End to End Delay in Local Area Networks

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Abstract

Previous local area computer communications were
based on centralized system architectures. The in-
creasing need for flexibility and reliability and
the decreasing costs of hardware direct more and
more to completely decentralized systems. In these
systems, multi-access-protocols are used to con-
nect users with each other via a common channel.
Most of the current research and development ef-
forts ignore that the channel allocation method is
only one of the many aspects influencing the total
system performance. This paper addresses some of
these aspects, caused by the network interface
structure. It will be shown that the system per-
formance is dominated by interface processing and
queueing rather than by the channel access and
protocol delays. Furtheron, a modified system
structure and a multi-access-protocol will be in-
troduced to improve the utilization of the network
interfaces, to combine the advantages of conten-
tion and reservation protocols, and to achieve
high efficiency, reliability, and stability of the
local area network system.

1. Introduction

Local area networks (LAN's) have drawn great atten-
tion in the past decade. They provide high band-
width communications over inexpensive transmission
media for many different users in a limited area.

Two basic interconnection topologies used in LAN's
have shown most practical among all investigated
networks: Ring systems, like the Cambridge Ring or
others [1, 2], are actually a series of connections
between the consecutive stations (repeaters) and
use active interfaces to connect the peripherals
to the network, whereas bus systems like the
Ethernet [3], consist of a passive common trans-
mission channel onto which all stations tap.

The mostly known channel assignment protocols for
the mentioned distributed systems are the CSMA/CD-
protocol and the token passing scheme for the bus
structured systems and the ring structured systems,
respectively.

These two protocols have been accepted for IEEE
standards and are analysed in great detail [3, 4,
5, 6, 7, 8]. The current research and development
efforts are dealing with the performance and com-
parison of those two channel partition methods

[5, 6], but most of them ignore the processing
time at the network access stations (NAS), the
time spent on interaction between different pro-
tocol levels, the buffer management at the access
units, the different load patterns, and the speed
mismatch between access network and the trans-
mission media.

In this paper, some of these factors are considered
in more detail and we show, that the system per-
formance is more dominated by the interface pro-
cessing and queueing rather than by the transmis-
sion protocol and the channel speed.

In Section 2 we describe the general system archi-
tecture which is subdivided into 3 main functional
layers: peripherals, network access controller
(NAC), and the communication subsystem, consisting
of the channel access module (CAM) and the trans-
mission medium.

In Section 3 the system is modelled and divided
into 3 submodels: the network access controller,
the channel access module, and the protocol model.
Within the last model, we introduce an access
protocol, combining the advantages of the conten-
tion protocols (CSMA) and the reservation proto-
cols (Token). These models are analysed and the
performance is discussed in terms of throughput,
flowtime, and waiting time.

Finally the main factors are identified which con-
tribute to the end to end delay.

2. System Architecture

2.1 Design Objectives

The basic idea behind local area networks is to
provide a cost-effective communication system bet-
ween host computers and terminals within a spa-
tially limited area. Under these conditions, de-
centralized structures become important using high
speed carriers and microelectronic integrated cir-
cuits. The demand for standardized interfaces like
CCITT X.25 and internetworking between local area
networks and public networks causes a higher func-
tionality of the interface between subscribers and
the network which are contradicting to a total de-
centralization. Another consequence of decentrali-
zation is that the network access must be reasona-
bly cheap because of the large number of peripher-
als and their low traffic intensities.

To combine the main advantages of a common carrier local area network with requirements of open networks interconnection, we conclude the following design objectives:

- communication protocol with high throughput and low transmission times
- clustering of peripherals to a network access module providing higher protocol functions for shared use and guaranteeing economic use of resources through reasonable traffic amounts.

From these requirements we conclude the need for

- a communication protocol combining the advantages of contention protocols (CSMA-CD) and fixed/demand assignment protocols (Polling)
- a hybrid structure of a decentralized communication subsystem with network access controllers for clustering a limited number of peripherals.

