A NEW MULTI-ACCESS PROTOCOL WITH DYNAMIC PRIORITIES FOR DISTRIBUTED SYSTEMS

- Software Structure, Performance Analysis, and Overload Control

Wikhard M. Kiesel and Paul J. Kuehn

Dept. of Communications, The University of Siegen, W.-Germany.

Abstract

A new multi-access protocol for distributed systems is described which is based on carrier-sense multi-access with collision detection using dynamic priorities (CSMA-CD-DP) for channel arbitration. The protocol allows special scheduling schemes to defeat unbalanced load and temporary overload. The basic protocol is described by means of a specification language. Analytic and simulation modelling tools are used to evaluate the performance of the protocol. Finally various case studies are reported to compare the new protocol with the basic CSMA-CD- and Token-protocols as well as various dynamic control schemes for unbalanced load and overload. The studies show the influence of the main system parameters giving rise to parameter optimization.

1. Introduction

In distributed systems, the communication channel assignment plays an important role to provide low response times for a large number of competing users at a reasonable efficient utilization of the communications resources. With the development of broadband carriers for data communications, random access techniques have recently become considerable interest forming a powerful alternative to the well-known fixed/demand-assignment techniques [4,6,10].

Multi-access contention protocols, as the ALOHA or the basic CSMA (carrier-sensed-multi-access) and their derivatives, were originally developed for digital radio communications. Similar techniques become now important for local computer networks and distributed systems where still centralized or decentralized assignment techniques as polling and token passing are dominating.

In the basic channel assignment technique, the access right for each station is implemented through an ordered scheme: When polling is used, a centralized station addresses the connected stations in turn requesting them to transmit, whereas with token passing, a control message (token) is passed around among the completely distributed stations enabling them to transmit [2,8,9].

In the basic CSMA protocol, a station senses the channel and transmits a message only when the channel has been sensed idle. Nevertheless, collisions may still occur due to the propagation delay between the stations. Collisions may be detected either through a cyclical redundancy check upon reception of a message, or immediately at the collision instant through a bit-by-bit comparison of the transmitted stream and the stream observed on the channel (CSMA-CD: CSMA with collision detection). In either case, a proper schedule has to control the retransmission of the collided messages. Various schemes have been proposed which are based on randomly chosen retransmission delays, or fixed deterministic retransmission delays [5,7,11,12].

In this paper we propose a generalization of the CSMA-CD protocol combining contention mode in the idle state of the channel and reservation mode in the busy state of the channel. In the reservation mode, all stations transmit according to a deterministic access scheme. The access rights are implemented through fixed delay times after a successful transmission; they are dynamically changed upon broadcasted acknowledgements.

Contribution to "NTG/GI-Conference on computer architecture and operating systems", Ulm, Germany, March 22-24, 1982.

Several options are discussed for the dynamical adjustment of access priorities depending on system state or specific performance requirements. This protocol limits the number of collisions strictly. It combines the advantages of contention protocols at low load and assignment protocols at heavy load, respectively.

In Section 2, we describe the software structure of the basic CSMA-CD-DP protocol and its extensions. In Section 3, we review aspects of modelling and performance analysis. Section 4 presents various numerical results for case studies showing the effectivness of different access schemes under balanced load, unbalanced load, and overload conditions. The influence of the main system parameters on the performance is shown, and issues of system optimization are identified.

2. Definition of the CSMA-CD-DP Protocol

2.1 System Architecture

We consider a local network type consisting of N stations and one common channel, c. f. Fig. 1. The physical configuration of the network can be of the linear bus, star, or ring network structure. Logically, the connected stations can be ordered arbitrarily.

