EB 348

5865

Implementation of the Link Access Procedure on the ISDN D-channel

D.F. van Egmond

Department of Electrical Engineering
Digital Information Systems Group
Eindhoven University of Technology

Eindhoven, December 6, 1991

Supervisor: Prof. Ir. M.P.J. Stevens
Coach: Ir. M.J.M. van Weert

The department of Electrical Engineering of the Eindhoven University of Technology does not accept any responsibility regarding the contents of student project- and graduation reports.

Abstract

The ISDN layer 2 protocol is called Link Access Procedure on the D-channel (LAP D). It is specified by the CCITT as a state machine. Using an operating system that can accommodate this state machine behaviour, LAP D is implemented. This implementation is device independent, and will ultimately be used on an ISDN Terminal Board developed by the Digital Information Systems Group. Device dependent hardware drivers link the LAP D software to the hardware realizing transmission and reception of data. For testing purposes, LAP D is implemented on two PC's using Mitel ISDN Express Cards. An interrupt handler serving the Mitel interrupts is designed.
Most errors of an earlier version of the LAP D software have been corrected. Some hard-to-find errors however, still prevent the software from being used. Testing is done using a tool called the protocol analyzer. This tool enables manipulating and observing specific items (states, messages) of the software. Further development of this tool is recommended. Testing has further revealed that the chosen implementation can meet all the timing restrictions imposed by the CCITT recommendations, in spite the relatively slow system on which the software is installed.

Acronyms and abbreviations

CCITT:	Commité Consultatif International de Télégraphique et Téléphonique
CEPT:	Conference of European Posts and Telecommunication Administrations
DLCI:	Data link connection identifier
DSC:	Digital Subscriber Controller
EOP:	End of Packet
ET:	Exchange Termination
FA:	Frame Abort
FCS:	Frame Check Sequence
FIFO:	First In First Out; is a queue operating on that principle
HDLC:	High level Data Link Control
IDPC:	Integrated Data Protocol Controller
IES:	ISDN Evaluation Software
ISDN:	Integrated Services Digital Network
LAPD:	Link Access Procedure on the D-channel
LT:	Line Termination
NET:	Normes Européenne de Télécommunication
NT:	Network Termination
OSI:	Open Systems Interconnection
PC:	Personal Computer
RxFIFO:	Receiver FIFO
SAPI:	Service Access Point Identifier
SNIC:	Subscriber Network Interface Circuit
TEI:	Terminal End Point Identifier
TxFIFO:	Transmitter FIFO

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Until the mid 1970s, telecommunication services were limited to voice and written communication. During the last 15 years or so, new demands on telecommunication services have arisen, such as videotext, fax, communicating microcomputers, etc. To meet a variety of needs by a large number of specialized networks has certain disadvantages for both the customer and the service providing companies. These disadvantages involve mainly high costs and inefficiency [5].

As a result of advances in technology, digital techniques are being intensively introduced in many countries. The result has been a general consensus in the world of telecommunication to lay down through the International Telegraph and Telephone Consultative Committee (CCITT) the basis elements of a universal network - the Integrated Services Digital Network (ISDN):

> "The main feature of the ISDN concept is the support of a wide range of voice and nonvoice applications in the same network. A key element of service integration for an ISDN is the provision of a range of services using a limited set of connection types and multi-purpose user-network interface arrangements." (Extract from Recommendation I.120.)

The ISDN is modelled according to the Open Systems Interconnection (OSI) concept. A brief discussion of the ISDN-protocol reference model is given in [7].

The above citation speaks of a 'limited set of connection types' and 'multi-purpose user-network interfaces'. The ideal situation would be one device that on the one hand connects to the network, and on the other hand provides a network access to a telephone, a fax, a personal computer, etc. In practice however, this will certainly not be the case, due to the diversity and enormous amount of interfaces the device should handle.

The Digital Systems Group of the Faculty of Electrical Engineering, Eindhoven University, is conducting research involving the ISDN. As a part of this, an ISDN terminal board has been designed. This board provides access to the ISDN and its services. The board is equipped with a parallel interface for connection to e.g. a personal computer, a connection for a digital phone and the so called S-interface (this is the point where the network is 'terminated'; roughly where the actual wire enters the customer premises). An Intel 80186 microprocessor resides at the heart of the hardware. The terminal will be used as an experimental ISDN terminal on which available and/or future services can be implemented and tested.

A dedicated operating system has been developed by Oudelaar [8]. It accommodates the ISDN lower layer protocols extremely well. An important advantage of the operating system is that the protocols can be implemented hardware independently. The only link to the hardware are the low level interrupt handlers that communicate with the operating system.

To assist with the implementation of the ISDN protocols, the Digital Systems Group is in the possession of two Mitel ISDN Express Cards. These make it possible to establish a 2B+D connection (S-interface) between two personal computers (PC's). Using this connection and the D-channel, layers 2 and 3 can be implemented and tested. When the implementation is completed, the result can be copied onto the ISDN terminal board with only minor modifications.

Layer 3, the Network layer, has been implemented by Lemmens [7]. Layer 2, the Data Link layer, was only partially functioning. In this report, it is described how the layer 2 implementation is completed, starting with the work of van de Kuilen [12].

Besides various errors in the software, the layer 2 software could not communicate properly with layer 1. Low level drivers had to be added to make data transportation possible. A question that arose during the project involved the performance of the implementation. What restrictions or problems would arise as LAP D would perform at its maximum rate? Would the operating system impose any restrictions as to the speed of the data transportation? These questions will be answered in chapter 6, where the implementation performance is examined.

The next chapter will give the reader a brief introduction to the ISDN user-network interface and the ISDN layer 2 protocol in particular. Chapter 3 discusses the implementation of the layer 2 protocol, independent of the hardware configuration. Chapter 3 does not require the knowledge of the layer 2 protocol. Chapters 4 and 5 go into detail about the hardware configuration that was used and the corresponding software. In order to fully understand chapter 5, it is advisable to read chapter 4 first. Chapter 6 will then look at the real time performance of the implementation. The conclusions are summarized in chapter 7, along with a few words on future work.

Chapter 2

Link Access Procedure D

This chapter describes in detail the ISDN protocol for the Data Link layer, the Link Access Procedure on the D-channel (LAP D). Additional information can be found in CCITT recommendations Q.920 and Q.921 [9].

2.1 ISDN User-Network Interface

The ISDN user-network interface is located at the S/T reference point (illustrated in figure 2.1). Two access scenario's are currently defined on this point:

Basic access: An interface at a usable rate of 144 Kbit s^{-1}. It supports two B-channels at the rate of 64 Kbit s^{-1} and one D-channel at the rate of 16 Kbit s^{-1}.

Primary rate access: An interface at a usable rate of either 1984 Kbit s^{-1} (Europe) or 1536 Kbit s^{-1} (USA & Japan). This interface supports 30 or 23 B-channels (64 Kbit s^{-1}), and one D-channel (64 Kbit s^{-1}).

The B-channels are used for 64 Kbit s^{-1} data transport whereas the D-channel is used to transport signalling information (16 Kbit s^{-1}). From here on, basic access will be used (2B+D).

As figure 2.1 shows, the characteristics of the physical layer is specified by CCITT recommendation I.430. This layer performs multiplexing of the D- and B-channels, D-channel contention resolution, synchronization, and activation/deactivation. The characteristics of the D-channel of the data link layer are specified by CCITT recommendations Q.920/Q.921. These are called the Link Access Procedures on the D-channel, or LAP D. The network layer's characteristics are specified by CCITT recommendations Q.930-Q.940. On these two layers, no B-channel restrictions are imposed. I will therefore restrict myself to the D-channel. Since the network layer has already been implemented, I will furthermore concentrate on the data link layer.

2.2 LAP D functions

The Link Access Procedures on the D-channel provide an error free data link connection to convey information between layer 3 entities across the ISDN user-network interface using

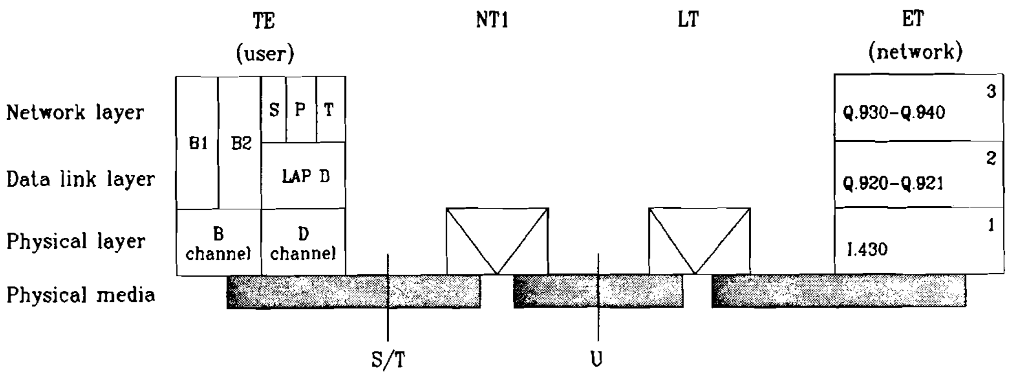


FIGURE 2.1: The ISDN protocol reference model layers 1 to 3 (basic access). NT2, not shown, would be positioned between TE and NT1. It much resembles the TE.

the D-channel. This can be between the terminals and NT2, between NT2 and ET (network node or exchange termination), or between user terminals and the subscriber serving exchange (NT1) (see figure 2.1). LAP D supports multiple terminal installations at the user-network interface and multiple layer 3 entities. To achieve this, LAP D performs the following functions:

1. demarcation by means of flags, alignment and transparency of the transported frames;
2. the multiplexing of several data links on the same D-channel;
3. frame sequence maintenance in case of numbered frames;
4. detection of errors;
5. flow control.

LAP D is based on the High Level Data Link Control (HDLC) protocol. This protocol is described in [4], together with the necessary changes.

2.3 LAP D frame format

All layer 2 peer-to-peer information is transmitted in frames conforming to the format in figure 2.2. The format defines several fields, which are described below.

Opening & Closing Flag: Used to synchronise frames.

Address field: Consists of a Service Access Point Identifier (SAPI), a Terminal Endpoint Identifier (TEI) and a Command/Response bit.
The SAPI indicates the type of service which can be signalling (SAPI=0) or packet data (SAPI=16), whereas SAPI=63 is used for layer 2 management.
The TEI can take on any value in the range of 0..127. Value 127, the group TEI, is assigned to the broadcast data link connection. Values 0-63 are selected by the user

Opening Flag 0 1 1 1 1 1 1 0			octet 1
SAPI	C/R	0	octet 2
TEI		1	octet 3
Control Field			octet 4(5)
Information Field			octet 6
Frame Check Sequence			octets N-2, N-1
Closing Flag 0 1 1 1 1 1 1 0			octet N

FIGURE 2.2: Format of layer 2 frames.

(non-automatic TEI assignment), values 64-126 are selected by the network (automatic TEI assignment).
The user sends command frames with the C/R-bit set to '0' and response frames with the C/R-bit set to '1'; the network does the opposite.

Control field: This field identifies the type of frame, which will be either a command or a response frame. Three types of control field formats are defined:

1. numbered information transfer (I-format). Used to perform layer 3 information transfers. Send and receive sequence numbers are included to enable acknowledgement.
2. supervisory format (S-format). Used for acknowledgements and requests for retransmission.
3. unnumbered information transfer and control functions (U-format). Used for data link control functions.

All three formats include a P/F-bit. Its use is defined by the peer-to-peer procedures. P stands for Poll, F stands for Final, indicating if a response is required.

Information field: The contents of this field are determined by the control field. In an information frame it will contain layer 3 information, and in e.g. a Frame Reject frame it will contain more specific information about the rejection.

Frame check sequence: These 2 octets are added to detect possible transmission errors.

A full description of the frame format is located in appendix B.

The SAPI and the TEI together form the Data Link Connection Identifier (DLCI). The DLCI identifies a LAP D data link connection. Figure 2.3 illustrates the identification of a LAP D connection. As can be seen by this figure, one terminal can have more than one TEI assigned to it (see TE2: it is assigned TEI values 3 and 8). A terminal is not identified by one TEI; the TEI merely identifies a specific connection endpoint within a service access point. In other words, within the signalling entity (a service access point), more than one data link connection can be processed.

