A New CSMA-CD Protocol for Local Area Networks with Dynamic Priorities and Low Collision Probability

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Abstract—This paper reports on the implementation of a local area network (LAN) operating under a new CSMA-CD protocol with dynamic priorities (CSMA-CD-DP). User terminals, host computers, and other servers are connected to a common broad-band channel through N network access stations in a clustered manner. This concept reduces the number of network access stations and enhances the utilization of hardware and software resources greatly. A new protocol has been developed which organizes the decentralized operation of the distributed network access stations and which allows for a number of specific features. In the idle state the channel is operated in the contention mode. After the beginning of a transmission, the channel is operated in a reservation mode. Channel arbitration after a completed transmission is resolved by staggered delays; at any time, each station owns a distinct transmission delay which is changed after every successful transmission by broadcasted acknowledgments. This protocol strictly limits the possibility of collisions and approaches the effectiveness of token and polling protocols with increasing load. Through specific allocations of transmission delays, static priorities or dynamic overload control can be realized easily. The performance of the CSMA-CD-DP protocol has been modeled and analyzed analytically as well as by simulation. Results for normal load and overload reveal high throughput and low transfer times which are basic for a wide range of applications in LAN's.

I. Introduction

In distributed systems, the communication channel assignment plays an important part in providing low response times for a large number of competing users at a reasonably efficient utilization of the communications resources. In the basic channel assignment protocols, 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 [1], [2], [3], [7], [12].

In the basic CSMA protocol, a station senses the channel and transmits a frame 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 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). Then, a proper schedule has to control the retransmission of the collided frames. Various schemes have been proposed which are based on randomly chosen retransmission delays, or fixed deterministic retransmission delays [1], [3], [6], [13], [14], [15].

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 staggered delay times after a successful transmission; they are dynamically changed upon broadcasted acknowledgments. The protocol allows several options for the dynamical adjustment of access priorities depending on the system state or specific performance requirements.

The new protocol limits the number of possible collisions of a frame to one; thus, the delay of an arriving frame is strictly bounded by an upper value. In the idle state of the channel, the protocol operates in the contention mode, i.e., it reveals small access delays as the well-known CSMA-CD-protocol for low traffic. In the heavy traffic region, the protocol operates effectively in the reservation mode revealing the same throughput and performance as the token protocol. The performance of the new protocol is decreased, however, with an increasing number of stations and with the extension of the bus medium; therefore, we suggest a cluster concept where a number of terminals share one access station to keep the number of necessary stations low and to utilize the station equipment economically [8]–[10].

The paper is organized as follows. In Section II the structure of the implemented LAN is motivated through both recommendations of the standardization bodies and user requirements concerning performance and costs. Section III introduces the new protocol in detail. Finally, Section IV addresses the modeling and performance analysis of the new protocol; typical results are reported relating throughput and delays to system and traffic parameters.

II. Local Area Network Architecture

The basic objective behind LAN's is to provide cheap

Manuscript received July 28, 1982; revised July 11, 1983. This work was supported by the German Research Society (DFG). Parts of this paper were presented at the National Telecommunications Conference, New Orleans, LA, November 29–December 3, 1981, and the NTG/GI-Conference on Computer Architecture and Operating Systems, Ulm, West Germany, March 22–24, 1982.

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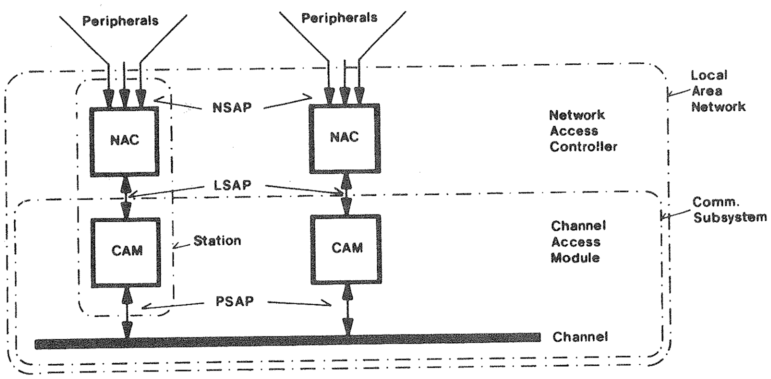

Fig. 1. Network structure. NAC = network access controller. CAM = channel access module. N-SAP = network service access point. L-SAP = link service access point. P-SAP = physical service access point.

