Abstract: The Cambridge Fast Ring is a high speed slotted ring. The features that make it suitable for use at very large transmission rates are the synchronous transmission, the simplicity of the MAC protocol and the possibility of immediate retransmission of erroneous packets. A new analytical model of the Cambridge Fast ring with normal slots is presented in this paper. The model shows to be 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) [24]. Examples are: the Cambridge Fast Ring (CFR) [20], Orwell [8], Upperbus [7], the proposed IEEE P802.6 standard [18] and FXNET [4]. The CFR has been developed starting from a medium speed ring: the Cambridge ring [10]. It implements acknowledgement at the MAC layer and offers the possibility of retransmission of erroneous packets, which distinguishes it from other slotted ring protocols e.g. Orwell and Upperbus.

The performance of the access mechanism (i.e. the MAC layer protocol) of CFR is studied in this paper. In the model only normal slots have been considered. The load is of the asynchronous type. Transmission rates in excess of 100 Mbit/s are assumed.

A new approximate analytical model of this access mechanism (AM) and a necessary and a sufficient stability condition are presented in this paper. The model considers the expected packet (i.e. LLC-PDU) delays. Only the queuing delays for access to the medium and the transfer delays are considered. Delays due to processing of the packets are not included. The model has been tested by exhaustive and detailed simulations in a number of cases typical for HSLANs.

On the basis of the results obtained from the model, a performance analysis of the CFR AM 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. One of the main questions is how the mechanism performs in different applications e.g. integrated services local area networks, backbone networks and interconnection networks in multiprocessors.

The paper is organized as follows. The CFR protocol is described in Section 2. The state of the art in analytical modelling of CFR is presented in Section 3. Notation is introduced and the workload model is presented in Sections 4 and 5. In Section 6 the stability condition is derived and a M/GII with bulk arrivals and server vacation periods model is presented in detail. In Section 7 this model is tested by comparing to simulations. The performance analysis of the AM is described in Section 8. Finally, some conclusions regarding the model and the performance of the CFR AM are presented in Section 9.

2. The Cambridge Fast Ring Access Mechanism

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.

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 active and compete for 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.

There are two classes of basic slotted ring AMs depending on which station empties a full slot: the source station, or the destination station. After emptying the slot there are two possibilities: the slot can be used by the station that empties it, or it must be passed to the next downstream station.

The CFR implements the following AM. The source station releases a slot that was full. Further there are two types of slots: normal and channel slots. A channel slot may be reused by the source and the normal slot must be passed on to the next downstream station which may use it (see Figure 2 for an illustration of the function of a normal slot). Only one slot at a time can be carrying mini-packets from the same source.

Channel slots are specially suitable for large bandwidth or bursty sources. However, a fair access to the medium is guaranteed by using the normal slots. Further, using source release of the slots and using one slot at a time by a station provides the opportunity of retransmitting the erroneous mini-packet immediately when a negative ack is received by the source. This in turn implies that the sequencing of the mini-packets is preserved. This is a property that other slotted ring protocols e.g. Orwell do not have.

In this paper the performance analysis is done for normal slots only. Analytical modelling of the operation with both normal and channel slots would be more complex. However, we did a simulative performance analysis for that case in [28].


A number of analytical models have been developed for the slotted ring protocols e.g. in [9], [11], [3] and [15]. However, these are either models of a slotted ring protocol where slots are released by the source and more than one slot at a time can be used by a station, or the workload, in particular the arrival process of mini-packets, is based on interactive users. In HSLANs however, high throughput users provide most of the load, not the interactive users. So, there is no appropriate analytical model available in the literature which can be used for the CFR.

For a complete overview of the state of the art and a short presentation of new models of the basic AMs of the slotted ring protocols the reader is referred to [25]. Further, peer studies presenting new analytical models we developed for slotted rings are [26] and [27].

