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**ON THE ANALYSIS OF REQUEST-RESPONSE COMMUNICATION IN A TOKEN PASSING RING**

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# ON THE ANALYSIS OF REQUEST-RESPONSE COMMUNICATION IN A TOKEN PASSING RING

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## Abstract

The paper investigates performance issues related to request-response communication in distributed systems built around a token passing ring. The objective of this paper is to construct a model of a distributed system using request-response communication, to point out the difficulties related to an exact analysis of the model in case of a cyclic server system, and then to discuss an approximation. The analysis is then carried out for a traditional system and for a modified cyclic server system.

## 1. INTRODUCTION

Request-response communication supports the client-server paradigm in distributed systems. In this form of communication, a client sends a request for service to a remote server, the request is processed and then the server responds [2].

Since request-response communication ultimately involves the exchange of some data and control packets, it can be treated just as another form of communication and can be implemented using traditional protocols. But it is also possible to exploit its characteristics, for example, to treat responses as implicit acknowledgements and to use functional addressing schemes as we have proposed [5].

To stress the importance of request-response communication, we point out that very recently Cheriton has released the specifications of a transport protocol designed to support this form of communication in Internet [3]. The motivation for the Versatile Message Transport Protocol (VMTP) are poor performance, weak naming scheme, and excessive complexity of the implementation of Remote Procedure Call protocols when standard transport protocols like TCP and UDP are used. We believe that proliferation of distributed systems consisting of workstations and servers, as well as availability of efficient protocols, will contribute to a wide spread use of this form of communication.

Let us now consider the performance related issues of request-response communication. Since protocols supporting it have appeared only recently, there are only a few performance studies in this area. The objective of this paper is to construct a model of a system using request-response communication, to point out the difficulties related to an exact analysis of the model and then to discuss an approximation. Though protocols like VMTP are designed for an internetwork consisting of local and wide area networks, we restrict our discussion to request-response communication in local networks only.

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From the practical standpoint, distributed systems spanning a local domain are of primary interest, and the performance analysis is probably more feasible in this case.

There is a close relationship between the performance of a request-response protocol and the medium access control method in a local network. We focus our attention on ring or bus topologies with a collision free multiple access method since we believe that it is reasonable to assume a rather heavy traffic in a distributed system using request-response communication.

Efficient, and easier to use request-response protocols will certainly increase the range and scope of distributed applications, with a corresponding increase in the network traffic. As we know token passing ring systems exhibit a better performance at heavy traffic load than the comparable systems using collision based multiple-access methods like CSMA/CD, or splitting algorithms. This motivate us to investigate request-response communication in a token passing system.

In this paper we call the communicating agents entities, and we recognize two types of them, namely client and server entities. Such entities would be processes, light weight processes, threads of control, tasks, etc. Thereafter we consider client and server entities, which are active on hosts interconnected by a token passing ring. We are primarily interested in the delay analysis and in ergodicity conditions for this type of system. The time elapsed between the moment a request is generated and the time when the response is received, is determined by communication delays, waiting and processing delays. The central topic of our investigation are the communication delays, which depend upon the multiple access control algorithm in case of a local network .

There are several remarkable studies of cyclic server systems which model a token passing ring [1], [7], [8]. A standard modeling assumption in traditional analysis of cyclic server systems is that the arrival process at all queues served by the cyclic server are independent Poisson processes. In the system we investigate the arrival process for the requests can still be modeled as Poisson processes, but response arrivals correspond to more general processes, which are also dependent upon the arrival of requests.

In case of request-response communication, it seems appropriate for the cyclic server to use different service disciplines for queues associated with client and with server entities. In this paper we assume an exhaustive service discipline for queues associated with server entities. The cyclic server serves all the responses in the queue. Other possible alternatives for server entities queues are semi-exhaustive or gated service disciplines, [1], but they will not be discussed here. For queues associated with client entities, we discuss two cases the 1-limited, and the exhaustive service discipline. We believe that different service disciplines are necessary since the number of client entities is usually considerably larger than that of server entities, and consequently the traffic associted with server entities is more intense than the one associated with client entities.

It seems also reasonable to investigate more intricate trajectories of the cyclic server. We have proposed a multiple-access method which correlates the allocation of the communication channel with server availability. In our scheme each service is identified by a function code which is unique system-wide, and multiple servers may provide the same service. In ADMA (Availability Driven Multiple Access), a client is allowed to send a request only when one of the servers sends out an explicit invitation stating that it is willing to perform that service. A detailed discussion of ADMA can be found in reference [6]. One of the main attractions of the scheme is that it leads to simple implementations of the server initiated load balancing strategies.

For simplicity we consider only the case when each server provides only one type of service. Such a system can be modeled as a cyclic server system in which the cyclic server performs a visit to all client nodes after visiting a server node. More precisely we recognize two types of cycles, a major and a minor one. During a major cycle, the cyclic server visits the queue associated with a server entity, then it performs a minor cycle visiting all queues associated with client entities requesting, then moves along to the next queue associated with a server entity and so on until it visits all queues associated with server entities. This scheme will be described in more detail in Section 5.

