ARCHITECTURE OF THE COMMUNICATION SUBSYSTEM FOR LOCAL AREA NETWORKS OPERATING UNDER A NEW CSMA-PROTOCOL WITH DYNAMIC PRIORITIES

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Abstract

A local area network with a completely distributed control is considered, where the connected peripherals (terminals, host computers) communicate with each other through addressed messages via a common high speed carrier. The network consists of three main layers: peripherals, network access controllers (NAC), and the communication subsystem. The higher levels of the network protocols are implemented within the NAC or the connected peripherals. The communication subsystem consists of the common high speed carrier and the channel access modules (CAM). The communication subsystem operates under a new carrier-sense-multiple-access (CSMA) protocol with collision detection and conflict resolution by dynamically controlled send priorities. This protocol combines both advantages of pure contention protocols for low traffic and fixed/demand assignment protocols for heavy traffic and reveals specific advantages with respect to overload control.

This paper aims specifically at the implementation of the communications subsystem. Starting off from the layered protocol structure as proposed by IEEE Project 802, the software structure for each CAM is developed by a top-down approach using the CCITT Specification and Description Language SDL. By a stepwise refinement the protocol functions are finally implemented by special high-speed integrated circuits with a bit-slice processor as the heart of a CAM. An experimental network has been built up which operates at 1 Mbit/sec. From this implementation, the functional modularization according to the protocol layering can be particularly motivated.

Contents:

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1. Introduction

In distributed systems, the communication channel assignment plays an important part 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 [7, 9, 16].

Multi-access contention protocols, as the ALOHA or the basic CSMA (carrier-sense-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, e.g. polling 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, 3, 4, 6, 10, 13].

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 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 messages. Various schemes have been proposed which are based on randomly chosen retransmission delays, or fixed deterministic retransmission delays [2, 4, 8, 14, 15, 17].

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. The protocol allows several options for the dynamical adjustment of access priorities depending on the system state or specific performance requirements. The protocol limits the number of possible collisions to a minimum and shows the advantages of contention protocols at low traffic (small delays) and fixed/demand assignment protocols at heavy traffic (highest throughput) [11, 12].

In chapter 2, communications protocols for LAN are discussed with respect to the layered protocol architecture as well as to performance requirements. In chapter 3, the new CSMA-CD-DP protocol is defined. Extensions of the basic protocol to static priorities, dynamic overload control, and broadcast operation are addressed. The main performance results for the new protocol are also referred to. In the main chapter 4, the architecture of a LAN operating under the new protocol is developed systematically by a top-down design approach using the symbolics of CCITT's SDL. This architecture has been implemented in an experimental LAN. The paper is concluded by results on the experimental operation of the network.

2. Communications Protocols for Local Area Networks

2.1 Objectives

The basic objective behind LAN's is to provide cheap communication between locally distributed terminals and computers. Early implementations of teleprocessing systems were characterized by Communications Controllers interfacing the spacially distributed terminals with the host computers (front-end network). Usually, terminals were connected to the Communications Controllers in a star-type network and compatibility was limited due to the lack of standardization.

The layered architecture of the ISO-Reference Model and CCITT-Recommendation X.25 form the basis for future open systems interconnection. High-speed carriers and powerful microelectronics allow new solutions of local computer communications fitting well into the commonly accepted layered architecture.

Since many applications are distributed among many hosts or company sites there is the need for a fast communication between any user and process. Thus, not only local computer communication must be provided but also internetworking between various LAN's and public packet networks as well. However, standardization and flexibility cause a higher functionality of the interfaces between terminals, computers, and the communications network. For this reason, a total decentralization of the communications functions contradicts with low-cost implementation and high utilization.

Summarizing, the following design objectives for LAN's are concluded:

- Standardized interfaces for open systems interconnection
- Clustering of terminals/hosts to provide high utilization through shared use of intelligent communications resources
- Communication protocol with high throughput and good performance, stability, adaptability to breakdown and overload situations.

Fig. 1 shows a typical structure of a LAN: Several stations (N) are connected to a common transmission medium, the "channel". Each station interfaces the channel with one or many peripherals (terminals, hosts). This basic structure is assumed for the following considerations.

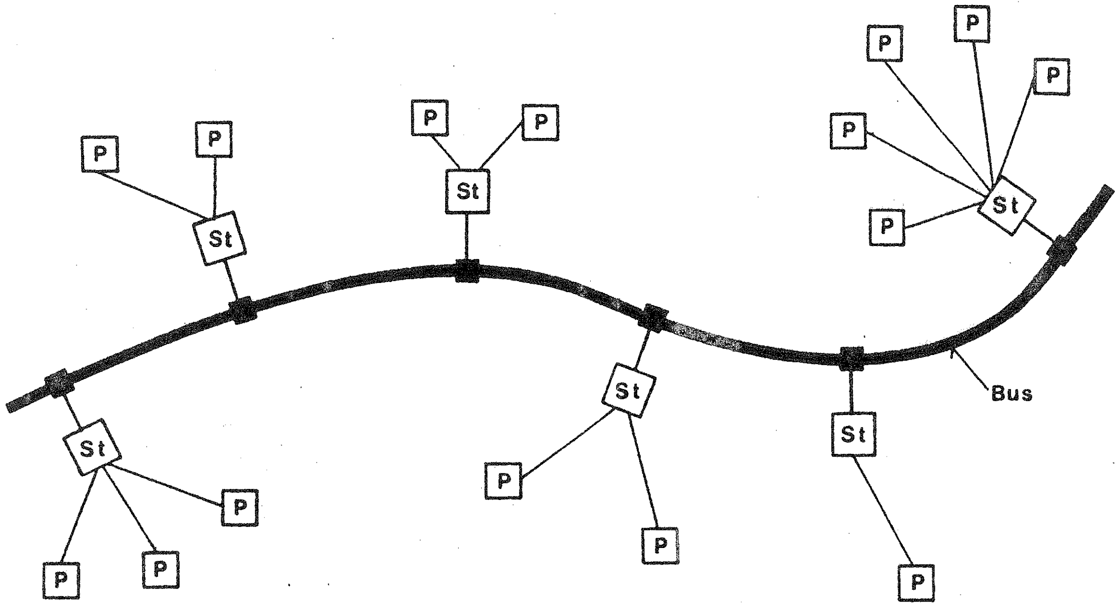


Fig. 1 *Local Area Network Structure*
St Stations P Peripherals (Terminals,Hosts)

2.2 Network Architecture and Protocols

In Fig. 2 the ISO reference model [19] is shown with its seven layers for open systems interconnection. This model is extended to meet the specific requirements for LAN's, namely multiple access and distributed switching, see [20]. According to the current state of standardization, level 2 is subdivided into two sublevels, Medium Access Control and Logical Link Control. The interface between any two neighbor levels is defined as a "service access point" SAP. From a SAP, the higher (lower) levels are seen through a particular set of signals/functions.

