Performance Modelling of a HSLAN Slotted Ring Protocol

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Abstract : The slotted ring protocol which is evaluated in this paper is suitable for use at very large transmission rates. In terms of modelling it is a multiple cyclic server system. A few approximative analytical models of this protocol are presented and evaluated vs the simulation in this paper. The cyclic server model shows to be the most accurate and usable over a wide range of parameters. A performance analysis based on this model is presented.

1. Introduction

Slotted ring protocols are suitable for high speed LANs (HSLANs) [ZANI'87]. The access mechanism (i.e. the MAC layer protocol) studied in this paper is a variant of the Cambridge Fast Ring (CFR) [TEMP'84]. We denote it by the CFRV. It is different from the CFR in that a number of slots can be used by a station at a time and only normal slots of the CFR are used. This basic access mechanism (AM) is also used in some other slotted ring networks e.g. Upperbus [GIBZ'86], a proposal for a metropolitan area network desrcibed in [SZE'85] and FXNET [CADG'86]. Our modelling and analysis is applicable to these systems as well.

The performance of the CFRV AM is studied in this paper. The load is of the asynchronous type, e.g. file transfer and interactive data. Transmission rates in excess of 100 Mbit/s are assumed.

The models consider the expected packet delay (i.e. the delay of a LLC_PDU in terms of the OSI model or the expected time spent in the system of the last customer in the bulk in terms of the model). Only the queueing delays for access to the medium and the transfer delays are considered. Delays due to processing of the packets are not included.

The AM of CFRV is a multiqueue multiple cyclic server system with a limited service discipline. A Poisson bulk arrival process has been used. In this paper a few approximative models are adapted and tried out for this protocol: a multiple cyclic server model based on the model of [MOWA'84], a cyclic server model (see e.g. [TAKL'86]) and a processor sharing model of [BUX'81]. The models have been tested by extensive and detailed simulations in a number of cases typical for HSLANs. The cyclic server model turns out to be the most accurate. As far as it is known to us the adaptation of a single cyclic server model to approximate a multiple server system has not been reported previously in the literature, except for our overview paper [ZANI'87a]. On the basis of the results obtained from this model, a performance analysis of the CFRV has been done. The sensitivity to the number of stations, the number of slots, the transmission rate, the expected packet length and the slot information field length has been evaluated.

The paper is organized as follows. The CFRV protocol is described in Section 2. The state of the art in analytical modelling of CFRV is evaluated in Section 3. Notation is introduced and the workload model is presented in Sections 4 and 5. The relationship between the expected mini-packet and packet waiting times and the packet delay is presented in Section 6. In Section 7 the stability condition is derived and the descriptions of the models are presented. In Section 8 the models are tested by comparing to simulations. The performance analysis of the AM is described in Section 9. Finally, some conclusions regarding the models and the performance of the CFR AM are presented in Section 10.

2. The HSLAN Slotted Ring Access Mechanism (CFRV)

The ring is partitioned into equal length slots (see Figure 1). We assume that this is achieved by introducing a latency register at the monitor station to virtually lengthen the ring to a multiple of the slot length.

Slots circulate around the ring and can be empty or full. A full slot is occupied by a mini-packet i.e. a MAC_PDU. Stations are actively coupled to the ring. They repeat or modify the slots. An empty slot may be filled by a mini-packet, if there is one. A full slot circulating around the ring, reaches the destination station which reads it and passes it on to a higher layer. We assume that each station is capable of using every empty slot that arrives and of reading every slot destined to itself.

The source station releases a slot that was full. A slot must be passed on to the next downstream station which may use it (see Figure 2). More than one slot and even all the slots at a time can be carrying mini-packets from the same source. We call this AM the CFRV, as opposed to the CFR where only one slot at a time can be used by a station. By permitting the usage of more slots it is expected that the performance improves.

3. State of the Art in Analytical Modelling of the CFRV

A number of analytical models have been developed for the slotted ring protocols e.g. the models given in [BUX'81], [YAGB'86], [HASH'71] and [KIMI'82] or [KIMI'87] .

In [HASH'71] and [KIMI'82] and [KIMI'87] the workload model is not suitable for HSLANs. In HSLANs high throughput users provide most of the load, not the interactive users as assumed in the models just mentioned. In [YAGB'86] an approximative model of this AM has been developed which can be used at high transmission rates. The case of multiple rings is studied as well. However, this model assumes a Poisson arrival process of mini-packets and provides an estimate of the expected mini-packet delay and it is not suitable for determining the expected packet delays. Moreover, the model is very approximate and it has not been tested extensively vs simulation in [YAGB'86]. These models are strongly based on a particular workload e.g. a closed queueing network model has been made. Because of that, we do not attempt to modify them for the case of a HSLAN workload.

So, with the exception of the processor sharing model of [BUX'81], there is no analytical model available in the literature which can be used for the CFRV.

For a short presentation of new models of basic AMs of slotted ring protocols the reader is referred to [ZANI'87a]. Further, peer studies presenting new analytical models we developed for slotted rings are [ZANI'87b] and [ZANI'88].

4. Notation

Let us introduce the following notation:

n - number of stations minus one;

S_i - i-th station in the ring, i=0,1,...n, and for simplicity of notation we assume that station S_0 can also be denoted as S_{n+1};

w - transmission rate (bit/µs or Mbit/s);

σ - duration of a slot (µs);

v - duration of an information field of a slot (µs), such that $v<\sigma$;

λ_i - packet arrival rate at station S_i (bit/µs or Mbit/s), i=0,...,n;

μ_i^{-1} - the expected duration of packet transmission at S_i, if transmitted at transmission rate w (µs), i=0,...,n;

Z_i - random variable denoting the bulk size of the arrival process at S_i, i.e. the number of mini-packets a packet is split into, i=0,...,n;

γ_i, EZ_i^2 - the first two moments of Z_i, i=0,...,n;

ρ - relative load, or the expected number of mini-packets arriving in the system during σ time units, such that

$$\rho = \sum_{i=0}^{n} \lambda_i \gamma_i \sigma \ ; \qquad (1)$$

X_i - random variable denoting a mini-packet service time in a particular model (µs), i=0,...,n;