We consider an approximate analysis such that the arrival processes are independent and study the behavior of this system. We use recent results of Boxma and Groenedijk [1], which have established pseudo conservation laws for cyclic server systems.

The paper is organized as follows. The modeling assumptions are spelled out in the next section. Then a common cyclic server system is analyzed and communication delays are approximated. A discussion of the remote execution follows. Finally we extend the approximations to a modified cyclic server system which models an ADMA system.

## 2. THE MODEL

In this section we describe the model of the system and the relevant modeling assumptions. We concentrate first upon the communication aspects and discuss two systems, an asymmetric system and a symmetric one. Then we discuss modeling assumptions relevant to the remote execution supported by the request-response communication.

### 2.1 Modeling assumptions - the communication side

The relevant assumptions concerning the configuration of the system as well as the communication aspects are summarized in the following.

1. The system consists of $M+N$ client nodes called $C$-nodes and $N$ server nodes called $S$-nodes. This model corresponds to a system with $M$ nodes, which host only client entities and $N$ nodes hosting both client and server entities. An example of such a system is a set of $M$ workstations (client nodes) connected with $N$ servers. Each server can, in turn, be a client to another server, hence we model a server as a pair consisting of a $C$-node and an $S$-node.
2. We assume a time slotted channel. Each slot size is equal to the transmission time of a packet.
3. The arrival processes at each queue is assumed to be independent of the arrival process at other queues. The arrival process at all queues are considered to be Bernoulli processes with batch arrivals. The first and the second moments of the arrival rates are assumed to be known.

4. The traffic generated at each $C$-node is due to requests. At each $C$-node, $C_i$, $1 \le i \le N + M$, there are $N$ queues $Q_{i,j}$, $1 \le j \le N$ one for each server. The first moment of the arrival process at each queue $Q_{i,j}$ is $\lambda_{i,j}^{req}$. The first moment of the total request rate at $C_i$ is

$$\lambda_i^{req} = \sum_{j=1}^{N} \lambda_{i,j}^{req} \tag{2.1}$$

Each request may consist of one or more packets. We denote

$$\begin{aligned} b_{i,j}^{req} &= \text{the number of packets per request for } Q_{i,j} \\ \beta_{i,j}^{req} &= E[b_{i,j}^{req}] \end{aligned} \tag{2.2}$$

The mean number of packets per request is

$$\beta^{req} = \frac{\sum_{i=1}^{M+N} \beta_i^{req}}{M + N} \tag{2.3}$$

The mean offered traffic associated with $Q_{i,j}$ at $C_i$ is

$$\rho_{i,j}^{req} = \lambda_{i,j}^{req} \cdot \beta_{i,j}^{req} \tag{2.4}$$

The total offered traffic at $C_i$ is

$$\rho_i^{req} = \sum_{j=1}^{N} \rho_{i,j}^{req} \tag{2.5}$$

Two service disciplines will be considered. First we discuss the exhaustive service discipline at each queue $Q_{i,j}$. In this case all packets of all requests are sent when the cyclic server visits the queue. Then we assume that the service discipline at each queue $Q_{i,j}$ is 1-limited. All the packets corresponding to one request only can be sent when the cyclic server visits the queue.

4. The traffic generated at each $S$-node, $S_j$, $1 \le j \le N$ is due to responses. The cyclic server serves a queue of responses called $Q_j$. The first moment of the response arrival process is

$$\lambda_j^{resp} = \sum_{i=1}^{M+N} \lambda_{i,j}^{req} \tag{2.6}$$

Each response may generate one or more packets. Let us denote

$$b_j^{resp} = \text{the number of packets per response for responses generated at } S_j \qquad (2.7)$$
$$\beta_j^{resp} = E[b_j^{resp}]$$

The mean number of packets per response is

$$\beta^{resp} = \frac{\sum_{j=1}^{N} \beta_j^{resp}}{N} \qquad (2.8)$$

The mean offered traffic at $S_j$ is

$$\rho_j^{resp} = \lambda_j^{resp} \cdot \beta_j^{resp} \qquad (2.9)$$

The service discipline at $Q_j$ is exhaustive.

6. There are no error control mechanisms other than those built-in the request-response communication itself. A client entity sends a request and the response serves also as an implicit acknowledgement.
7. Each queue has an infinite buffer capacity. There are $N(N+M)$ queues at $C$-nodes and $N$ queues at $S$-nodes.
8. The average transmission time for a request-response for a channel with maximum transmission rate $R$ is

$$T_{trans} = \frac{\beta^{req} + \beta^{resp}}{R} \qquad (2.10)$$

**2.2 An asymmetric system**

Let us now consider an asymmetric system with different arrival rates and average number of packets per request/response at each node. The global request-response arrival rate in the system is:

$$\lambda = \sum_{i=1}^{M+N} \lambda_i^{req} + \sum_{j=1}^{N} \lambda_j^{resp} \qquad (2.11)$$