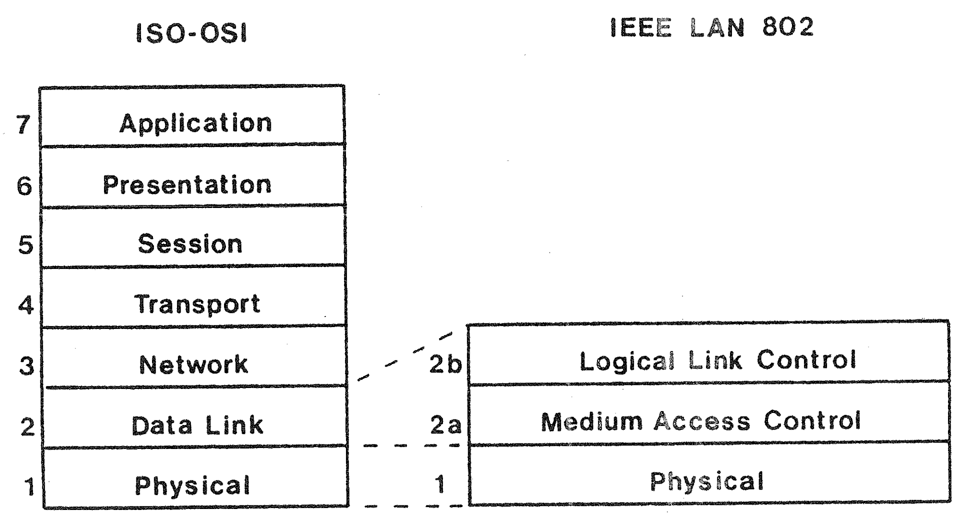


Fig. 2 *Extended ISO-Reference Model for Local Area Networks*

2.2.1 Physical Layer

The Physical Layer provides the capability of transmitting and receiving bits between Physical Service Access Points (P-SAP). The physical layer consists of the transmission medium (e.g., a coaxial cable), the physical medium attachment unit, modulation and demodulation, and clock synchronization. The P-SAP forms the interface between the Physical Level and the Medium Access Control Level.

2.2.2 Medium Access Control Sublayer

The Medium Access Control (MAC) performs the functions of accessing the common transmission media and the control of an access protocol. Specifically, this protocol includes functions as

- framing
- addressing
- error detection
- channel allocation
- contention resolution
- initialization

The MAC-Sublayer interfaces the Physical Layer through the P-SAP and the Logical Link Layer through the MAC-SAP.

2.2.3 Logical Link Control Sublayer

The Logical Link Control (LLC) performs the functions of error recovery and flow control analogously to the commonly known HDLC (Level 2 of CCITT X.25). The LLC receives frames from the MAC through the MAC-SAP; it interfaces the network Level 3 through the L-SAP.

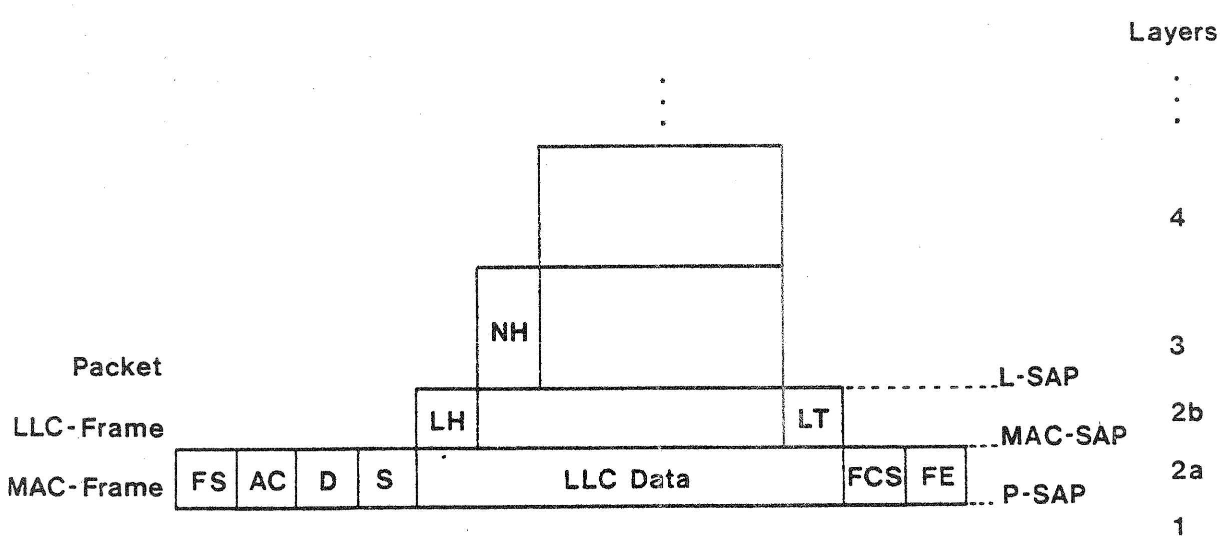


Fig. 3 Network Layers and Data Encapsulation

FS, FE	*frame delimiters*	*FCS*	*frame check sequence*
AC	*medium access control field*	*LH, LT*	*header/trailer of link level*
D, S	*destination/source addresses*	*NH*	*header of network level*

2.2.4 Network Layers and Data Encapsulation

According to the layered network architecture, the basic information units (user data) are encapsulated in a hierarchical manner. Fig. 3 shows the lower network level structures as applied for LAN's.