Y_i - random variable denoting a packet service time in a particular model (µs), i=0,...,n;

G_i - random variable denoting switchover time from S_i to S_{i+1} in the cyclic server model (µs), i=0,...,n;

EY_i - the first moment of Y_i, i=0,...,n;

EH_i - the expected time between the beginnings of service of two consecutive mini-packets in a batch at S_i (µs), i=0,...,n;

p_{ij} - an element of the packet communication source-to-destination matrix, $\|p_{ij}\|_{n+1 x n+1}$ that represents the relative traffic intensity from source S_i to destination S_j, and

$$0 \le p_{ij} \le 1, \quad \text{and} \quad \sum_{j=0}^{n} p_{ij} = 1, \quad i,j = 0,...,n \ ; \qquad (2)$$

s - the number of slots in the ring;

τ_{ij} - propagation time from S_i to S_j including the latency at station S_j (µs), i,j=0,...,n;

τ - slot rotation time or τ_{ii} for all i (µs), such that

$$\tau = s\sigma \ ; \qquad (3)$$

τ_i - the expected propagation time of a packet or a mini-packet sent by S_i from S_i to the destination (µs), i=0,...,n;

EV_i - the expected mini-packet waiting time i.e. the expected queueing time of a mini-packet from its arrival till the beginning of its transmission at S_i (µs), i=0,...,n;

EW_i - the expected packet waiting time i.e. the expected queueing time of a packet from its arrival till the beginning of transmission of its first mini-packet at S_i (µs), i=0,...,n;

ET_i - the expected packet delay or the expected duration of MAC layer service per packet of S_i i.e. the expected packet delay from arrival at S_i till its complete delivery at the destination (µs), i=0,...,n.

5. Workload Model

Let us now specify the workload model. It includes the arrival process of packets and of mini-packets, the distribution of their lengths and the traffic pattern in the ring.

We assume that packets arrive at the MAC layer of station S_i according to a Poisson process with intensity λ_i. Packets (LLC_PDUs) are segmented and MAC protocol control information (PCI) is added to form a number of mini-packets (MAC_PDUs) of which the expected value is γ_i. So, the arrival process of mini-packets at S_i can be considered to be a bulk Poisson process.

An exponential distribution of packet length with the expected value μ_i^{-1} is assumed. Note that in the remainder of this paper, when talking about packet lengths, it is sometimes assumed that the length is expressed in time units, i.e. that it represents the duration of packet transmission if transmitted at rate w.

The information field of a MAC_PDU (mini-packet) in the slotted ring protocol has a constant length v x w (bits). The PCI of a mini-packet has a constant length too. So, the length of a mini-packet is constant and equal to s x w (bits) i.e. a slot length.

Because of the assumption of an exponential packet length distribution and a constant slot length, the random variable Z_i, denoting the number of mini-packets a packet is split into, has the following geometric distribution :

$$P\{Z_i = z\} = \Omega_i^{z-1} (1-\Omega_i) , \qquad z = 1,2,... \qquad (4)$$

where

$$\Omega_i = e^{-\mu_i v} , \qquad (5)$$

and i=0,...,n. The first two moments of Z_i are given by

$$\gamma_i = \frac{1}{1-\Omega_i} \quad \text{and} \quad EZ_i^2 = \frac{1+\Omega_i}{(1-\Omega_i)^2} , \qquad (6)$$

where Ω_i is given in (5) and i=0,...,n.

Let us now define the traffic pattern. We allow each station to send to any other station including itself i.e. p_{ij} can take any value such that relation (2) holds.

6. The Expected Mini-packet Waiting Time, Packet Waiting Time and Packet Delay

In this section the relationships between the expected mini-packet waiting time (EV_i), the expected packet waiting time (EW_i) and the expected packet delay (ET_i) are determined.

The cyclic server model used for modelling queueing at S_i (see Section 7.1) is a $M^B|G|1$ queue with server vacation [DOSH'86]. A $M^B|G|1$ model with and without server vacation period has been studied in [HALF'83], [WHIT'83] and [KUEH'79]. From there we have for the case of an exponential packet length distribution i.e. a geometric bulk size distribution:

$$EW_i = EV_i - (\gamma_i - 1)EH_i , \qquad i=0,...,n. \qquad (7)$$

The expected packet delay consists of the following components: (1) the expected packet waiting time (EW_i), (2) the expected service times of all but the last mini-packet of a packet ($(\gamma_i-1)EH_i$), (3) the transmission time of the last mini-packet (σ), and (4) the expected propagation time of the last mini-packet from S_i to the destination (τ_i). So, we have

$$ET_i = EW_i + (\gamma_i - 1)EH_i + \sigma + \tau_i , \qquad i=0,...,n. \qquad (8)$$

From (7) and (8), we get

$$ET_i = EV_i + \sigma + \tau_i , \qquad i=0,...,n. \qquad (9)$$

Note that relations (7) and (9) have been determined using the assumption of an exponential packet length distribution.

7. Models of the CFRV

In this section the cyclic server model of the CFRV protocol is presented. The multiple cyclic server model and the processor sharing model are only briefly introduced.

7.1 Cyclic Server Model

The cyclic server model of the CFRV represents an attempt at adapting an existing model of a similar cyclic server system for a slotted ring protocol.

Model Description

Let us present the main idea of a cyclic server model of the slotted ring. The case where there is only one slot in the ring is discussed first, and then the case with more than one slot is treated.

Suppose that there is only one slot in the ring. After serving a station it is freed by the source and passed to the first downstream station. Let the slot correspond to a server. The mini-packet service time is a constant. This is a cyclic server system, and a cyclic server model can be used directly. In case there are more slots in the ring a single cyclic server model of a multiple (s) slot system is made in which the slot is circulating s times faster than in a system with s slots, under the same workload.

Since only one mini-packet can be carried by a slot, a limited (ordinary) cyclic server model with one customer served during a server visit is used (see [TAKL'86] and [BOME'86]). A mini-packet is a customer in this system.

The assumption underlying the modelling approach is that the slots (servers) are independent i.e. that the state of one slot (full/empty) does not give information about the state of the other slots (servers). A new study in [ARDM'87] indicates that in a single station slotted ring, correlation between the states of the slots is indeed small.