2.2 Station Structure

Fig. 1 shows a block diagram of the station structure indicating a basic three-level architecture: peripherals, network access controller (NAC), and the communication subsystem.
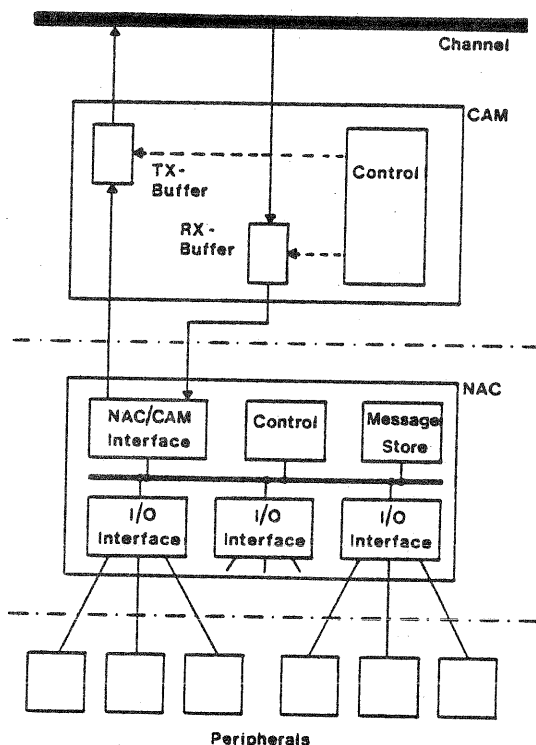

Fig. 1: Station Structure

The communication subsystem is subdivided into the common high speed carrier and the channel access modules (CAM). The CAM's are built of high speed logic which is compatible to the transmission speed of the common carrier. Communication among the CAM's runs under the control of a new carrier-sense-multiple-access (CSMA) protocol with collision detection and conflict resolution by dynamic

send priorities. These send priorities are realized by staggered transmission delays with respect to all stations which are dynamically changed to provide fair access chances or privileged access depending on high priority requests or overload control. Each CAM consists essentially of a Send-Buffer, a Receive-Buffer, and a Control Part. The basic functions of the Control Part are channel sensing, collision detection, processing of control information, and acknowledgement generation.

The NAC consists of Interface-Modules to provide parts of the particular host/terminal protocols, whereas the call functions and the data flow control functions are centralized in the NAC-Control Processor with an associated Message Store. The NAC/CAM-Interface connects the NAC to the communication subsystem.

In terms of the ISO reference model of layered architecture [11] and the extension for LAN's [12], the CAM includes the functions of levels 1 (Physical Level) and 2a (Medium Access Control). The NAC performs all higher protocol functions, i.e., levels 2b (Logical Link Control) and up.

3. Modelling and Performance Analysis

3.1 System Modelling

Besides the costs being involved by hardware and software implementation, the usefulness of a distributed system depends heavily on its throughput and delay performance. These characteristics are most sensitive to

- resource allocation schemes
- overhead
- traffic statistics.

The quantitative qualification is subject to modelling and performance analysis. The main issues are

- throughput and delay
- system response with respect to unbalanced load and dynamic overload
- identification of the most critically influencing system parameters.
- optimization of system parameters.

Due to the complexity of the total system, it is divided into three submodels:

- the network access controller (NAC)
- the channel access module (CAM)
- the access protocol (CSMA-CD-DP).

Each of these models is analysed individually, to elaborate the different influences upon the system performance.

3.2 The Network Access Controller

3.2.1 Modelling

In addition to the call control functions, the main communications processing functions of the NAC are:

- receiving of messages from the peripherals
- transmission of messages to the peripherals
- packetizing/depacketizing of messages
- buffering of messages/packets
- address processing
- transmission of packets to the CAM
- receiving of packets from the CAM

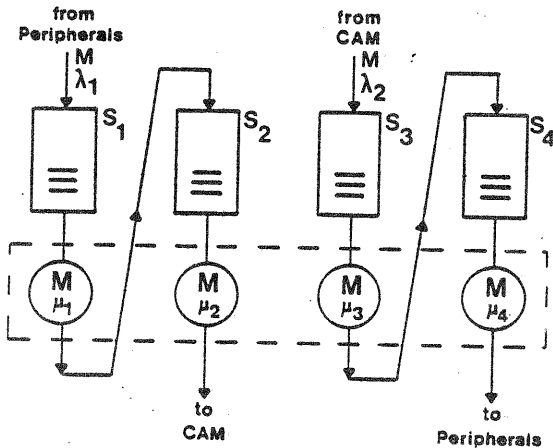The functions are modelled by a processor model with 4 server phases, see Fig. 2:

Fig. 2: Queueing model of the Network
Access Controller (NAC)

Phase 1 describes the transmission of a message from the input-buffer into the NAC-buffer. It is assumed, that the parts of a message (characters, bytes) are collected by the interfaces and arrive at the input-buffer as complete packets.