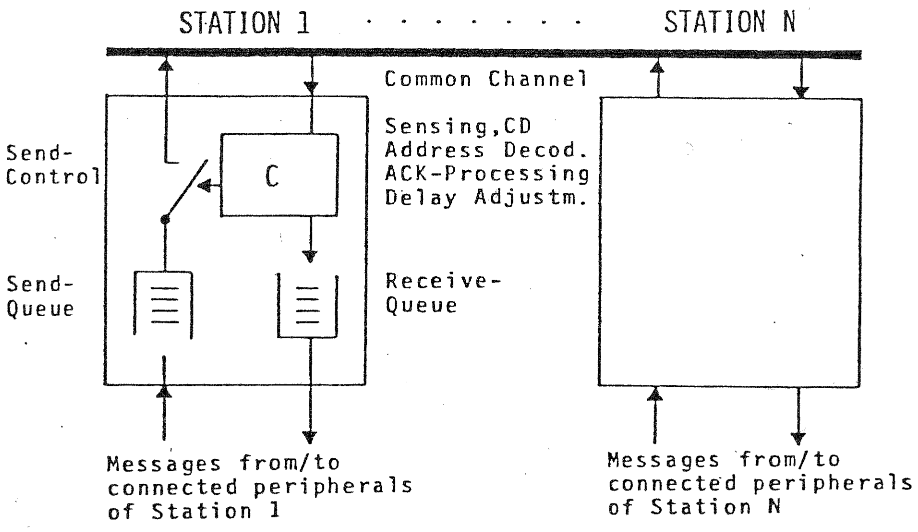


Fig. 1. Basic system architecture

Each station consists essentially of a Send-Queue, a Receive-Queue, and a Control C which performs the basic functions of channel sensing, sending, collision detection, address decoding, acknowledgement detection, and delay (priority) adjustment.

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

a) fair access through cyclically changing of the staggered transmission delays (basic CSMA-CD-DP protocol)

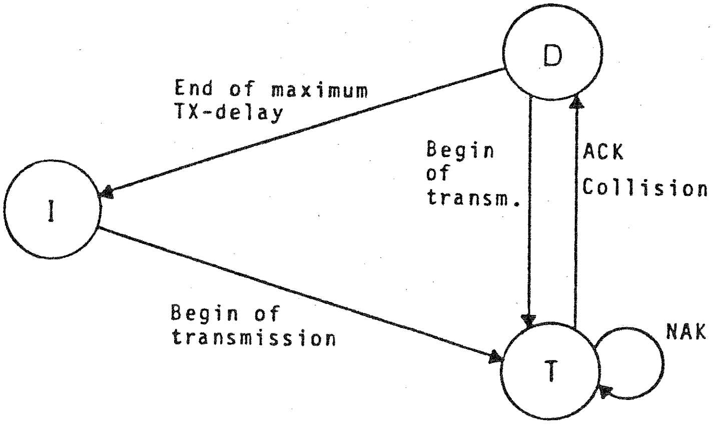
b) fixed prioritized access through fixed assignment of transmission delays to each station or a class of stations (static priority schedules like the Hyperchannel protocol)

c) dynamic prioritized access through adaptive assignment of transmission delays according to criteria of unbalanced load or overload.

2.2 Definition of the Basic CSMA-CD-DP Protocol

The basic CSMA-CD-DP protocol is an extention 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.

The channel can essentially be described by three states, see. Fig. 2.



Symbols:

I Idle State
T Transmission state
D Delay state

Fig. 2. State transition diagram of the common channel

The protocol being executed by each station can be defined as follows:

(1) Immediate transmission of an arriving message when the channel is sensed in the idle state (transition I → T).

(2) Collision detection during transmission. Under normal operation, collisions can only occur during a small time window following the transition I → T.

Upon the occurence of a collision, the channel is considered to switch in the delay state D (transition T → D). All stations proceed now according to their transmission priority in the same manner as after reception of an ACK.

(3) Upon a successful message transmission, the receiving station broadcasts a positive acknowledgement ACK by which the channel is considered to change in the delay state D (transition T → D).

(4) At any time, each station owns an individual deterministic transmission delay time (TX-delay) $i \cdot t_0$, $i = 1,2,\dots,N$. Upon detection of an ACK, each station updates its current TX-delay through cyclic incrementation by t_0, modulo N (cyclically changing transmission priority).

(5) A station with a message ready for transmission waits at least its current TX-delay after the preceding ACK. If another station transmits prior to this instant, the message waits further on until the next ACK where the same procedure is repeated. In case of no transmission up to this instant, the waiting message is immediately transmitted (transition T → T).

(6) Upon an unsuccessful (but complete) message transmission, the receiving station broadcasts a negative acknowledgement NAK; the sending station then immediately retransmits the message (transition T → T).

(7) If no transmission occurs until $(N+1) \cdot t_0$ after the preceding ACK, the channel is considered to change in the idle state (transition D → I).

The basic software structure of each station can be described by a high level language, the Specification and Description Language (SDL) of CCITT, see Fig. 3.