Note that in any time interval τ (equal to the ring delay) more than one mini-packet from S_i may be served by the cyclic server. The protocol also permits more than one slot at a time to be used by a station.

Service and Switchover Time Distributions

A slot arriving at S_i is passed empty to station S_{i+1}. This happens either immediately upon the slot arrival if there are no packets to be sent at S_i, or after a full slot rotation time if a mini-packet is sent by S_i.

In the single slot case, this implies that in the model the (cyclic) server switchover time from S_i to S_{i+1}, is $\tau_{i,i+1}$ and the mini-packet service time is τ.

In a single cyclic server model of a slotted ring with $s > 1$, it is assumed that the server switchover time from S_i to S_{i+1} and the mini-packet service time are s times smaller than in a single slot system with the same characteristics as this one. So, we assume that the cyclic server switchover time G_i and the mini-packet service time are constant, and:

$$P\{ G_i = \frac{1}{s}\tau_{i,i+1} \} = 1 , \qquad i=0,...,n \qquad (10)$$

and

$$P\{ X_i = \frac{1}{s}\tau \} = 1 , \qquad i=0,...,n. \qquad (11)$$

Stability Condition

Because of the pseudo-work conservation law [BOGR'87], the expected server rotation time equals (see e.g. [TAKL'86])

$$ER = \frac{\sum_{j=0}^{n} EG_j}{1-\rho} = \frac{\sigma}{1-\rho} \qquad (12)$$

where ρ is given by relation (1).

The necessary and sufficient condition for all queues to be stable in this model is that for all i,

$$\lambda_i\gamma_i\, ER < 1 , \qquad i=0,...,n. \qquad (13)$$

From (12) and (13) it follows that

$$\lambda_i\gamma_i\sigma < 1-\rho , \qquad i=0,...,n. \qquad (14)$$

Note that the assumption $\rho < 1$ which is necessary for ER to be positive is implicit in relation (14).

It will be seen later on in Section 7.2 that this stability condition for the cyclic server model which is an approximative model of the CFRV, is an exact one for the CFRV.

In the remainder of the paper we assume that all the queues are stable, i.e. that relation (14) holds for every i, i=0,...,n.

Additional Assumptions

A mini-packet is a customer in the cyclic server model. Exact formulas for the expected waiting time in the limited cyclic server model have been shown only under certain symmetry assumptions and for a general arrival process and a general packet length distribution [TAKL'86]. In the asymmetric case some approximations for the case of a Poisson arrival process have been obtained in [BOME'86]. We limit ourselves to a symmetric load and a symmetric configuration and use the exact results for the limited cyclic server of [TAKL'86].

So, it is assumed that the load is identical at all stations, i.e.

$$\lambda_j = \lambda, \quad \gamma_j = \gamma, \qquad j=0,...,n. \qquad (15)$$

It is also assumed in [TAKL'86] that stations are equidistantly placed in the ring, so

$$\tau_{j,j+1} = \frac{\tau}{n+1} , \qquad j=0,...,n. \qquad (16)$$

The latter assumption is not an essential one.

Waiting Times

According to results for the limited cyclic server model of [TAKL'86], we have

$$EV = \frac{\lambda\gamma\sigma(n+2) + 2\,EZ^2\gamma^3 - 1}{2(1 - \lambda\gamma\sigma(n+2))}\,\sigma , \qquad (17)$$

where subscript i is omitted in EV_i and EZ_i^2 because of symmetry.

The expected packet delay ET_i can now be evaluated using formula (9).

Discussion

A model of a single slot ring is used to approximate a multiple slot ring i.e. a single cyclic server model is used as an approximation of a multiple cyclic server model. The model is exact for s=1. It could be expected that the model is inaccurate if s>1. (This will turn out not to be the case.) At low loads an overestimate could be expected. The reason is that a mini-packet in the model has to wait for the server to visit all the queues i.e. to make a full round after carrying the previous mini-packet. In the real system mini-packets can be sent using consecutive empty slots.

The assumption of an exponential packet length distribution can be relaxed. It has not been used to determine EV in formula (17). To determine ET_i and EW_i, a formula similar to (7) which has been derived for an arbitrary packet length distribution in [WHIT'83] and [KUEH'79] could be used. In this case however, an estimate of the expected mini-packet service time in the $M^B|G|1$ model i.e. EH_i has to be made.

7.2 Multiple Cyclic Server Model

In this section the multiple cyclic server model of [MOWA'84] is introduced. This model has been modified for a Poisson bulk arrival process, and implemented for the CFRV protocol.

Model Description

One can exactly represent a slotted ring as a multi-queue system of n+1 queues and s cyclic server as depicted in Figure 3. A mini-packet is a customer in this system. The i-th queue is denoted by S_i. Each server corresponds to a slot. A server is passed cyclically from S_i to S_{i+1}. This corresponds to passing an empty slot from S_i to S_{i+1}. The server switchover time from S_i to S_{i+1} is equal to $\tau_{i,i+1}$. When a station that is visited by a server is not empty, the server first removes and then starts serving the oldest customer. In the slotted ring protocol, this corresponds to a situation where an empty slot arrives at S_i and there is a mini-packet to be sent, so the slot is filled with the oldest mini-packet. The service time corresponds to the time a slot is full i.e. to the ring delay. So, the service time is a constant and equal to the ring delay τ. After processing one customer the server departs from the queue. Thus, the service discipline at the queue S_i is a limited FIFO discipline, with at most one customer served per visit to the queue.

Note that more than one server at a time can be serving a particular queue. The protocol also permits more than one slot at a time to be used by a station. In this model all servers are symmetric. They follow the same path, and the service rates are the same.

No exact solution for this model is available in the literature. Approximative multiple cyclic server models have been developed by Morris and Wang [MOWA'84] and by Raith [RAIT'85]. Morris and Wang assume a pure Poisson arrival process and a general service time distribution. Such a model could not directly be used for the slotted ring, if a Poisson bulk arrival process were assumed. The model [MOWA'84] has been tested with simulation for a set of parameters. It performs well in all cases studied except when the switchover time (i.e. the time distance between two consecutive stations) is small relative to the station service time. However, a comparison for the case of limited service where at most one customer is served per visit, is not presented. Raith develops a multiqueue multiple cyclic server model with Poisson arrival processes and individual Markovian service times. Neither the arrival process nor the service time distribution are suitable for our case.