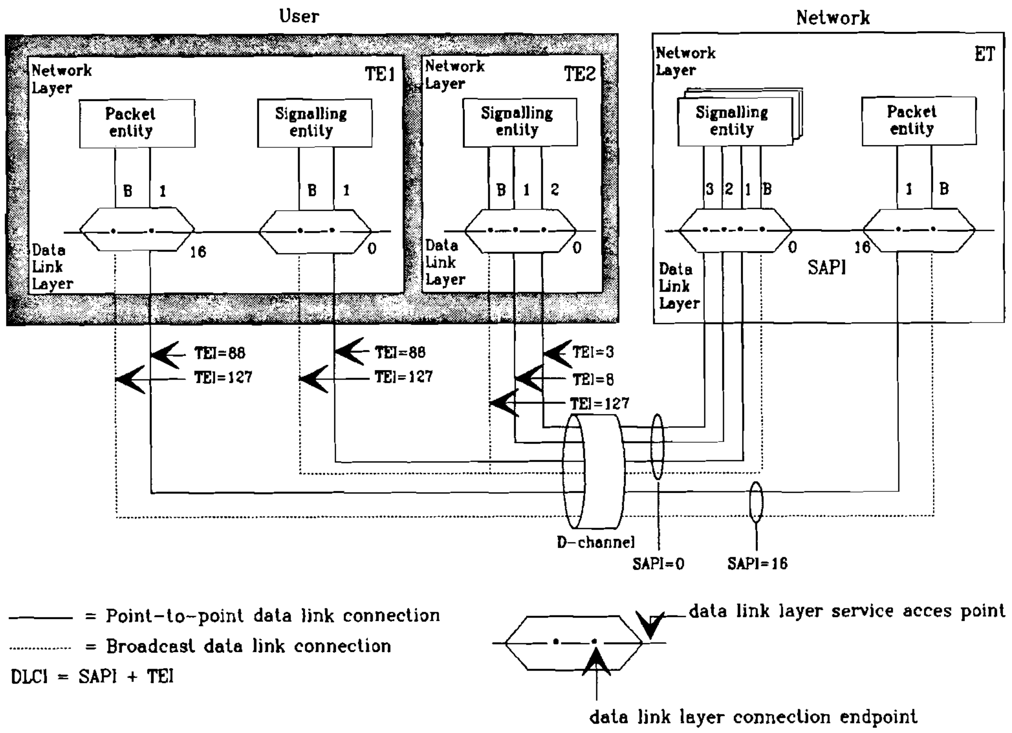


FIGURE 2.3: Multiplexing of data links using SAPI and TEI.

2.4 Modes of operation

The data link layer supports two modes of operation for layer 3 information transfer. Both modes may exist on one D-channel at the same time.

Unacknowledged information transfer

This mode can also be named the connectionless mode. No error correction or flow control is used to transfer U-frames. I-frames cannot be transferred in this mode. The mode can be used for point-to-point communication between a user and the network or for multi-point communication for the broadcast of frames to several terminals (e.g. TEI verify procedure).

Acknowledged information transfer

This mode is only possible when a data link connection has been established. A connection is made using the Set Asynchronous Balanced Mode Extended (SABME) command. This is an inheritance of HDLC.

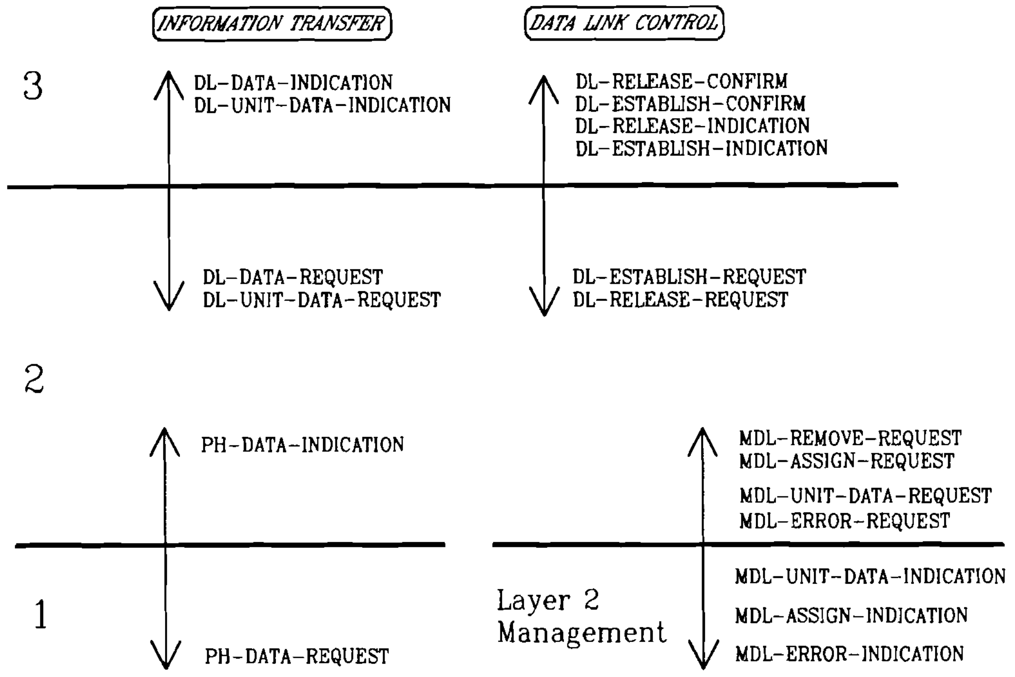


FIGURE 2.4: Layer 2 primitives associated with the interaction between layer 3 and the management entities.

2.5 Layer 2 interfaces

Layer 2 communicates with layers 1 and 3 as well as the management layer through messages called service primitives. The messages to and from layer 1 concern layer 2 frames that are transmitted and received. Layer 3 not only passes down its own information frames, but also commands to layer 2. These commands control the data links. Communication with management includes TEI-assignment and error report. Figure 2.4 shows the layer 2 interfaces and the possible primitives. Layer 1 communicates (lower left) with layer 2 through the PH_DATA primitives. This concerns layer 2 frames that have been received or are to be transmitted. Layers 2 and 3 exchange similar primitives, now concerning layer 3 frames (upper left). The second group of primitives exchanged between layers 2 and 3 concern the initiation and termination of a data link (upper right). This leaves the primitives exchanged with layer 2 management. Here there are three types of primitives: those concerning management information frames (MDL_DATA), those concerning TEI assignment or removal (MDL_REMOVE, MDL_ASSIGN), and those concerning error handling (MDL_ERROR).

These primitives are conceptual and are not necessarily implemented. They provide the procedural means to specify conceptually how a data link user can invoke a service. Through the use of primitives a point-to-point data link layer connection endpoint can be triggered from one state to the other.

A data link layer connection endpoint can be in one of four basic states, illustrated in

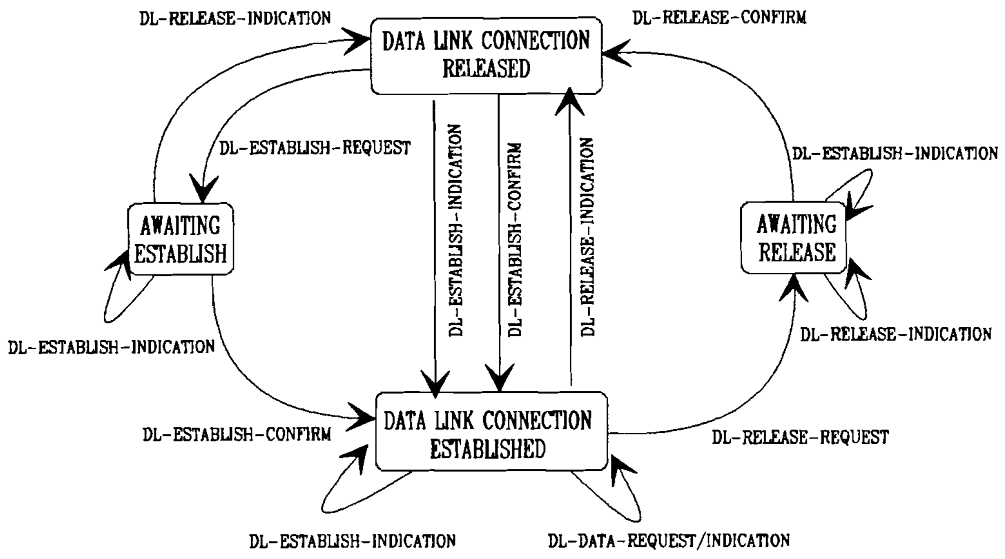


FIGURE 2.5: State transition diagram of the data link connection endpoints (between layers 2 and 3).

figure 2.5:

- link connection released state (stable state);
  In this state the data link is idle. It will be activated when layer 3 asks for a data link establishment (DL_ESTABLISH_REQUEST) or when layer 2 indicates an established data link (DL_ESTABLISH_INDICATION).

- awaiting establishment state (transition state);
  A data link has signalled its peer to establish a data link. As soon as a positive acknowledgement is received (DL_ESTABLISH_CONFIRM), a data link is considered established.

- awaiting release state (transition state);
  A data link is waiting for its peer to acknowledge the request to release the data link.

- link connection established state (stable state).
  In this state information transfer is possible.

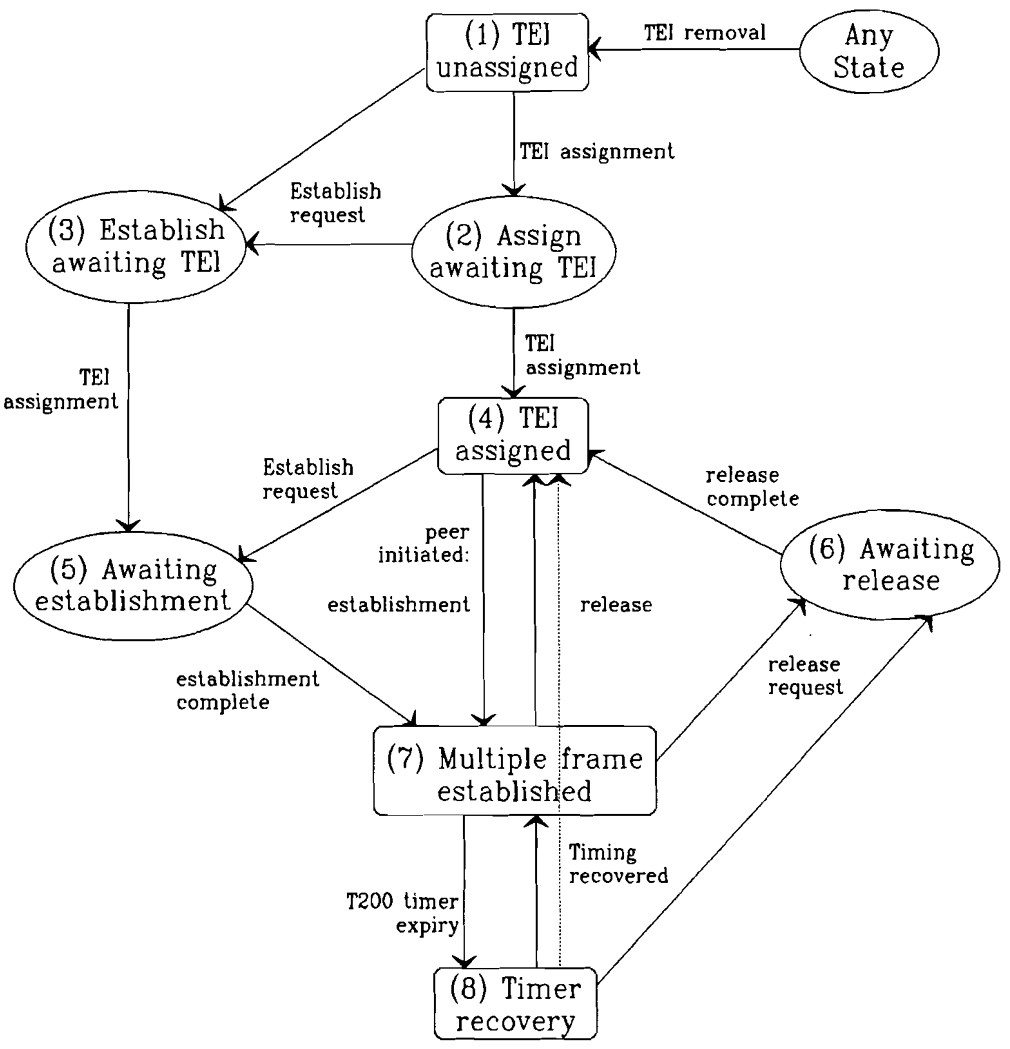
The illustration shows that primitives occur in all four basic states. In a normal situation, however, a data link connection endpoint passes through the states counter-clockwise. Its peer, only reacting to requests, merely switches between the link connection released and established states. The next section discusses the data link connection procedures in more detail.

TABLE 2.1: Protocol mechanisms in LAP D.

Function:	*Protocol Mechanism*
connection establishment	SABME and UA frames
connection release	DISC and UA frames
addressing & multiplexing	TEI and SAPI
framing	flags and zero insertion
flow control	sliding window and RNR-frames
error detection & -correction	FCS-test sliding window time-out REJ-frames P/F-checkpointing
reset	SABME and UA frames

2.6 LAP D protocol mechanisms

This section will describe how data links are established, how information transfer happens and what functions the management entity performs. Table 2.6 shows how the most important protocol functions are realized in LAP D. These functions are discussed below. In the previous section, a state diagram of the data link connection endpoints was shown (figure 2.5). When looked at from the layer 2 side, a more complex state diagram can be seen; see figure 2.6 on the next page. Nonetheless, the four basic states can be seen: the top four (1-4) form the link connection released state, the lower two (7-8) form the link connection established state. The awaiting establishment and awaiting release states have similar names (5-6). A global description of each state is included in figure 2.6.