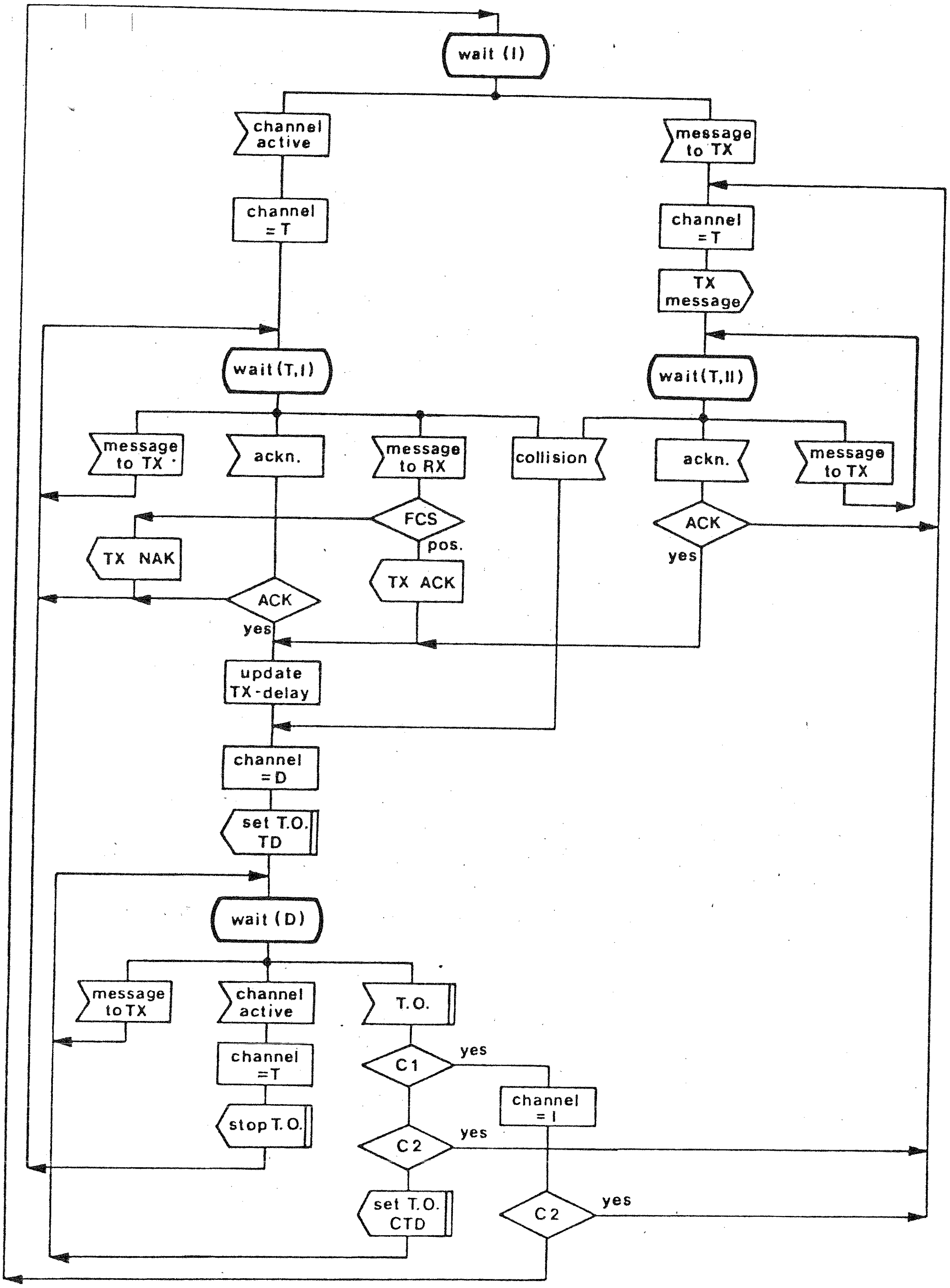


Fig. 3. Software structure in SDL

TX/RX	transmit/receive
ACK/NAK	pos./neg. acknowledgement
FCS	frame check sequence
T.O.	time out
I,T,D	channel states

TD	actual TX-delay time
CTD	complementary TX-delay time $CTD = (N+1) \cdot t_O - TD$
C 1	maximum TX-delay $(N+1) \cdot t_O$
C 2	message to transmit

Another option of the basic protocol can be defined without use of an acknowledgement; the transmission delays could be adjusted upon recognition of the end of message event as well.

The dimensioning of the basic delay time t_0 refers to the maximum two-way propagation delay between the spacially most distantly located stations, extended by a certain time for detection and processing of signals. Both parameters, t_0 and N, form the effective restriction with respect to the range of applicability of the protocol. According to current optical transmission and high-speed circuit technology, the protocol seems applicable to a wide range of local network topologies as well as distributed control or computing applications.