Its second moment is denoted by $\lambda^{(2)}$. Using (2.1) and then (2.6) $\lambda$ can be expressed as

$$\lambda = \sum_{j=1}^{N} \left[ \sum_{i=1}^{M+N} \lambda_{i,j}^{req} + \lambda_j^{resp} \right] = 2 \sum_{j=1}^{N} \lambda_j^{resp} \tag{2.12}$$

From (2.11) and (2.12) it follows that

$$\sum_{i=1}^{M+N} \lambda_i^{req} = \sum_{j=1}^{N} \lambda_j^{resp} \tag{2.13}$$

This is a flow conservation relation which expresses the fact that any request generated at some $C$-node has associated with it a response provided by some $S$-node. From (2.12) and (2.13) it follows that

$$\sum_{i=1}^{M+N} \lambda_i^{req} = \frac{\lambda}{2} \tag{2.14}$$

The offered traffic in the network is

$$\rho = \sum_{i=1}^{N+M} \rho_j^{req} + \sum_{j=1}^{N} \rho_j^{resp} \tag{2.15}$$

Let us define

$$\beta = \sum_{i=1}^{N+M} \frac{\lambda_i^{req}}{\lambda} \beta_i^{req} + \sum_{j=1}^{N} \frac{\lambda_j^{resp}}{\lambda} \beta_j^{resp} \tag{2.16}$$

and

$$\beta^{(2)} = \sum_{i=1}^{M+N} \frac{\lambda_i^{req}}{\lambda} \beta_i^{(2)req} + \sum_{j=1}^{N} \frac{\lambda_j^{resp}}{\lambda} \beta_i^{(2)resp} \tag{2.17}$$

with $\beta_i^{(2)req}$ and $\beta_j^{(2)resp}$ the second moments of the number of messages in a request or response. The total traffic $\rho$ can be expressed as (see 2.15)

$$\rho = \lambda \beta \tag{2.18}$$

### 2.3 A symmetric system

Let us now examine a symmetric system. In this case all arrival rates at $C$-nodes are equal, all response rates at $S$-nodes are equal, the average number of packets in a request are the same, and the average number of packets in a response are the same.

Since the mean request arrival rates of all $C$-nodes are equal

$$\lambda_i^{req} = \lambda^{req} \quad \text{for } 1 \le i \le M + N \tag{2.19}$$

It follows (see 2.14) that

$$\lambda^{req} = \frac{\lambda}{2\,(M+N\,)} \tag{2.20}$$

Similarly, the average response arrival rates of all $S$-nodes are equal

$$\lambda_j^{resp} = \lambda^{resp} \qquad \text{for } 1 \le j \le N \tag{2.21}$$

From (2.12) it follows that

$$\lambda^{resp} = \frac{\lambda}{2\,N} \tag{2.22}$$

Let us now examine the offered traffic. The symmetry implies that all requests have the same average number of packets

$$\beta_{i,j}^{req} = \beta^{req} \qquad \text{for } 1 \le i \le M+N, \text{ and } 1 \le j \le N \tag{2.23}$$

The offered traffic at $C$-node $i$ due to requests becomes

$$\rho_i^{req} = \sum_{j=1}^{N} \rho_{i,j}^{req} = \beta^{req}\,\lambda^{req} \tag{2.24}$$

It follows that

$$\rho_i^{req} = \rho^{req} = \beta^{req}\,\frac{\lambda}{2(M+N)} \qquad \text{for } 1 \le i \le M+N \tag{2.25}$$

Similarly all responses have the same average number of packets

$$\beta_j^{resp} = \beta^{resp} \qquad \text{for } 1 \le j \le N \tag{2.26}$$

From (2.9) it follows that

$$\rho_j^{resp} = \rho^{resp} = \beta^{resp}\,\frac{\lambda}{2\,N} \qquad \text{for } 1 \le j \le N \tag{2.27}$$

The expressions for $\beta$ and $\beta^{(2)}$ become (see 2.16 and 2.17)

$$\beta = \frac{\beta^{req} + \beta^{resp}}{2} \tag{2.28}$$

$$\beta^{(2)} = \frac{\beta^{(2)req} + \beta^{(2)resp}}{2} \tag{2.29}$$

## 3. A COMMON CYCLIC SERVER SYSTEM

In this section we present the analysis of request-response communication in a token passing ring. We discuss the communication aspects only, and present first a cycle time analysis followed by a discussion of the delays for two cases. First we consider the case when the service discipline at $C$-nodes is exhaustive and then we analyze the 1-limited service discipline case.

The system consists of $M + 2N$ queues as follows. There are $N$ queues, one at each $S$-node. Then we aggregate the $N$ queues $Q_{i,j}$ at any $C$-node $C_i$, $1 \le i \le N + M$ into a single queue, $Q_i$ and assume an aggregate mean arrival rate equal to $\lambda_i^{req}$ at each queue $Q_i$, $1 \le i \le N + M$. We study the mean cycle time and then we attempt a delay analysis of the equivalent system. First we assume exhaustive service at all $Q_j$, $1 \le j \le N$ associated with server entities and at all $Q_i$, $1 \le i \le M + N$, associated with client entities. Then we discuss the case when the service discipline is 1-limited at queues associated with client entities. The pseudo conservation laws of Boxma and Groenedijk [1] allow us to express weighted sums of the delays in a system using a mix of service disciplines.