1. TEI_UNASSIGNED: This is the initial state a data link layer entity is in. Only acknowledged information transfer is possible.
2. ASSIGN_AWAITING_TEI: The data link layer entity is waiting for TEI assignment from management. Layer 3 has indicated it wants to transport numbered information. This is an indirect DATALINK _ESTABLISH_REQUEST.
3. ESTABLISH_AWAITING_TEI: The datalink layer entity is waiting for TEI assignment from management. Layer 3 has requested the establishment of a datalink connection.
4. TEI_ASSIGNED: The datalink layer entity is ready for action, which will be the establishment of a datalink connection or the removal of the TEI value.
5. AWAITING_ESTABLISHMENT: A request for a datalink connection has gone out to the peer of the datalink layer entity. This is a wait state, waiting for response from the peer in order to enter multiple frame operation.
6. AWAITING_RELEASE: The datalink layer entity is waiting for response form its peer. A datalink connection is about to be disconnected.
7. MULTIPLE_FRAME_ESTABLISHED: In this state both kinds of information transfer (numbered and unnumbered) are possible. A datalink is established.
8. TIMER_RECOVERY: The datalink layer entity is recovering from a synchronization problem.

FIGURE 2.6: State transition diagram of a data link in layer 2.

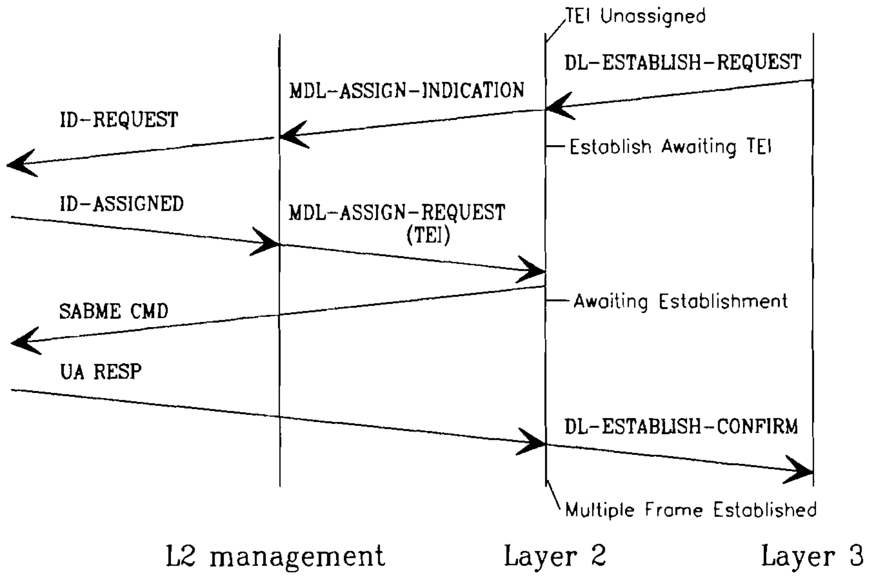


FIGURE 2.7: Example of the procedure to establish a data link connection.

2.6.1 Connection establishment

There are several states a data link must go through before it can transfer information. Assuming the data link is in the TEI_UNASSIGNED state, it must first obtain a TEI value. Without this TEI value, the data link could not be identified properly. Considering layer 2 receives a DL_ESTABLISH_REQUEST primitive from layer 3, the data link will ask management for a TEI value (MDL_ASSIGN_INDICATION). The data link will await a response from management in the ESTABLISH_AWAITING_TEI state. This process is illustrated in figure 2.7.

If the user equipment is of the non-automatic TEI assignment category, management can choose any unoccupied TEI value in the range of 0..63 and assign it to the data link layer entity. This is done using an MDL_ASSIGN_REQUEST. If the user equipment is of the automatic TEI assignment category, an Identity request message is sent to the network. Several parameters are included in the message, one of which is a Reference number. This randomly generated number helps the network to distinguish between different requests, since no other identification of the data link is available (no TEI assigned!). The network can respond with an Identity assigned message, confirming the assignment of a certain TEI, which is included in the message. It is also possible for the network to deny a request, e.g. when all available TEI information/resources are exhausted. In such a case the network will, on its own, start verifying each TEI it has assigned. This might reveal multiple TEI assignments (one TEI value assigned to more than one terminal).

After a TEI value has been assigned, the data link layer entity will try to make a connection. It initiates a request for the multiple frame operation by transmitting the SABME command to its peer. If its peer is able to comply it will respond with a UA response. The connection is now established and acknowledged information transfer is possible. Both data link layer entities are in the MULTIPLE_FRAME_ESTABLISHED state. In case the peer data link layer does not respond with a UA frame, a data link cannot be properly set up, and appropriate action (as specified by LAP D) is taken.

2.6.2 Acknowledged information transfer

This section only applies to I-frames, because U-frames require no special treatment. I-frames, however, are transmitted with several control field parameters. Through these parameters flow control is realised. LAP D makes use of the sliding window protocol (go back n). The parameters and the associated variables are listed below. Figure 2.8 shows how the control field is made up.

Encoding of bits	
1	2 3 4 5 6 7 8
0	N(S)
P/F	N(R)

FIGURE 2.8: Control field parameters of an I-frame.

N(S): Send sequence number; send sequence number of transmitted I-frames. It is included in each transmitted I-frame.

V(S): Send state variable; the sequence number of the next I-frame to be transmitted (V(A) $\leq$ V(S) $\leq$ V(A)+$\underline{k}$).

V(A): Acknowledge state variable; identifies the last frame (V(A)-1) that has been acknowledged by its peer.

N(R): Receive sequence number (V(A) $\leq$ N(R) $\leq$ V(S)); expected send sequence number of next received I-frame. It is included in each transmitted I-frame.

V(R): Receive state variable; denotes the sequence number of the next in-sequence I-frame expected to be received.

$\underline{k}$: determines the size of the sliding window. Sequence numbers are numbered modulo 128. For information about the sliding window mechanism, see [11].
LAP D uses a window size of 1 in the case the data link is used for signalling. When used for packet data, the window size is 3.

Information from layer 3 in a DL_DATA_REQUEST primitive is transmitted in a layer 2 I-frame. An I-frame can be transmitted only when VS $\leq$ V(A)+$\underline{k}$, i.e. when less than $\underline{k}$ frames are outstanding. On transmission of an I-frame, the control field parameters N(S) and N(R) are assigned the values of V(S) and V(R), respectively.

On reception of an I-frame with N(S) equal to the current V(R), the information field of the received frame is passed to layer 3 using the DL_DATA_INDICATION primitive. Furthermore, V(R) is incremented by one. The I-frame is acknowledged with another I-frame or Supervisory frame with N(R) set to V(R).

Acknowledgement occurs upon reception of a valid I-frame or Supervisory frame. The acknowledging entity included N(R) in the control field of the response frame, saying it next

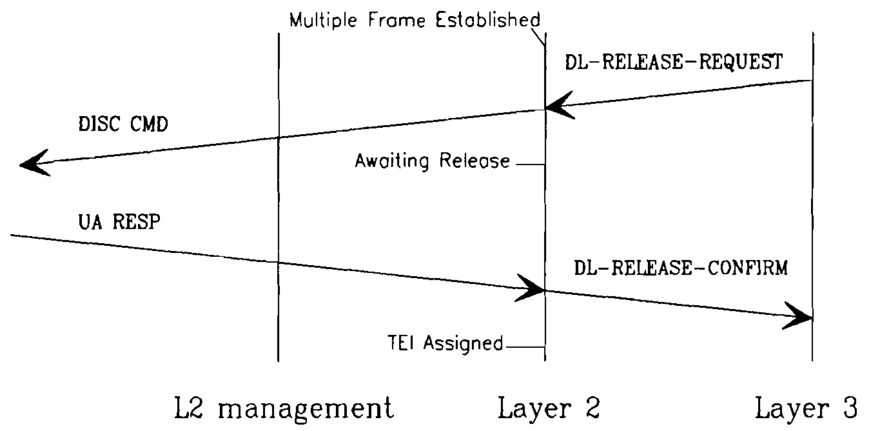


FIGURE 2.9: Example of a procedure to release a data link connection.

expects a frame with sequence number N(R). The peer entity treats N(R) as the acknowledgement for all the I-frames that have been transmitted with a send sequence number N(S) up to and including the received N(R)-1. The acknowledge state variable is set to N(R).

Sequence errors

N(S) sequence error In this case the receiver did not receive the frame it expected: N(S) $\neq$ V(R). The information field in the frame is discarded, and no acknowledgement takes place. If the frame is otherwise error-free, N(R) is used as acknowledgement as explained above. A REJect frame is transmitted to initiate recovery of the correct frame sequence. The side that receives the REJ frame will use the N(R) in the REJ frame as the next send sequence number. V(A) is also set to N(R), which indicates the last frame that was received correct. The requested frame (N(R)) is then retransmitted as soon as possible, as well as any other frames with a sequence number greater than N(R) (go back n principle).

N(R) sequence error This error occurs when N(R) is not in the range of [V(A)...V(S)]. If N(R) $<$ V(A), a frame is acknowledged for the second time. If N(R) $>$ V(S) a frame is acknowledged that never has been sent. The information field of the received frame, if in sequence, is passed on to layer 3. An N(R) sequence error causes the data link layer entity to initiate re-establishment of the data link.

2.6.3 Connection release

A connection is released in much the same way as it is established (see figure 2.9). Instead of a SABME command a DISConnect command is used. The data link will wait in the AWAITING_RELEASE state until a UA frame is received. After release, the data link layer entity is in the TEI_ASSIGNED state.

2.6.4 Timing restrictions

Every transmitted command (SABME, DISC, UA, I-frame, etc.) must be answered within T200 seconds (a LAP D parameter). If no response is received in time, the command (except the I-frame) is retransmitted. Retransmission may occur up to N200 times. If, after N200 retransmissions, still no response is received, a connection error is assumed. Depending on several variables, a data link may try to re-establish itself, or will return to the TEI_ASSIGNED state.

2.6.5 Errors

There is a number of errors that may occur during data transportation. Those errors that cannot be resolved by the data link layer entity itself are passed to the layer management for processing. In Recommendation Q.921 only a handful of error responses is listed; most other responses are left for the designer to design and implement.

Summary

In this chapter, the ISDN layer 2 protocol, LAP D, on the user-network interface was described. The peer-to-peer frame format has been shown, as well as the interaction between layers 1 and 3, and layer 2 management. After discussing the four basic states of a data link connection endpoint, a detailed view of the behaviour of a data link connection itself was given. Three elements were discussed in particular: connection establishment, information transfer and connection release.

The next step towards implementing LAP D is creating the appropriate data structures to accommodate the state machine behaviour of LAP D. The following chapter will elaborate on this.

Chapter 3

LAP D implementation

As could be seen in the previous chapter, LAP D is specified as a state machine. Each data link layer entity is always in a defined state. The entities communicate with adjacent layers by primitives. We can regard the different data link layer entities as processes that communicate by messages. This yields the schematic of figure 3.1. The lines between the entities (or processes) indicate communication (messages).

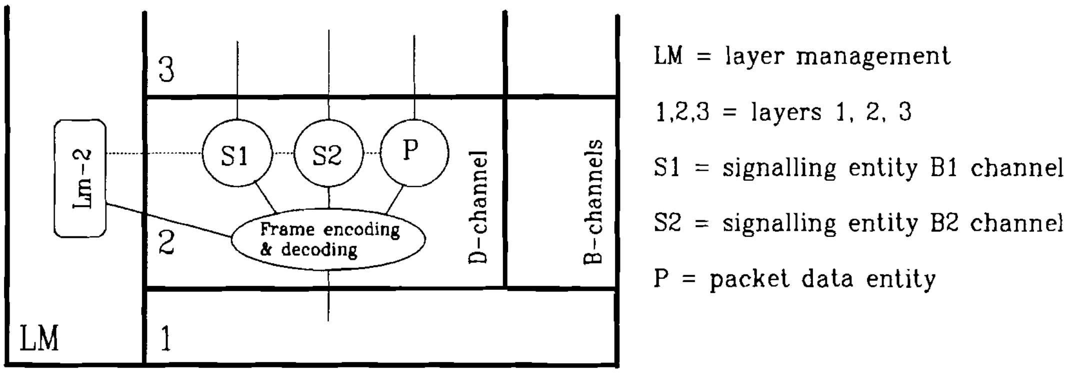


FIGURE 3.1: The basic data link layer entities.

To accommodate the LAP D protocol on the ISDN terminal board, an operating system supporting the above approach has been created by Oudelaar [8]. It was developed keeping in mind the following considerations:

- it should provide support for a large number of processes (entities). This enables us to implement layer 3 in the same way (this has been done by [7]).
- it should allow a priority mechanism for the processes Layer 2 processes have stricter timing constraints than layer 3 processes, and thus sometimes need priority treatment.
- it should allow a small number of hardware interrupts. The interrupt handlers of those interrupts must be fast in order not to stall any process.

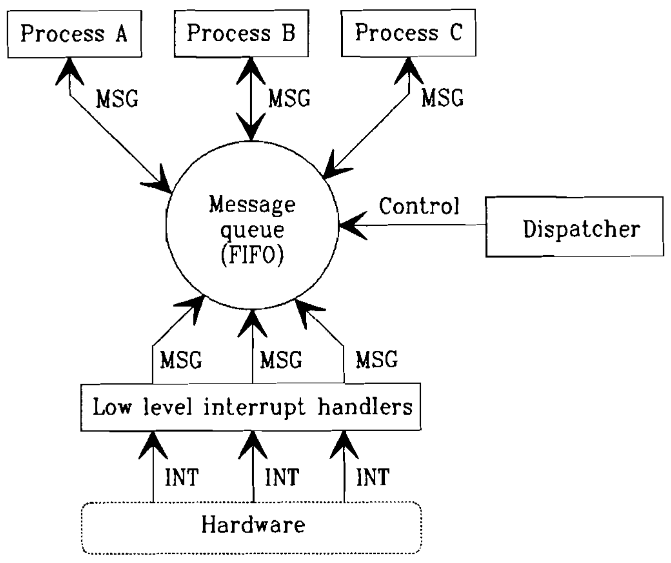


FIGURE 3.2: Schematic view of the operating system.