In the residual part of the paper, we are concentrating on levels 1 and 2a which are the essential parts of a Local Area Network. The messages passed between different stations in both sublayers of level 2 are named frames, see. Fig. 3.

3. The CSMA-CD-DP Protocol

In this Section, a new CSMA-CD protocol is introduced which is characterized by very low probability of collisions and stability. It has been developed under the following set of requirements:

- combining advantages of CSMA-CD and Token
  (immediate access for idle channel, maximum throughput for peak load)
- fair access or prioritized access according to user requirements
- dynamic prioritized access for adaptive overload or unbalanced load defeat.

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

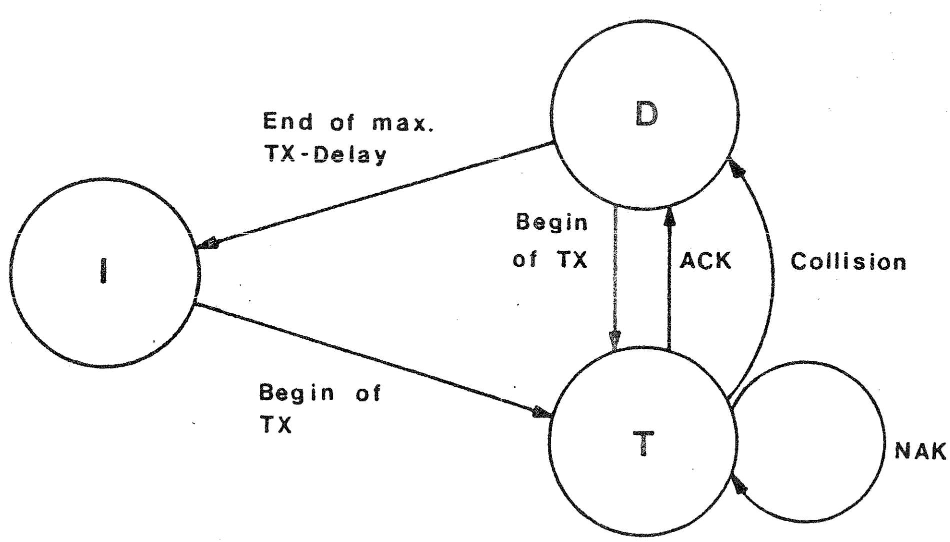


Fig. 4 *State Transition Diagram of the Channel*
I idle state T transmission state D delay state

From the viewpoint of the common channel, three different states can be distinguished, see Fig. 4. 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 → 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 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) $i \cdot t_o$, $i = 1,2,\ldots,N$. Upon detection of an ACK, each station updates its current TX-delay through cyclic incrementation by t_o, 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 → T).

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

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

Another option of the basic protocol can be defined without use of an acknowlegement; the transmission delays could be adjusted upon recognition of the correctly received frame.

3.2 Extensions

3.2.1 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.

3.2.2 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.

3.2.2.1 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.

3.2.2.2 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 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.

Similary, a receiving station may broadcast its overloaded status by a Receiver Overload Indication (ROI) bit being set within an acknowledgement upon which the sending stations may withhold their messages 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.

3.2.3 Broadcasting

An other extension of the protocol deals with 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 acknowledgement process upon reception of the frame, the timing of it is controlled by the current transmission delays of each of the receiving stations.

This mechanism can 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 BCI-bit, the system is monopolized by that station. All other stations are passive and can be supplied with the new information.

3.3 Performance Aspects

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 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
- identification of the most critically influencing system parameters
- optimization of system parameters.

The CSMA-CD-DP protocol has been modeled by a modified M/G/1 multi-queue system and extensivly analyzed by simulation and queuing theory, see [11, 12]. The main features of these performance studies are as follows:

- performance characteristics (throughput, delay) as CSMA-CD for low traffic and token/polling for heavy traffic
- fair access for all stations in the basic protocol mode and arbitrary static priorities for different user requirements
- dynamic defeat of unbalanced load or temporary overload
- real-time capability in the sense of an absolute upper bound for delay for any waiting frame.

These results indicate a good compromize between different performance requirements so that the new protocol seems to be adequate for a wide range of applications. Restrictions of the applicability are primarily dictated by two parameters, the delay time t_o - which is related to the two-way propagation delay between the spacially most distantly located stations - and the number of stations, N. The latter can be kept small to 10-20 when clustering of peripherals is enforced as in the concept being proposed.

4. Architecture and Implementation

4.1 Functional Division

In a system with distributed control the functional subdivision is a principal problem covering aspects of hardware, software, system recovery, reliability, etc. Examples of functional subdivision can be found, e.g., for CSMA-CD [1] or Token Passing [5].

Ideally, functions should be divided analogously to the layered architecture shown in Fig. 2. In reality, many other aspects resulting from the technological point of view have to be considered, too.