The approach of [MOWA'84] is followed here. The model is modified for a bulk Poisson arrival process. The modification is straightforward. An estimate of the expected packet waiting time EW_i is obtained. We do not present the model itself, because of its length. The reader is referred to [ZANI'87c] for the details concerning this modification.

Let us now present the stability condition for the CFRV and give an introduction to the approximate solution for this multiple cyclic server model.

Stability Condition

If the system is stable, according to the pseudo-work conservation law, we have

$$ER = \frac{\tau}{1 - \frac{1}{s}\sum_{j=0}^{n} \lambda_j \gamma_j \tau} = \frac{\tau}{1-\rho}, \qquad (18)$$

where ρ is given in relation (1).

The necessary and sufficient condition for all queues to be stable is, due to the pseudo-work conservation law, that for all i,

$$\lambda_i \gamma_i \, ER < s, \qquad i=0,\ldots,n. \qquad (19)$$

From (3), (18) and (19) it follows that

$$\lambda_i \gamma_i \sigma < 1-\rho, \qquad i=0,\ldots,n. \qquad (20)$$

Note that the assumption $\rho < 1$ which is necessary for ER to be positive is implicit in relation (20).

Let us assume again that all the queues are stable, i.e. that relation (20) holds for every i, i=0,...,n.

Note that since the system can exactly be represented as a multiple cyclic server model the stability conditon (20) is also an exact one for the CFRV. Note also that this stability condition is the same as the one obtained for a single cyclic server approximative model given in relation (14).

Packet Waiting Time

This model differs from the one presented in [MOWA'84] only in the way P_k (notation according to [MOWA'84]) are determined. The difference is a consequence of the assumption of a bulk Poisson arrival process.

The model provides an estimate of EW_i. At this moment we do not attempt to estimate ET_i or EV_i starting from EW_i, since the estimate of EW_i turns out to be inaccurate as will be explained in Section 8.

Discussion

The model assumes a constant cycle time. The variance of the cycle time could have a large impact on the expected delays, especially under high loads, where an underestimate is expected. The effect of clustering the servers mentioned in [MOWA'84] may also have a large influence on the delays. A numerical procedure is required to find EW_i by solving a set of linear equations.

7.3 Processor Sharing Model

The processor sharing model of this AM is introduced now. For the detailed description of the model the reader is referred to [BUX'81].

Introduction to the Model

The model assumes a Poisson arrival process and a general distribution for packet lengths. It is a mixed queueing network model. There is only one closed loop in the model and it models the slots when empty due to the protocol overhead. There is one server in the network. The service discipline is processor sharing.

The packet length distribution is to be determined from the relation

$$Y_i = Z_i \sigma, \qquad i=0,\ldots,n \qquad (21)$$

and is given in relation (4) with time unit σ.

The expected packet delay is evaluated in the model. It is equal to

$$ET_i = \frac{2}{1-\rho} \cdot EY_i + \tau_i, \qquad i=0,\ldots,n, \qquad (22)$$

where ρ is given in relation (1).

Discussion

The inaccuracy of the model may be caused by:
- the assumption of a processor sharing service discipline, and
- the way the service overhead due to the protocol is modeled.

8. Testing and Analysis of the Models

The simulation model of the CFRV protocol against which the analytical models are checked is a detailed one. It is written in SIMULA and is documented in [LAND'87]. The analytical model has been tested by comparing the expected packet delays to the results of simulations. 90% confidence intervals have been obtained except for the runs where the correlation between the samples was too large. In those cases only a point estimate of the delay is shown in the figures.

Configurations, system parameters and workload models expected to be typical for HSLANs have been used. We present them here: (1) configuration: cable length = 5 and 1 km, number of stations = 40 and 10; (2) system parameters: transmission rate = 140 Mbit/s, slot information field = 512 bits, overhead in slot = 48 bits, latency register = 24 bits; and (3) workload: expected packet length = 7100 and 3000 bits, a symmetric load, and a symmetric traffic pattern. In all the examples an equal distance between the neighbouring stations has been assumed, hence relation (16) holds.

Note that in the CFR [TEMP'84] the slot information field length is 256 bits. We have taken another value because of the following. We are presently conducting a comparative performance analysis of a number of slotted ring protocols. In order to be able to compare them on equal terms a common information field length of 512 bits has been chosen. Such a choice does not change the qualitative behaviour of the protocol.

The expected packet delay (ET) of the CFRV AM vs load is shown in Figures 4 through 7. The expected mini-packet waiting time (EV) vs load is depicted in Figure 8. The expected packet waiting time (EW) vs load is depicted in Figure 9.

In the **cyclic server model** the asymptote representing the maximum throughput is exact since the stability condition of the cyclic server model is an exact stability condition for the CFRV itself. At low loads the model slightly overestimates the delays. The reason for the inaccuracies is that we use a single server model to represent a multiple cyclic server system. Namely, in the model it is impossible for a station to send a number of mini-packets one after another since a slot which has been used must be passed to the next downstream station. In the CFRV consecutive empty slots can be used by a station. This causes inaccuracy of the model at low loads.

The model is insensitive to the number of slots in the ring except for the propagation time τ_i which grows linearily in the number of slots. The protocol has the same property (see also Figure 10)!

The model gives a slightly better estimate if the number of stations is larger.

The expected mini-packet waiting time (EV_i) vs load is depicted in Figure 8 for the same case as in Figure 4. The results of the simulations and of the cyclic server model are shown. This figure shows that the cyclic server model provides a very good estimate of the expected mini-packet waiting time in this case. The estimate is expected to be better with a larger number of stations, e.g. it is very good if the number of stations is larger than 40 and all the other parameters are as chosen in Figure 4.