2.3 Extensions

The basic protocol CSMA-CD-DP of Section 2.2 can be extended in several directions:

2.3.1 Static priority schedules

In case of staggered transmission delays but without a cyclical change, the stations with the lower transmission delays have effectively a higher priority. More general, stations of higher (nonpreemptive) priority can easily be formed through a fixed allocation of the lower transmission delay times and exclusion of those stations from the cyclically changing priority schedule.

Furthermore, priority classes can be formed by grouping of stations into delay classes where the cyclically changing priority schedule is restricted to each class. Again, the number of priority stations limits the applicability due to the ground transmission delays for the low-priority stations.

2.3.2 Dynamic priority schedules, overload control

Through a consequent use of the possibilities of a distributed system with broadcasting facilities, the transmission delays could be dynamically changed according to a commonly accepted algorithm taking the actual status (queue lengths, failures, load etc.) into account.

2.3.2.1 Complementary priorities

To limit the influence of unbalanced load on lower loaded stations, a complementary priority scheme can be used [3]. For implementation within the CSMA-CD-DP protocol, each of the stations switches alternatively between a lower and a higher momentary priority (TX-delay). The ordering is such that station i switches between priority i and (N+1-i) upon an ACK, respectively.

2.3.2.2 Queue-length dependent priorities

To defeat overload being caused by unbalanced load or temporary fluctuations, a dynamic scheme is used by which each station monitors its queue lengths and may monopolize the channel during a period of excessive queue length. Once a station gets access and its queue exceeds an upper level Q_1, the station transmits repeatedly with minimum TX-delay t_0 until the queue length drops below a lower level Q_2. The overloaded station sets a status bit within the control field of a regular message. Upon recognition of this status bit, the other stations disable their access rights during the overload period. Such an overload control strategy has the special advantage of operating at the lowest possible overhead, i. e. it defeats the overload with maximum transmission capacity.

Furthermore, a similar mechanism could be used to perform maintenance or administrative functions (e. g., extending the number of stations). An arbitrary station can be used as network control center; by setting the status bit, the system is monopolized by that station. All other stations are passive and can be supplied with the new informations.

3. Modelling and Performance Analysis

3.1 Modelling

The CSMA-CD-DP protocol has been modeled by a queueing system having one central server (the transmission channel) and N send queues, see Fig. 4.

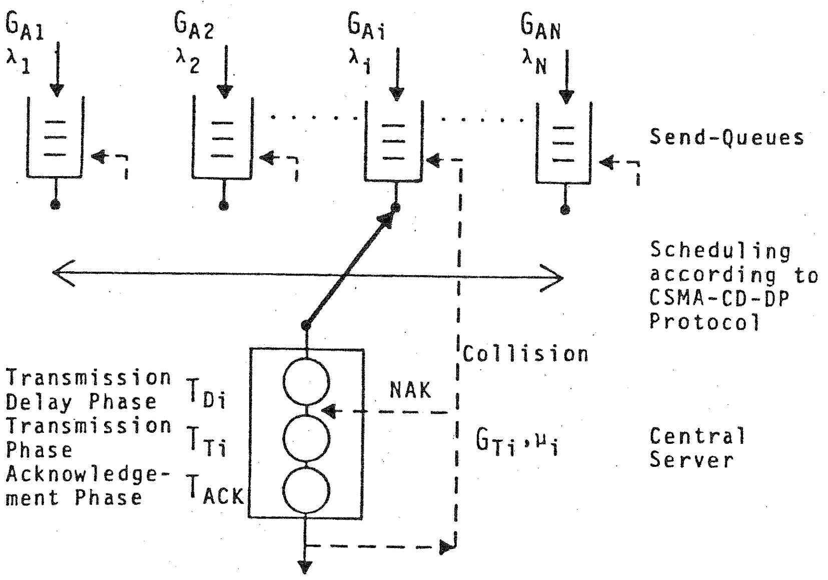


Fig. 4. Queueing model for performance analysis

Symbols:

N	number of connected stations
G_A	general message arrival process
G_T	general message transmission process
λ	arrival rate of messages
μ	service rate of messages
T_D	transmission delay time ($t_0, \ldots, N \cdot t_0$)
T_T	transmission time
T_{ACK}	acknowledgement time
i	index for station no. i, i=1,2,...,N

The total service phase of the central server exists of three serial phases representing TX-delay, transmission, and ACK-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 message transmission.

A large variety of message arrival processes and message length distributions allows the analysis of almost all practical cases.