and fast communication between locally distributed terminals, computers, file servers, print servers, etc. In many applications, local distribution is limited to a few buildings and the equipment may be grouped with respect to organizational units (departments, institutes, etc.). In addition, LAN's may be connected to each other through bridges or to public data networks through gateways. In most cases, only two peripherals communicate through the common transmission media simultaneously. Under these circumstances, it may not be wise to connect each peripheral device to the medium through an individual controller. Clustering of several devices located nearby a common controller greatly reduces the number of controllers. On the other hand, this concept allows a higher functionality with respect to provision of standardized interfaces to the connected peripheral devices in the sense of open systems interconnection, as well as with respect to the media access protocol handling to improve on throughput and transfer time. Such cluster controllers may also be able to handle internal traffic without use of the common transmission media and can be utilized to a much greater extent compared to individual controllers.

Fig. 1 shows the basic structure of the LAN with the common transmission medium (channel) and a number of stations. Each station consists of a communications access module (CAM) and a network access controller (NAC).

The CAM interfaces with the common channel through the physical service access point (P-SAP), it performs all those protocol functions which require a fast operation either at the bit rate used for the common carrier or to minimize time gaps on the common carrier

- channel sensing,
- collision detection,
- channel coding/decoding,
- recovery of data timing,
- generation/processing of cyclical redundancy check (CRC),
- input/output buffering,
- generation/processing of acknowledgment frames.

In terms of the reference model [16], [17], the CAM basically performs functions of layers 1 and 2. The layer 2 functions are usually subdivided into two sublayers, 2(a) and 2(b) for media access control and logical link control; the interface between them is defined as the media access control service access point (MAC-SAP).

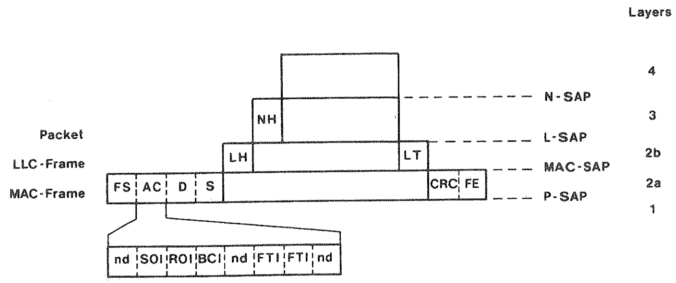

Fig. 2. Network layers and data encapsulation. FS, FE = frame delimiters. AC = medium access control field. D, S = destination and source addresses. CRC = cyclic redundancy check. LH, LT = header and trailer of link level. NH = header of network level. SOI = sender overload indication. ROI = receiver overload indication. BCI = broadcast frame indication. FTI = frame type indication (data, ACK, NAK). nd = not defined.

The NAC basically performs the functions of level 3, i.e., framing, call handling, internetworking, and interfacing data terminal equipment.

The NAC interfaces with the CAM through the link service access point (L-SAP) and with the clustered end devices through the network service access point (N-SAP).

The logical structuring has been oriented to the current standardization recommendations of IEEE Project 802 and ECMA. The implementation follows the concept to provide physical interfaces at the particular service access points defined between the logical protocol layers. Information units are exchanged across these interfaces using a well-defined frame format; see Fig. 2. A slight extension has been made within the medium access control field to provide for special functions as broadcasting, overload control, frame type indication (data, acknowledgment); see Fig. 2.

The common channel and the CAM's form the communications subsystem. Details on the CAM structure and its implementation have been reported in [10].

III. The CSMA-CD-DP Protocol

In this section, a new CSMA-type protocol which we call CSMA-CD-DP (carrier sense multiple access with collision detection and dynamic priorities) is introduced. The objectives for the new protocol are

- combination of the advantages of the CSMA-CD and token passing protocols (immediate access during the idle periods, maximum throughput during peak load periods),

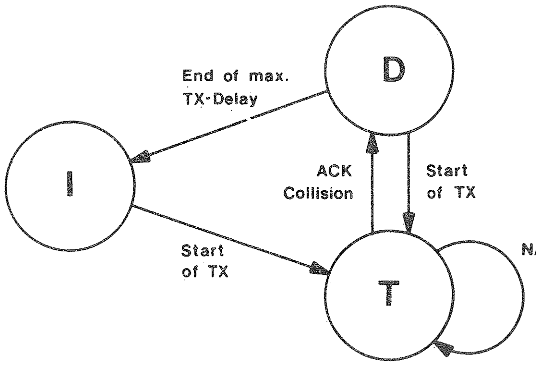

Fig. 3. State-transition diagram of the channel. I = idle state. T = transmission state. D = delay state.