4. Notation

Let us introduce the following notation:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>n</td>
<td>number of stations minus one</td>
</tr>
<tr>
<td>Si</td>
<td>i-th station in the ring, i=0,1,...,n</td>
</tr>
<tr>
<td>s</td>
<td>duration of a slot (μs)</td>
</tr>
<tr>
<td>σ</td>
<td>packet service time in the model (μs)</td>
</tr>
<tr>
<td>λi</td>
<td>random variable denoting the expected duration of packet transmission at Si</td>
</tr>
<tr>
<td>μi</td>
<td>random variable denoting the expected duration of packet transmission at Si</td>
</tr>
<tr>
<td>ρ</td>
<td>relative load, or the expected number of mini-packets arriving in the system during one time unit, such that</td>
</tr>
<tr>
<td>ρ = Σ λiρiσ , i=0 n</td>
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5. Workload Model

We assume that packets arrive at the MAC layer of station Si according to a Poisson process with intensity li. 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 $g_i$. So, the arrival process of mini-packets at $S_i$ can be considered to be a bulk Poisson process.

Packet lengths are assumed to be independent identically distributed (i.i.d.). Note that often when talking about packet lengths it is 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 $v$ (bits). The PCI of a mini-packet has a constant length too. So, the length of a mini-packet is constant and equal to $v \times w$ (bits), i.e. a slot length.

The random variable $Z_i$, denoting the number of mini-packets a packet is split into, has a distribution which is derived from the packet length distribution.

We allow each station to send to any other station including itself i.e. $p_0$ can take any value such that relation (2) holds.

6. MGII Model with Bulk Arrivals and Server Vacation Periods

Model Description

A MGII model with bulk arrivals of mini-packets and individual service (corresponding to one mini-packet sent per slot visit) [5] can be used for modelling queuing at $S_i$. A mini-packet is a service unit in this model. This model has to be extended to take into account the periodical inavailability of the server at the queue. The server vacation periods are introduced therefore. Server vacation models have been studied in [5], [6] and [17].

It will be explained in the section on stability conditions that the CFR can also be represented as a multiple cyclic servers system with a limited service discipline, with the restriction that only one server at a time can be serving each queue. An approximate analytical model for a single cyclic server system with a limited service discipline is given in [13] and an exact solution for a symmetric case in [19]. However, we cannot use these results because they treat a single cyclic server case and because of the restriction that each queue can be served only by one server at a time. This argument does not hold if $s=1$. For the $s=1$ case the reader is referred to [27] which presents a modelling study of the CFR where the restriction that only one slot at at time can be used by a server is released.

However, it is interesting to notice that the results of [13] are the same as for a server vacation model where a cyclic cycle duration is interpreted as a vacation period (for a view of a cyclic server system as a server vacation model see [6]). A server vacation model is used here as well.

A MGII queue with server vacation has been studied in [1]. However, as will be explained later on, we use a MGII model only to make a companion MGII model with server vacation and use the latter one for analysis. So, we do not use the results for the bulk arrival case.

Bulk arrivals according to a Poisson arrival process with intensity $\lambda_i$ and with a bulk size $Z_i$.

The mini-packet service time $X_i$ is evaluated as the time between the following two moments: the beginning of transmission of a mini-packet at $S_i$ and after this mini-packet has returned back to $S_i$ the next arrival of an empty slot that can be used by $S_i$. When a server finds the queue at $S_i$ empty it takes a vacation of duration $O_i$. It is assumed that $X_i$ as well as $O_i$ are i.i.d. and mutually independent.

A companion model of this MGII bulk arrival model can be made. It is a MGII model where a packet is a service unit [5]. The server takes vacation the same way as in the former model. The intensity of the arrival process is $X_i$. The distribution and moments of the packet service time $Y_i$ can be evaluated from the distribution of $Z_i$ (the bulk size) and of $X_i$. Again, the server vacation time is $O_i$. The model is illustrated in Figure 3.