### 3.1 The cycle time analysis

Let us now assume that the system is in equilibrium and call $s_i$ the mean switch over time from the $k^{th}$ to $(k + 1)$ queue, and $s^{(2)}$ the second moment of the switch over time. Then the first two moments of the total switch over time are

$$s = \sum_{k=1}^{M+2N} s_k \tag{3.1}$$

and

$$s^{(2)} = \sum_{k=1}^{M+2N} s_k^{(2)}$$

Now the mean visit times at an $S$-queue and at a $C$-queue are respectively

$$E[V_j] = \rho_j^{resp}\, E[C] \quad \text{for} \quad 1 \le j \le N \tag{3.2}$$

and

$$E[V_i] = \rho_i^{req}\, E[C] \quad \text{for} \quad 1 \le i \le M + N \tag{3.2'}$$

with $E[C]$ the mean cycle time, the mean interval between two consecutive visits of the cyclic server at a given queue. Summing over all visits for a cycle, we obtain

$$\sum_{i=1}^{M+N} E[V_i] + \sum_{j=1}^{N} E[V_j] = E[C] - \sum_{k=1}^{M+2N} s_k$$

or

$$\sum_{i=1}^{M+N} \rho_i^{req} E[C] + \sum_{j=1}^{N} \rho_j^{resp} E[C] = E[C] - s$$

and

$$E[C] = \frac{s}{1-\rho} \tag{3.3}$$

with $\rho$ given by expression (2.18). The expected visit time and intervisit time for the queues, associted with server entities are

$$E[V^{resp_j}] = \rho_j^{resp} \frac{s}{1-\rho} \tag{3.4}$$

$$E[I^{resp_j}] = E[C] - E[V^{resp_j}] = \frac{s}{1-\rho} [1 - \rho_j^{resp}] \tag{3.5}$$

for $1 \le j \le N$

The corresponding visit and intervisit time for the queues associted with client entities are

$$E[V^{req_i}] = \rho_i^{req} \frac{s}{1-\rho} \tag{3.6}$$

$$E[I^{req_i}] = E[C] - E[V^{req_i}] = \frac{s}{1-\rho} [1 - \rho_i^{req}] \tag{3.7}$$

for $1 \le i \le N + M$.

Note that for a symmetric system

$$E[V^{req_i}] = E[V^{req}] \text{ for } 1 \le i \le M + N \tag{3.8}$$

From (2.18) and (2.25) it follows that

$$E[V^{req}] = \beta^{req} \frac{\lambda}{2(M+N)} \frac{s}{1-\lambda\beta} \tag{3.9}$$

Then the average number of requests arriving at queue $Q_i$ located at $C$-node $C_i$ during a cycle time is

$$E[N^{req}] = \frac{\lambda}{2(M+N)} \frac{s}{1-\lambda\beta} \tag{3.10}$$

Similarly from (2.18) and (2.27)

$$E[V^{resp}] = \beta^{resp} \frac{\lambda}{2N} \frac{s}{1-\lambda\beta} \tag{3.11}$$

The average number of responses arriving at queue $Q_j$ located at $S$-node $C_j$ during a cycle time is

$$E[N^{resp}] = \frac{\lambda}{2N} \frac{s}{1-\lambda\beta} \tag{3.12}$$

### 3.2 Delay analysis when the service discipline is exhaustive at all queues

Let us consider first the case when the service discipline is exhaustive at all queues. In this case

$$\sum_{i=1}^{M+N} \rho_i^{req} EW_i^{req} + \sum_{j=1}^{N} \rho_j^{resp} EW_j^{resp} =$$

$$\frac{\lambda\beta^{(2)}}{2(1-\rho)} \rho + \frac{(\lambda^{(2)} - \lambda^2 - \lambda)\beta}{2\lambda(1-\rho)} \rho + \rho \frac{s^{(2)}}{2s} - \frac{1}{2}\rho \tag{3.13}$$

$$+ \frac{s}{2(1-\rho)} \left[ \rho^2 - \sum_{i=1}^{M+N} (\rho_i^{req})^2 - \sum_{j=1}^{N} (\rho_j^{resp})^2 \right]$$

$EW_i^{req}$ is the mean waiting time of a request arriving at a $C$-node $C_i$, and $EW_j^{resp}$ is the mean waiting time of a response generated at an $S$-node $S_j$.