• fair access or prioritized access to meet specific user requirements,

• dynamic prioritized access for adaptive overload control, and

• low collision probability and limiting the number of collisions per frame to one.

The basic protocol and its extensions are described subsequently in more detail.

A. The Basic CSMA-CD-DP Protocol

The basic CSMA-CD-DP protocol is an extension of the well-known CSMA-CD protocol where an immediate acknowledgment is used after each transmission of a data frame. By this acknowledgment signal, the distributed stations are synchronized with respect to the control of their access rights. The basic means for control of the access rights is a slot time t_0 which is related to the maximum two-way propagation delay time within the LAN. At any time, each of the N stations owns a current transmission priority which is realized by a distinct deterministic transmission delay time (TX delay) $i \cdot t_0$, $i = 1, 2, \cdots, N$. In the basic protocol, this TX delay is cyclically changed after each positive acknowledgment to provide fair access to all stations.

The operation of the access protocol can be viewed from two points, the common channel and a single station.

From the viewpoint of the common channel, three different states can be distinguished; see Fig. 3. The transitions between the states "idle," "transmission," and "delay" are as follows.

1) Immediate transmission of an arriving frame when the channel is sensed in the idle state (transition $I \rightarrow T$).

2) Collision detection during transmission. Under normal operation, collisions can only occur during a small collision time window ($\leqslant t_0$) following the transition $I \rightarrow T$. During the following busy period no further collisions can occur due to the transmission priority mechanism. Upon the occurrence of a collision, the channel is considered to switch in the delay state D (transition $T \rightarrow D$). All stations proceed now according to their transmission priority in the same manner as after reception of a positive acknowledgment (ACK). Note that transmitting stations detect a collision by bit comparison, whereas listening stations detect a collision by channel sensing using a time criterion.

3) Upon a successful transmission, the receiving station broadcasts an ACK by which the channel is considered to change into the delay state D (transition $T \rightarrow D$).

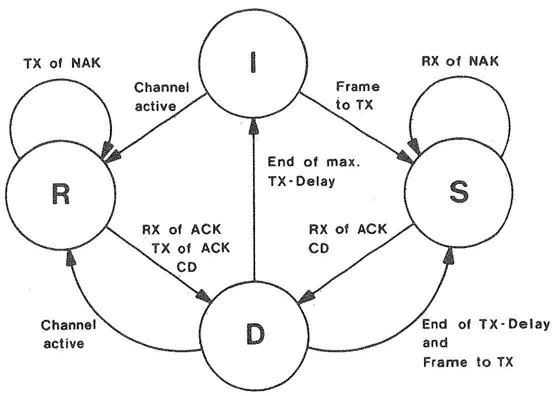

Fig. 4. State-transition diagram of a station. I = idle state. R = receiving state (listening and receiving station). S = sending state. D = delay state. CD = collision detected.

4) 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 frame ready for transmission waits at least its current TX delay after the preceding ACK. If another station transmits prior to this instant, the station waits further on until the next ACK where the same procedure is repeated. In case of no transmission up to this instant, the waiting frame is immediately transmitted (transition $D \rightarrow T$).

6) Upon reception of a frame with a CRC error, the receiving station broadcasts a negative acknowledgment (NAC); the sending station then immediately retransmits the frame (transition $T \rightarrow T$).

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

Another option of the basic protocol can be defined without use of an acknowledgment. The transmission delays can also be adjusted upon recognition of the frame end delimiter.

Fig. 4 describes the global state transitions from a station's point of view. The channel transmission state T of Fig. 4 breaks down into two substates: receiving state R and sending state S depending on whether the particular station is listening/receiving or actively transmitting, respectively. The station changes into the delay state D upon a positive acknowledgment or a collision.

For the implementation, the protocol has been specified in more detail using the formal specification and description language SDL of CCITT. The lowest level of this top-down specification has been directly used to develop the control software of the CAM processor [10].

B. Extensions

The basic protocol CSMA-CD-DP can be extended in several directions.

1) Static Priority Schedules: In case of staggered transmission delays without a cyclical change, the stations with the lower transmission delays effectively have a higher priority. More general, stations of higher (nonpreemptive) priority can be easily 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. However, the number of priority stations limits the applicability due to the basic transmission delays for the low-priority stations.

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.

a) Complementary Priorities: To limit the influence of unbalanced load on lower loaded stations, a complementary priority scheme can be used [2]. 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.

b) 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 frame (SOI: sender overload indication). 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.