In the case that the number of slots is larger than the number of stations in the ring, i.e. if $s>n+1$, a part of the system capacity is wasted because stations have to pass on empty slots unused whenever they have already a slot in use. The server overhead in which this results depends on the pattern that the ring operation follows. These patterns differ in the order of empty slots that visit each particular station. In the case which has the best performance it never happens that a station has a full slot in the ring when an empty slot arrives. So, the order of empty slots which visit each particular station is the same as the physical order of slots in the ring. In the case which has the worst performance each empty slot has to skip (s-1) stations since the other (s-1) slots are occupied by packets of these stations. It can be shown that both patterns which have been described are such that if they are entered they will not be changed with probability one.

Let us now look at the system when each queue is in the stable state, so, each station is empty with a nonzero probability. In this case the system is randomly changing patterns of operation due to visiting empty stations.

We give here a necessary condition and a sufficient condition for all the queues to be stable (see Figure 4). For determining the necessary condition we assume the worst case pattern of passing empty slots. For determining the sufficient condition we assume a worst case pattern. Note that both of the patterns are not realistic (though possible) under a random arrival process unless all the queues are instable.

Consider now the best case pattern. So, each slot after being emptied is used by the first downstream station. In this case we can represent the system as a multiple cyclic server system as follows. The service time is equal to a mini-packet transmission time i.e. $\sigma$. The switchover time is equal to $\tau$.

According to the results available for a multiple cyclic server system (see [16]) which are based on the pseudo-work conservation law [2], we have the following stability condition. Let $ER_i$ denote the expected server rotation time in this case. We have

$$\tau \leq \sum_{j=0}^{s-1} \frac{1}{\lambda_j} \mathbb{E} \left[ R_{ij} \right],$$

where $p_i$ is given in (1). For all the queues to be stable it is required that

$$\sigma < 1,$$

and

$$\lambda_j \mathbb{E} \left[ R_{ij} \right] < s, \quad \text{for each } j=0, \ldots, n.$$
nonempty but has a full slot in the ring. We approximate $q_i$ as follows.

$$q_i = P \{ \text{on arrival of an empty slot at some station } S_k, k \neq i, \text{ either station } S_k \text{ is empty and there is a nonempty station } S_j \text{ that has no full slot in the ring } (j \neq i, j \neq k), \text{ or station } S_k \text{ is nonempty and has a full slot in the ring } \} ,$$

$$k \in \{0,...,n\}, k \neq i , \quad (9)$$

with

$$P_{1,i} = P \{ \text{station } S_k \text{ is empty and there is a nonempty station } S_j \text{ that has no full slot in the ring, } j \neq i, j \neq k \} ,$$

$$P_{2,i} = P \{ \text{station } S_k \text{ is nonempty and has a full slot in the ring } \mid \text{ an empty slot arrives at } S_k \} ,$$

$$k \in \{0,...,n\}, k \neq i . \quad (10)$$

Further, we have

$$P_{1,i} = \frac{1}{n} \sum_{k=0}^{n} P(S_k \text{ is empty}) \cdot \left(1 - P(S_i \text{ is empty or is nonempty}) \right) ,$$

$$P_{2,i} = \frac{1}{n} \sum_{k=0}^{n} P(S_k \text{ has a full slot}) \cdot \left(1 - P(S_i \text{ has a full slot}) \right) .$$

(An approximation because of taking the average over the probabilities concerning each $S_k, k \neq i$)

$$1 \frac{1}{n} \sum_{k=0}^{n} \left(1 - \lambda_k \gamma_k \text{EX}_k \right) \cdot \left(1 - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_j \right) \right) ,$$

$$k \neq i , \quad j \neq i , \quad j \neq k . \quad (11)$$

(Probability that $S_k$ is nonempty is approximated by $\lambda_k \gamma_k \text{EX}_k$, $k \neq i$)

$$1 \frac{1}{n} \sum_{k=0}^{n} \left(1 - \lambda_k \gamma_k \text{EX}_k \right) - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_k \right) ,$$

$$k \neq i . \quad (12)$$

Note that if $n=1$, i.e. there are two stations in the ring, expression (10) takes a value of 0.