In case of a symmetric system we have

$$EW_i^{req} = EW^{req} \qquad 1 \le i \le M+N \tag{3.14}$$

$$EW_j^{resp} = EW^{resp} \qquad 1 \le j \le N \tag{3.14'}$$

$$\rho^2 = \lambda^2 \left[ \frac{\beta^{req} + \beta^{resp}}{2} \right]^2 \tag{3.14''}$$

We note that when $N$ and $N + M$ are large the following approximation is justified

$$\sum_{i=1}^{M+N} (\rho_i^{req})^2 + \sum_{j=1}^{N} (\rho_j^{resp})^2 = (M+N) \left[ \frac{\beta^{req}\lambda}{2(M+N)} \right]^2 + N \left[ \frac{\beta^{resp}\lambda}{2N} \right]^2 \ll \rho^2 \tag{3.15}$$

With this approximation (3.13) becomes

$$\frac{\beta^{req}}{\beta} EW^{req} + \frac{\beta^{resp}}{\beta} EW^{resp} = \tag{3.16}$$

$$= \frac{1}{(1-\lambda\beta)} \left[ \lambda\beta^{(2)} + \frac{\lambda^{(2)}}{\lambda}\beta - \lambda^2\beta - \lambda\beta + s\lambda\beta \right] + \lambda\beta \left[ \frac{s^{(2)}}{s} - 1 \right]$$

Finally we note that when $\beta^{req} = \beta^{resp}$ the average request-response communication time is given by

$$T_{comm} = EW^{req} + EW^{resp} = \tag{3.17}$$

$$= \frac{\beta}{(1-\lambda\beta)} \left[ \lambda\,(c_\beta + s) + c_\lambda + 1 - \lambda^2 \right] + \lambda\beta c_s$$

The following notation is used for random variables $\lambda$, $\beta$ and $s$

$$c_x = \frac{x^{(2)}}{x} - 1 \tag{3.18}$$

with $x$ and $x^{(2)}$ the first and the second moments of random variable $X$.

### 3.3 Delay analysis when the service discipline is 1-limited at $C$-nodes

We examine now the case when the service discipline is 1-limited for queues associated with client entities and exhaustive for the ones associated with server entities. If we denote the corresponding mean waiting times by $E[W_i^{req}]$ and $E[W_j^{resp}]$ and we apply the results from [1] we obtain

$$\sum_{i=1}^{M+N} \rho_i^{req} \left[ 1 - \frac{\lambda_i^{req} \cdot s}{1-\rho} \right] EW_i^{req} + \sum_{j=1}^{N} \rho_j^{resp}\, EW_j^{resp} =$$

$$\frac{\lambda\beta^{(2)}}{2(1-\rho)}\,\rho + \frac{(\lambda^{(2)} - \lambda^2 - \lambda)\beta}{2\lambda(1-\rho)}\,\rho + \rho\,\frac{s^{(2)}}{2s} - \frac{1}{2}\,\rho + \tag{3.19}$$

$$+ \frac{s}{2(1-\rho)} \left[ \rho^2 + \sum_{i=1}^{M+N} (\rho_i^{req})^2 + \sum_{j=1}^{N} (\rho_j^{resp})^2 + 2 \sum_{i=1}^{M+N} \frac{(\lambda_i^{req})^{(2)} - \lambda_i^{req}}{2\lambda_i^{req}}\, \rho_i^{req} \right]$$

The case of a symmetric system is considered now. We use the approximation discussed previously, (3.15). In addition we have

$$2 \sum_{i=1}^{M+N} \frac{(\lambda_i^{req})^{(2)} - \lambda_i^{req}}{2\lambda_i^{req}} \rho_i^{req} = \lambda \beta^{req} c_\lambda \tag{3.20}$$

With these approximations the expression (3.19) becomes

$$\frac{\beta^{req}}{\beta} \left[ 1 - \frac{\lambda^{req} \cdot s}{1 - \rho} \right] EW^{req} + \frac{\beta^{resp}}{\beta} EW^{resp} = \tag{3.21}$$

$$= \frac{1}{(1 - \lambda\beta)} \left[ \lambda\beta^{(2)} + \frac{\lambda^{(2)}}{\lambda}\beta - \lambda^2\beta - \lambda\beta + s\lambda\beta \right]$$

$$+ \lambda\beta \left[ \frac{s^{(2)}}{s} - 1 \right] + \frac{s}{1 - \rho} \lambda \beta^{req} c_\lambda$$

Using the notations defined by (3.18) this expression becomes

$$\frac{\beta^{req}}{\beta} \left[ 1 - \frac{\lambda^{req} \cdot s}{1 - \rho} \right] EW^{req} + \frac{\beta^{resp}}{\beta} EW^{resp} = \tag{3.22}$$

$$= \frac{\beta}{(1 - \lambda\beta)} \left[ \lambda\, (c_\beta + s) + c_\lambda + 1 - \lambda^2 \right] + \lambda\beta c_s + \frac{s}{1 - \rho} \lambda \beta^{req} c_\lambda$$

## 4. ANALYSIS OF REMOTE EXECUTION

The request-response communication discussed in this paper supports the client-server paradigm used to move computations from a client node to a server node of the system. In the following, we assume that at each $S$ node $S_n$, $1 \le j \le N$ there is a server $\sum_j$. We are concerned with the delay analysis, namely the time spent by a request at $\sum_j$, as well as the ergodicity conditions associated with remote execution.

For simplicity, we consider a symmetric system. The assumptions related to modeling of remote execution are:

(1) There are $N$ identical server $\sum_j$, $1 \le j \le N$, one located at each $S$-node of the network.