The good estimates obtained by the cyclic server model can be explained as follows. The system can be exactly represented as a multiple cyclic server system as introduced in Section 7.2. It was indicated in [MOWA'84] that the servers in a multiple cyclic server system tend to cluster especially at higher loads and visit the same or the neighbouring queues. It turns out here that the servers appear as one server which is s-times faster except at low loads. This may be a consequence of clustering of the servers. This also suggests that other cyclic server models could possibly be used as approximative models for the CFRV, e.g. a limited cyclic server model where up to s customers are served per servers visit (For recent approximations for such a model see [FUWA'88].) Furthermore, a multiple slotted ring system (consisting of a number of slotted rings in parallel) with a random assignment of the mini-packets to the rings could be expected to have a similar performance to a single ring system. This property has also been reported in [YAGB'86]. This can now be explained by the fact that each of the rings as well as a system of parallel rings appear as a single slot ring.

The results obtained from the **multiple cyclic server model** compared to the simulations are depicted in Figure 9. The expected packet waiting time (EW_i) vs load is depicted for the same case as in Figure 4. This figure shows a very large underestimate of the expected packet waiting times for all the load values. We suspect that the main reason for this is the variance of the cycle time which may play an important role and it cannot be assumed that it is zero. However, the asymptote representing the maximum throughput is determined exactly. So, this model is not accurate if used for performance analysis of a CFRV. Note that the CFRV can be represented accurately as a multiple cyclic server system, however there are no exact solutions available for this model.

The **processor sharing model** behaves at low loads similarly to the single cyclic server model. However, the cyclic server model seems to be slightly more accurate at those loads. The processor sharing model significantly underestimates the delays at high loads. The asymptote is also highly overestimated. The reason is the way the overhead due to the protocol is taken into account. The model is not to be used at higher loads. The problem with the model is that it is impossible to determine when it becomes drastically inaccurate. The model also provides estimates of the delays independent of the number of stations in the ring, while the simulation shows a difference. It becomes more accurate with a larger number of stations.

So, the cyclic server model provides the best approximation of the expected packet delay for the CFRV AM, in all the cases studied.

9. Performance Analysis of the CFRV

The results of the performance analysis of the CFRV AM using the cyclic server model are shown in Figures 4 through 14. Figures 4 through 9 also show simulation results and have already been discussed in the previous section. Figures 10 through 14 are used to study the sensitivity of the expected packet delays with respect to the following parameters: the number of slots, the number of stations, the expected packet length, the slot information field length and the transmission rate. All the other parameters are kept unchanged and are the same as for Figure 4. A load intensity of 80 Mbit/s is used in all the figures except in Figure 15 where a relative load of 0.65 is used. The same relationship is shown in Figure 14 as in Figure 4 except that the slot information field is also 256 bits as in the original CFR. In some figures the delays of the CFR in which only one slot at a time can be used by a station, are shown for comparison. The results have been obtained using the model of [ZANI'88]. Let us now evaluate the performance of this AM.

The **stability condition** of the CFRV AM (see relation (20)) shows that the maximum carried load depends on the number of stations, the slot duration and the first moments of arrival processes and bulk sizes. It does not depend on the number of slots. Hence, it also does not depend on the ring latency.

Relation (20) represents also the necessary stability condition (not the sufficient one) for the CFR as obtained in [ZANI'88].

The **maximum carried load** in the CFRV AM is not far off from its transmission rate e.g. about 115 Mbit/s in the case of Figure 4.

When ρ converges to the **maximum value** then EV tends to infinity and has the following asymptotic behaviour:

$$EV = (EZ^2 \gamma^3 - \frac{1}{2}) \sigma \frac{1}{\varepsilon} + o\left(\frac{1}{\varepsilon}\right), \qquad (23)$$

$$\text{with} \quad \varepsilon = 1 - \frac{n+2}{n+1} \rho \quad \text{and} \quad \varepsilon \to 0.$$

Since the convergence is of the first order with respect to ρ, it can be concluded that no sudden or very sharp increase of the delays appear when the load increases as in the case of some other slotted ring protocols e.g. the Cambridge Fast ring [ZANI'87b]. However, if $EZ^2\gamma^3$ is small the convergence can be sharp, see also results in [ZANI'88a].

The expected packet delays change very little with respect to the **number of slots** in the ring (see Figures 6, 7 and 10). The analytical results have been checked vs simulation in Figure 10. The results fall within the confidence intervals. Table 1 shows the relation between the ring length and the number of slots. The delay increase shown in Figure 10 for the CFRV is linear and is due to the change in ring latency, i.e. τ_i increases (see relations (9) and (17)). This property could be explained by the fact that a slotted ring appears as a single slot ring. Namely, introducing a new slot increases the number of servers but does not change the system capacity, so slotted rings with a different number of slots appear as the same single slotted ring.

So, the ring length has almost no influence on the performance of the CFRV. This is a property that the CFR does not have. A similar property of the maximum system utilization has been obtained for this AM in [ZANI'87].

The expected delays depend on the **number of stations** in the ring for small numbers of stations e.g. less than 10 (see Figures 4, 6 and 11). If ρ is kept constant, the delays decrease to a horizontal asymptote, for $n \to \infty$. Because of the constant load, queueing at S_i is larger if the number of stations is smaller. This can be observed in some other slotted ring protocols as well (see [ZANI'87b]).

The expected packet delay varies with respect to the **expected packet length** (see Figures 4, 5 and 12). Note that when the expected packet length changes, the load on the network also changes. This happens because of the change in the expected number of mini-packets in a packet which causes a change in the expected number of mini-packets that are the last ones in a packet. These mini-packets are only partially filled in by data. Table 2 shows the relative load ρ vs the expected packet length (see relation (1)). This is why the performance strongly degrades when the expected packet length is smaller than the slot information field length. However, this is not to be expected in a typical slotted ring.

Let us now analyse the case when the expected packet length is larger than the slot information field. The larger the expected value the larger the packet delay. Note that when the expected packet length increases, the load on the network decreases. The increase of the delays in Figure 12 is mainly due to the longer packet transfer time, while the waiting times are smaller. Since a packet is split into a number of mini-packets each having its own PCI, the packet transmission time is approximately σ/ν times the transmission time of an unsegmented packet.

The sensitivity of the CFRV AM with respect to the **slot information field length** for load values 60, 80 and 100 Mbit/s is shown in Figure 13 (see also Figure 14). The delay functions are discontinuous because of the change in the number of slots with the increase of the information field length. Table 3 contains the number of slots in the ring vs the slot information field length for this case. The relative load ρ vs the slot information field length for 80 Mbit/s load is shown in Table 4.