Let us now evaluate $P \{ \text{station } S_k \text{ is nonempty and has a full slot in the ring } \mid \text{ an empty slot arrives at } S_k \} , k \in \{0,...,n\}, k \neq i$. When discussing this probability the reader is referred to the discussion about the stability conditions. It is argued there that a number of stable patterns of operation may exist where all the queues are stable. Since a number of patterns is stable, there is no limiting value of $P \{ \text{station } S_k \text{ is nonempty and has a full slot in the ring } \mid \text{ an empty slot arrives at } S_k \} , k \in \{0,...,n\}, k \neq i$. When the load converges to the limiting value to be carried by the network. In the state that has the best performance, this probability is zero (note that it is assumed that $\gamma > 1$). If all the queues are stable, the system can stay in one pattern at very high loads relative to the duration of a packet transmission. This has a large influence on the variance and on the expected value of the time a packet spends in the system and it may eventually lead to instability of all the queues. However, this effect is incorporated only by its mean into the model. We approximate $P_{2,i}$ as follows:

$$1 \frac{1}{n} \sum_{k=0}^{n} \left(1 - \lambda_k \gamma_k \text{EX}_k \right) - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_k \right) ,$$

$$k \neq i . \quad (13)$$

(An approximation because of taking the average over the probabilities concerning each $S_k, k \neq i$)

$$1 \frac{1}{n} \sum_{k=0}^{n} \lambda_k \gamma_k \text{EX}_k \cdot \left[1 - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_j \right) \right] ,$$

$$k \neq i , \quad j \neq i , \quad j \neq k . \quad (14)$$

(Probability that $S_k$ is nonempty is approximated by $\lambda_k \gamma_k \text{EX}_k$, $k \neq i$)

$$1 \frac{1}{n} \sum_{k=0}^{n} \lambda_k \gamma_k \text{EX}_k \cdot \left[1 - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_j \right) \right] ,$$

$$k \neq i , \quad j \neq i , \quad j \neq k . \quad (15)$$

(Probability that $S_k$ is nonempty is approximated by $\lambda_k \gamma_k \text{EX}_k$, $k \neq i$)

$$1 \frac{1}{n} \sum_{k=0}^{n} \lambda_k \gamma_k \text{EX}_k \cdot \left[1 - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_j \right) \right] ,$$

$$k \neq i , \quad j \neq i , \quad j \neq k . \quad (16)$$

(Probability that $S_k$ is nonempty is approximated by $\lambda_k \gamma_k \text{EX}_k$, $k \neq i$)

From (9), (10) and (11), we have that

$$1 \frac{1}{n} \sum_{k=0}^{n} \left(1 - \lambda_k \gamma_k \text{EX}_k \right) \cdot \left[1 - \Pi \left(1 - \lambda_k \gamma_k \text{EX}_j \right) \right] ,$$

$$k \neq i , \quad j \neq i , \quad j \neq k . \quad (17)$$

The time between two consecutive arrivals of a slot at $S_k$ that can be used by $S_k$ is a multiple of $\tau$. We assume the following distribution of the server vacation period $O_i$, recalling the assumption of independent slots:

$$2.3$$
A mini-packet service time consists of the slot rotation time and the waiting time for a slot that can be used by the station. The former time is a constant and equal to $\tau$. For the latter time the distribution (18) is taken. So, a mini-packet service time distribution is approximated by

$$D = O_i + \tau, \quad i=0,...,n$$  \hspace{1cm} (19)

where $D$ denotes equality in the distribution.