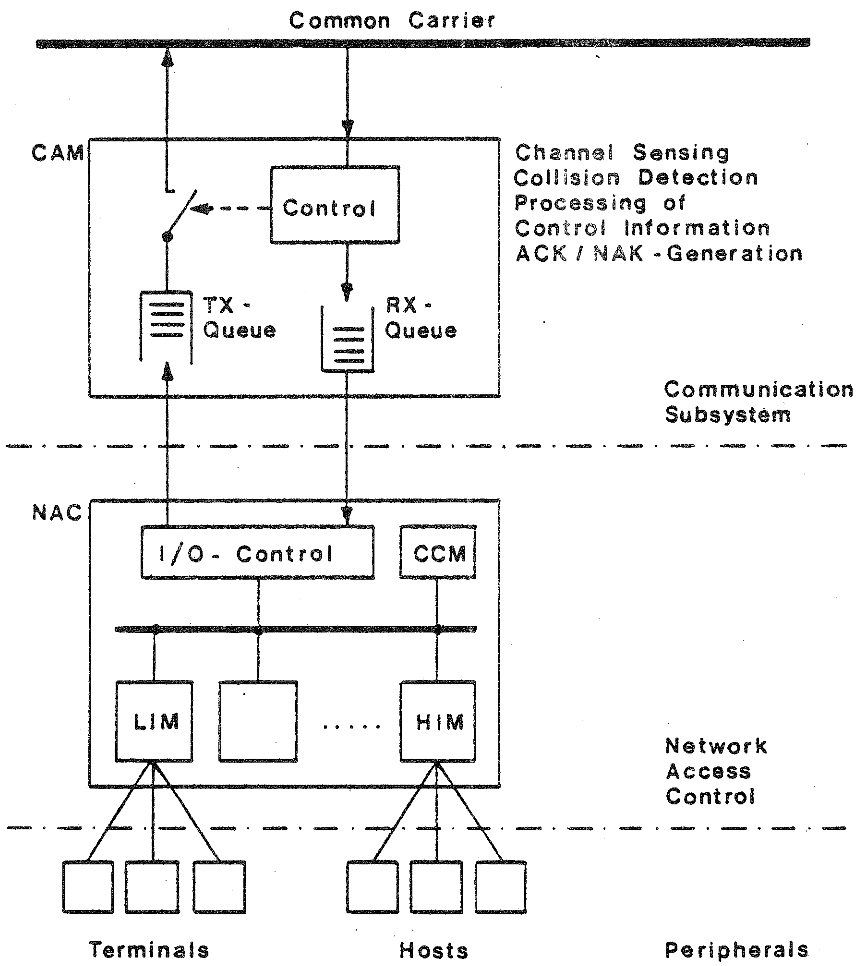


Fig. 5 Station Structure

CAM channel access module
NAC network access controller
CCM call control module
LIM line interface module
HIM host interface module

Fig. 5 shows the global structure of the stations. Two modules can be distinguished: the Communications Acess Module (CAM) and the Network Access Controller (NAC). The CAM performs all those functions which have essentially to be processed by the speed of the common carrier; in terms of the layered architecture model of Fig. 3, the CAM includes functions of levels 1 and 2a. The NAC performs all higher protocol functions, i.e. levels 2b and up. The interfaces between the CAM and the common carrier and the CAM and the NAC are the physical connection to the common carrier and the MAC-SAP, respectively. Two main data paths can be identified referring to the TX- and RX-direction.

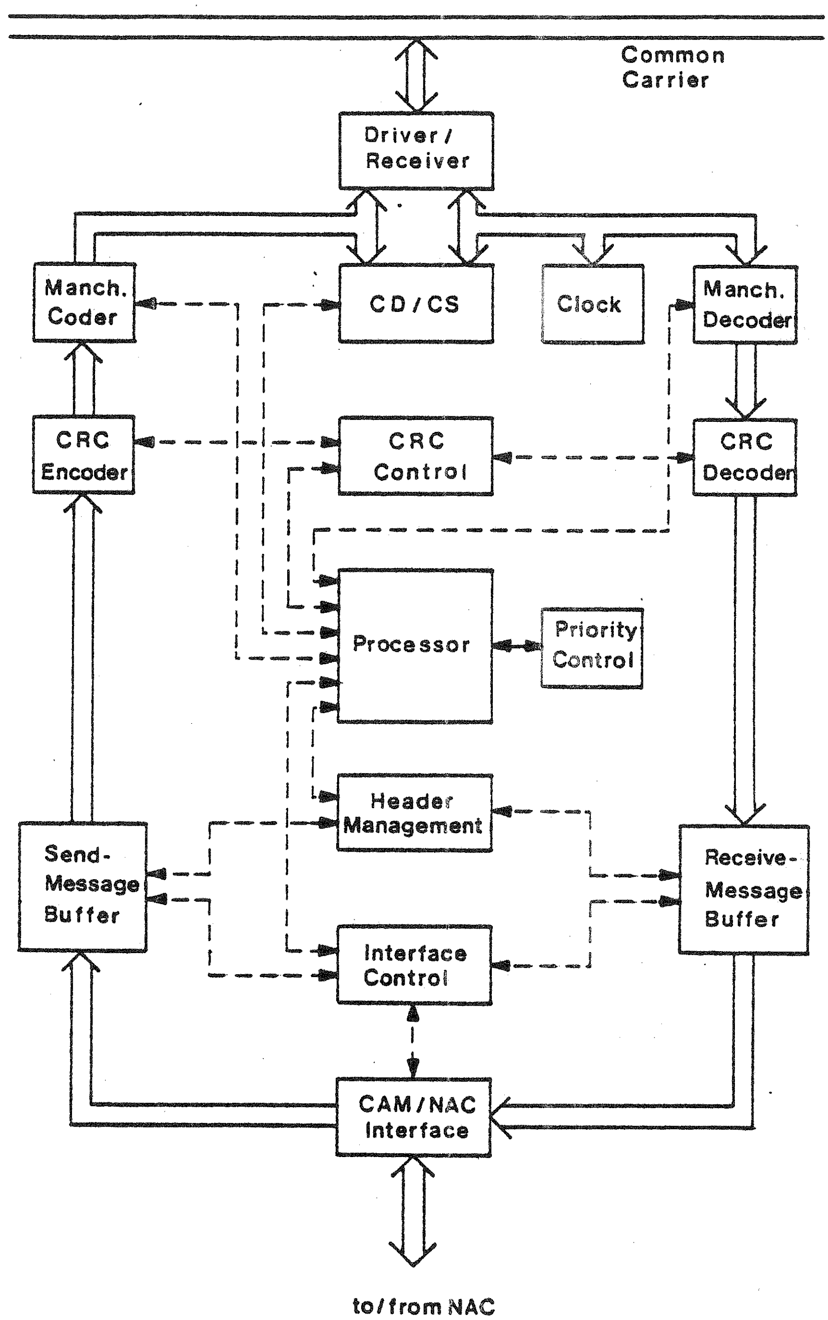


Fig. 6 *Structure of the Channel Access Module CAM*

4.1.1 Channel Access Module (CAM)

The principal block structure of the CAM is shown in Fig. 6. The CAM is controlled by a central bit slice processor performing basically the protocol functions. The Processor exchanges events/signals with some high-speed functional modules as CD/CS, Coder/Decoder, CRC-Controller, Header Management and NAC-Interface Control. The access rights are implemented by a special module Priority Control through a timing mechanism initialized by the Processor. Some of the functional modules are operated in parallel whereas the Processor operates in a strict sequential order according to the state-transition logic given in Section 4.2.