Phase 2 deals with the transmission of the message from the NAC-buffer into the CAM-buffer. This phase includes also the parallel/serial conversion and the address processing.

Phase 3 describes the transmission of a received message from the CAM-buffer to the NAC-buffer, including the serial/parallel conversion and the additional processing overhead.

Phase 4 corresponds to the transmission of the received message to the peripheral units.

The scheduling of the NAC-processor follows a non-preemptive priority scheme. The specification of the scheme, however depends on the particular circumstances, e.g., stations with unbalanced load (sending or receiving) may prioritize the direction into or out of the CAM, respectively. Due to the limited storage capacity, a dynamic internal priority schedule is used to avoid internal blocking: Reaching a preset capacity limit of the NAC-buffer, highest priority is given to phases 2 and 4 to empty the NAC-buffer.

3.2.2 Analysis

The model is analysed by establishing the multi-dimensional state-transition diagram and the resulting set of probability state equations for Markovian arrival and service processes. The system

of equations is solved, using the method of successive iteration with overrelaxation [13]. Furthermore, a simulation program has been developed allowing the analysis of general arrival and service processes.

3.2.3 Results

The most important results of this model are

- flow time (sending/receiving direction)
- blocking probabilities
- optimization of store partitioning

We define the flow times as follows:

$T_{F_{Send}}$ = Waiting time in Input-buffer
+ Service time phase 1
+ Waiting time in NAC-buffer
+ Service time phase 2

$T_{F_{Rec.}}$ = Waiting time in CAM-buffer
+ Service time phase 3
+ Waiting time in NAC-buffer
+ Service time phase 4
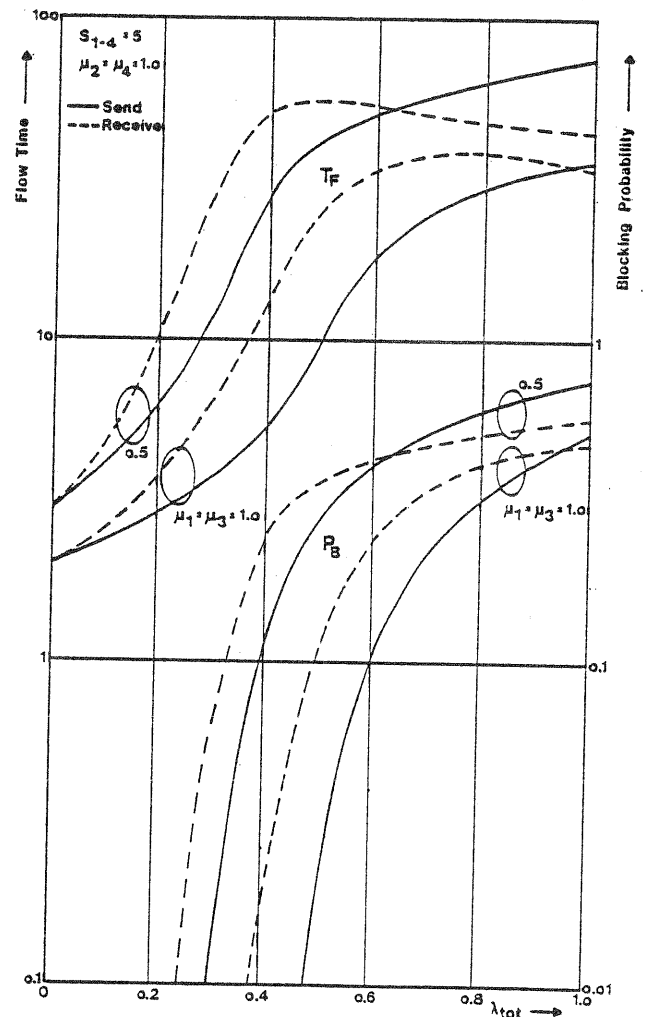

Fig. 3: Flow time and blocking probability of the input buffers versus total arrival rate
$\lambda_{tot} = \lambda_1 + \lambda_2$

Fig. 3 gives results on the flow time in sending
and receiving direction and the blocking probabil-
ity in the input-buffer and the CAM-buffer versus
the total arrival rate $\lambda_{tot} = \lambda_1 + \lambda_2$, with $\lambda_1 = \lambda_2$,
for different service
rates μ_i, $i = 1,...,4$.