This AM performs best with an information field length between 512 and 1536 bits. If ν changes then σ and γ_i, and hence also ρ change. If the information field length decreases the relative load increases since the overhead gets large relative to the slot length. If the information field increases the relative load also increases. This happens because of the decrease of the expected number of mini-packets in a packet which causes the same effect as already explained in the case of a change in the expected packet length.

Note however, that the choice of the information field length in practice is to a large extent determined by the packet length distribution. Namely, if the most dominant traffic class has a constant packet length (e.g. voice) the best performance of the protocol could be expected if the packet length fits into an integer number of slots. The slot information field length should be chosen such that the ratio between the relative load and the offered load is small.

For the workload used here, the CFRV AM with a 256 bit information field length as proposed for the CFR in [TEMP'84] has worse performance at moderate and high loads than with 512 bits (see Figure 14). Figure 13 shows that information field lengths between 256 bits and 2048 bits provide good performance.

The packet delay vs the **transmission rate** is shown in Figure 15. The relative load is held constant at 0.65, e.g. 80 Mbit/s load at 140 Mbit/s transmission rate. The expected packet delay decreases with increasing transmission rate. If the transmission rate tends to infinity then $\sigma \to 0$. So, $EV \to 0$ and $ET \to \tau_i$. This property is a consequence of the decrease of the packet duration by shortening the slot duration (σ) when the transmission rate increases. In terms of the cyclic server model this property is a consequence of the fact that for a given utilization ρ and everything else remaining the same, a server with a higher service rate performs better than a slower one. This property of the CFRV makes it very interesting for implementation at very high transmission rates (of the order of 1 Gbit/s). The CFRV is in strong contrast with the CFR which exhibits an increase of the delays which is mainly due to the increase of the number of slots in the system (see Figure 15).

10. Conclusion

The CFRV AM has been analysed. A bulk Poisson arrival process of mini-packets and an exponential packet length distribution have been assumed. Three analytical models have been adapted and/or tried out for determining the packet delays in this AM. The cyclic server model has been found to be the most accurate. A performance analysis of the CFRV AM has been done using this model.

The exact necessary and sufficient stability condition for the CFRV AM has been presented. It has been derived starting from the pseudo-work conservation law, directly using the results for a multiple cyclic server system. It is independent of the arrival process and packet length distribution except for their first moments.

The conclusions concerning the cyclic server model when used for the CFRV can be summarised as follows:

- the cyclic server model provides a good estimate of the expected packet delays (in this multiple cyclic server system) over a wide range of parameters under a symmetrical load and traffic pattern; at low loads it overestimates the delays and at medium loads it is rather accurate;

- the model is exact if s=1; for s>1 the accuracy of the model does not depend on the number of slots in the ring except possibly at low loads;

- the model is slightly more accurate with more stations in the ring; and

- the model provides a very good estimate of the expected mini-packet waiting times if the number of stations is large e.g. > 40; this estimate is valid for an arbitrary packet length distribution (not only an exponential one).

The conclusions concerning the performance of the CFRV AM can be summarised as follows:

- the CFRV AM shows to be able to carry loads that are not far off from its transmission rate;

- the packet delays in the CFRV AM show a small sensitivity to the number of slots;

- the packet delays in the CFRV AM show a small sensitivity to the number of stations in the ring except if it is small e.g. less than 10;

- the performance of the CFRV AM is also good with expected packet lengths which are larger than the slot information field length;

- the CFRV AM has very good performance at high transmission rates e.g. of the order of 1 Gbit/s;

- a slot information field length between 256 bits and 1536 bits provides good performance for representative system parameters and workloads; and

- because of the properties of the CFRV AM, in particular the high throughput and the relative insensitivity with respect to the number of stations and slots, we can conclude that it should perform well over a wide range of applications e.g. backbone networks, multiprocessor interconnection structures, gathering office LANs, etc.

We are in the process of using this model as well as other analytical models we developed [ZANI'87a] in a comparative analysis of slotted ring protocols at high speeds (e.g. CFR, Orwell, their variants and uniframe slotted ring) for particular applications. The analysis is conducted by means of simulation and analytical modelling. It includes asymmetrical cases and workloads consisting of synchronous and asynchronous traffic. For this analysis see [ZANI'88a].

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no of slots	2	10	20	30	40
ring length (km)	0	6.63	14.63	22.63	30.63

Table 1.
The ring length vs the number of slots in the case of Figure 10.

exp. pack. leng.(10^3bit)	0.5	2	7.1	14	28	56
relative load	0.999	0.708	0.648	0.636	0.631	0.628

Table 2.
The relative load ρ vs the expected packet length in the case of Figure 12.

inf. field length (bit)	256	512	1024	2048	4096	8192
no of slots	1	8	5	3	2	1

Table 3.
The number of slots vs the slot information field length in the case of Figure 13.

inf. field length (bit)	256	512	1024	2048	4096	8192
relative load	0.69	0.65	0.64	0.67	0.76	0.97

Table 4.
The relative load ρ for a 80 Mbit/s load vs the slot information field length in the case of Figure 13.

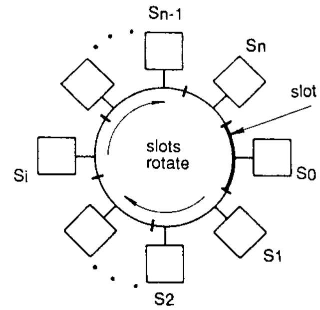

Figure 1.
The slotted ring structure.

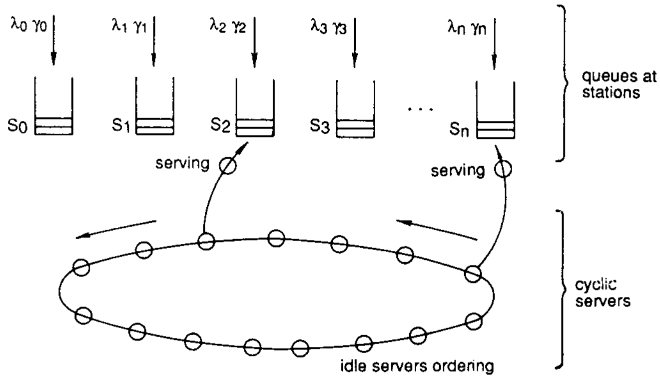

Figure 3.
A multiqueue multiple cyclic servers model of a slotted ring.