The first two moments of $O_i$ are given by

$$\sigma = (1-\pi_i)^{m_i}$$  \hspace{1cm} (20)

$$\sigma^2 = \sum_{k=1}^{m_i} (1-\pi_i)^{m_i-k}$$  \hspace{1cm} (21)

where $\pi_i$ denotes the slot occupation probability of slot $i$. Components: (1) the expected packet waiting time ($EW_i$), (2) the expected service time of all but the last mini-packet of a packet ($EX_i = \sum_{j=1}^{k-1} E_{X_i}$), (3) the transmission time of the last mini-packet ($ET_i$), and (4) the expected propagation time of the last mini-packet from $S_i$ to the destination ($T_i$). So, we have

$$EW_i = \sum_{j=1}^{k-1} E_{X_i} + \sigma + t_i, \quad i=0,...,n$$  \hspace{1cm} (22)

Packet Waiting Time

Now the results for the MGI1 queue with server vacation are obtained by the simulations (see also [12]).

$$EW_i = \gamma_1 EX_i + \sigma + t_i, \quad i=0,...,n$$  \hspace{1cm} (23)

Packet Service Time $Y_i$

Since a packet consists of $Z_i$ mini-packets, the packet service time $Y_i$ is equal to

$$Y_i = \sum_{j=1}^{Z_i} X_i$$  \hspace{1cm} (24)

where random variable $X_i$ denotes the service time of the $j$-th mini-packet within a packet arriving at $S_i$, $j=1,2,...,i=0,...,n$. We assume that $X_0(0,1,2,...,n)$ are i.i.d. with the distribution (19). Let us now evaluate the first two moments of $Y_i$. From (24) we get

$$EY_i = \sum_{j=1}^{Z_i} EX_i \quad \text{and} \quad EY_i^2 = \sum_{j=1}^{Z_i} (EX_i)^2 + \sum_{j=1}^{Z_i} (EX_i)^2$$  \hspace{1cm} (25)

Packet Delay

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

$$ET_i = EW_i + (\gamma_i-1)EX_i + \sigma + t_i, \quad i=0,...,n$$  \hspace{1cm} (26)

Discussion

The model provides an implicit estimate of $\eta_i$ (and thus $EX_i$) and of $\pi_i$. An explicit solution would demand solving a system of $n+1$ equations each of the order $m_i$, $i=0,...,n$. In a symmetric case this reduces to solving one equation of the same order. So, a numerical procedure has to be used in the general case to determine values of $\pi_i$ and of $\eta_i$. The convergence of the procedure is ensured if $\pi_i$ in the first iteration is chosen the smallest possible, i.e. with $q=0$. Since the procedure consists of a straightforward usage of the formulas derived here, it is an efficient one. We do not elaborate further on the numerical properties of such a procedure.

Let us now summarize the basic modelling assumptions:

- The load from all the stations $S_j$ ($j\neq i$) can be represented solely by the load intensity $\eta_j$. This way only the first moments of interarrival times and packet lengths at $S_j$ ($j\neq i$) are used;
- the protocol overhead due to passing empty slots can be adequately modelled by including it in $\eta_i$;
- slots are independent i.e. it is assumed that the state of one slot does not give any information about the states of the other slots; and
- $O_i$ and $X_i$ are i.i.d., and consequently the queue lengths at $S_i$ are independent, $i=0,...,n$.

These assumptions may cause inaccuracy especially at very high or asymmetric loads, where an underestimate of the expected packet delays is expected.

The assumption $\pi_i$, $i=1,...,n$ has been used for determining the stability conditions and for the recognition of the best and the worst performance pattern if all the queue lengths are unstable. However, it is not an essential one for the delay estimate. It has been used only to obtain $m_i$.

The model is accurate in the limit, when $\lambda_i > 0$, $i=0,...,n$.