Figure 3.2 gives a schematic view of what is from now on called the Oudelaar operating system. As it turned out, a very interesting property of the operating system was that it is hardware independent. It allows implementation and testing on different systems. In my case this means I can use ISDN hardware that is operational ("known good") to test the approach of this chapter. When it is finished, it will be transported to the ISDN terminal board.

3.1 Messages

All action is based on the exchange of messages. They can be generated by a certain process to pass on information to another process. In LAP D for example, the information may be service primitives like DL_RELEASE_REQUEST. Each message unit must at least contain information about the type of message and the destination of the message. Figure 3.3 shows the data structure of the messages (implementation is in C language). The `nucleo` field holds the message type (this can be DL_ESTABLISH_REQUEST, SABME, etc.). The `dest` and `orig` fields hold the destination and originating processes' identities, respectively. The five parameter fields constitute the information field of the message. A DL_ESTABLISH_REQUEST primitive has no information fields, whereas a DL_UNIT_DATA_INDICATION contains a layer 3 frame. Figure 3.3 shows what information is usually stored in the five parameters.

Messages are collected in a FIFO (First In First Out) queue. This is done in the form of a pointer to a buffer, which holds the actual message. The message queue is entirely controlled by the dispatcher. A process can only put messages in the queue, not remove them (there is one exception that will be explained in chapter 6). In order to favour the retrieval of a certain message over others, several message queues are used. Each queue resembles a priority. Priorities can range from 0 (highest priority) to `MAXPRIO` (lowest priority). The value of `MAXPRIO` is for this time unrelevant, but will be given in chapter 6.

```
struct message
{
   word nucleo;                 /* Holds the message type */
   byte dest;                   /* Destination process */
   byte orig;                   /* Originating process */
   union scratch param_1;       /* Received N(S) */
   union scratch param_2;       /* Received N(R) */
   union scratch param_3;       /* Received P/F */
   union scratch param_4;       /* Received C/R */
   union scratch param_5;       /* Pointer to buffer of */
                                /* information field */
}
```

FIGURE 3.3: Declaration of the message structure.

The queues are accessed by three functions. These are described in below.

`void message (word Mes, byte Dest, byte Orig, byte Par1, byte Par2 byte Par3, byte Par4, byte Par5) { ... }`

This function is called by the various processes to place a message in the message queue indicated by the priority of the Destination process.
`Mes`: message
`Dest`: destination process
`Orig`: originating process
`Prio`: priority of message
`Par#`: information

`byte getmsg (byte Prio) { ... }`

This function checks the queue for messages and returns the message that is in the front of the queue. `Prio` indicates which queue should be checked. `getmsg` returns a byte pointing to a message buffer holding the actual message elements. The message is *not* removed from the queue, it is just read. This is done in order to prevent the buffer to be replaced by a new message, destroying the current contents.

`void updatequeue (byte Prio) { ... }`

This function is called by the dispatcher after a message has been processed. At that time the information in the message buffer is used and the buffer no longer needed. `updatequeue` does the required removal by updating the queue pointers, where `Prio` indicates which queue is to be updated.

3.2 Processes

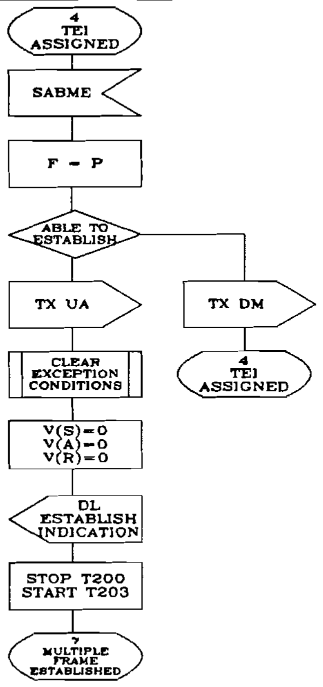
The messages described in the previous section, activate the various processes. These processes, each representing a data link layer entity, all have an associated process descriptor. This descriptor holds vital information about the process, and is saved each time a process is deactivated. All process descriptors are held in an array, where the indexes identify the processes. This is illustrated in figure 3.4.

```
define unsigned char byte;

define MAXPRIO #   /* maximum priorities of process:  [0..MAXPRIO] */
define MAXPROC #   /* number of defined processes */

union scratch
{
   unsigned char byte;
   unsigned int word;
   unsigned char *pbyte;
   unsigned int *pword;
}

struct process
{
   byte               PublStat;   /* Status (Blocked or Running) */
   byte               Priorid;    /* Priority */
   struct state far   *State;
   byte               Substate;   /* Extra for LAP D processes */
   union scratch      Data1;      /* Parameters */
   union scratch      Data2;
   union scratch      Data3;
   union scratch      Data4;
   union scratch      Data5;
   union scratch      Data6;
   union scratch      Data7;
   union scratch      Data8;
}

struct process Process[MAXPROC]
```

FIGURE 3.4: Definition of a process descriptor.

Each descriptor consists of twelve elements. First of all, the `PublStat` field holds the status of the process. It is either Blocked or Running. A Blocked process cannot receive messages, until it becomes Running. Once a process is Blocked, it can only be unBlocked by another (unBlocked) process. If, for example, no packet data is supported, layer management may block the packet data entity process. The `Priorid` field holds the process's priority. All messages for a certain process are placed in the queue with the corresponding priority value. The `State` field provides information about the current state the process is in. It points to the state table that should be used if a message is received. Some processes need to register several important conditions (Own Receiver Busy, Peer Receiver Busy). These are saved in the `Substate` field. `Data1` – `Data8` are storage space for variables unique to a process. These can be send and receive state variables, a retransmission counter, etc. As an example, I have included the declaration of the signalling entity for the B-channel:

Process[LAPD_S1].PublStat = RUNNING;
Process[LAPD_S1].Priorid = 1;



```
void far sabme_4(void)
{
   if (ABLE_TO_ESTABLISH)
   {
      tx(UA, P, 1);       /* F=P , response */
      message(DL_ESTABLISH_INDICATION, LAYER3,
               ProcAct, 0, 0, 0, 0, 0);
      VS = 0;
      VA = 0;
      VR = 0;
      stoptmr(T200_TIME_OUT, ProcAct);
      runtimer(T203_TIME_OUT, ProcAct, T203);
      SUBSTATE = 0;       /* clear exceptions */
      NEWSTATE = MULTIPLE_FRAME_ESTABLISHED;
   }
   else
   {
      tx(DM, P, 1);       /* F=P , response */
   }
}
```

FIGURE 3.5: SDL-representation of SABME response (left) and corresponding C-code (right).

```
Process[LAPD_S1].State        = TEI_UNASSIGNED;
Process[LAPD_S1].Substate     = 0;
Process[LAPD_S1].Data1.byte   = 0;      /* SAPI */
Process[LAPD_S1].Data2.byte   = 200;    /* TEI, 200 = not assigned */
Process[LAPD_S1].Data3.byte   = 0;      /* VS Send state variable */
Process[LAPD_S1].Data4.byte   = 0;      /* VA Acknowledge variable */
Process[LAPD_S1].Data5.byte   = 0;      /* VR Receive state variable */
Process[LAPD_S1].Data6.byte   = 0;      /* RC Retransmission counter */
Process[LAPD_S1].Data7.byte   = 0;      /* Able to establish flag */
Process[LAPD_S1].Data8.byte   = 0;      /* Acknowledge pending flag */
```

As mentioned above, the `State` field points to a state table. The state tables for all processes involved were derived from the CCITT Recommendation Q.921, Annex B [9]. Annex B provides the SDL representation of the point to point procedures of the data link layer entity. The SDL diagrams do not describe all of the possible actions and conditions of the data link layer entity. The shortcomings are minor and of little concern to the basic performance of the data link layer entities. It should be noted though, that the text of the recommendation prevails over any SDL inconsistency.

The translation of the SDL diagrams is illustrated in figure 3.2. Here I assume a data link layer entity to be in the TEI_ASSIGNED state, receiving a SABME command. The relation between the diagram on the left and the code on the right speaks for itself. I will not go into the detail of discussing precise implementation of VS, VA, NR, etc. All implemented functions are collected in state tables. These state tables are made up of rows containing a possible input message and the corresponding function that must be executed on receipt of

```
struct state
{
   word nucleo;           /* The incoming message */
   void (*transi)(void)   /* The function to be executed (transi) */
};

void dummy(void)          /* Empty function */
{  }                      /* Does nothing */
```

Each state defines a state table, which is an array of the above structure:

```
state StateTable[ ]=
{
   {message_a, function_a},
   {message_b, function_b},
   {message_c, function_c},
   ...
   {DEF, dummy}
};
```

FIGURE 3.6: Declaration of the state structure.

the message.

Figure 3.6 shows the necessary declarations. The state table of a data link layer entity in the TEI_ASSIGNED state would look as follows:

```
state TEI_ASSIGNED[ ] =
{
   { DL_ESTABLISH_REQUEST, dlestreq_4 },
   { DL_RELEASE_REQUEST, dlrelreq_4 },
   { DL_UNIT_DATA_REQUEST, dlunitdatareq_4 },
   { UI_FRAME_IN_QUEUE, uiframe_4 },
   { MDL_REMOVE_REQUEST, mdlerrresp_2 },
   { SABME, sabme_4 },
   { DISC, disc_4 },
   ...
   { DEF, dummy }
};
```

Every state table must terminate with the entry {DEF, dummy} . This entry will guard the process against messages that are not allowed in the current state by executing a dummy (empty) function should such a message occur (see figure 3.6).

Besides the three data link layer entities, several other processes were created. They are summed up below:

1. LAPD_S1
2. LAPD_S2

3. LAPD_P
4. MANAGEMENT
5. TRANSMISSION
6. MONITOR
7. layer 3 processes

The LAPD processes are implemented using the SDL diagrams. The MANAGEMENT process is derived from the text of Q.921. It is constantly in one state. Through this process, TEI assignment and removal are realized, as well as the other functions of the layer 2 management entity described in the previous chapter. The TRANSMISSION process is the link to the hardware. Besides frame assembly and disassembly, the process initiates the transmitter on the S/T-interface and can receive frames from the receiver on the S/T-interface. This process is discussed in detail in chapter 5. The MONITOR process can be used to monitor the status of the data links. It was originally introduced by Oudelaar ([8]) to be used on the ISDN terminal board. I have not used this process. To monitor the data links I made use of the protocol analyzer written by Lemmens ([7]). The analyzer is discussed in a later chapter.

3.3 The dispatcher

In figure 3.2, where a schematic view of the operating system is shown, the dispatcher can be seen to control the message queue. The dispatcher is always active. Its structure is shown in figure 3.7. It checks the message queues for messages, starting with the highest priority queue. Once the dispatcher finds a message in one of the queues, the destination process and current state of that process will automatically have been determined by `getmsg`. If the destination process is running (not Blocked), the corresponding state table is searched for the message's nucleo. The function that is found is executed. When no entry for the nucleo is found, a dummy (empty) function is executed. Next, the message queue is updated and the priority is set to 0, to start the next scan for messages with the highest priority. If the destination process is Blocked, the message is discarded by updating the queue. This procedure will then repeat itself.

The dispatcher can be integrated into a larger structure, as has been done in the case of the protocol analyzer. Each message that is read by the dispatcher, is displayed on the screen, providing information on the status of the data links. An important condition is that the dispatcher's body is executed sufficient times to guarantee continuation of the various processes controlled by the dispatcher.

```
dispatcher()
{
   byte Pri;
   word AuxComp;
   struct state far *TablState;

   Pri = 0; /* High priority */

   while(1)
   {
      if(getmsg(Pri) == Present) /* message present ?  */
      {
         if(destination_process != Blocked)
         {
            look_up_nucleo_in_state_table();
            (*(TablState->transi))();      /* execute function */
            updatequeue(Pri);              /* discard message */
            Pri = 0;
         }
         else /* destination_process blocked */
         {
            updatequeue(Pri);              /* discard message */
         }
      }
      else /* no message present */
      {
         Pri = ++Pri % MAXPRIO;            /* increment priority */
      }
   } /* endless while-loop */
}
```

FIGURE 3.7: General structure of the dispatcher.

3.4 Interrupts

For layer 2 to communicate with its peer, it must transmit and receive frames over the S/T-interface. The link with the transmitter and receiver hardware is laid through interrupt handlers that control the hardware. These interrupt handlers are different for each hardware configuration the ISDN software is installed on. What can be the sources of the interrupts? I will name a few.

- the receiver has detected a flag on the D-channel indicating the start of a packet.
- the receiver has been receiving a packet and has now filled its (relatively) small buffer.
- the receiver has detected an end-of-packet flag.
- the transmit buffer is running empty.
- the transmitter is signalling it has transmitted a complete packet.