The CAM receives frames from the NAC and buffers them intermediately. Then, the frame format is completed by the Header Management. Finally, when the frame is transmitted, the CRC-information is added.

Arriving frames from another station are firstly analyzed with respect to their destination; if the considered station is the destination station of the frame, the full frame is stored intermediately for CRC and acknowledgement processing. After the frame has been positively acknowledged, the received frame is forwarded to the NAC; otherwise, the CAM signals by a NAK that the frame has to be retransmitted.

4.1.2 Network Access Controller (NAC)

The basic functions of the NAC are identical to common facilities of modularized packet switching network access controllers: microprocessor-based line interface modules (LIM) and host interface modules (HIM) for the realization of standardized terminal and host protocols and call control modules (CCM) for the establishment and control of virtual circuits. Generally, these functions refer to levels 3 and up in the layered architecture model. Additionally, the logical link control (level 2b) is also implemented in the NAC.

Frames to be transmitted are prepared by the NAC according to the frame format shown in Fig. 7 (except Sync. and CRC-information). The global format corresponds with the recommendations of the IEEE Project 802 [20]. The control field contains a number of indicator bits and the length of the data field. Indicator bits are such as for overload control and broadcasting (see Section 3.2). With FTI, the type of the frame (data or acknowledgement) is indicated. With another DTI bit, a special frame can be identified to be used for network control purposes. The length of the frame has been limited initially to 256 Bytes; there is no difficulty to expand this field to meet other user requirements.

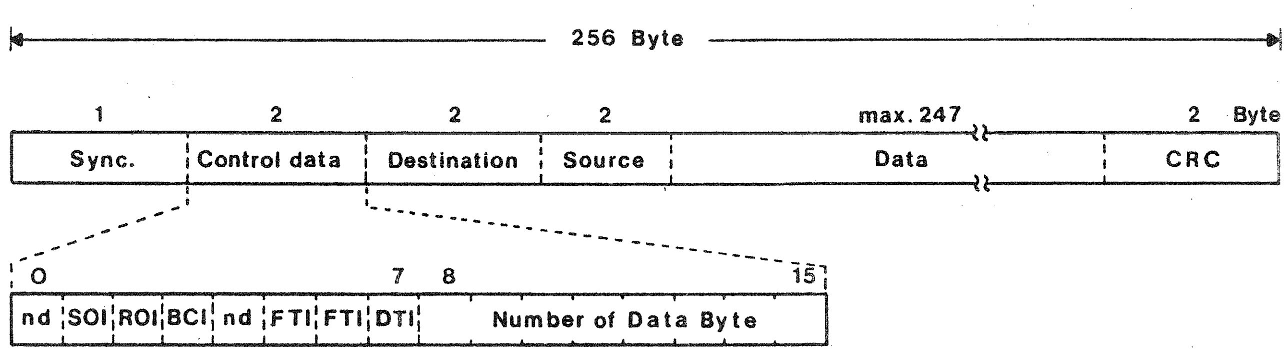


Fig. 7 *Frame Format*

SOI	*sender overload indication*	*ROI*	*receiver overload indication*
BCI	*broadcast indication*	*FTI*	*frame type indication*
DTI	*data type indication*	*nd*	*not defined*

4.2 Software Structure

4.2.1 CCITT Specification and Description Language SDL

To adequately describe the logic of a process and the intercommunication between various processes, CCITT has recommended a symbolic flow-chart language which is based on the concept of finite-state automata [18]. The basic elements of this language and their meaning are given in Table 1. SDL specifically features the possibility of describing functions of and interactions between various processes and is, therefore, adequate to describe protocols for distributed systems. At any time, the process is in a certain state. Upon the arrival of an input signal ("event"), the event is analyzed (task) and causes eventually an output signal to another process; after reception and processing of the input signal, the considered process changes in general into another state.

We therefore adopt SDL for specification of the protocol as well as for describing detailed functions which are found by stepwise refinement.

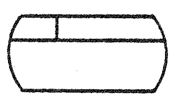
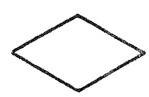
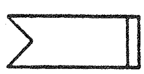
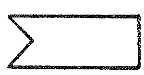
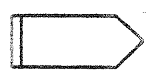
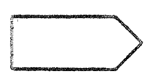
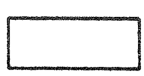
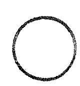
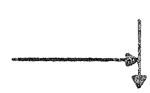
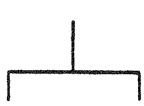
Symbol	Meaning	Symbol	Meaning
	State		Decision
 	Input Internal External	 	Output Internal External
	Task		Connector
	Flow Line		Convergence
	Divergence		Comment

Table 1 *Elements of SDL*

4.2.2 Global State Transition Diagram

Since the channel is completely passive with no central control, the whole logic of the protocol must be implemented within each of the station's MAC-units.

Fig. 8 describes the global state transitions of the protocol from a station's point of view. The channel transmission state T of Fig. 4 breaks down into two sets of substates: receiving states and sending states depending on whether the particular station is listening/receiving or actively transmitting, respectively. When the station is in the "receiving states", it changes into the "delay states" upon reception of an ACK when listening, or generation and transmitting of an ACK when receiving; on the other hand, when the station is in the "sending states", it changes into the "delay states" upon reception of an ACK from the foreign station to which the frame had been sent. In either case, the station changes into the "delay states" when a collision is detected. From the "delay states", the station changes into the "receiving states" upon activation of the channel by some other station with a higher transmission right; it changes into the "sending states" with an own transmission or into the "idle state" if none of the stations has a frame to transmit.