3.2 Performance Analysis

The performance analysis of the basic protocol and its extensions has been carried out by means of simulation. For the special case of the basic CSM-CD-DP protocol for fair channel access, an approximate analytic analysis has been carried out which is based on a state-dependent M/G/1 queue [7]. The key idea behind this approach is the inclusion of the (dynamic) TX-delay- and ACK/NAK-phases within an inflated "service time" or "virtual transmission time". Numerical results and validation by simulation are reported in [7] and will not further be treated in this paper.

4. Performance Results

4.1 Issues Subject to Analysis

Besides the costs being involved by hardware and software implementation, the usefulness of a protocol for distributed systems 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 performance analysis. The main issues are

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

4.2 Comparison of Various Protocols Under Balanced Load

4.2.1 Throughput characteristics

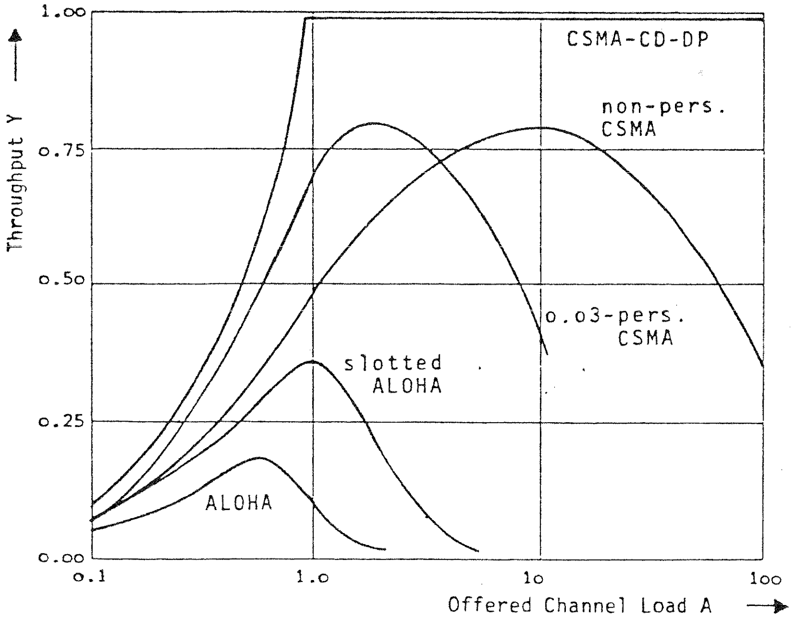


Fig. 5. Throughput of various contention protocols

Parameters: $t_O/E[T_T] = 0.01$ $E[T_{ACK}] = 0$

Fig. 5 shows results on the throughput Y (successfully transmitted messages) versus the offered channel load A. The curve for the CSMA-CD-DP protocol is compared with other contention protocols [12]. Due to the low collision rate, the new protocol reveals an excellent behaviour; the maximum throughput is given by