The interrupt handlers servicing one of the above requests generate, if necessary, messages for the TRANSMITTER process. This process is described further in chapter 5.

An entirely different type of low level software concerns timers. Timers are necessary in the LAP D communication process, as explained in section 2.6.4. In the current implementation, each timer tick generates an interrupt, after which the active timers are updated. An expiring timer generates a TIME_OUT message for the process that initiated the timer.

Summary

An overview of the LAP D implementation was given. It is best illustrated by figure 3.8. An operating system was created by Oudelaar [8] to accommodate the LAP D state machine. It regards data link layer entities as processes communicating by messages. We have also seen that a dedicated dispatcher is in control. The behaviour of the data link layer entities was translated from SDL diagrams into state tables. The link with the hardware elements was shown to involve interrupts and interrupt handlers.

The behaviour of LAP D is fully documented by the CCITT. In order to discuss the behaviour, and, more important, the implementation of the lower level handlers, we must first explore the associated hardware. This is done in the next chapter, after which the implementation of the lower level handlers can be discussed.

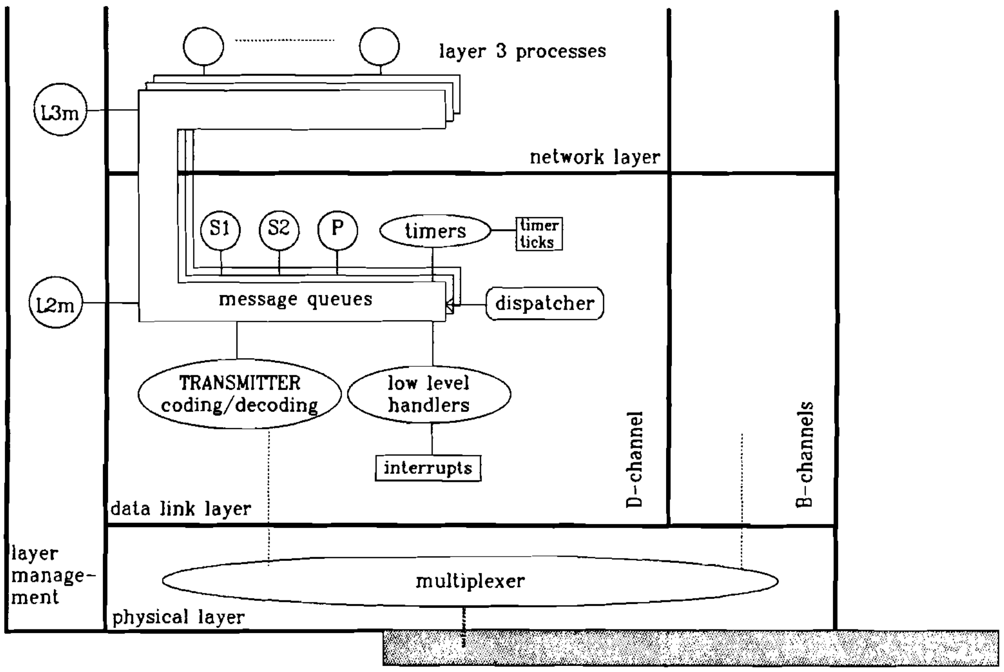


FIGURE 3.8: The basic data link layer entities shown as processes (the circles). The service primitives are exchanged as messages via the message queues. The dispatcher keeps track of the queues and delivers the messages to the processes.

Chapter 4

Hardware aspects

The software described in this report will eventually be implemented on the ISDN Terminal Board developed in the Digital Systems Group. The software is first tested on the Mitel ISDN Express Card. This chapter will describe the two systems.

4.1 ISDN Express Card Kit

The ISDN Express Card Kit with ISDN Evaluation System (IES) software is an integrated hardware/software package, giving easy access to several ISDN reference points. The hardware can handle low level protocol functions, while the software can control all of the components on the card.

4.1.1 Hardware overview and block diagram

The hardware includes components for the basic access reference points (S & U), primary rate reference points (T1 and CEPT), a digital telephone set component with speakerphone capability, and devices for digital switching, clock generation and synchronization and low-level protocol functions. Figure 4.1 shows a block diagram of the card. The Digital Crosspoint switch in the middle can interconnect any of its ports, allowing for several different configurations. In this case, a connection between the S-interface and the Digital Phone will be used (see the user manual [13] on how to make such a connection). The connection is illustrated by a dashed line. The clock generator and DPLL provide necessary timing signals to synchronise all the hardware and (optionally) the interfaces on the various reference points. All four reference points on this card are connected to specialized circuits that perform layer 1 and part of layer 2 functions.

The most important device in relation to LAP D is the device connected the S-interface, namely the Subscriber Network Interface Circuit (SNIC). It is a device that implements the CCITT I.430 Recommendation for the ISDN S and T reference points. The SNIC may be used at either side of the subscriber line (NT or TE). Some of its features are:

- point-to-point, point-to-multipoint and star configurations
- full duplex 2B+D
- on chip HDLC D-channel protocoller (LAP D is a subset of HDLC, see section 2.2)

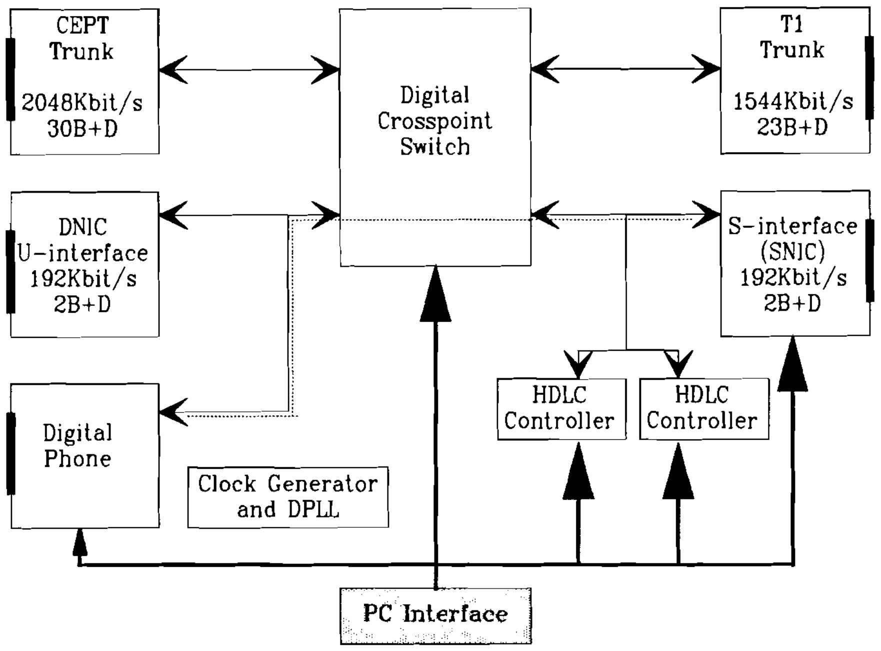


FIGURE 4.1: Block diagram of the ISDN Express Card.

- microprocessor interface (offering full control over the SNIC circuit)

Via the microprocessor interface, the D-channel can be rerouted to the PC-Interface, offering the PC full control over the SNIC. This could also be achieved through the HDLC controllers, be it with slightly more overhead. Appendix A contains full information about the SNIC, including a number of functions to make the D-channel accessible by the PC. The SNIC can then be used to send and receive frames on the D-channel. Interfacing the chip to the LAP D software will be discussed in the next chapter.

4.1.2 ISDN Evaluation Software System

The IES software that comes with the Mitel card, is a menu driven application. It allows the user to manipulate control registers and display status registers. More important, the D-channel connection between two Mitel cards is made using this software. Unfortunately the sources of the IES could not be adapted for integration into the ISDN software being discussed in this report. Initialization of the Mitel card is therefore done with the IES. The software manual [13] includes a full description of this procedure. Information on how to use the IES is can also be found in the Designer's Manual [6].

4.2 ISDN Terminal Board

The ISDN Terminal Board (see [14]) has been designed so that it can operate as a stand-alone ISDN Terminal. It is equipped with multiple interfaces to allow various kinds of data com-

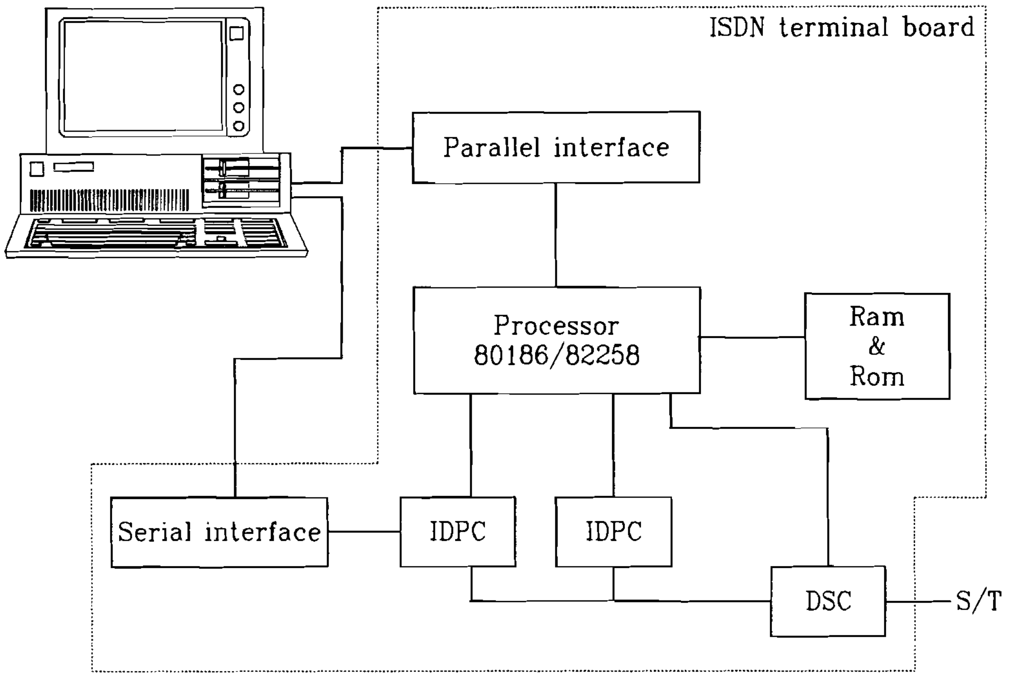


FIGURE 4.2: Block diagram of the ISDN Terminal Board.

munication. The block diagram in figure 4.2 of the Terminal Board is very similar to that of the ISDN Express Card. The Digital Subscriber Controller (DSC) handles the layer 1 multiplexing. It is comparable to the SNIC of the Mitel card as they perform the same functions. It gives the two Integrated Data Protocol Controllers (IDPC's) access to the B-channels. An optional phone can be connected directly to the DSC offering voice communication. The DSC can also perform some layer 2 functions such as Frame Check Sequence (FCS) computation. All other protocol functions have to be implemented in software. The IDPC's can be used to). Each IDPC has a serial interface to which a data terminal can be connected. handle bit-oriented protocols for the B-channels (HDLC, LAP D, LAP B (X.25)). Each IDPC has a serial interface to which a data terminal can be connected.

The used microprocessor is an Intel 80186. This processor is equipped with:

- a clock generator
- two independent DMA channels
- a programmable interrupt controller
- three programmable 16-bit timers
- a local bus controller

Unfortunately, two DMA channels are insufficient as four are required (the two B-channels are bidirectional). An 82258 DMA Coprocessor has been added to provide the needed capacity.

The terminal board is equipped with 512K Ram. This fairly large amount was chosen with future expansion of the board's functions, as the board will be used to develop (new) ISDN services. For more detail on the board's hardware, I recommend the reading of the graduation report of Beijnsberger [2].

Comparing the Mitel card and the ISDN terminal board, we can see that the last could be a part of the first. It would roughly replace the SNIC circuit with the DSC and the two HDLC controllers with the two IDPC's (which actually are two HDLC controllers). The PC interface indicated in figure 4.1 would be located at the parallel (and/or serial) interface of the terminal board.

Summary

A brief description of the Mitel ISDN card and the ISDN terminal board were given. On the Mitel card, the SNIC chip was pointed out as the relevant circuit for LAP D. Its equivalent on the terminal board is the DSC. Both ISDN systems are accessible through a PC interface. LAP D software is developed on the Mitel card, and will be transported to the terminal board upon completion. The link between the Mitel card and the LAP D software will be explained in the next chapter.

Chapter 5

Implementation of low level drivers

This chapter discusses the implementation of the low level interrupt handlers in reference to the operating system in figure 3.2. These interrupt handlers together form the TRANSMISSION process, which is the link to the Mitel card hardware. The TRANSMISSION process can access the SNIC circuit and so control the D-channel access.