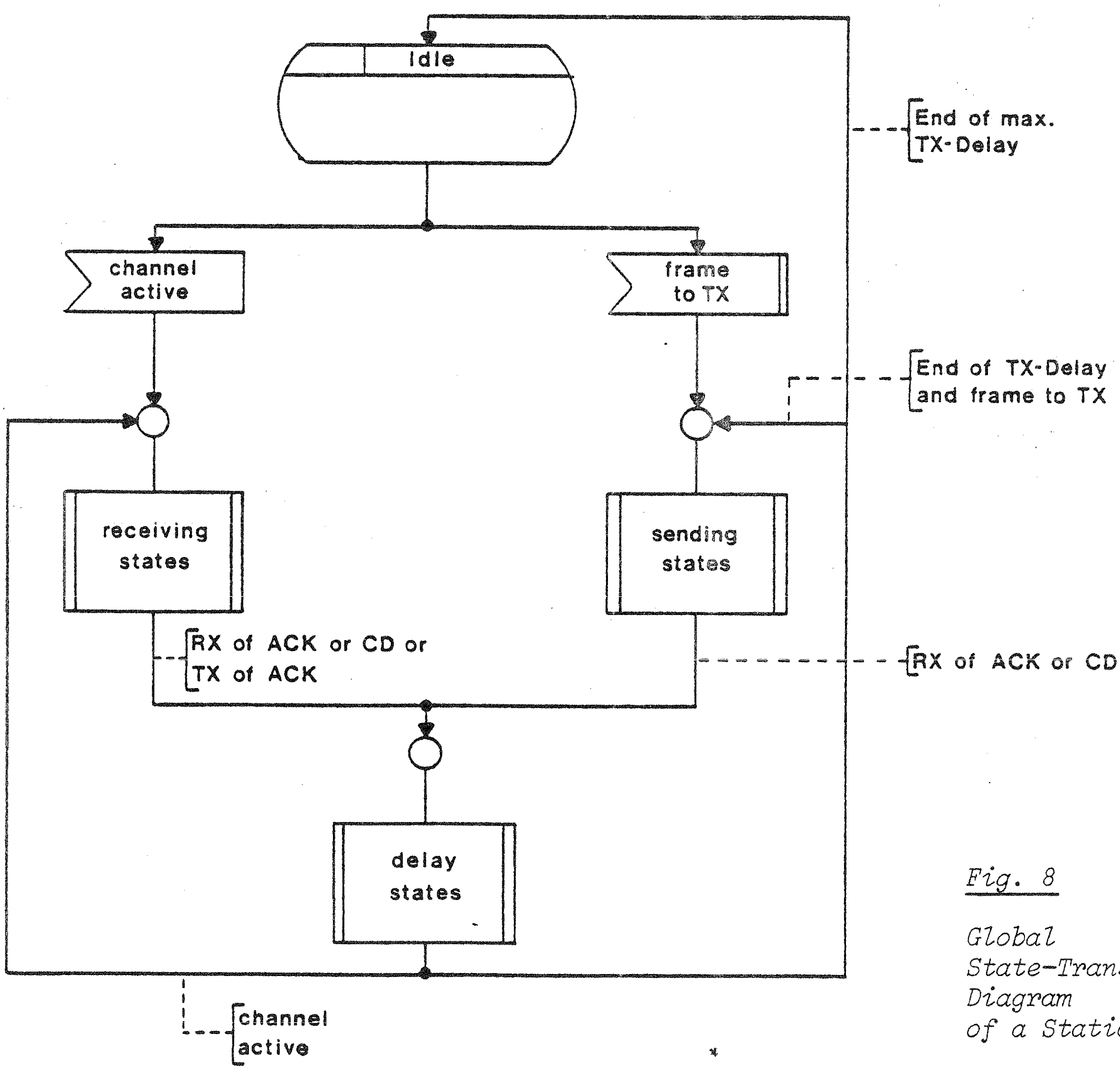


Fig. 8

Global State-Transition Diagram of a Station

4.2.3 Specification of the R, S, and D Modules

Fig. 9 displays the functions within the module "receiving states" R in greater detail. Upon detection of a channel activity, the collision detection module is activated by setting of a timer for the duration of the collision window time TC. At the same time the synchronization module is activated. If there is a collision, the station changes into the "delay states" D, otherwise the station proceeds within the "receiving states" R. After the end of synchronization the header must be analyzed to find out the type (data frame, acknowledgement) and its destination. If a data frame is destinated for the considered station, the cyclic redundancy check CRC has to be waited for; upon this the station responds accordingly (ACK or NAK). If the activity resulted from an acknowledgement, the station acts differently depending on whether it is an ACK or a NAK; in case of an ACK, the current transmission delay is incremented whereas for a NAK the station waits on until the data frame is repeated. If the detected data frame were destinated for some other station, the station waits on until the appearance of the responding acknowledgement of that particular station.

Fig. 10 shows the functions within the module "sending states" S. If the station has a frame to transmit while the channel is in the idle state, it immediately starts the transmission and activates the addition of the CRC-information at the end of the message. During the begin of the transmission a timer TC decides whether an occuring collision is "allowed" (i.e. it appears within the collision window) or not. In all other cases of collision occurences, collisions can only be caused by some malfunctioning devices (not shown in the diagram). After transmission, the station waits for the acknowledgement of the destination station. In case of a NAK, the message is repeated immediately, whereas in case of an ACK, the transmission delay is incremented.

For reasons of failure recovery, an outstanding acknowledgement is detected by a time-out control mechanism. If an acknowledgement is missed, or a NAK is received the transmission is repeated. If a particular transmission action cannot be finally completed, the sending station actively sends an ACK upon which the system changes into the delay state as in case of an ordinarily completed transmission action. For ease of reading, these recovery procedures are not included in the SDL-diagram.

