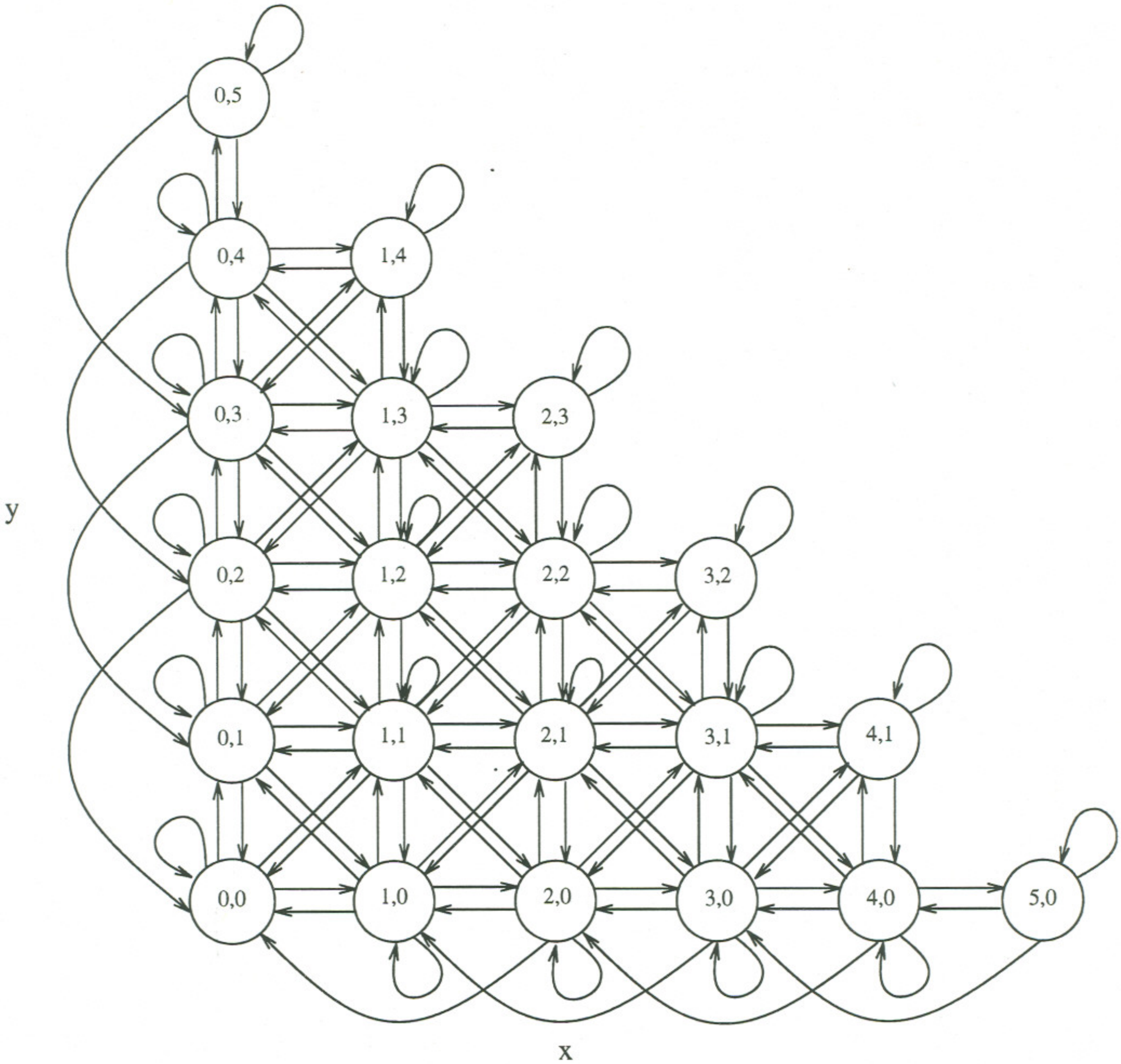

Figure 6 State transition diagram for a queueing system using the SBPPS strategy with N=5

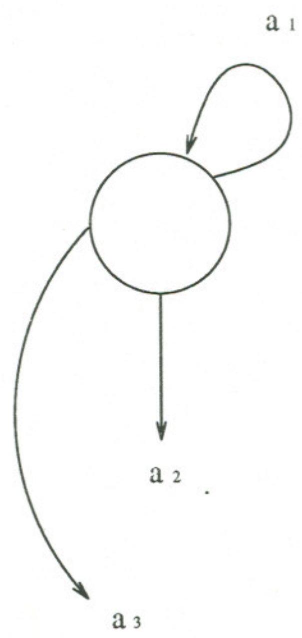

Figure 7.1 State transition probabilities for state (0,N)