It is assumed, that the priority scheme is corre-
sponding with the numbering of the service phases
(phase 1 highest priority).

Because of the limited buffer capacity, the block-
ing probability of the input-buffers is rapidly
increasing. Hence, it follows a limiting of the
number of accepted packets. Therefore, the flow
time is bounded.

3.3. The Channel Access Module

3.3.1 Modelling and Throughput Considerations

Besides processing the protocol functions, the
channel access module has to buffer incoming or
outgoing packets to balance the speed mismatch
between network access controller and channel.

To estimate the maximum reachable throughput of
this intermediate buffering, we first analyse the
model shown in Fig. 4a. This model represents the
global structure of the intermediate stores, used
in the CAM, for each direction. Each queue (1...S)
is equivalent to one buffer place for storing one
packet. Only one server can access one packet
buffer at a time to transmit a packet into or out
of the buffer. The packets are served according to
the FIFO discipline. Assuming an infinite arrival
rate λ, the throughput boundary results from the
probability that all packet buffers are filled and
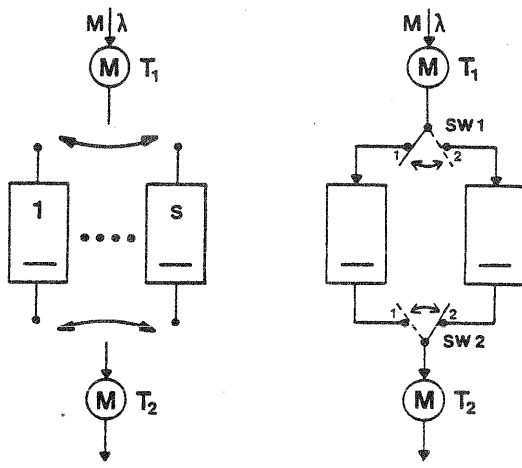server 1 will be blocked.

Fig. 4 a,b: Queueing models of the channel access
              module

Establishing the state equitations for Markovian
service processes, this probability is given by

$$P_b = \frac{1}{\sum_{i=0}^{S}\left(\frac{\mu_2}{\mu_1}\right)^i}$$

Therefore, we find for the maximum throughput

$$D_{max} = (1 - P_b) \cdot \mu_2$$

Fig. 5 shows the maximum throughput versus μ_2/μ_1,
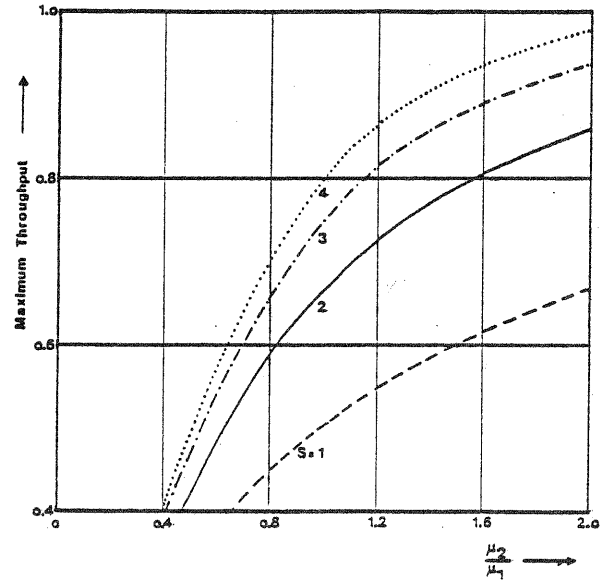for some values of S, the number of packet buffers.

Fig. 5:   Maximum throughput versus μ_2/μ_1
          S: Number of packet buffers

3.3.2 Double Buffering

Estimating the necessary control functions and
considering the reachable throughput, we restrict
the number of packet buffers to S = 2. The resulting
double buffering model for one direction, for exam-
ple, the sending one, is shown in Fig. 4b.

Servers 1 and 2 stand for the transmission times
of a packet from the NAC to the CAM and via the
channel, respectively. The switches (SW1,SW2) re-
present the access rights of the servers to the
buffers.