Similarly, a receiving station may broadcast its overloaded status by a receiver overload indication (ROI) bit being set within an acknowledgment upon which the sending stations may withhold their message to that overloaded station. Resetting of the receiver overload status can be done by using the same mechanism after actively sending a blind message to itself and acknowledging it.

3) Broadcasting: Another extension of the protocol deals with the sending of frames to all stations at the same time. This broadcasting of frames is indicated by a control bit within the header (BCI bit). After detection of a broadcast frame, each receiving station activates an individual acknowledgment process upon reception of the frame, the timing of it is controlled by the current transmission delays of each of the receiving stations.

C. System Recovery

Distributed systems are especially prone to system failures. The CSMA-CD-DP protocol provides various mechanisms for system recovery for situations such as, e.g., missing acknowledgment, permanent negative acknowledgments, and duplicated transmission priorities.

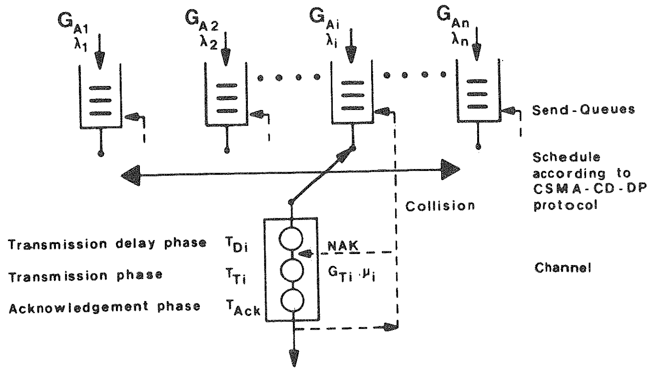

Fig. 5. Queueing model for performance analysis. N = number of connected network access stations. G_A = general arrival process. G_T = general transmission process. λ = arrival rate. μ = service rate. T_D = transmission delay time $(t_0, \cdots, N \cdot t_0)$. T_T = transmission time. T_{Ack} = acknowledgment time. i = index of station number $i = 1, 2, \cdots, N$.

A missing acknowledgment is detected by a time-out mechanism upon which a determined number of retransmissions is invoked. If NAK's are received permanently, then retransmissions are aborted after a determined number of times; after this the transmitting station generates an ACK, and the network can continue with normal operation. Duplicated transmission priorities cause a collision during the busy period which can be detected by the CD mechanism. To recover from this situation, each station resets its transmission priority to the predetermined distinct initial value.

IV. Modeling and Performance Analysis

A. Modeling

Aside from the costs 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, and traffic statistics.

The quantitative qualification is subject to modeling and performance analysis. The main issues are throughput and delay under various access schemes, system response with respect to unbalanced load and dynamic overload, and identification of the system parameters which critically affect performance.

The CSMA-CD-DP protocol has been modeled by a queueing system consisting of one central server (the transmission channel) and N send queues; see Fig. 5. The central server is allocated to the various send queues according to the distributed schedule of the CSMA-CD-DP protocol.

The total service phase of the central server consists of three serial phases representing TX delay, transmission, and acknowledgment 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 acknowledgment is generated by a given probability standing for a transmission error.

The arrivals of data frames are described by general arrival processes G_{Ai} with arrival rates λ_i, and the variable

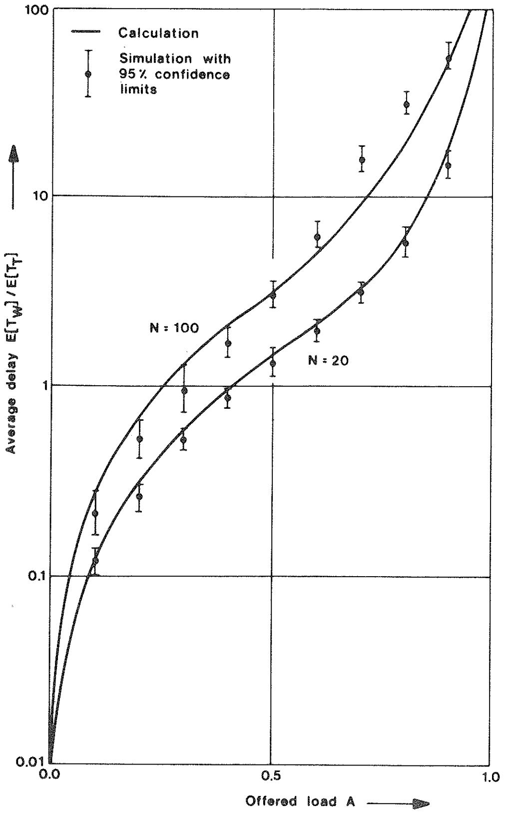

Fig. 6. Average delay versus offered load. Protocols: —— basic CSMA-CD-DP. ---- 1-persistent CSMA-CD with buffering. -·-·- token or polling with nonexhaustive service. $t_0/E[T] = 0.1, 0.01$. $E[T_{Ack}] = 0$. Frame length distribution: Constant. Number of stations N: 20.