5.1 SNIC access

Figure 5.1 shows the functional block diagram of the SNIC. The microprocessor interface allows complete control of the HDLC transceiver and access to all data, control and status registers. The HDLC transceiver handles the bit oriented protocol structure and formats the D-channel as per level 2 of the X.25 packet switching protocol defined by CCITT. It transmits and receives the packetized data (information of control) serially in a format shown in table 5.1. The data field refers to the Address (SAPI+TEI), Control and Information fields

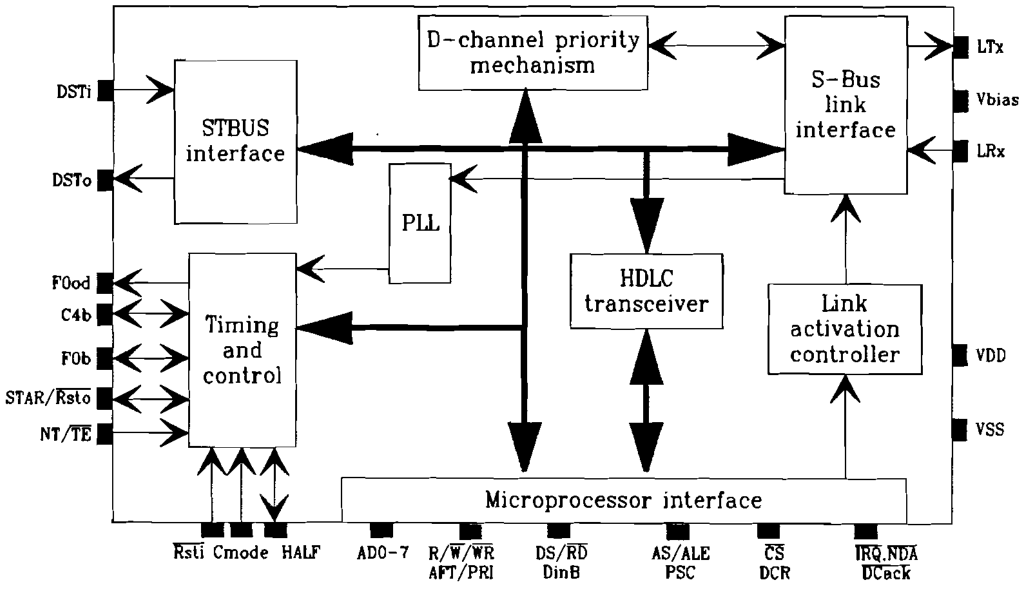


FIGURE 5.1: Functional block diagram of the Subscriber Network Interface Circuit (SNIC).

TABLE 5.1: HDLC Transceiver frame format.

FLAG	DATA FIELD	FCS	FLAG
one byte	n bytes ($n \geq 2$)	two bytes	one byte

TABLE 5.2: Description of the SNIC registers.

	Address	Write	Read
A	0xb00	Master Control Register	verify
S	0xb01	ST-BUS Control Register	verify
Y	0xb02	HDLC Control Register 1	verify
N	0xb03	HDLC Control Register 2	HDLC Status Register
C	0xb04	HDLC Interrupt Mask Register	HDLC Interrupt Status Register
	0xb05	HDLC Tx FIFO	HDLC Rx FIFO
	0xb06	HDLC Address Byte #1 Register	verify
	0xb07	HDLC Address Byte #2 Register	verify
S	0xb08	C-channel register	DSTi C-channel
Y	0xb09	DSTo C-channel	C-channel Status Register
N	0xb0a	S-Bus Tx D-channel	DSTi D-channel
C	0xb0b	DSTo D-channel	S-Bus Rx D-channel
	0xb0c	S-bus Tx B1-channel	DSTi B1-channel
	0xb0d	DSTo B1-channel	S-Bus Rx B1-channel
	0xb0e	S-Bus Tx B2-channel	DSTi B2-channel
	0xb0f	DSTo B2-channel	S-bus Rx B2-channel

illustrated in figure 2.2. A valid frame should have a data field of at least 16 bits.

The HDLC transceiver is controlled through several registers. They are listed in table 5.2. For more information, see [6] or appendix A. Most of the asynchronous registers (ASYNC) are relevant to data communication on the D-channel. First there is the HDLC Control Register 1. This is a write-only (read to verify) register. It can be used to enable/disable the transmitter as well as the receiver. It is also used to direct the D-channel to the HDLC transceiver, as the D-channel is normally routed to the STBUS interface (see figure 5.1). The HDLC Control Register 2 is used to tag bytes that are written into the transmit FIFO. Bytes can be tagged as end-of-packet (eop) indicating it is the last byte of the packet, or as frame-abort (fa), indicating the packet should be aborted after the byte. This register reads back the HDLC Status Register. It reports the condition of the transmitter and receiver FIFO's (full, empty) and the status of the packet being received (top of receive FIFO is first byte of packet, last byte of packet, packet is good or bad). The transmitter and receiver FIFO's are accessible through their corresponding registers: HDLC Tx FIFO and HDLC Rx FIFO. The HDLC Interrupt Mask Register is used to (un)mask interrupts generated by the transceiver. Reading the HDLC Interrupt Status Register shows which interrupts occurred (interrupts are reset after this action).

The above registers are the most important in relation to the transmission and reception of bytes on the D-channel. The Data Book includes algorithms to accomplish this. I have used these algorithms as a basis from which I developed a more advanced method. Before describing this method, I shall first introduce the interrupts generated by the HDLC transceiver. I will then describe the method to receive packets and transmit packets, respectively.

5.2 HDLC transceiver interrupts

The SNIC chip on the ISDN Express Card is able to generate eight maskable interrupts. These occur upon a certain condition in the HDLC transceiver. These interrupts are:

GA	Indicates that a go-ahead sequence has been detected on the received HDLC D-channel. I will not use it.
EOPD	End of Packet Detected. Indicates that an end of packet has been detected on the HDLC receiver. The packet can either be a good packet, an invalid packet or an aborted packet.
TEOP	Transmit End of Packet. According to the Data Book, this indicates that the receiver has finished sending the closing flag of the last packet in the Tx FIFO. Note: If the transmitter is disabled *immediately* after the TEOP interrupt occurs, the receiving party will receive an aborted packet. Clearly the TEOP interrupt occurs sometime *before* the transmitter sends the closing flag. Advise: do not disable the transmitter after a TEOP.
FA	Frame Abort. Indicates that the receiver has detected a frame abort sequence on the received data stream.
TxFL	Transmit FIFO Low. Indicates that the device has only 4 bytes remaining in the Tx FIFO. This bit has significance only when the Tx FIFO is being depleted and not when it is getting loaded.
TxFun	Transmit FIFO Underrun. Indicates that the Tx FIFO is empty without being given the 'end of packet' indication. The HDLC will transmit an abort sequence after encountering an underrun condition.
RxFF	Receive FIFO Full. Indicates that the HDLC controller has accumulated at least 15 bytes in the Rx FIFO.
RxFov	Receive FIFO Overflow. Indicates that the Rx FIFO has overflown (i.e. an attempt to write to a full Rx FIFO). The HDLC will always disable the receiver once the receive overflow has been detected. The receiver will be re-enabled upon detection of the next flag.

In order to make use of the interrupt mechanism of the SNIC-chip, several registers must be initiated correctly:

on the Mitel card:

- HLDC Interrupt Mask register: interrupts should be unmasked
- Master Control register: enable $\overline{IRQ}$/NDA pin for HDLC interrupts.

on the PC:

- Interrupt Mask register of 8259 programmable interrupt controller: unmask hardware interrupt number 7 (IR7)
- Redirect software interrupt number 15 (which is generated upon IR7) to the SNIC interrupt service routine.

These actions are implemented in the function `inithardw`.

An interesting but annoying problem occurred trying to program the Master Control register: bit B2 should be set to "0" according to the data book to enable the NDA/$\overline{IRQ}$ pin for HDLC interrupts. However, tests on the PC revealed that no interrupt 15 would occur when an EOPD interrupt occurred on the Mitel card. A logic analyzer was therefore applied, which showed a 125μs clock signal. This is what the data book describes as the New Data Available (NDA) signal, which should only appear on the NDA/$\overline{IRQ}$ pin when bit B2 is set to "1". My suspicions were then confirmed: the programming of bit B2 should be exactly opposite: a "1" for interrupt functioning, a "0" for NDA functioning.

5.3 Receiving packets

When the HDLC receiver is enabled, it can receive incoming packets. An incoming packet is examined on a bit-by-bit basis, the FCS is calculated and the data bytes are written into the 19 byte receive FIFO. However, the FCS and other control characters i.e. flag and abort, are never stored in the receive FIFO. All the bytes written to the receive FIFO are flagged with two status bits. The status bits are found in the HDLC status register and indicate wether the byte to be read from the FIFO is the first byte of the packet, the middle of the packet, the last byte of the packet with good FCS or the last byte of the packet with bad FCS. This status indication is valid for the byte that is to read from the receive FIFO. The incoming data is always written to the FIFO in a byte-wide manner. Receive overflow occurs when the receive section attempts to load a byte to a full receive FIFO. All attempts to write to the full FIFO will be ignored until the receive FIFO is read. When overflow occurs, the rest of the present packet is ignored as the receiver will be disabled until the reception of the next opening flag.

It is now possible to design an algorithm to receive packets through the microprocessor interface. The algorithm offered by the data book is shown in figure 5.2 (left). The upper dashed box shows the loop where the software waits for the beginning of a packet. If a byte is received (the Rx FIFO will not be empty) it is checked if it is indeed the first byte of a packet. If it is, the next byte is read. If it is the last byte, the packet is tested on its FCS. If it isn't the last byte, more bytes will be read when the Rx FIFO is not empty. Should, during this receiving process, the Rx FIFO run empty, a waiting loop is entered (lower dashed box). Please note that "first byte", "last byte" and "good FCS" conditions apply to the byte that is in front in the FIFO. This explains the extra "read RxFIFO" in figure 5.2 (right) after the "good FCS" test.

The dashed boxes show where the algorithm uses the polling technique to wait for a Rx FIFO not empty situation. This is very time consuming. I have chosen to use the generated interrupts to skip the waiting parts of the algorithm. Four of the interrupts are used. The RxFF and EOPD interrupts are a signal to start reading the receive FIFO. In the RxFF case the receiver is still receiving bytes and an Rx FIFO empty situation may occur while reading the FIFO. Reading the FIFO is suspended until the next RxFF or EOPD interrupt. in the EOPD case a complete packet has been received and can be read from the FIFO. The RxFov and FA interrupts are a signal to abort the current packet. In the RxFov case one or more bytes have been lost due to a full FIFO. In the FA case a frame abort sequence has been received.

The algorithm in figure 5.2 (right) shows the actions to be taken when an RxFF or EOPD

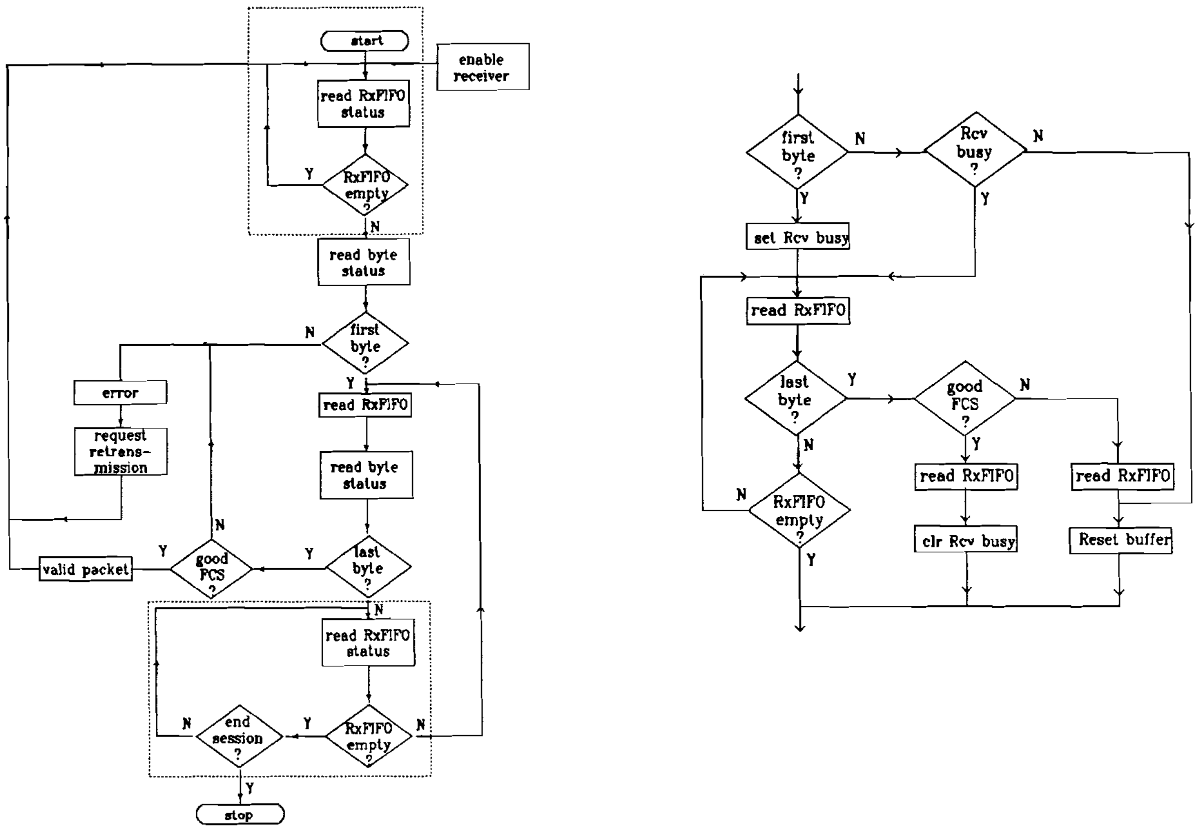


FIGURE 5.2: Receive packet algorithm using polling (left) and interrupts (right).

interrupt occurs. A status indicator Rcv_busy has been added to indicate that a packet is being read. Thus when reading a byte that is not the beginning of a packet, a test should be made to see if Rcv_busy is true. In that case the byte and its successors are part of a packet of which the first part (2 or more bytes) has already been read. If Rcv_busy is false, an error has occurred and it is best to reset the Rx FIFO. The function `readRxFIFO()` reads the receive FIFO and places the byte into a receive buffer.