$$\lambda_{max} = \frac{1}{E[T_T] + t_O + E[T_{ACK}]} .$$

4.2.2 Delay performance

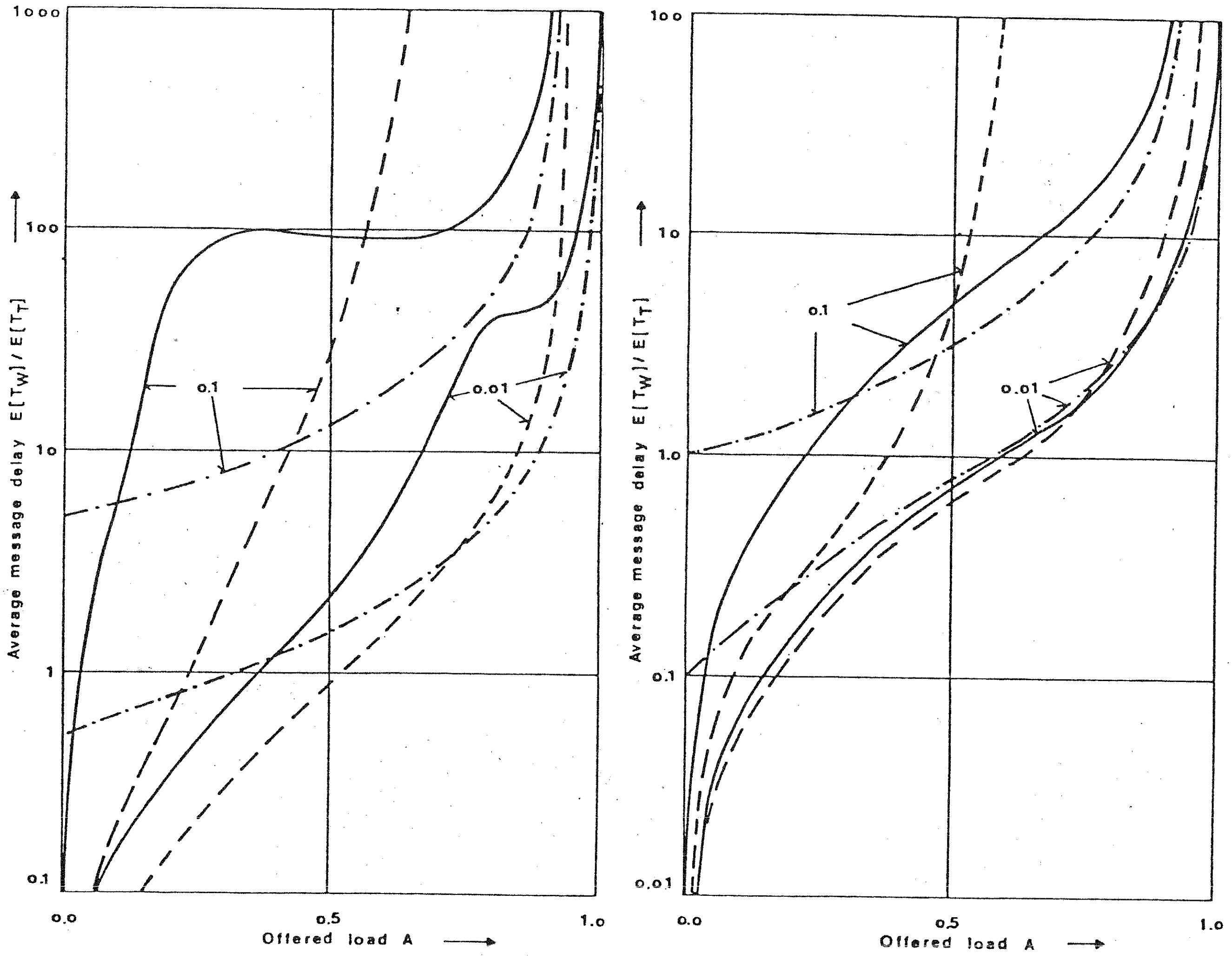


Fig. 6a. N = 100
$t_O/E[T_T]$ = 0.1 ; 0.01
$E[T_{ACK}]$ = 0
constant message lengths
balanced load

Fig. 6b. N = 20
$t_O/E[T_T]$ = 0.1 ; 0.01
$E[T_{ACK}]$ = 0
constant message lengths
balanced load

Fig. 6. Average message delay versus offered load

Protocols:

———— CSMA-CD-DP with cyclically changing priorities
– – – – – CSMA-CD with buffering of messages
–·–·– Token-passing resp. Polling with nonexhaustive Service

Figs. 6a,b give results on the average message delay versus the offered load $A=\lambda/\mu$. Two further access protocols are compared to the basic CSMA-CD-DP with cyclically changing priorities: 1-persistent CSMA-CD with buffering of arriving messages in the communication access module [13], and Token-passing or, equivalently, Polling with nonexhaustive service [1,2,8,9].

Figs. 6a,b clearly indicate the trade-off between the contention and reservation modes: contention mode is favourable for low load and reservation for heavy load. The new protocol CSMA-CD-DP features both advantages. The dependence on the parameters N and $t_O/E[T_T]$ reveals, that a good system performance is achieved especially for small N, or $t_O/E[T_T]$, or both. It has been shown in [7], that this protocol limits the number of collisions per successful transmission strictly; at both limits of low and heavy load, the collisions vanish completely.

4.3 Comparison of Various Protocols Under Unbalanced Load

4.3.1 Delay performance for unbalanced load

To compare various protocols in case of unbalanced load distribution among the stations, Fig. 7 shows the average message delays in case of N=21 stations, where station no. 11 has a significant higher load than all the residual stations.