lengths of frames are reflected by general transmission times described by transmission processes G_{Ti} with service rates μ_i, $i = 1, 2, \cdots, N$.

B. Performance Analysis by Simulation

The queueing model of Fig. 5 has been implemented by a flexible simulation program allowing the analysis of almost all possible parameters for system structures, process characteristics, and protocol options. Below, some typical results are given to show the performance of the protocol.

1) Comparison of Various Protocols: Fig. 6 gives results on the average delay of frames versus the total offered load $A = \lambda/\mu, \lambda = \lambda_1 + \lambda_2 + \cdots + \lambda_N, \lambda_i = \lambda/N, i = 1, 2, \cdots, N$ (balanced load). Three basic access protocols are considered: basic CSMA-CD-DP as defined in Section III-A, 1-persistent CSMA-CD with buffering of arriving frames and repeated transmission trials according to the binary exponential backoff time, and token. In any case, the slot time t_0 is used for transmission delay unit, backoff time unit, and token passing.

Fig. 6 clearly indicates the tradeoff between the contention and reservation modes: contention mode is favorable for low load; reservation mode for heavy load. These characteristics are known from other studies for CSMA-CD [15], token [2], [3], and polling [7] which is effectively equivalent to token. The new protocol CSMA-CD-DP features both advantages. This protocol limits the number of collisions per successful transmission strictly: for $\lambda \to 0$, the collision probability tends to zero since the probability for the arrival of more than one frame within the collision time window is $(\lambda t_0)^2/2$ (Poisson arrivals). For $A = \lambda/\mu \to 1$, almost every station has a frame to send; then, the busy period tends to infinity and the protocol operates only in the reservation mode. Most collisions may occur within the medium load range; however, for typical parameter cases the average number of collisions per frame was found to be less than 1 percent [11]. Contrary to the normal CSMA-CD protocol, the number of collisions per frame is strictly limited to one, since each collision initiates the reservation mechanism. We mention that the delay time of the nth frame in a particular station is limited by an upper value: since only one collision can occur in the worst case and FIFO is applied within each station, the delay is limited by n service cycles for that particular queue; each service cycle is limited by a maximum value according to the reservation mechanism.

Comparing the performance sensitivity of the various protocols with respect to the main system parameters N (number of stations) and t_0 (slot time), we observe the following: with increasing t_0, the throughput of all protocols decreases. Increasing N, the delay increases for the token protocol in the low and medium load range and for the CSMA-CD-DP protocol in the medium load range. The new protocol is especially sensitive to large N in the medium load range because of high channel reservation times. For this reason we recommend a clustering concept where several nearby located terminals share one station; this concept reduces the network costs and enhances the utilization of the expensive station equipment greatly. According to our investigations [8], the number of cluster stations N and the product $N \cdot t_0$ should be limited by $N < 50$ and $N \cdot t_0 < 0.2 \cdot E[T_T]$ to guarantee a high throughput and good delay performance.

2) Unbalanced Load: To compare various protocols in case of unbalanced load distribution among the stations, Fig. 7 shows the average frame delays in case of $N = 21$ stations where station 11 has a significantly higher load than all the residual stations.

The diagram compares four different strategies: CSMA-CD-DP to ordinary cyclically changing priorities, CSMA-CD-DP to static (fixed) priorities, CSMA-CD-DP to 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 such as token passing or, equivalently, polling.