A packet, which is ready to send (arriving), is
transmitted by server 1 into a buffer, according
to the position of SW1. Server 2 carries the pack-
ets out, according to the position of SW2. After
each completion of a service the accompanying
switch changes its position . If both switches are
in position 1 or 2 a server has to wait (it is
blocked) until the other server has finished its
transmission and releases the buffer. In case of
an empty system, server 1 is always able to trans-
mit a packet into a buffer, without regard to the
position of the switches.

Fig. 6 shows the resulting state-transition-dia-
gram. The arrival of packets is given by the ar-
rival rate λ, the transmission speeds are given by
the service rates μ_1 and μ_2. This system is solved
explicitly and results are obtained for example
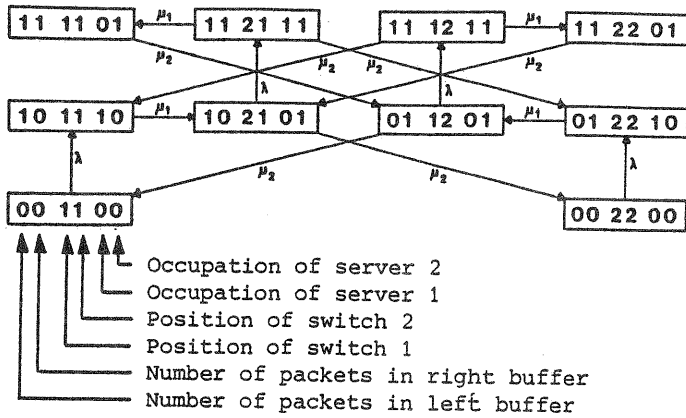for the mean number of buffered packets, the mean
flow and waiting times.

Fig. 6: State-transition diagram of double buffering

Fig. 7 displays the waiting time versus the load λ/μ_2 for $\mu_2 = 1.0$ and different values of μ_1. With respect to the limited buffer capacity, the blocking probability of server 1 increases with increasing load. Therefore the waiting time is bounded.
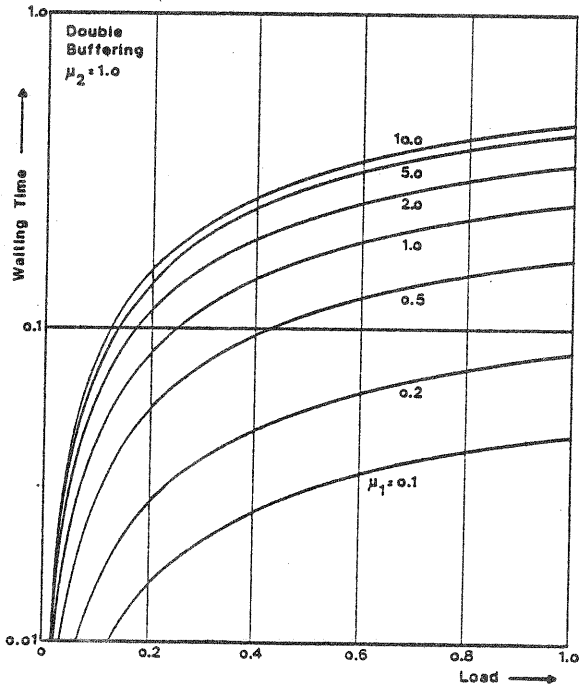

Fig. 7: Waiting time of accepted packets versus load λ/μ_2

3.3.3 Network Retroaction

The next step in the analysis of the channel access module is to take into account the influences which are caused by the other sending stations. Fig. 8 shows the extended model used in this analysis. The partitioning of the channel between the sending direction of the considered CAM and the other stations is modelled by the service time T_2 (CAM) and the "vacation time" T_S (other stations). After each service of the considered CAM, the server turns over to the second phase, handles the

demands of all other stations, and returns after the time T_S.