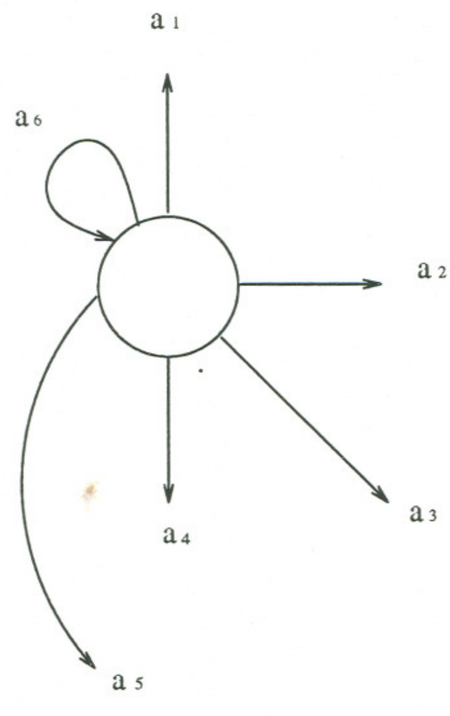

Figure 7.2 State transition probabilities for state (0,N-1)

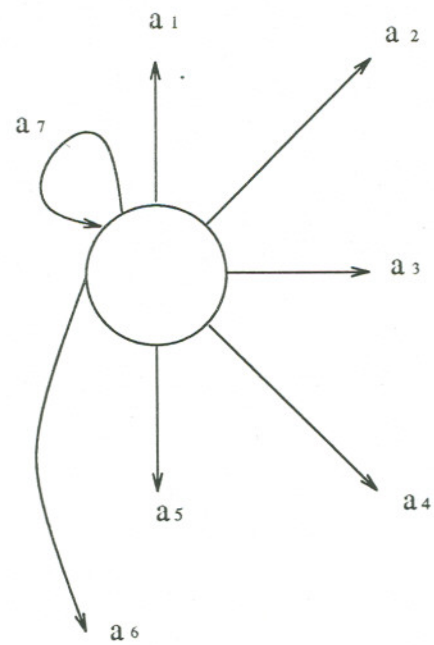

Figure 7.3 State transition probabilities for the states
{(x,y)|x=0,1<y<(N-1)}

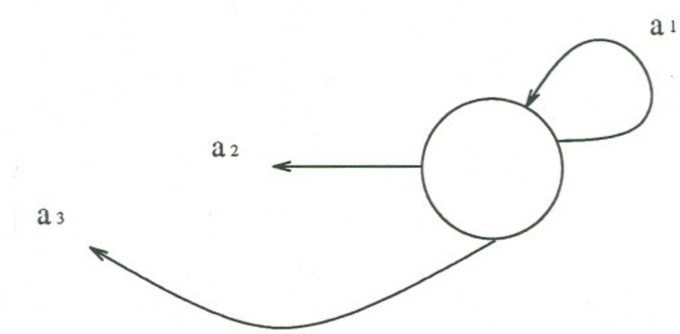

Figure 7.4 State transition probabilities for state (N,0)

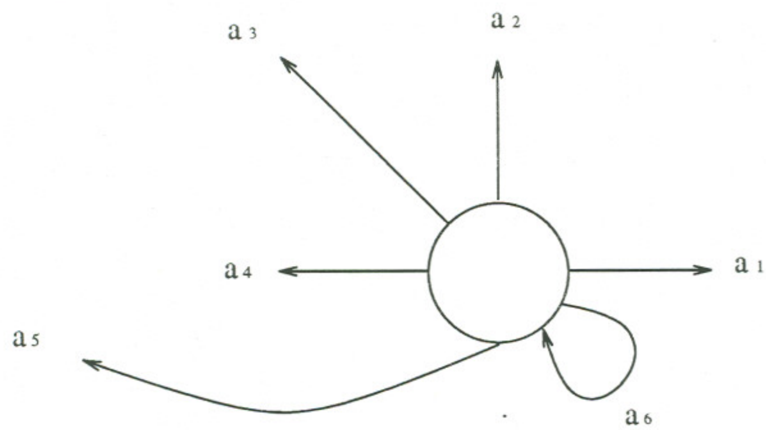

Figure 7.5 State transition probabilities for state (N-1,0)