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 III-B2). The control levels Q_1, Q_2 have a significant effect on the average 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 frames is reduced. For the examples of Fig. 8, the average total delay

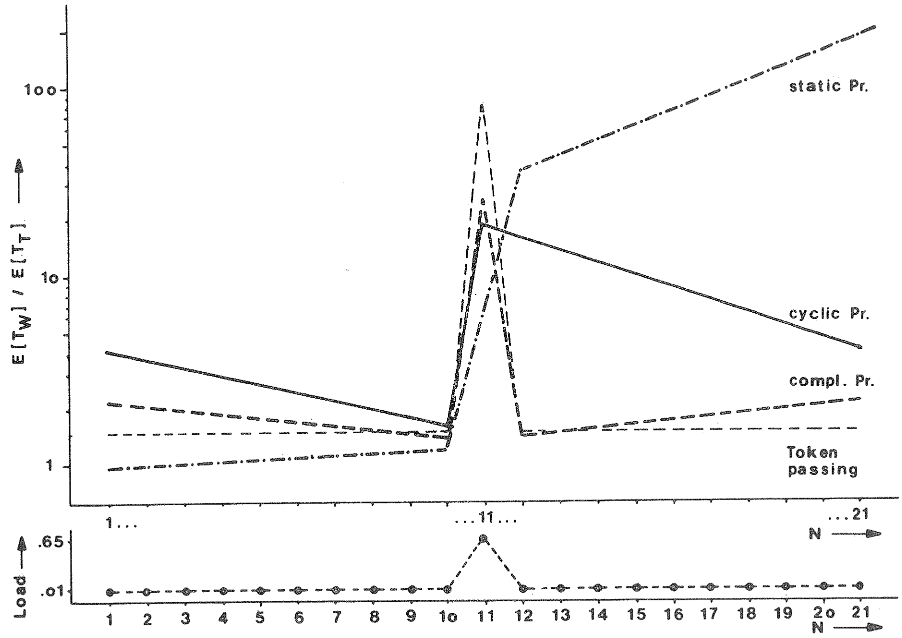

Fig. 7. Average delay for unbalanced load. Protocols: —— CSMA-CD-DP with cyclic priorities (basic CSMA-CD-DP). -·-·-· CSMA-CD-DP with static priorities. ---- CSMA-CD-DP with complementary priorities. ---- token or polling with nonexhaustive service. $t_0/E[T]=0.01$. $E[T_{\text{Ack}}]=0$. Frame length distribution: Exponential. Number of stations N: 21.

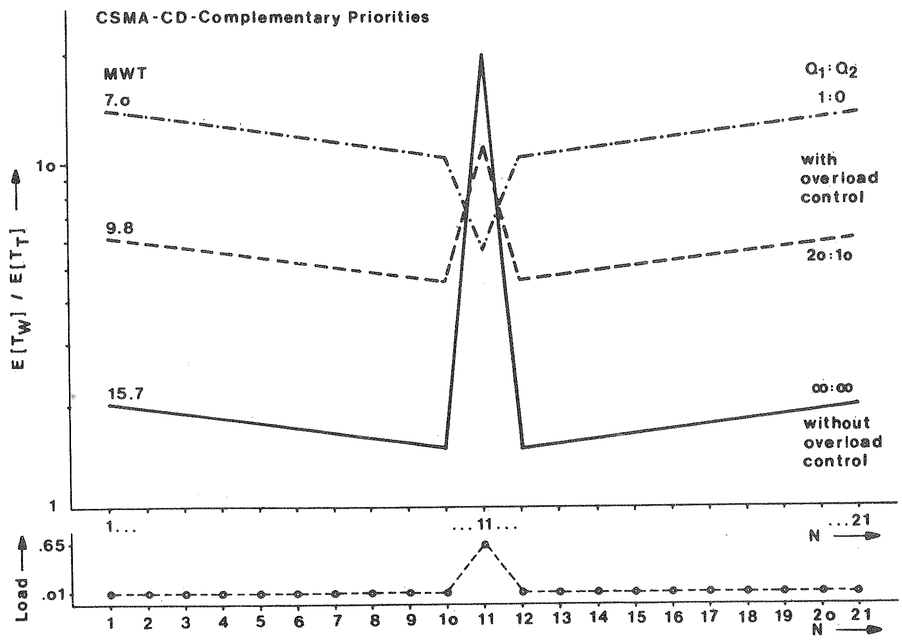

Fig. 8. Average delay for unbalanced load with dynamic overload control. Protocol: CSMA-CD-DP with complementary priorities and queue-length dependent control mechanism. MWT = mean waiting time with respect to all stations. $t_0/E[T]=0.01$. $E[T_{\text{Ack}}]=0$. Frame length distribution: Exponential. Number of stations N: 21. —— without overload control. ---- with overload control $Q_1=20$, $Q_2=10$. -·-·-· with overload control $Q_1=1$, $Q_2=0$.

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.

C. Analytical Performance Evaluation

An exact analytic performance analysis does not seem feasible due to the complex protocol. We therefore restrict ourselves to approximate analysis methods and the case of Poisson arrivals and balanced load.