Once a packet is received, it is passed on to the TRANSMISSION process. This is done by generating a PH_DATA_INDICATION message, in which the packet's buffer pointer is passed along. The message is put in the highest priority queue 0. Please note that the use of the PH_DATA_INDICATION primitive is *within* layer 2, and not *between* layer 1 and 2 as illustrated in figure 2.4. A new receive buffer is then allocated to receive the next packet.

The TRANSMISSION process will, upon reception of the PH_DATA_INDICATION message, decode the received packet. When the destination process is determined a message is generated for that process and the information will then find its way further up the OSI layers or stay in layer 2 if it is a peer-to-peer message.

The TRANSMISSION process has the highest priority in the operating system. The reason for this are the timing restrictions that apply to layer 2 peer-to-peer messages. All transmitted packets must have a response within T200 seconds. T200 is default 1 second (CCITT parameter). As soon as a packet is received, it is to be decoded and given to the data link layer entity in question. In chapter 6 I will verify if the implementation can function under the current 'one second restriction'.

5.4 Transmitting packets

To transmit a packet, the reverse of the actions in the previous section are taken. Management or a data link layer entity will queue information in a special transmission queue, which is accessed through the function `putqueue(L1_QUEUE, UIQUEUE, information buffer pointer)`. The transmitting entity will then signal the TRANSMISSION process that a packet is ready to be transmitted by means of a PH_DATA_REQUEST message to the TRANSMISSION process.

The TRANSMISSION process can be in one of two states: IDLE or BUSY. These states only influence the transmit procedure, not the receive procedure. In the BUSY state, the transmitter is currently transmitting a packet. The PH_DATA_REQUEST message is then regenerated to be processed in another dispatcher cycle through the message queues. This does not affect the sequence of the packets, as the PH_DATA_REQUEST message only indicates that a packet is available for transmission. The sequence of the packets is entirely determined by the order in which they appear in the transmission queue. If the TRANSMISSION process is in the IDLE state, packet transmission can be started. First, the packet in front of the transmission queue is fetched. Then the function `xmt_buff()` is called. It initializes several transmit variables (address of the first byte of the packet, number of bytes in the packet), disables the transmitter and fills the transmitter FIFO of the HDLC transceiver. The FIFO can hold 19 bytes. The transmitter is then enabled, and the remaining bytes are sent by the interrupt handler.

Filling the transmitter FIFO is accomplished using the algorithm in figure 5.3. Bytes are written to the FIFO as long as it isn't full. If it is full, the transmitter is enabled and the algorithm is suspended until the next call. Before writing the last byte to the transmit FIFO, it should be tagged as end-of-packet. This will tell the transmitter to calculate the FCS and send the closing flag after the last byte is sent.

As the transmit FIFO is being emptied, the HDLC transceiver will generate a TxFL interrupt as soon as only 4 bytes remain in the FIFO. If the packet is at most 4 bytes long, this interrupt will not be generated. It is only generated when there have been at least 5 bytes in the FIFO. The TxFL interrupt is a signal to refill the FIFO if necessary. This is why a Transmit Buffer Byte Count variable is used. If non-zero, the packet is not yet completely transmitted. If zero, the packet has been transmitted and the TxFL interrupt can be ignored. As soon as the FIFO runs empty, and the last byte in the FIFO was marked as the last byte of a packet, a TEOP interrupt is generated. Should the FIFO run empty and expect more bytes, a TxFun interrupt is generated and the transmitter should be reset. In both cases the transmit variables are reset and the TRANSMISSION process's state returns to IDLE. Another packet can now be transmitted.

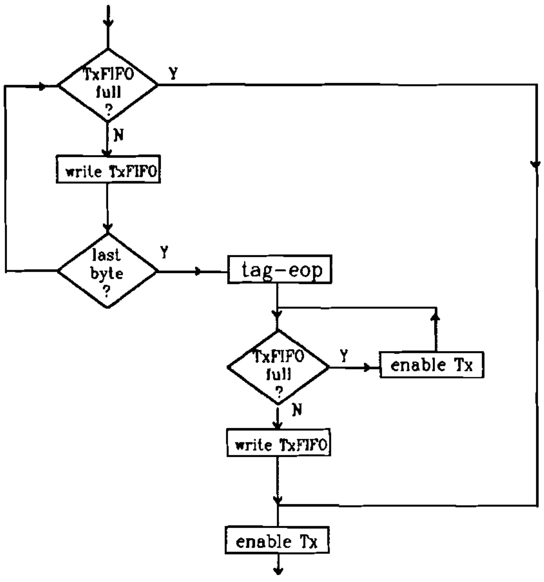


FIGURE 5.3: Transmit packet algorithm with the use of interrupts.

5.5 Interrupt handler

The interrupts are serviced in an interrupt handler. On the following page, Figure 5.4 sums up the two previous sections, resulting in an outline of the interrupt handler.

```
while (HDLC Interrupt Status register() not 0)
{
   if (RxFov or FA)  :  ...
   {
      reset Rx FIFO;
      clear Rcv_busy;
   };
   if (RxFF.or EOPD
   {
      if (first byte OR Rcv_busy)
      {
         set Rcv_busy;
         while (Rx FIFO not empty)
         {
            read Rx FIFO;
            if (last byte)
            {
               if (good FCS)
               {
                  read last byte from Rx FIFO;
                  clear Rcv_busy;
                  pass information to LAP D;
               }
               else
               {
                  read last byte from Rx FIFO;
                  clear Rcv_busy;
               };
               exit;
            }
         }
      }
      else
         reset Rx FIFO;
   };
   if (TFL)
      if (Transmit Buffer Byte Count > 0) fill FIFO with bytes;
   if (TEOP)
   {
      reset transmit variables;
      TRANSMISSION newstate = IDLE;
   };
   if (TFUN)
   {
      reset Tx FIFO;
      reset transmit variables;
      TRANSMISSION newstate = IDLE;
   };
};
out 0x20,0x20      /* end of interrupt signal to interrupt*/
                   /* controller */
```

FIGURE 5.4: Outline of the interrupt handler.

```
void far timecheck (void)
{
   word timer;

   for ( timer=0 ; timer < MAXTIMER; timer++ )
      if (Timer[timer].Used == USED) timedec(timer);
}

void timedec(word timer)
{
   if( --Timer[timer].MainTimer == 0 )
   {
      Send_Time-out_message_to_process();
      Timer[timer].Used = FREE;
   }
}
```

FIGURE 5.5: Timer interrupt handler.

5.6 Timer interrupts

LAP D makes use of several timers to ensure correct data transfer. These timers are listed in appendix C. Implementation of these timers is accomplished through software interrupt 0x1C, which happens once every 54.95 ms on an IBM XT. The timer interrupt handler, illustrated in figure 5.5, checks which timers are active and have to be updated. Timers which expire result in a message for the process that started the timer.

The timers are accessed by the following functions:

`void runtimer(word msg, byte dest, word time)` Start a timer with length `time`.

`void stoptmr(word msg, byte dest)` Stop a certain timer. If the timer has already generated a Time-out message, the function `remove_tmr_msg` is called.

`void restarttimer(word msg, byte dest, word time)` Resets timer count to `time`.

`byte timer_stat(word msg)` Checks if a certain timer is running. Status is returned as a byte: '0' if the timer isn't not running, '1' if it is.

`remove_tmr_msg (word msg, byte dest)` Removes a timer message from the message queue when a timer has expired but must be stopped. This is an exception of the rule that only the dispatcher can access the message queues.

Summary

In this chapter the LAP D software was expanded with the TRANSMISSION process. This process controls the transmission and reception of LAP D packets. It uses the SNIC circuit on the Mitel card. From a description of this SNIC circuit it was possible to derive transmit and receive algorithms on an interrupt basis. The resulting interrupt handler code outline was shown. To complete the low level functions, the implementation of the LAP D timers was discussed.

The LAP D software has now been completed and can be tested. There are two types of tests on which I have focussed briefly. The first concerns the functionality of LAP D. It shows whether the data link layer entities follow the correct procedures. The second concerns the real-time performance of the software. This test can reveal if the software has the capacity to perform within the timing restrictions of LAP D. In other words: how efficient is the implemented code? The next chapter will answer this question, as the results of both tests are discussed.

Chapter 6

Testing

Before claiming that the software "works", it should be subjected to tests. As I found out, testing takes a considerable amount of time. There is no such thing as The Test after which conclusions can be drawn. In fact, I recognized several types of tests, each giving answers to different questions:

- Coverage test: is all code reachable? Is there code that has no function?
- Decision test: do conditional statements provide for all conditions that may occur?
- Protocol implementation test or conformance test: does the code actually implement the protocol?
- Performance test: does the code operate within the restrictions? Does it allow (in this case) the terminal to be connected to an existing ISDN terminal?

Making a suitable test case that is comprehensive enough to facilitate this validation is a major problem. The main reason for this is the fact that the number of inputs of the system is substantial. Due to the state machine behaviour of the protocol, its testing is comparable to testing a sequential state machine in hardware in regard to the number of different input/output combinations. In [3], a total of 238 different transition identifiers is recognized.

During some random tests, some persistent and unexplainable errors occurred. The subsequent debugging did cost considerable time, preventing me from actually performing thorough testing. What I did do, however, was test if the basic functions were working. This will be discussed in the next sections. Additionally I will give an answer to the question raised in the introduction about the performance of the LAP D software, using measurements of the code's execution time

6.1 Limited conformance test

Frame level

In this section, the interrupt handlers for receiving and transmitting frames are tested. The test configuration is shown in figure 6.1. The tests and their results are listed below. Though the tests are meant to check the transmission process, they implicitly include some functional aspects as to the response of the TE.

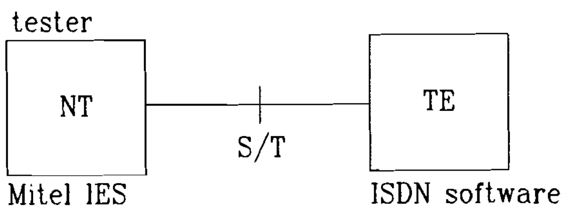


FIGURE 6.1: Test configuration for testing transmission and reception of packets. On the left PC the Mitel IES software is used to transmit and receive packets to/from the PC on the right, where the ISDN software is installed. The ISDN software is running under Turbo Debugger to ease examination of variables and monitoring program progress.

Test 1

Conditions: NT and TE are connected and in the Active state concerning bus activity. All of the TE's data link layer entities are in the TEI_UNASSIGNED state.		
Tester (NT)		TE
ID_ASSIGN, byte sequence (FE, FF, 03, 0F, 00, 01, 02, 03)	⟶	breakpoint at `rcv_broadcast` should be reached.
Results: Using step by step tracing after the breakpoint was reached, correct reception of the bytes was revealed. The ID_ASSIGN command was also directed correctly to the management process.		

Test 2

Conditions: NT and TE are connected and in the Active state concerning bus activity. All of the TE's data link layer entities are in the TEI_UNASSIGNED state. TEI value "1" is assigned to a data link layer entity.		
Tester (NT)		TE
ID_CHECK, byte sequence (FE, FF, 03, 0F, 00, 00, 06, FF)	⟶	breakpoint at `rcv_broadcast` should be reached.
	⟵	Response should be: byte sequence (FE, FF, 03, 0F, ??, ??, 05, 03) where ??,?? indicates a random value.
Results: Using step by step tracing after the breakpoint was reached, correct reception of the bytes was revealed. Management did respond with the correct byte sequence.		

Test 3

Conditions: NT and TE are connected and in the Active state concerning bus activity. All of the TE's data link layer entities are in the TEI_UNASSIGNED state. At least one TEI value is assigned to a data link layer entity.		
Tester (NT)		TE
ID_REMOVE, byte sequence (FE, FF, 03, 0F, 00, 00, 04, FF)	⟶	All TEI values are to be removed.
Results: Using step by step tracing after the breakpoint was reached, correct reception of the bytes was revealed. The command was also correctly directed to the management process. On the tester, the expected sequence was received.		

Test 4

Conditions: NT and TE are connected and in the Active state concerning bus activity. The TE should be in the MULTIPLE_FRAME_ESTABLISHED state. Layer 3 is assumed sending a (maximum size) information packet.		
Tester (NT)		TE
	⟵	I-frame (maximum size)
Results: – Sometimes a three byte frame was received on the tester, instead of a 264 byte frame. The error was that no provision had been made for back tracking along the transmission queue. This has been corrected. – Sometimes a (randomly positioned) byte is received twice, increasing the length of the frame by one. The error could be either at the transmitter or the receiver side. Debugging showed it must be an interrupt handler problem or hardware problem. The error has not yet been corrected.		