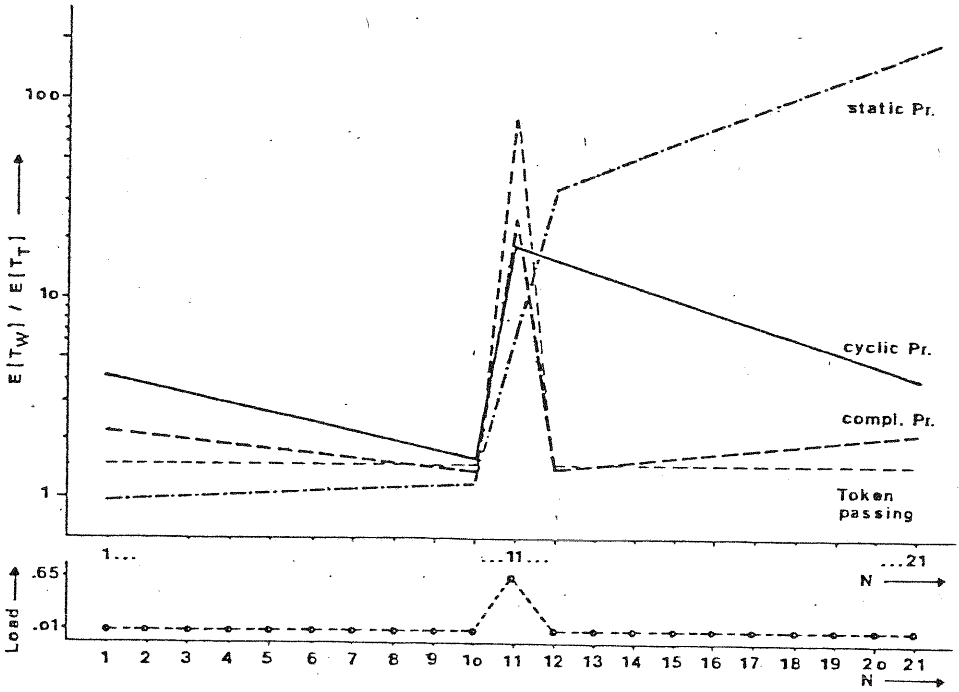


Fig. 7. Average message delay versus unbalanced offered load

Protocols:

———— CSMA-CD-DP with cyclically changing priorities
—·—·— CSMA-CD-DP with static priorities
— — — — CSMA-CD-DP with complementary priorities
— — — — Token-passing resp. Polling

Parameters: N = 21
$t_O/E[T_T] = 0.01$ $E[T_{ACK}] = 0$
exponentially distributed message lengths

The plot compares four different strategies: CSMA-CD-DP with ordinary cyclically changing priorities, CSMA-CD-DP with static (fixed) priorities, CSMA-CD-DP with complementary priorities, and Token-passing. Fig. 7 shows that the choice of an adequate strategy limits the negative influence of a highly loaded station on the lightly loaded stations. The complementary priority in a distributed system performs equally well as more centralized schemes like Token-passing or Polling.

4.3.2 Delay performance for overload

Fig. 8 illustrates how an overload situation can be defeated by a dynamic overload control strategy. The underlying protocol uses both complementary priorities and a queue-length dependent control mechanism as described in Section 2.3.2.2. The level control $Q_1:Q_2$ has a significant effect on the average message delay and may even overcompensate the load pattern. Since the dynamic overload enforces the channel to operate at minimum TX-delays, the total delay with respect to *all* waiting messages is reduced. For the examples of Fig. 8, the average total delay reduces from 15.7 (without overload control) to 9.8 ($Q_1:Q_2$=20:10), and 7.0 ($Q_1:Q_2$=1:0), respectively.