Considering the transmission channel as the common server, we model the system by an $M/G/1$ queue. Dropping the very small probability for collisions and false transmissions, a resulting service time per transmission can be formed by

$$T = T_T + T_D(X) + T_{\text{ACK}}. \tag{1}$$

In (1), the TX-delay time $T_D(X)$ is a random variable; its actual value depends on the system state X.

Step 1—Evaluation of the TX-Delay Time $T_D(X)$: $T_D(X)$ can be determined exactly only in case of a detailed state description $X=(x_1, x_2, \cdots, x_N; P)$, where x_i defines the number of waiting frames of station i and P indicates that station with the currently minimum TX-delay time. This detailed state description is approximately replaced by a single state variable x, i.e., $X = x$, where x defines the number of waiting frames left behind by a departing frame. Each of the x single frames is assumed to have a random position relative to that station currently owning the minimum TX-delay time. Thus, the TX delay T_{Dj} of each of the x waiting frames occurs with probability density function (pdf)

$$f_j(t) = \frac{1}{N} \cdot \sum_{\nu=1}^{N} \delta(t - \nu t_0) \tag{2a}$$

and probability distribution function (df)

$$F_j(t) = \frac{1}{N} \cdot \sum_{\nu=1}^{N} u(t - \nu t_0), \qquad j = 1, 2, \cdots, x \tag{2b}$$

where $\delta(t)$ and $u(t)$ are the impulse and unit step functions, respectively.

Assuming independence, the actual TX delay in the state x, $T_D(x)$, is the minimum of all individual TX delays

$$T_D(x) = \min(T_{Dj}), \qquad j = 1, 2, \cdots, x. \tag{3}$$

Thus, we find for its df, pdf, and ordinary moments

$$F(t|x) = 1 - \{1 - F_j(t)\}^x \tag{4a}$$

$$f(t|x) = \sum_{\nu=1}^{N} \left\{ \left(1 - \frac{\nu - 1}{N}\right)^x - \left(1 - \frac{\nu}{N}\right)^x \right\} \cdot \delta(t - \nu t_0) \tag{4b}$$

$$E\left[T_D^k(x)\right] = \sum_{\nu=1}^{N} (\nu t_0)^k \cdot \left\{ \left(1 - \frac{\nu - 1}{N}\right)^x - \left(1 - \frac{\nu}{N}\right)^x \right\}, \quad k = 1, 2, \cdots. \tag{4c}$$

Note that (1)–(4) have been derived for $x > 0$. After transmission of the last frame ($x = 0$), the channel stays reserved for the time $T_D(0) = N \cdot t_0$. Equation (4) includes this result when extended to the case $x = 0$.

Step 2—Queueing Analysis: With $T_D(x)$ according to (3), (4), an $M/G/1$ analysis can be performed on the basis of an imbedded Markov chain. This analysis will not be pursued here.

A simpler analysis can be performed using only average values. As mentioned above, x defines the number of waiting frames left behind by a departing frame. According to a general theorem for $GI/G/1$ queues [11], the distribution of x is identical to the distribution of frames met by an arriving frame which is, in case of $M/G/1$, the same as the state distribution $p(x)$ for an arbitrary time instant. To further simplify the averaging, we use the state distribution for the $M/M/1$ instead of the $M/G/1$. We find for the pdf $f(t)$ of the (unconditioned) TX-delay time T_D

$$f(t) = \sum_{x=0}^{\infty} p(x) \cdot f(t|x) = \sum_{x=0}^{\infty} (1 - \rho)\rho^x \cdot f(t|x) \tag{5}$$

where ρ defines the utilization (load) factor of the queuing system. From (5), (4b), and (4c), finally, the first and second ordinary moments of the (unconditioned) TX delay T_D follow as

$$E[T_D] = (1 - \rho)t_0 \cdot \sum_{\nu=0}^{N-1} 1 \Big/ \left\{1 - \rho\left(1 - \frac{\nu}{N}\right)\right\} \tag{6a}$$

$$E\left[T_D^2\right] = (1 - \rho)t_0^2 \cdot \sum_{\nu=0}^{N-1} (2\nu + 1) \Big/ \left\{1 - \rho\left(1 - \frac{\nu}{N}\right)\right\}. \tag{6b}$$

Note that both limits $E[T_D] \to N \cdot t_0$ for $\rho \to 0$ and $E[T_D] \to t_0$ for $\rho \to 1$ follow correctly from this approximation.