Note that at high loads the variance of the packet delay can be large because of the large variance of the duration of the protocol overhead due to passing empty slots in the ring. Note also that if the sufficient stability condition is not satisfied and the necessary one is, the model provides an estimate of the expected delays in the most probable pattern of operation given that all the queues are stable. In that case not only the variance of the delay is large, but also the queue lengths may become unstable and the delays infinite. The larger the load, the larger the probability that this happens.

7. Testing and Analysis of the Model

The simulation model of the CFR protocol against which the analytical model is checked is a detailed one. It is written in SIMULA and is documented in [14] and [21]. 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. In all the examples an equal distance between the neighbouring stations has been assumed, i.e. $t_{i+1} = t_j + 1$, $i,j=0,...,n$. An exponential and a bimodal packet length distribution have been assumed.

We consider the following configurations, system parameters and workload models:

- Configuration: cable length $= 5$ and $1$ km, number of stations $= 40$ and 10; system parameters: transmission rate $= 140$ Mbps, slot information field $= 512$ bits, overhead in slot $= 48$ bits, latency register $= 24$ bits; and workload: expected packet length $= 7100$ and $3000$ bits, a symmetric load, and a symmetric traffic pattern.

Note that in the CFR [20] the slot information field length is 256 bits. We have taken another information field 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 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 of the CFR AM vs load is depicted in Figures 5 through 9. An exponential packet length distribution has been used except for the case of Figure 9 where the following bimodal distribution has been taken:

$$P\{\text{packet length} = x\} = \begin{cases} 0.78, & x = 512 \text{ (bit)} \\ 0.22, & x = 30000 \text{ (bit)} \end{cases}$$  \hspace{1cm} (30)

This distribution has been chosen because we would like to test the model using a distribution with the same expected value of 7100 bits and a second moment about twice as large as in the case of the exponential distribution. Moreover, a bimodal distribution was thought to be a realistic one for the packet lengths [22]. Let us now discuss the accuracy of the model.

The MGI1 with bulk arrivals and server vacation periods model has the following properties. Its estimates fall within the confidence intervals (halfwidths of which are less than 10% of the necessary one is the mean obtained by the simulations) of the expected delays for low and moderate loads until a utilization of about 0.7. At very high loads the model has an underestimate of the expected delays. The cause of the underestimate is that the packet interarrival times and packet length distributions at $S_j$, $j\neq i$ are represented only by their first
moments and because of the assumption that $X_0$ and $X_t$ are i.i.d. (this is strongly related to the assumption of independent slots).

The model is more accurate for a larger number of stations (see Figures 5 and 7). We attribute this to the smaller correlation between activities at $S_i$ and other stations in these cases. So, the assumption that $O_i$ and $X_t$ are i.i.d. is less justifiable in this case (and so is the assumption of independent slots).

The model is expected to be more accurate if there are more slots in the ring (see Figures 6 and 7). The smaller accuracy when there are less slots in the ring appears because of independent modelling of the slot occupancy, which is more justifiable when there are more slots in the ring. However, this property is not clearly visible from the figures.

Note that if $n=0$ and $s=1$, the solution for $T_1$ is exact. It is however, not exact for $s=1$ and $n=0$. An exact solution for that case under a symmetric load is given in [27].

The accuracy of the model seems not to depend very much on the expected packet lengths in the experiments conducted (see Figures 5 and 6). The model is however, slightly more accurate with shorter packets. The accuracy of the model seems also to be very good for different packet length distributions (see Figures 5 and 9).

So, the bulk arrival model is very accurate in all the cases studied except at very high loads and for $s=1$.

8. Performance Analysis of the Cambridge Fast Ring AM

The results of the performance analysis of the CFR AM using our analytical model are shown in Figures 5 through 15. Figures 5 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 CFR AM with respect to the following parameters: the expected packet delays with respect to the number of stations, the expected packet length and the slot information field length, respectively. All the other parameters are kept unchanged and are the same as for Figure 5. A load intensity of 80 Mbit/s is used except in Figure 14 where a load intensity of 0.65 is used. This relationship is shown in Figure 15 as in Figure 5 except that the slot information field is 256 bits as in the original CFR. In some of the figures the delays of the CFR where a station is released are shown for a comparison (this protocol is denoted by CFRV). The results for the CFRV have been obtained using the model of [27]. Let us now evaluate the performance of the CFR AM.