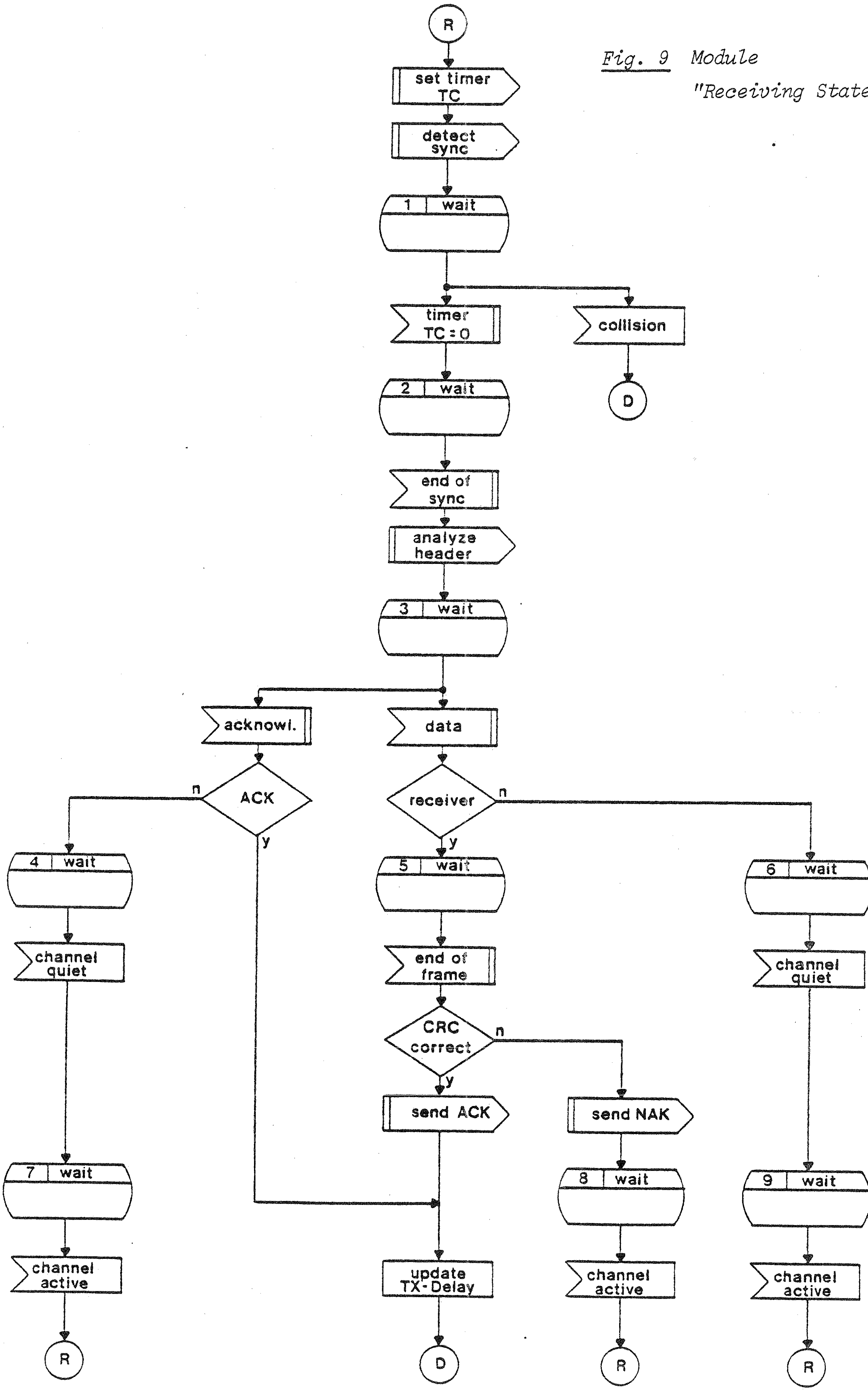


Fig. 9 *Module "Receiving States" R*

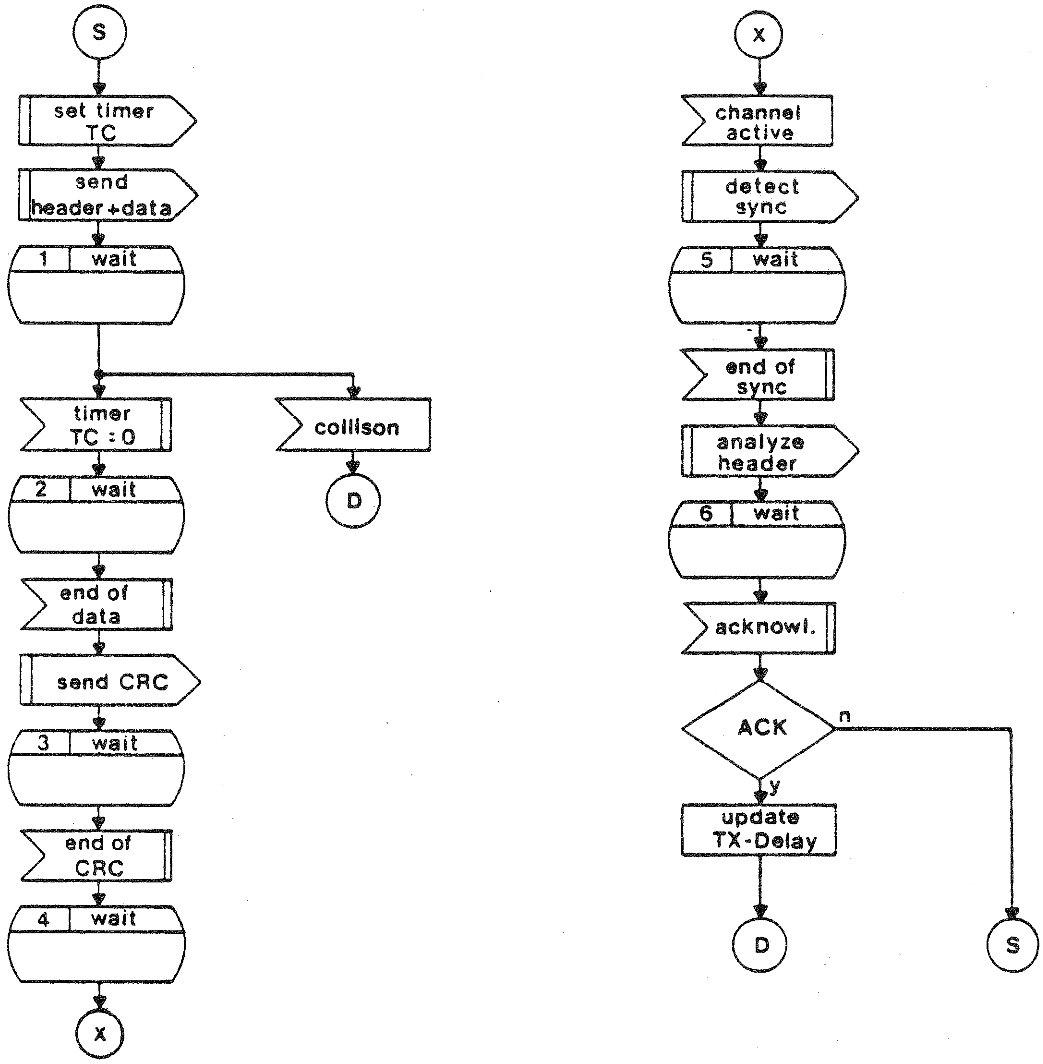


Fig. 10 Module "Sending States" S

Fig. 11 describes the functions within the module "delay states" D. Entering the delay state, each station starts from a defined initial state by setting two timers with the actual transmission delay time TD of that station and the maximum transmission delay time TDMAX, respectively. Upon expiration of the current transmission delay time, the station is allowed to transmit unless another station had started transmitting prior to that instant (channel active). Hence, the station enters the sending state or receiving state accordingly. Otherwise, the station waits further on. In case of the expiration of the maximum transmission delay time, the station changes into the idle state (no station has data to transmit) or sending state (if a new frame had arrived in the meantime); otherwise, the station changes into the receiving state upon detection of an activity by some other station.

The simplified Figs. 9-11 include only those functions of a station which are related to the channel. They have to be completed by those functions being related to the user side of a station (forwarding of received data and acception of data).

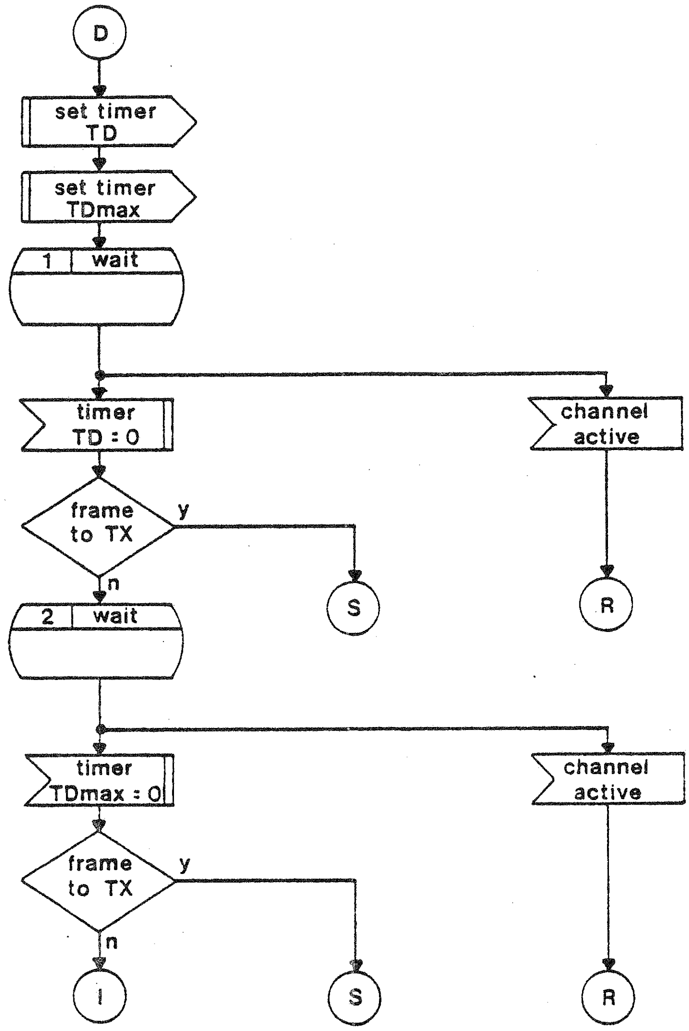


Fig. 11 Module
"Delay States" D

4.2.4 Firmware Implementation

The various diagrams have been further refined by continued hierarchical subdivision using again the SDL technique. In the lowest level, these SDL-diagrams define logical signals exchanged between the various hardware components of the CAM as shown in Fig. 6. The central logic of the diagrams is coded directly with the instruction set of a high-speed bit-slice processor (AM 2910) forming the firmware which is located within a RAM. The firmware for the basic protocol and its extensions amounts to about 3K Bytes memory. These extension include already overload functions, broadcasting, and testing.

The higher functionality (compared to simpler protocols) requires slightly more hardware, but these additional costs are small because conventional LSI-components are used.

4.3 Experimental Operation

At the current state, the LAN has been implemented completely with carriers and CAM's; the operation of the higher levels (NAC) is simulated by special hardware to operate the LAN experimentally. By these facilities special tests can be run as operation at maximum throughput, overload condition (sender/receiver), station malfunctioning, or breakdown.

The experimental LAN operates at a speed of 1 Mbit/sec; the hardware configuration allows, however, operation up to 5-10 Mbits/sec.

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 new protocol has been implemented in an experimental LAN. Experience from this implementation allows the following conclusions:

- The software structure can be implemented straightforwardly through a stepwise refinement down to standard hardware modules.
- The specifications of the IEEE Project 802 are very useful for functional division of software and hardware.
- The costs of the CAM, which can be clearly estimated from its implementation, are shared by all connected peripheral devices. The concentrator concept makes also sure that the CAM- and NAC-devices are sufficiently high utilized. Costs may further be reduced by use of customized LSI-circuitry.

From these facts we conclude, that the new protocol is adequate for a wide range of applications in Local Area Networks.

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