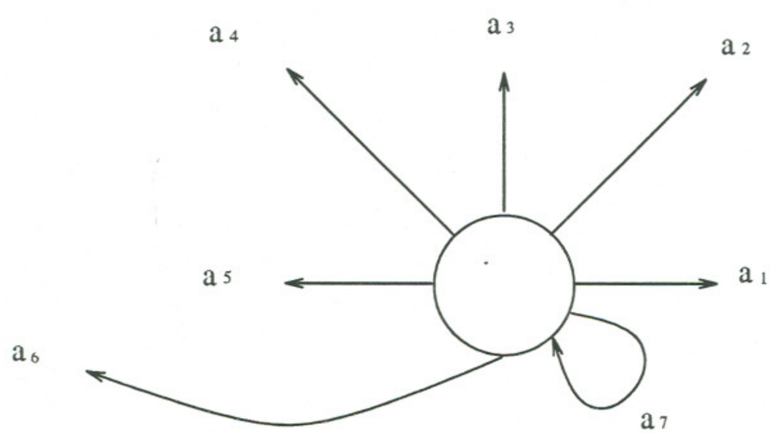

Figure 7.6 State transition probabilities for the states
{(x,y)|y=0,1<x(N-1)}

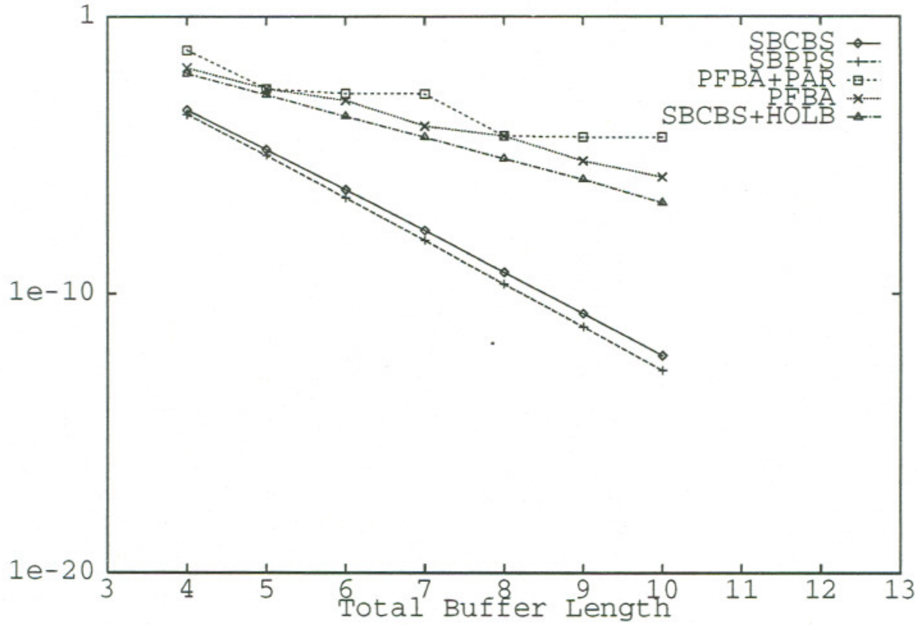

Figure 8.1 Average loss rate for $p_1 = 0.2$ $p_2 = 0.2$

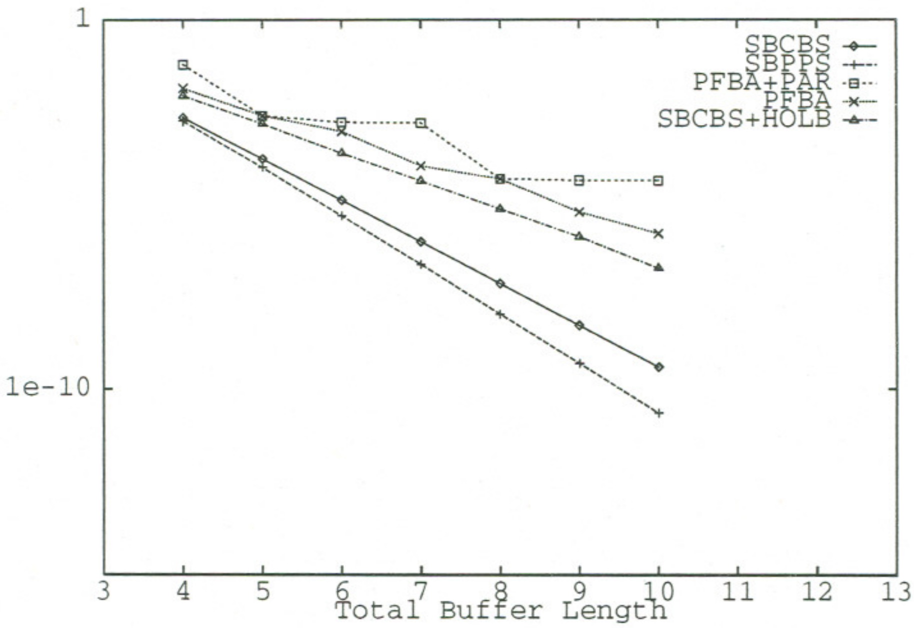