The state-transition-diagram is an extension of the diagram shown in Fig. 6, and the system of state equitations is solved again explicitly for Markovian arrival and service processes.
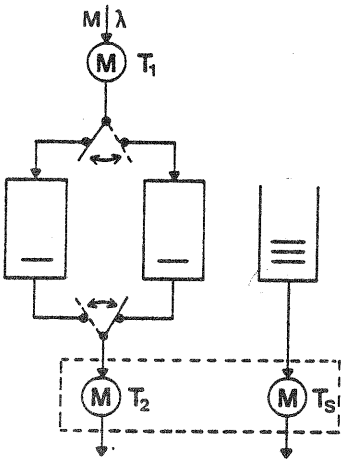

Fig. 8: Extended queueing model of double buffering

Fig. 9 shows results of the waiting time versus the load λ/μ_2 for $\mu_2 = 1.0$ and different service rates μ_1 and μ_S. It is indicated that the waiting time is dominated by the service time of the other stations. On the other side, if we fix the service rate μ_S, the waiting time in the considered CAM is determined by the service rate μ_1, the packet transmission time of the accompanying NAC.
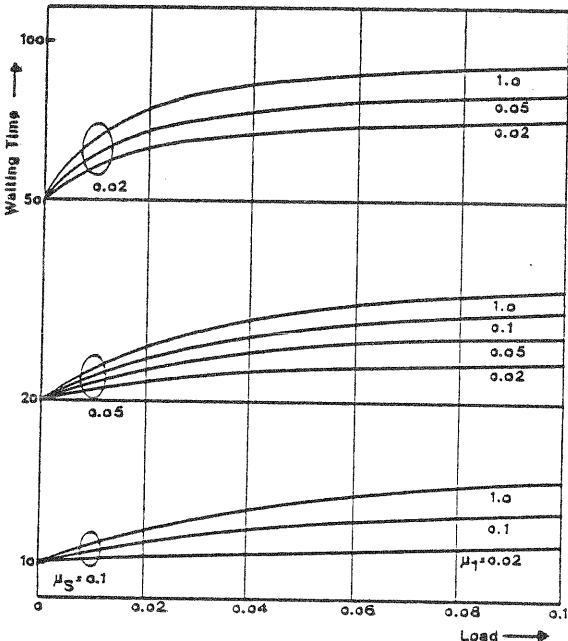

Fig. 9: Waiting time versus load λ/μ_2 Extended double buffering model

3.4 The Access Protocol

The operation of the network underlies a general CSMA-CD protocol with dynamic priorities (DP) for the channel access using deterministically staggered transmission delays for each station. The transmission delays can be distributed according to different requirements:

- fair access through cyclically changing of the staggered transmission delays (basic CSMA-CD-DP protocol)
- fixed prioritized access through fixed assignment of transmission delays to each station or a class of stations (static priority schedule)
- dynamic prioritized access through adaptive assignment of transmission delays according to criteria of unbalanced load or overload.

3.4.1 The Basic CSMA-CD-DP-Protocol

The basic CSMA-CD-DP protocol is an extension of the CSMA-CD protocol using an immediate acknowledgement after each transmission. Each station owns a specific transmission delay time which is cyclically incremented upon reception of the broadcasted acknowledgement message to provide fair access rights for each station.

3.4.2 Modelling

The CSMA-CD-DP protocol has been modelled by a queueing system having one central server (the transmission channel) and N send-queues, see. Fig. 10. The central server is allocated to the various send-queues according to the distributed schedule of the CSMA-CD-DP protocol.
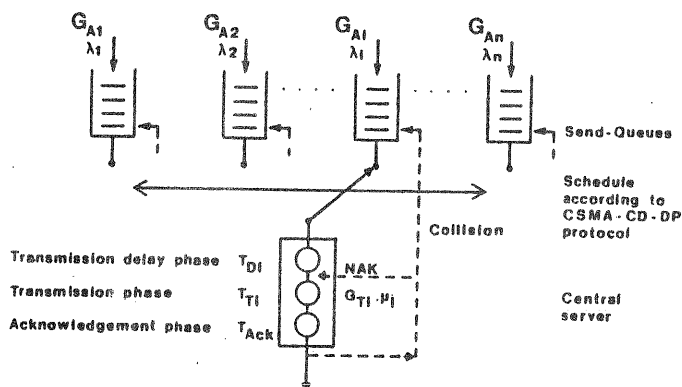

Fig. 1o: Queueing model of the channel access protocol CSMA – CD – DP

The total service phase of the central server consists of three serial phases representing TX-delay, transmission, and acknowledgement time. The dashed feedback loops indicate the retransmission after a collision or reception of a NAK. The collision is entirely determined by the arrival process and system state, whereas the negative acknowledgement is generated by a given probability standing for false transmission.