The stability conditions of the CFR AM (see relations (7) and (8)) show that the maximum carried load depends on the number of stations, the slot duration, and the first moments of arrival process and bulk size. The sufficient condition also depends on the number of stations, the slot duration, and the first moments of arrival process.

Let us now analyse the stability condition expressed in terms of the relative load or the total arrival rate depending on the number of stations. The sufficient condition also states that the relative load is less than the slot information field length.

The sensitivity of the CFR AM with respect to the slot information field length is shown in Figure 10. The delay function is discontinuous because of the change in the number of slots with the increase of the information field length (see Table 4). The relative load $p$ is shown in Table 5.

This AM performs the best with the information field length between 1024 and 2048 bits. This is because of the change in relative load and the number of slots in the ring. If the information field length decreases the relative load increases since the overhead gets large in relation 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 the change in the expected packet length. The sharp increase in delays in Figure 14 can be compared to the increase in delays when the offered load is changed (e.g. in Figures 5 through 9) which happens if the utilization is larger than about 0.7. This effect is however, combined with the effect of changing the number of slots. If the information field is between 1024 and 2048 bits the relative load is small and the number of slots as well, so the performance of the CFR is the best.

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 traffic) 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 on one hand, the ratio between the relative load and the offered load is small, and on the other hand the number of slots in a typical application is small. For the workload used here, the CFR AM with 256 bits information field length as proposed in [20] has much worse performance than with 512 bits (see Figures 5 and 15).

Figure 14 shows that information field lengths between 512 bits and 3072 bits provide good performance. However, when the information field length is in this range the delays for eventual packet transmission becomes unacceptable. A uniframe PCM like scheme over the CFR protocol would improve the performance for voice in this case. However, the study in [28] shows that in that case the delays for long packets belonging to the asynchronous traffic become large.

The packet delay vs transmission rate is shown in Figure 12 (see also Table 2 which shows the number of slots in the ring vs the transmission rate for the case of Figure 12). The relative load is held constant at 0.65, e.g. 80 Mbit/s load at 140 Mbit/s transmission rate. Above 300 Mbit/s the CFR has increasing delays, mainly because of the slot information field length.

Applications: Because of the properties of the CFR AM, we can conclude that it can perform well when the number of slots is small or moderate relative to the number of stations. This means that in a backbone application with a small number of stations and a large cable length with a large number of slots, this protocol...
performs worse than in e.g. an application as a multiprocessor or packet switch or internetwork structure where the number of slots is small relative to the number of stations. The CFR AM could also be used as an integrated services network, provided that the number of stations is large enough relative to the number of slots which is in general to be expected. However, fulfillment of the QoS requirements for the different traffic classes e.g. synchronous and asynchronous traffic is a subject of the study in [28].

9. Conclusion and Further Work

The CFR AM has been analysed. A new analytical model has been developed and a performance analysis has been done. The conclusions concerning the analytical model can be summarised as follows:

- the exact necessary and sufficient stability condition for the CFR AM has been derived starting from the pseudo-work conservation law used for multiple cyclic server models;
- the MGI1 with bulk arrivals and server vacation period model provides a good estimate of the expected packet delays over a wide range of parameters under a symmetrical load and traffic pattern for s=1; it gives a good qualitative insight into the delays and at lower and medium loads an accurate delay estimate as well; and
- the model is more accurate with more stations in the ring.