Figure 8.2 Average loss rate for $p_1 = 0.2$ $p_2 = 0.4$

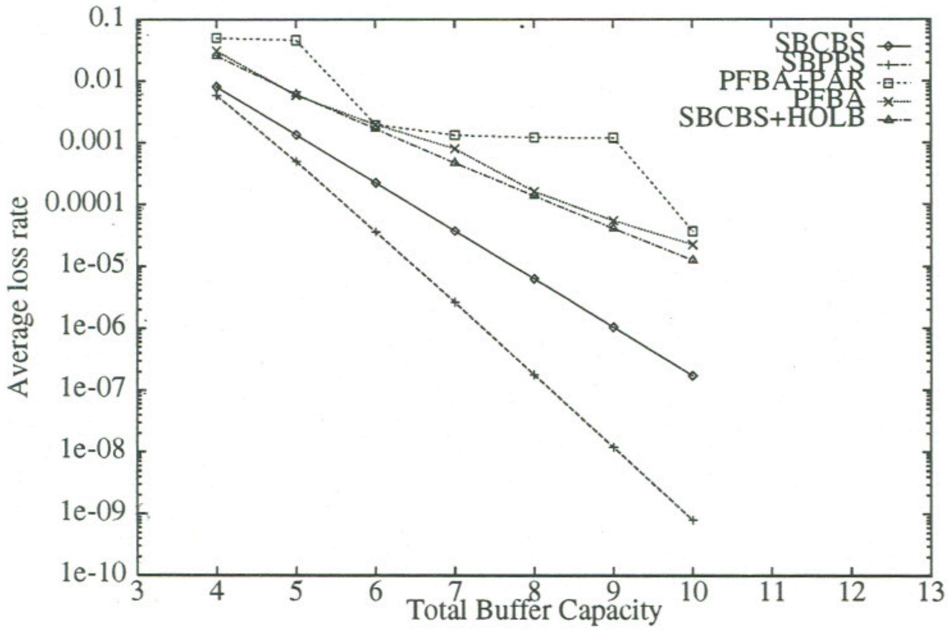

Figure 8.3 Average loss rate for $p_1 = 0.2$ $p_2 = 0.6$

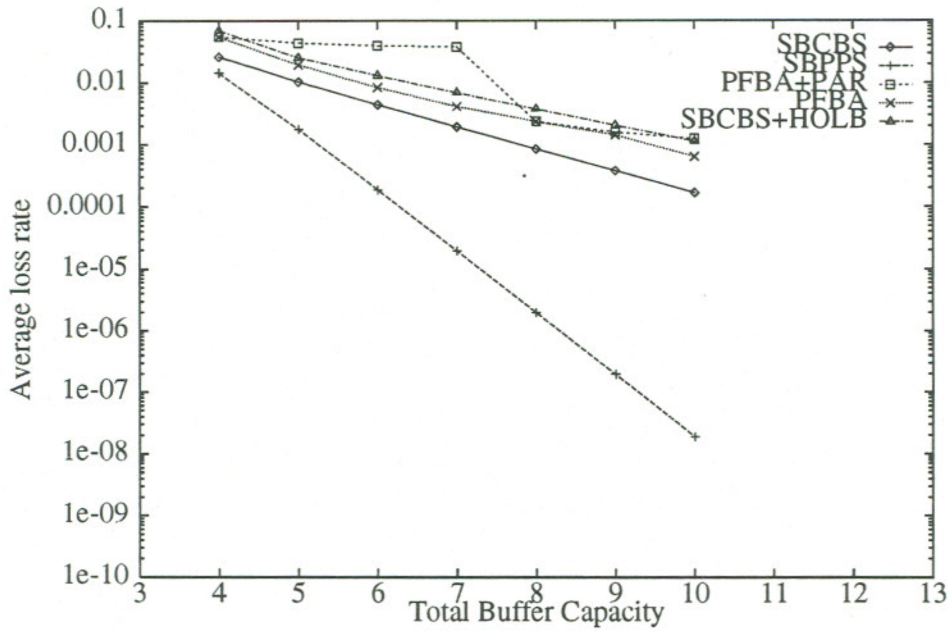

Figure 8.4 Average loss rate for $p_1 = 0.2$ $p_2 = 0.8$

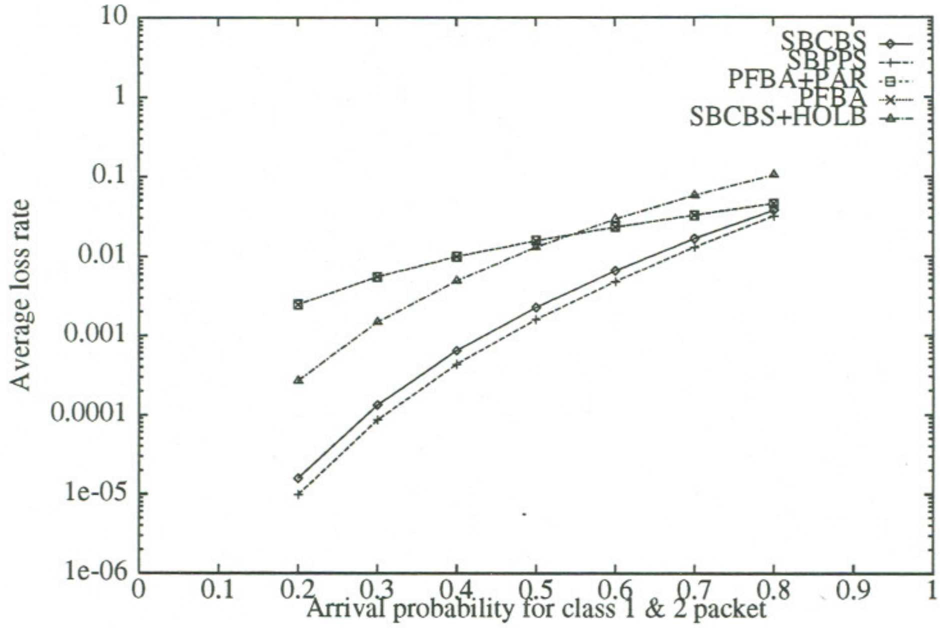