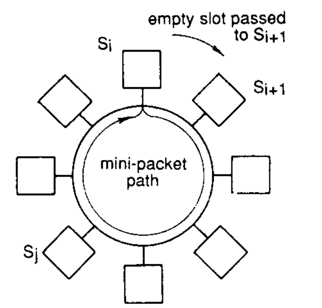

Figure 2.
Path of a mini-packet sent from S_i to S_j in the CFRV AM.

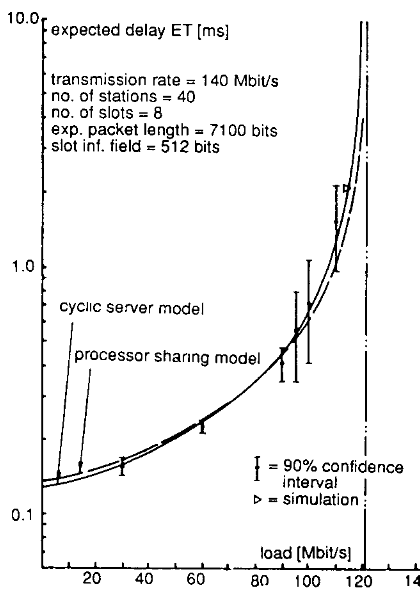

Figure 4.
Packet delay vs offered load with 40 stations, 8 slots, and an expected packet length of 7100 bits.

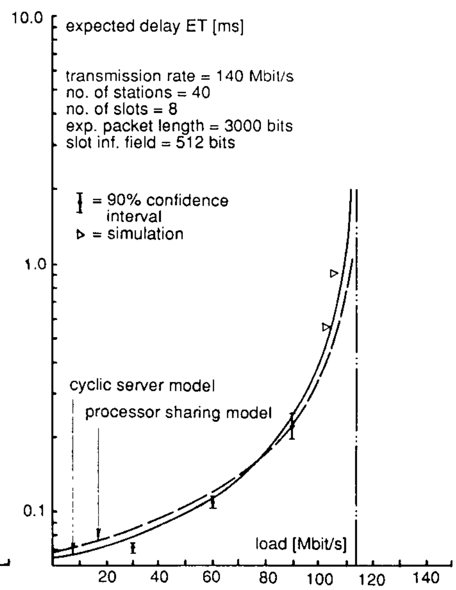

Figure 5.
Packet delay vs offered load with 40 stations, 8 slots, and an expected packet length of 3000 bits.

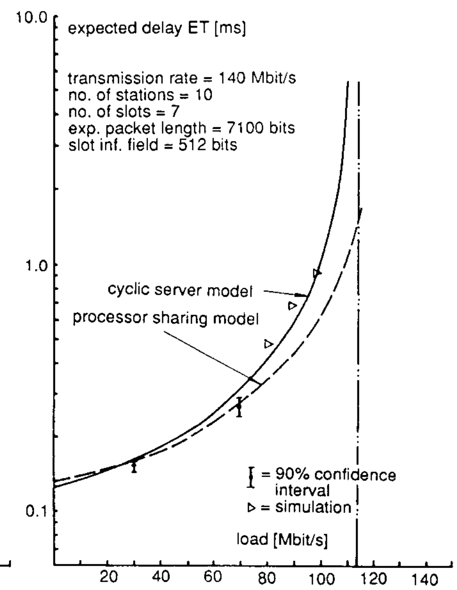

Figure 6.
Packet delay vs offered load with 10 stations, 7 slots, and an expected packet length of 7100 bits.

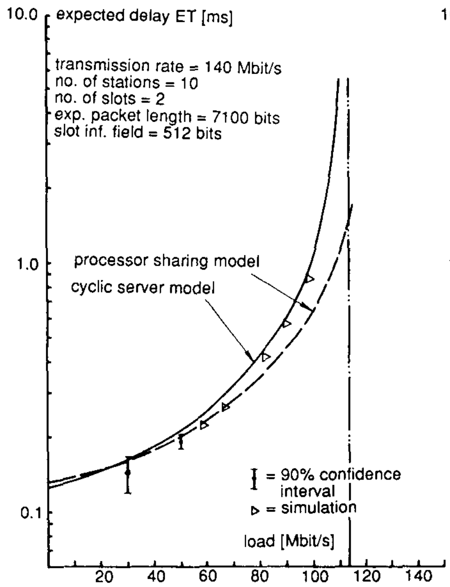

Figure 7.
Packet delay vs offered load with 10 stations, 2 slots, and an expected packet length of 7100 bits.

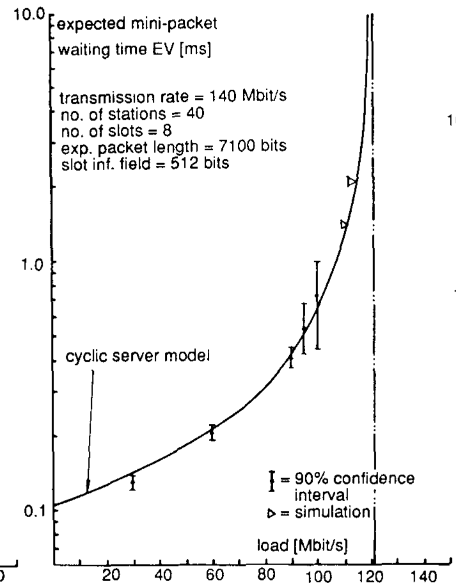

Figure 8.
Mini-packet waiting time vs offered load with 40 stations, 8 slots, and an expected packet length of 7100 bits.