The arrivals of packets are described by general arrival processes G_{Ai} with arrival rates λ_i, the variable lengths of packets are reflected by general transmission times described by transmission processes G_{Ti} and service rates μ_i, $i=1,2,\ldots,N$.

3.4.3 Performance Analysis

The model of Fig. 10 has been implemented by a flexible simulation program allowing the analysis of almost all cases of parameters for system structure, process characteristics, and protocol options. Results of this analysis are reported in [9, 10], considering especially comparisons of different protocols and the extensions of the protocol, operating under unbalanced load and overload.

Furtheron, an analytical analysis has been performed for Markovian arrival processes by collecting all waiting packets into one queue and establishing a virtual service-time, depending on the mean number of waiting packets. Interesting results may therefore be calculated for the resulting M/G/1-system. This analysis is reported in [9] too, comparing analytical and simulative results.

4. End to End Delay

The end to end delay of a message in the considered system is composed of the following components:

- the flow time through the sending NAC
- the waiting time in the accompanying CAM
- the channel transmission time including protocol overhead
- the waiting time in the destination CAM
- the flow time through the receiving NAC.

The most influencing factors contributing to the end to end delay have been identified and modelled by specific submodels:

- processing and waiting times concerning the network access controller (NAC)
- intermediate buffering in the channel access module (CAM)
- channel access delays and protocol overhead.

The parameters of the various submodels have to be chosen such that the interfaces between these models are adequately represented. This will be demonstrated by an example case study.

4.1 Analysis Procedure

The analysis of the end to end delay proceeds as follows:

1. Step:

    Calculation of the average virtual transmission time for a transmission activity taking into account the given packet length, the transmission speed of the channel, the network configuration and the protocol overhead (see section 3.4)

2. Step:

Consider the transmission part of a particular CAM according to the model of Fig. 8. From the source-destination traffic matrix the arrival rate λ and the average "vacation time" $E[T_S]$ can be derived. With the average virtual transmission time $E[T_2]$ calculated in the first step, the analysis of the model in Fig.8 yields the waiting time within the CAM.

3. Step:

Calculation of the flow times through the sending and receiving NAC's according to the model of Fig. 2 and with the corresponding packets rates found from the source-destination traffic matrix.

4.2 Case Study

We consider a particular message path from a terminal to a distinct host of two different access stations and we calculate the end to end delay of a one-packet message.
The relevant parameters of the models are:

Virtual channel transmission time: $E[T_2] = 1.0$
(used as time unit)

Resulting channel occupation time: $E[T_S] = 20.0$

Transfer time
NAC to CAM, CAM to NAC: $E[T_1] = 1.0$

Packet arrival rate
sending station: $\lambda = 0.04$
receiving station: $\lambda = 0.15$

Service times of the NAC's
phase 2 and phase 4: $\mu_{2,4} = 1.0$
phase 1 and phase 3: $\mu_{1,3} = 0.5$

Storage capacity: $S_{1-4} = 5$

Total arrival rate
sending NAC: $\lambda_1 + \lambda_2 = 0.08$
receiving NAC: $\lambda_1 + \lambda_2 = 0.30$

The results are:

Flow time sending NAC: 3.95

Waiting time sending CAM: 28.92

Waiting time receiving CAM: 0.07

Flow time receiving NAC: 12.01

Total transmission time
terminal to host: 46.04

Conclusion

The structure of a local area network operating under a new CSMA protocol which combines the advantages of contention and reservation protocols has been presented. The access stations of this network have been included and the resulting network model is analysed by separating the system into three submodels:

- network access controller (NAC)
- channel access module (CAM)
- access protocol.

This system model reflects the main effects contributing to the end to end delay of packets. The individual submodels also allow the evaluation of typical bottleneck mechanisms as, e.g., the intermediate buffering within the CAM and its improvement by changing from single buffering to double buffering which is of especially importance for stations with so-called "back to back" transmissions.

As shown by a case study the delays within the access station can be so large that the end to end delay is completely dominated by these delays. This allows the conclusion that in many cases the performance of a local area network should be primarily characterized by the maximum channel throughput and the packet end to end delay; specific trade-offs between particular access protocols may be then of minor interest.

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