(2) The arrival process at each $\sum_j$ is a general stochastic process with average arrival rate $\lambda^{exec}$. We restrict our discussion to a system at equilibrium. In this case the average arrival rate of requests at $\sum_j$ equals the average

response rate at the corresponding $Q_j$, given by (2.22).

$$\lambda^{exec} = \lambda^{resp} = \frac{\lambda}{2N} \tag{4.1}$$

(3) The arrival process at $\sum_j$ depends upon the service discipline associated with the cyclic server at $C$-nodes. In case of 1-limited service discipline, requests arrive at $\sum_j$ one at a time at a rate given by (4.1). When the service discipline at $C$-nodes is exhaustive, all requests from $C_i$ to $\sum_j$ are sent at once, and we model this case as a batch arrival process. The average number of requests queued at a $C$-node waiting to be transmitted, is given by (3.10). Due to the symmetry of the system, we can estimate the average batch size as

$$q^{exec} = \frac{E[N^{req}]}{N} \tag{4.2}$$

The corresponding batch arrival rate is

$$\lambda_q^{exec} = \frac{\lambda^{exec}}{q^{exec}} \tag{4.3}$$

4. The average processing time associated with every request is $\frac{1}{\mu}$. The ergodicity condition is then $\frac{\lambda}{2\mu N} < 1$.

An exact analysis of remote execution is fairly difficult. We'll outline such an analysis for the case when the cyclic server discipline at $C$ nodes is 1-limit. The service process at each $\sum_j$ is a Poisson process. In this case, the remote execution can be modeled as a G|M|1 system with

- arrival process $A(x)$,
- average arrival rate $\lambda^{rexec}$,
- average service rate $\mu$.

As shown in [4], the average time in system is

$$T_{exec} = \frac{1}{\mu} \frac{1}{1-\sigma} \tag{4.4}$$

with $\sigma$ the unique root of

$$\sigma = A^*(\mu - \mu\sigma) \tag{4.5}$$

in the range $0 < \sigma < 1$. $A^*$ is the Laplace transform of $A(x)$.

In the special case

$$A(x) = 1 - e^{-\lambda^{exec} t} \qquad (t \geq 0) \tag{4.6}$$

we have

$$A^*(\mu - \sigma\mu) = \frac{\lambda^{serv}}{\mu - \sigma\mu + \lambda^{serv}} \tag{4.7}$$

As expected for an $M/M/1$ system we have $\sigma = \dfrac{\lambda^{serv}}{\mu}$ in this case.

## 5. A MODIFIED CYCLIC SERVER SYSTEM

Let us now consider a cyclic server which serves a system consisting of the $N$ queues, $Q_j^{resp}$, $1 \leq j \leq N$ each located at $S$-node $S_j$, and of the $N(N+M)$ queues $Q_{i,j}^{req}$, $1 \leq i \leq M+N$, $1 \leq j \leq N$ located at the $C$-nodes.

The cyclic server proceeds as follows

1. The cyclic server arrives at $S$-node $S_j$. Then it starts a minor cycle and visits precisely one queue at each of the $M+N$, $C$-nodes, namely $Q_{i,j}^{req}$, $1 \leq i \leq M+M$, the queue of requests for $S_j$ at $C_i$.
2. After completing the minor cycle, it serves $Q_j^{resp}$, the queue of responses produced by server $\sum_j$.
3. It moves to the next $S$-node, $S_{j+1}$ and repeats steps $1-3$ such that during the minor cycle it serves the queues $Q_{i,j+1}^{req}$ for $1 \leq i \leq N+M$.
4. The major cycle is completed when the cyclic server arrives at the reference $S$-node, $S_j$.

The trajectory of the cyclic server is illustrated in Figure 1.

Let us call $V_{i,j}''$ the visit time of the cyclic server at $Q_{i,j}^{req}$, and let $E[C'']$ be the mean major cycle, cycle time called in the following, the cycle time. Then we call $V_j''$ the visit time of the server at the $Q_j^{resp}$ queue. If $\rho_{i,j}^{req}$ and $\rho_j^{resp}$ are the traffic intensities associated with $Q_{i,j}^{req}$ and $Q_j^{resp}$ respectively, we can express the mean visit times as

$$E[V_{i,j}''] = \rho_{i,j}^{req}\, E[C''] \quad \begin{array}{l} 1 \leq i \leq M+N \\ 1 \leq j \leq N \end{array} \tag{5.1}$$

and

$$E[V_j''] = \rho_j^{resp}\ E[C'']\ \ 1 \le j \le N \tag{5.2}$$

Summing over all visits of the server during a cycle (a major cycle), we obtain:

$$\sum_{j=1}^{N} \left[ \sum_{i=1}^{M+N} E[V_{i,j}''] + E[V_j''] \right] = E[C''] - s'' \tag{5.3}$$