Figure 9.1 Average loss rate when the load from both classes packets are the same total buffer capacity N=5

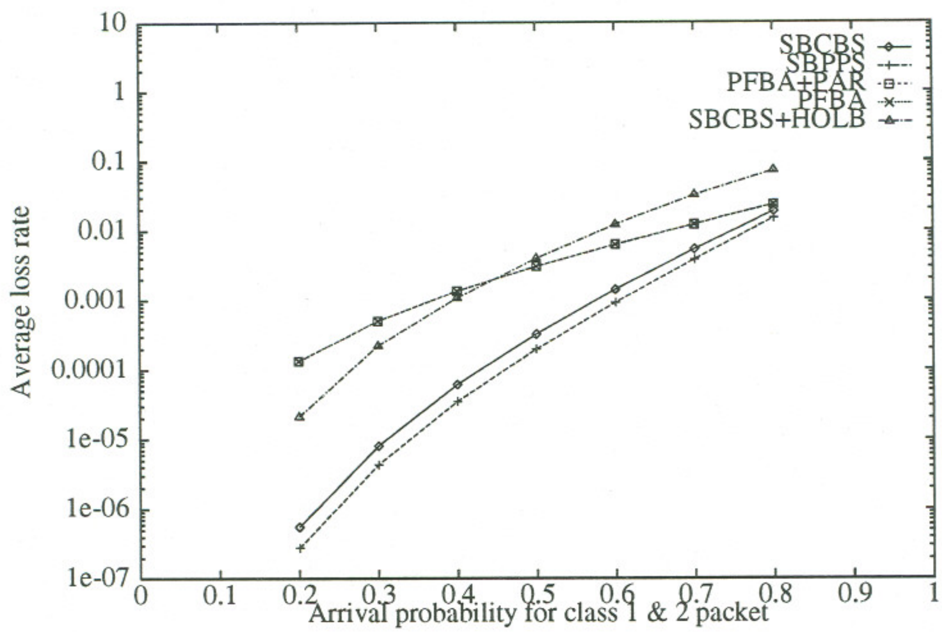

Figure 9.2 Average loss rate when the load from both classes packets are the same total buffer capacity N=6