The utilization (load) factor ρ of the $M/G/1$ queue is

$$\rho = \lambda \cdot E[T] = \lambda \cdot (E[T_T] + E[T_D] + E[T_{ACK}]). \tag{7}$$

For stationarity, ρ may not exceed 1; this results in the maximum throughput rate the system can handle

$$\lambda_{max} = 1/(E[T_T] + t_0 + E[T_{ACK}]). \tag{8}$$

Since $E[T_D]$ itself is a function of ρ [see (6a)], the load factor ρ has to be iterated properly according to (6a) and (7) to reach consistency.

Finally, with the consistent ρ we find all the interesting values from the well-known $M/G/1$ formulas. The mean waiting time $E[T_W]$ of an arbitrary frame is

$$E[T_W] = \rho \cdot \frac{1 + c^2}{2(1 - \rho)} \cdot E[T] \tag{9a}$$

where

$$c^2 = E[T^2]/E[T]^2 - 1 \tag{9b}$$

is the squared coefficient of variation of T and

$$E[T^2] = E\left[T_T^2\right] - E[T_T]^2 + E\left[T_D^2\right] - E[T_D]^2 + E[T]^2. \tag{9c}$$

Step 3—Validation of the Approximate Analysis: To validate the approximate analytic results against simulation, Fig. 9 gives some results of the delay performance. For small system overhead (small t_0 or N), the approximation generally fits very well. For larger overheads, i.e., $N \cdot t_0 > 0.2\ E[T_T]$, we found that the analytic results show increasing deviations from simulation. These deviations result from the fact that in the range of medium loads, the average transmission delays $E[T_D]$ are greater than the values obtained from the uniformly distributed transmission delays in (2a). The approximation results are generally within the confidence levels of simulation in the range of $N \cdot t_0 \leqslant 0.2 \cdot E[T_T]$; this range, however, is identical to the range of high throughput and good performance for which the new protocol is recommended.

V. Conclusion

A new CSMA-type protocol for a distributed system with one common channel and clustered network access has been presented. The protocol uses carrier sensing with collision detection and dynamically staggered transmission delays for channel arbitration. Appropriate choice of the assignment of transmission delays to stations allows a very flexible adaptation to load characteristics as unbalanced

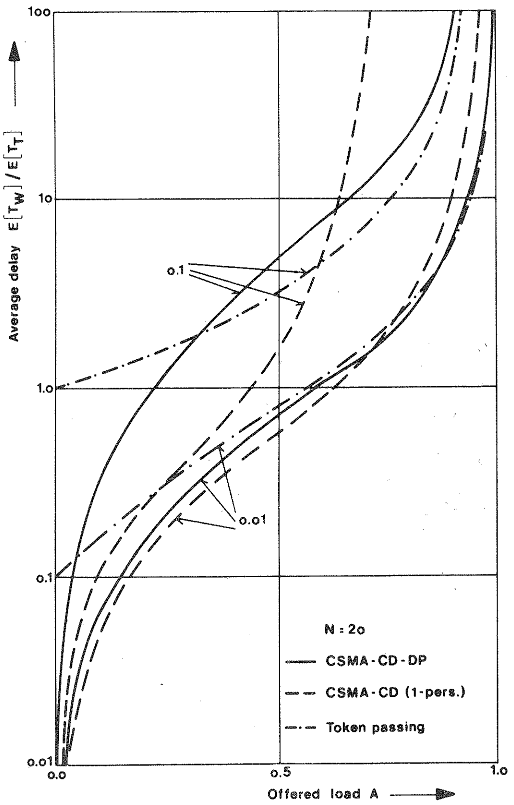

Fig. 9. Validation of analytic results. Average delay versus offered load. $t_0/E[T] = 0.01$. $E[T_{Ack}] = 0$. Frame length distribution: Exponential. Number of stations N: 100, 20.

load or dynamic overload or to station priority requirements. The performance results show the basic influence of the main system parameters and indicate that the new protocol combines the advantages of contention modes for low traffic and reservation modes for heavy traffic. The implementation has shown that the new protocol supports the concept of clustered access and owns enough flexibility to adapt to specific user requirements. In summary we conclude that new controller equipment should be designed with respect to optional programming of special protocol features.

Acknowledgment

The initiatives of Dipl.-Ing. H. Schroeder and Dipl.-Ing. A. Schwanke for the implementation of the LAN are greatly appreciated.

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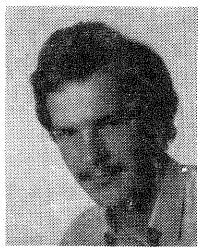

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