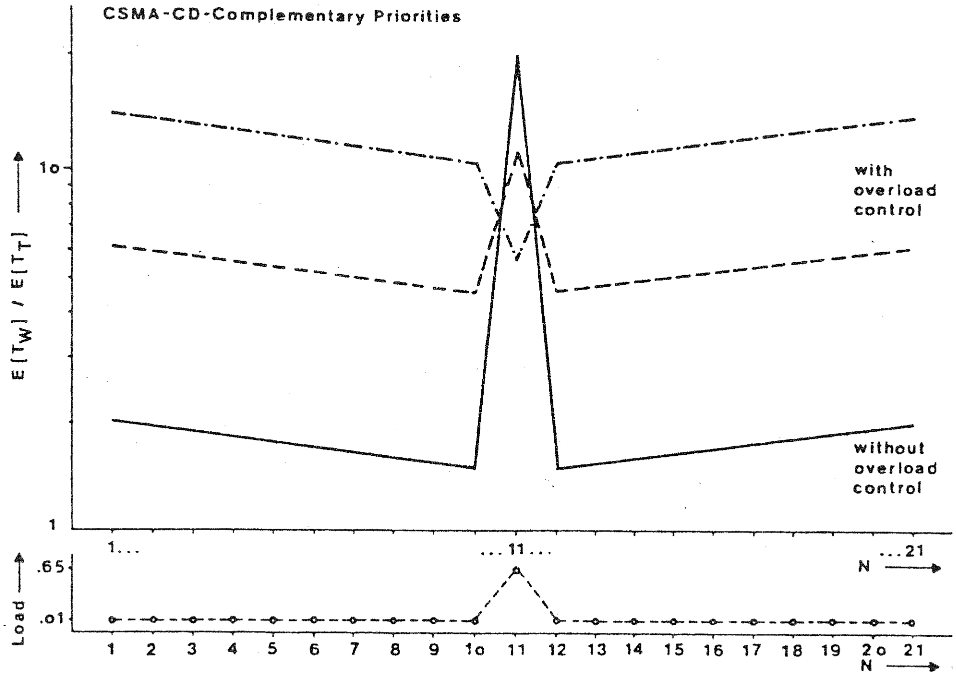


Fig. 8. Average message delay versus unbalanced offered load with dynamic overload control

Protocol: CSMA-CD-DP with complementary priorities and queue-length dependent control mechanism

Parameters: N = 21

$t_0/E[T_T] = 0.01 \qquad E[T_{ACK}] = 0$

exponentially distributed message lengths

———— $Q_1:Q_2 = \infty : \infty$ without overload control

— — — — — $= 20 : 10$ with overload control

—·—·—· $= 1 : 0$ with overload control (exhaustive service)

5. Conclusion

A new CSMA-type protocol for a distributed system with one common channel has been presented. The protocol uses carrier sensing and dynamically staggered transmission delays. Appropriate choice of the distribution of transmission delays allows a very flexible adaptation to load characteristics as unbalanced load or dynamic overload. The performance results show the basic influence of the main system parameters and indicate that the new protocol combines the advantages of contention modes at low load and reservation modes at heavy traffic. Therefore, no stability problems are involved when approaching the system capacity.The still relatively simple software structure allows the conclusion, that the new protocol is favourable for certain types of local networks, or systems with distributed control.

This work is supported by the Deutsche Forschungsgemeinschaft (DFG).

REFERENCES

(1) Arthurs,E., Stuck,B.W.,"A theoretical performance analysis of polling and carrier sense collision detection communication systems", Int. Conf. on Performance of Data Communication Systems and Their Applications, Paris, Sept. 14-16, 1981.

(2) Bux,W., "Local area subnetworks: A performance comparision", IEEE Trans. Comm., Vol. COM-29, October 1981, pp. 1465-1473.

(3) Bux,W., "Analysis of a local area bus system with controlled access", Int. Conf. on Performance of Data Communication Systems and Their Applications, Paris, Sept. 14-16, 1981.

(4) Clark,D.D., Pogran,K.T., Reed,D.P., "An introduction to local area networks", Proc. IEEE,Vol.66, Nov. 1978, pp. 1497-1517.

(5) Franta,W.R., Bilodeau,M.B., "Analysis of a prioritized CSMA protocol based on staggered delays", Acta Informatica, Vol. 13, 1980, pp. 299-324.

(6) Jacobs,I.M., Binder,R., Hoversten,E.V., "General purpose packet satellite networks", Proc. IEEE, Vol. 66, Nov. 1978, pp. 1051-1068.

(7) Kiesel,W.M., Kuehn,P.J., "CSMA-CD-DR: A new multi-access protocol for distributed systems", National Telecommunications Conference (NTC), New Orleans, Nov. 29-Dec. 3, 1981.

(8) Kuehn,P.J., "Performance of ARQ-protocols for HDX-transmission in hierarchical polling systems", Performance Evaluation, Vol. 1, 1981, pp. 19-30.

(9) Kuehn,P.J., "Multiqueue systems with nonexhaustive cyclic service", Bell System Techn. J., Vol. 58, March 1979, pp. 671-698.

(10) Metcalfe,R.M., Boggs,D.R., "ETHERNET: Distributed packet switching for local computer networks", Comm. ACM, Vol. 19, July 1976, pp.395-403.

(11) Spaniol,O., "Analysis and performance evaluation of HYPERchannel access protocols", Performance Evaluation, Vol. 1, 1981, pp. 170-179.

(12) Tobagi,F.A., "Multiaccess protocols in packet communication systems", IEEE Trans. Comm., Vol. COM-28, April 1980, pp. 468-488.

(13) Van As,H.R., "Congestion control in gateway nodes of local networks", NTG/GI-Conference on computer architecture and operating systems, Ulm, Germany, March 22-24, 1982.