with the first two moments of the switch time

$$s'' = \sum_{k=1}^{N(N+M+1)} s_k \tag{5.4}$$

$$s''^{(2)} = \sum_{k=1}^{N(N+M+1)} s_k^{(2)} \tag{5.4'}$$

Then it follows

$$E[C''] = \frac{s''}{1-\rho} \tag{5.5}$$

Some remarks concerning ergodicity are in order. We observe first that the necessary conditions for ergodicity are the same for the original system and for the modified one, namely, $\rho < 1$. This condition is also sufficient for $S-$ nodes, since in both cases we assume an exhaustive service. The condition is sufficient for the $C$-nodes when we assume an exhaustive service. In case of 1-limited service the additional ergodicity condition for $C-$ nodes in the original system is

$$\frac{\lambda_i^{req} s}{1-\rho} < 1 \ \text{for} \quad 1 \ \le i \le N+M \tag{5.6}$$

while for the modified system the additional condition for $Q_{i,j}^{req}$ are

$$\frac{\lambda_{i,j}^{req}\, s''}{(1-\rho)} < 1 \quad \begin{array}{l} 1 \le i < N+M \\ 1 \le j \le N\,. \end{array} \tag{5.7}$$

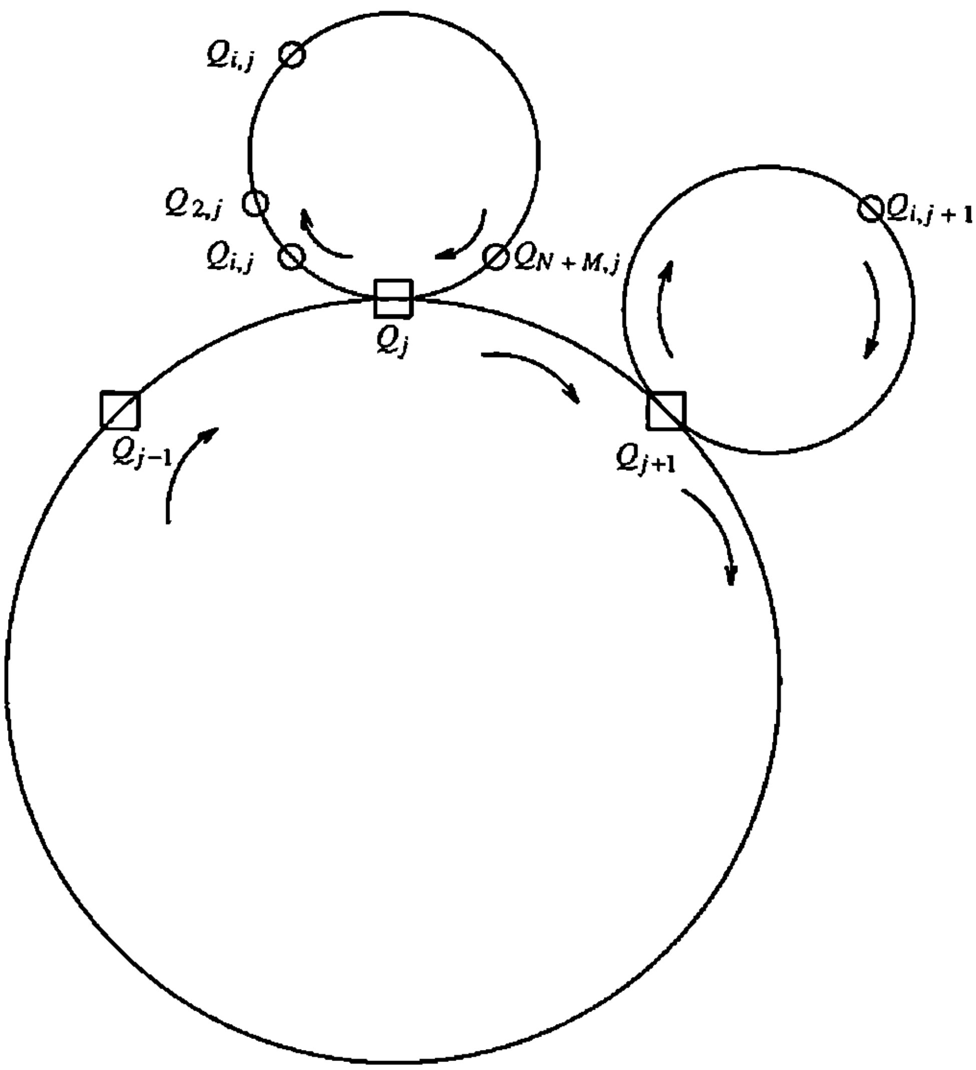


**Figure 1.** The modified cyclic server system.

We consider first the case of exhaustive service at all nodes. Then we have

$$\sum_{j=1}^{N} \left[ \sum_{i=1}^{N+M} \rho_{i,j}^{req} \; EW_{i,j}^{req} + \rho_j^{resp} \; EW_j^{resp} \right] =$$

$$\frac{\lambda\beta^{(2)}}{1(1-\rho)} + \frac{(\lambda^{(2)} - \lambda^2 - \lambda)\beta}{2\lambda(1-\rho)} + \rho \, \frac{s''^{(2)}}{2s''} - \frac{1}{2}\rho + \tag{5.8}$$

$$\frac{s''}{2(1-\rho)} \left[ \rho^2 - \sum_{j=1}^{N} \left( \sum_{i=1}^{M+N} (\rho_{i,j}^{req})^2 + (\rho_j^{resp})^2 \right) \right]$$