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

- the CFR AM shows to be able to carry loads that are not far off from its transmission rate;
- the CFR AM performs better if the ratio between the number of slots and the number of stations is smaller;
- the performance of the CFR AM is better with smaller expected packet lengths; the CFR AM shows a good performance at higher transmission rates only if the number of slots is small relative to the number of stations;
- the following two parameters have the strongest influence on the performance of the CFR if the system parameter slot information field length is changed: the ratio between the relative and the offered load, and the number of slots; the smaller they are the better the performance is; a slot information field length between 512 and 3072 bits provides good performance for representative system parameters and workloads; and
- the performance of the CFR AM makes it interesting for applications where the ratio between the number of stations and the number of slots is large or moderate e.g. as multiprocessor or packet switch or internetwork structure.

We are in the process of using this model as well as other analytical models we developed [25] in a comparative analysis of slotted ring protocols at high speeds (e.g. CFR, Orwell, their variants and uniframe slotted ring). The asymmetrical cases and workloads consisting of synchronous and asynchronous traffic are included (see e.g. [28]).

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References


<table>
<thead>
<tr>
<th>no of slots</th>
<th>1</th>
<th>2</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
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<tr>
<td>cable length (km)</td>
<td>1</td>
<td>0</td>
<td>1.631</td>
<td>14.63</td>
<td>22.63</td>
<td>30.63</td>
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Table 1. The cable length vs the number of slots in the case of Figure 9.

<table>
<thead>
<tr>
<th>transmission rate (Mbit/s)</th>
<th>1</th>
<th>0</th>
<th>1.40</th>
<th>5.65</th>
<th>10.0</th>
<th>14.84</th>
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<tbody>
<tr>
<td>no of slots</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>12</td>
<td>27</td>
<td>38</td>
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<table>
<thead>
<tr>
<th>exp. packet length (10^12bit)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>7</th>
<th>14</th>
<th>28</th>
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<tr>
<td>relative load</td>
<td>11.0</td>
<td>10.71</td>
<td>10.65</td>
<td>10.64</td>
<td>10.63</td>
<td>10.63</td>
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Table 3. The relative load $p$ vs the expected packet length in the case of Figure 12.

<table>
<thead>
<tr>
<th>inf. field length (bit)</th>
<th>64</th>
<th>128</th>
<th>256</th>
<th>512</th>
<th>1024</th>
<th>2048</th>
<th>4096</th>
<th>8192</th>
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<tbody>
<tr>
<td>no of slots</td>
<td>1</td>
<td>3</td>
<td>32</td>
<td>12</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
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</table>

Table 4. The number of slots vs the slot information field length in the case of Figure 14.
Table 5. The relative load $\rho$ for a 80 Mbit/s load vs the slot information field length in the case of Figure 14.

Figure 1. The slotted ring structure.

Figure 2. Path of a mini-packet sent from $S_i$ to $S_j$ in the CFR using a normal slot.

Figure 3. A $\text{M/G/1}$ model with bulk arrivals of mini-packets and server vacation periods.

Figure 4. An illustration of stable and unstable regions with respect to the load at $S_j$, $\rho_j$, ..., $\rho_n$.

Figure 5. Packet delay vs offered load with 40 stations, 8 slots, and an expected packet length of 7100 bits.

Figure 6. Packet delay vs offered load with 40 stations, 8 slots, and an expected packet length of 3000 bits.

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

Figure 8. Packet delay vs offered load with 10 stations, 2 slots, and an expected packet length of 7100 bits.
Figure 9. Packet delay vs offered load with 40 stations. 40 stations, an expected packet length of 7100 bits and bimodal packet length distribution.

Figure 10. Packet delay vs the number of slots.

Figure 11. Packet delay vs the number of stations.

Figure 12. Packet delay and offered load vs transmission rate.

Figure 13. Packet delay vs the expected packet length.

Figure 14. Packet delay vs the slot information field length.

Figure 15. Packet delay vs offered load with 40 stations, 15 slots, an expected packet length of 7100 bits and the slot information field length 256 or 512 bits.