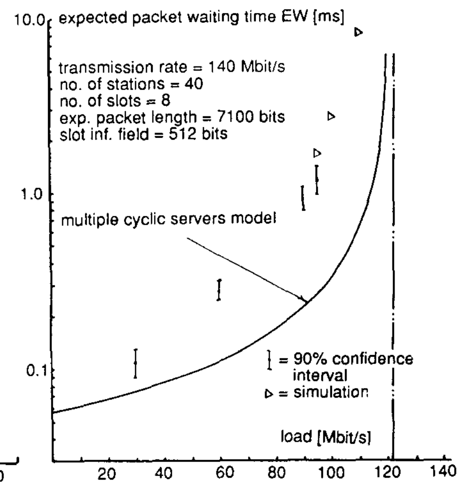

Figure 9.
Packet waiting time vs offered load with 40 stations, 8 slots, and an expected packet length of 7100 bits.

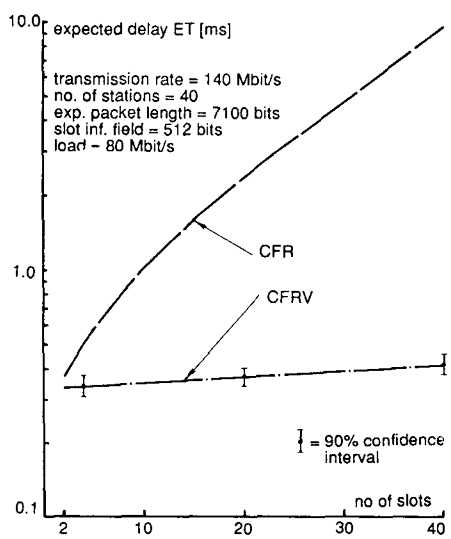

Figure 10.
Packet delay vs the number of slots.

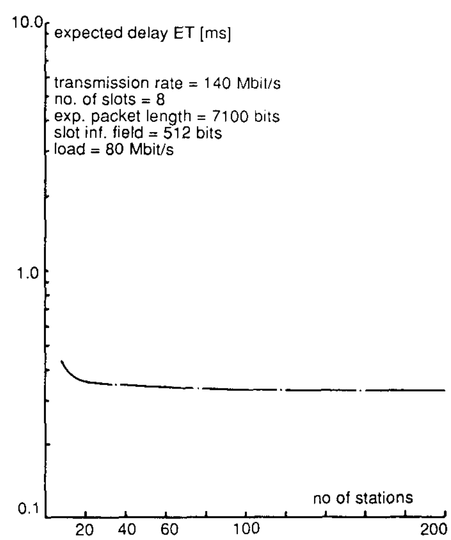

Figure 11.
Packet delay vs the number of stations.

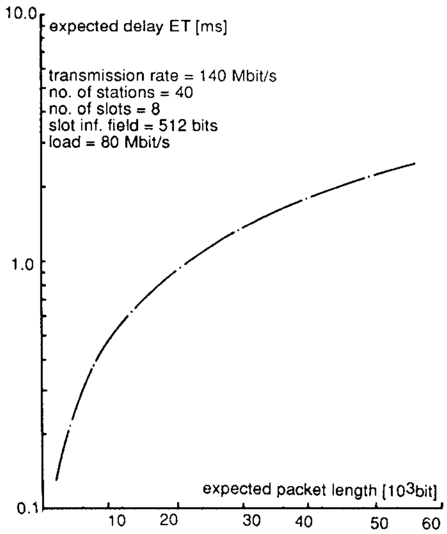

Figure 12.
Packet delay vs the expected packet length.

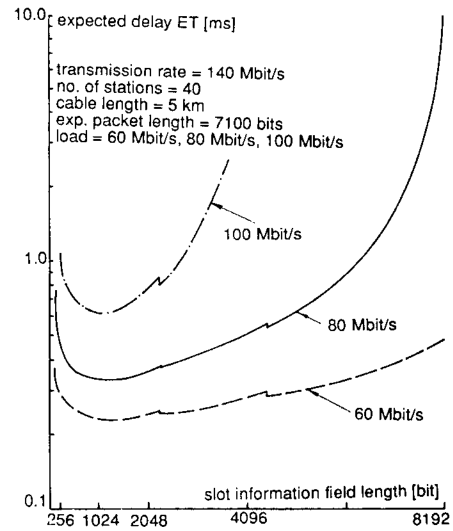

Figure 13.
Packet delay vs the slot information field length.

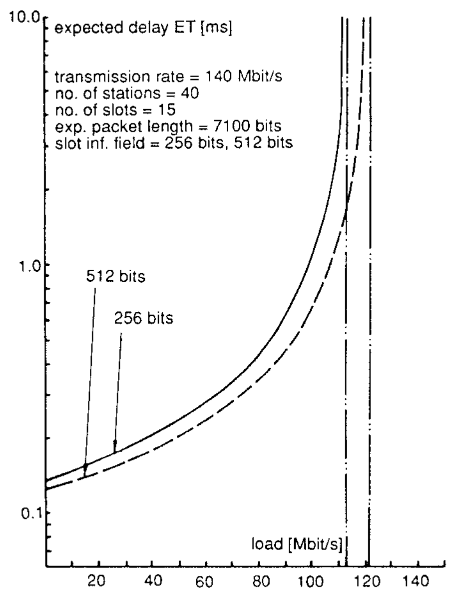

Figure 14.
Effect of slot information field length.

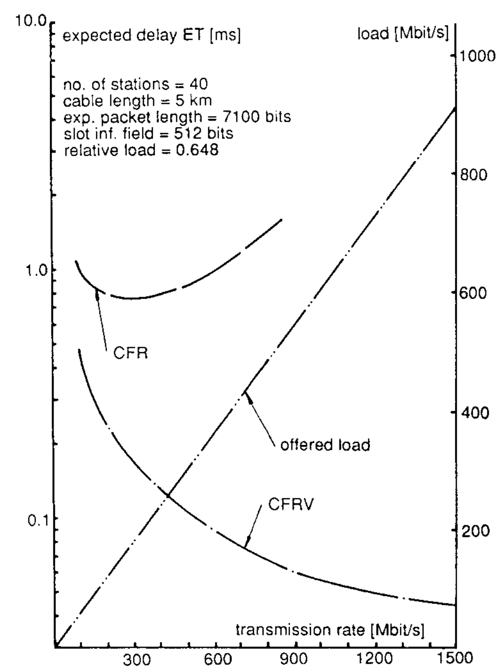

Figure 15.
Packet delay vs transmission rate.