We concentrate upon symmetric systems and use the approximation given by (3.15). We note that in this case

$$\lambda_{i,j}^{req} = \frac{\lambda^{req}}{N}$$

with $\lambda^{req}$ given by (2.20). Then we can easily transform (5.8) into:

$$\frac{\beta^{req}}{\beta} EW^{req} + \frac{\beta^{resp}}{\beta} EW^{resp} = \tag{5.9}$$

$$= \frac{1}{(1-\lambda\beta)} \left[ \lambda\beta^{(2)} + \frac{\lambda^{(2)}}{\lambda}\beta - \lambda^2\beta - \lambda\beta + s''\lambda\beta \right] + \lambda\beta \left[ \frac{s''^{(2)}}{s''} - 1 \right]$$

When $\beta^{req} = \beta^{resp}$ the average request-response communication time is given by

$$T_{comm} = EW^{req} + EW^{resp} = \tag{5.10}$$

$$= \frac{\beta}{(1-\lambda\beta)} \left[ \lambda\,(c_\beta + s'') + c_\lambda + 1 - \lambda^2 \right] + \lambda\beta\, c_{s''}$$

Note that(5.9) and (5.10) can be obtained from (3.16) and (3.17) respectively by replacing $s$ by $s''$ and $c_s$ by $c_{s''}$.

When the service discipline is 1-limited at $C$-nodes we have

$$\sum_{j=1}^{N} \left\{ \sum_{i=1}^{N+M} \rho_{i,j}^{req} \, \frac{1 - \lambda_{i,j}^{req} s''}{1-\rho} \, EW_{i,j}^{req} + \rho_j^{resp} \, EW_j^{resp} \right\} =$$

$$\frac{\lambda\beta^{(2)}}{1(1-\rho)} + \frac{(\lambda^{(2)} - \lambda^2 - \lambda)\beta}{2\lambda(1-\rho)} + \rho\,\frac{s''^{(2)}}{2s''} - \frac{1}{2}\rho +$$

$$\frac{s''}{2(1-\rho)} \left[ \rho^2 - \sum_{j=1}^{N} \left\{ \sum_{i=1}^{M+N} (\rho_{i,j}^{req})^2 + (\rho_j^{resp})^2 \right\} \right] + \tag{5.11}$$

$$\frac{s''}{1-\rho}$$

$$\left[ \sum_{j=1}^{N} \left\{ \sum_{i=1}^{M+N} (\rho_{i,j}^{req})^2 + (\rho_j^{resp})^2 - \frac{(\lambda_{i,j}^{req(2)}) - \lambda_{i,j}^{req}}{2\lambda_{i,j}^{req}} \, \rho_i \right\} \right]$$

Following the same steps describeed earlier (see 3.22) we obtain

$$\frac{\beta^{req}}{\beta}\left[1-\frac{\lambda^{req}\cdot s''}{1-\rho}\right]EW^{req}+\frac{\beta^{resp}}{\beta}EW^{resp}= \tag{5.12}$$

$$=\frac{\beta}{(1-\lambda\beta)}\left[\lambda\,(c_\beta+s'')+c_\lambda+1-\lambda^2\right]+\lambda\beta c_{s''}+\frac{s''}{1-\rho}\lambda\,\beta^{req}\,c_\lambda$$

## CONCLUSIONS

In this paper we discuss a model for request-response communication in a token passing ring. We carry out an approximate analysis of the delay related to request-response communication which involves both communication related delays (waiting and transmission times) as well as delays related to the remote execution. Using the pseudo-conservation laws [1] we can approximate the communication delays when the service discipline is exhaustive at all queues for the common cyclic server system (3.17) and for the modifyed one (5.10) for a totally symmetric system, when the average number of packets per request is equal to the average number of packets per response. For other symmetric systems we give expressions for the sum of weighted waiting times.

We show that the ergodicity condition for the modified cyclic server system are the same as for the common cyclic server system when the service is exhaustive at all queues. In general the communication delays of the modified system are larger than the ones for the common cyclic server system due to an increase in the switch over times.

As a subject of further research we would like to point out that a generalization of the pseudo-conservation laws for servers with arbitrary distribution of vacation times would probably lead to exact solutions for the weighted sums of communication delays for request-response communication.

We should point out that in any real life system the actual delays in request-response communication have an additional component which has a significant contribution to the total delay, namely the delay associated with the networking software. This delay depends upon the networking environment, the actual implementation of diferent communication protocols, the speed and the load of the machines involved in communication. For example in Berkeley Unix environment, a very simple remote procedure call protocol requires execution of at least 11,000 machine instructions in kernel mode. As a result the delay associated with a "null remote procedure" can be as high as 20 msec but rarely under a few milliseconds assuming a communication channel with a speed no less than 10 Mbps.

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