The tests show that information transfer is only guaranteed for "short" packets. Not all packet sizes have been tested. Fortunately, most commands and supervisory frames are very short and are transmitted correctly.

Protocol level

The results of the previous section enable us to continue with the functional aspect of the test, as long as only small packets are involved. For this purpose, a slightly different test configuration is used, illustrated in figure 6.2.

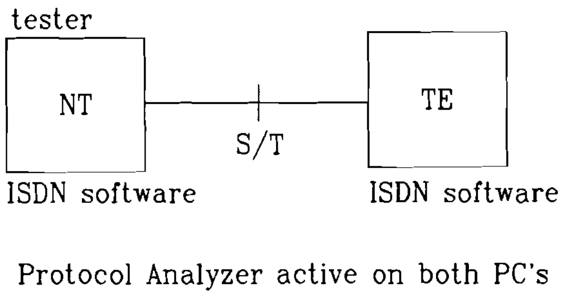


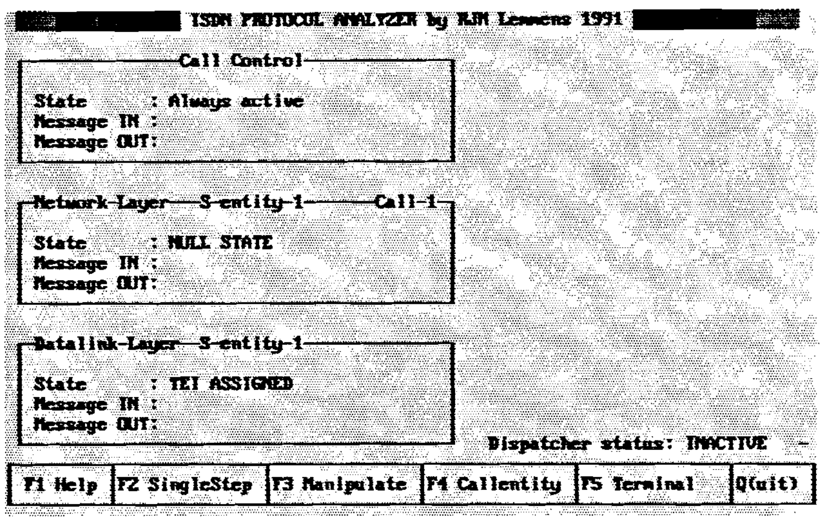
FIGURE 6.2: Test configuration for monitoring the functional behaviour of the protocol. On both PC's the ISDN with the protocol analyzer is used. The analyzer displays both states and incoming messages of each data link layer entity. A single step feature enables a close watch of the dispatcher's actions.

A protocol analyzer was developed by Lemmens [7]. It is used to observe and manipulate the actual states of the data link layer entities. The analyzer makes use of several windows, in which the states, incoming and outgoing messages are displayed of the various entities, including layer 3 entities.

Figure 6.3 shows the initial screen of the analyzer. To assist in the observation of the processes, it is possible to slow down the dispatcher. It can be run freely, put in Single Step mode and deactivated. In Single Step mode, the dispatcher executes a single cycle. This means that the dispatcher will check the message queue once, and process the present message. In any state of the dispatcher, it is possible to generate an incoming message for an entity, or alter its current state. A complete description of the analyzer and its functions is given in the software manual, see [13].

The following tests were performed using the analyzer. Both sides of the S/T-interface were put into an initial state, and on one side a message was generated. The ISDN software is meant for the TE side of the configuration. It is, however, possible to modify the code so the software can be used on the NT side as well (layer 2 peer-to-peer only). This involves the coding of the Command/Response bit. The use of this bit is as follows:

Command/Response	direction	C/R value
Command	network ⟶ user	1
	user ⟶ network	0
Response	network ⟶ user	0
	user ⟶ network	1



```
ISDN PROTOCOL ANALYZER by RJM Lemmens 1991

Call Control
State       : Always active
Message IN  :
Message OUT:

Network-Layer  S-entity-1       Call-1
State       : NULL STATE
Message IN  :
Message OUT:

Datalink-Layer  S-entity-1
State       : TEI ASSIGNED
Message IN  :
Message OUT:
                                   Dispatcher status: INACTIVE  -
F1 Help | F2 SingleStep | F3 Manipulate | F4 Callentity | F5 Terminal | Q(uit)
```

FIGURE 6.3: Layout of the protocol analyzer. Through function keys the displayed entities can be manipulated.

Using two TE's (users) implementing the above convention, the receiver (not an NT but as TE) will always receive a command when a response was sent, and receive a response when a command was given. The solution is to invert the received C/R-bit on both sides. It should be noted that in case the TE is connected to a real NT, this inversion is not necessary.

The following tests were successfully completed (the first primitive or command was generated by the tester):

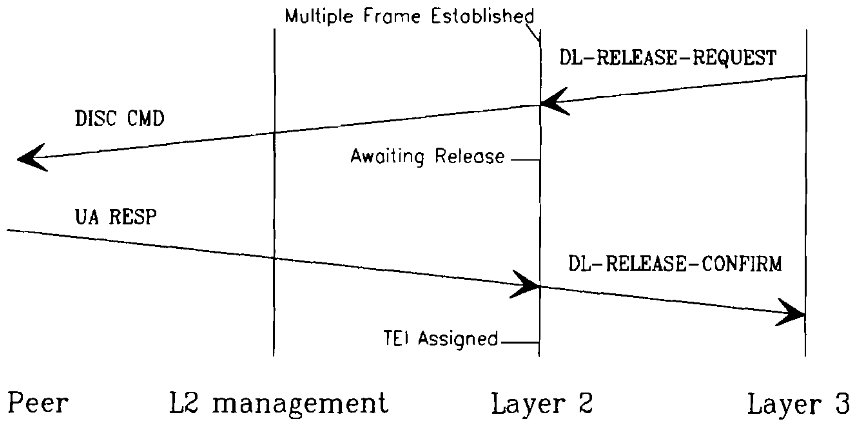


FIGURE 6.4: Test for data link layer release.

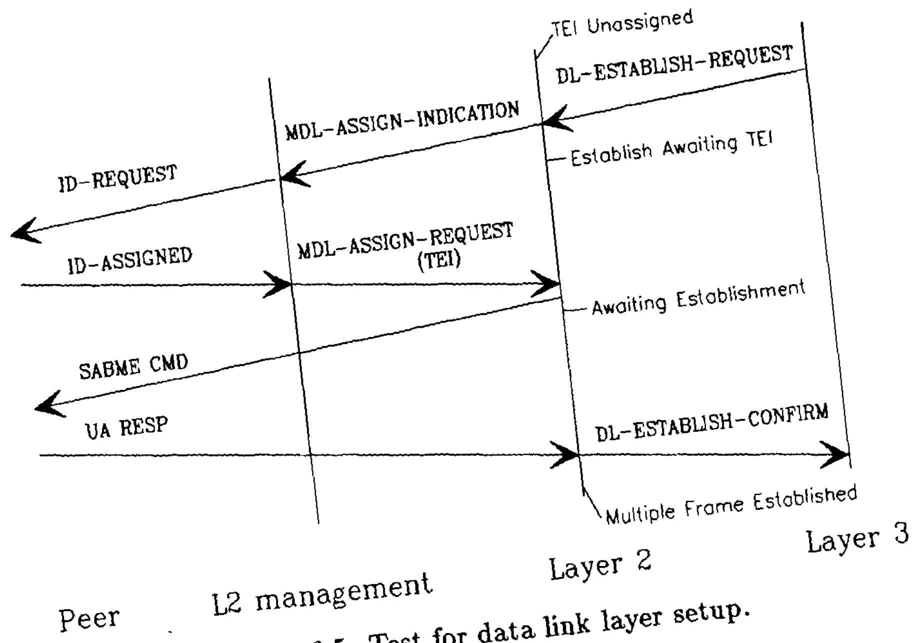


FIGURE 6.5: Test for data link layer setup.

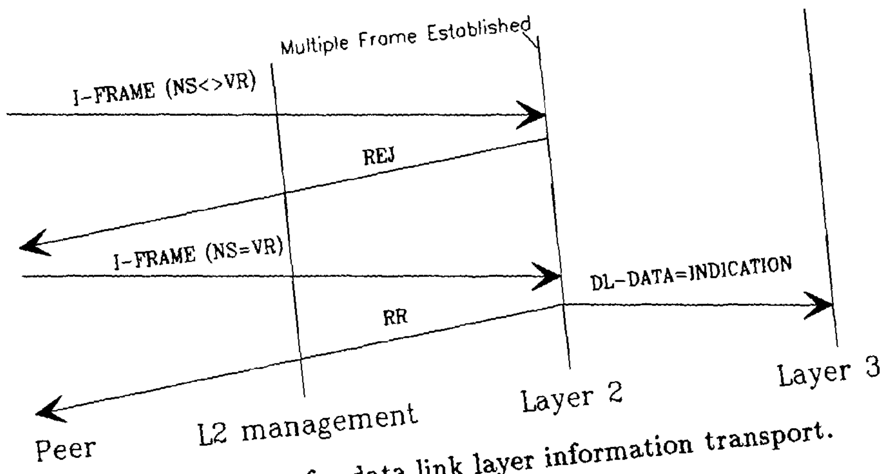


FIGURE 6.6: Test for data link layer information transport.

If an extensive conformance test is to be performed in the future, I recommend the use of the tests supplied by the Conference of European Posts and Telecommunication Administrations (CEPT). Their technical specifications are known as Normes Européenne de Télécommunication (NET), and are recognized by most European countries. In this specific case, NET 3 would apply [10].

6.2 Performance test

It is essential for LAPD to function real-time in order to be able to function conform its specifications. As most of LAPD is implemented in software on a (relatively) slow PC, the question arises if the implementation is fast enough. Conformance testing can perhaps reveal correct response to specific stimuli, but it does not say anything about the overall performance.

A first indication that the implementation might not be functioning 100 percent, came when activating all three data links. After a while, one or more data links would release itself after a timeout situation. Even without the time consuming functions associated with the protocol analyzer, this problem returned.

In order to gain a better and more substantial insight in the performance of the implementation, C-code execution time has been measured. For this reason, special (assembler) code was used. This code, known as the ZTimer, was found in [1]. It enables accurate (up to 1 μs) measurements of code performance.It makes use of the built in timers of the IBM PC. There are two restrictions the ZTimer imposed: first, interrupts should be disabled inside the code segment to be measured. Second, the code could not take longer than 54 ms to execute (if not, the measured time will read -1). There is a ZTimer version without this last restriction, but all segments I needed to measure were shorter than 54 ms. The general use of the ZTimer is as follows:

```
ZTimerOn();                 /* Start timer */
...  code to be measured ...
ZTimerOff();                /* Stop timer */
time = ZTimerReport();      /* Calculate used time, not counting overhead */
```

Most functions have separately been timed with the use of ZTimer, in combination with Turbo Debug. The results are listed in table 6.1. The first column lists the functions that were measured. `tx(SABME)` for example, takes 1620 μs to execute, under the condition that a free buffer is found at once. If this is not the case, the execution times measured under this condition rise slightly. Looking at the figures, we see that as the information field increases (and thus the number of bytes to be sent), execution time tends to rise sharply. It is, unfortunately, impossible to gain a more precise insight by experiment. The unpredictable occurrence of interrupts, which may not be disabled, prevent using the ZTimer. A theoretical approach where the timers are not considered, and transmission speed is assumed equal to the speed on the D-channel (16 Kbit s^{-1}), is used from here on.

One worst case situation will show if the implementation is able to deal with a burst of short packets. Assume three data link layer entities start to set up a data link connection at the same time. As soon as each data link layer entity executes `tx(SABME)`, time becomes a crucial factor, since a response must be received in one second. I will sum up all actions by the ISDN software on both sides of the connection to obtain an indication of the duration of the entire procedure.

TABLE 6.1: Duration of basic functions measured by ZTimer. Measured on an IBM PC running on 4.77 MHz. Functions implemented with Turbo C 2.0. In some functions the interrupt enable/disable commands were disabled.

Function:	Duration (μs)	Condition:
getmsg(), none found:	16	
getmsg(), msg found:	637	
updatequeue(), empty queue:	14	
updatequeue(), queue used:	96	
message(), room in queue:	997	
message(), queue full:	117	
tx(SABME)	1620	getbuff() finds a free buffer at once
tx(RR)	1711	,,
tx(DISC)	1696	,,
tx(UA)	1726	,,
tx(I_FRAME), max. inf. field	40846	,,
tx(UI_FRAME), max. inf. field	41508	,,
tx(DM)	1578	,,
tx(RNR)	1681	,,
tx(REJ)	1636	,,
tx(FRMR)	2194	,,
tx(XID)	2889	,,
putqueue(), room in queue:	353	
putqueue(), queue full:	183	
timecheck(), 0 timers running:	1118	no timer expires during check
timecheck(), x timers running:	1118 + x*61	,,
		each expiring timer adds 487
runtimer(), no timers running	145	
runtimer(), x timers running	145 + x*39	
stoptimer(), timer at array[x]:	140 + x*98	timer still running
stoptimer()	2676	timer expired, time_out message removed
dispatcher cycle, no action:	1600	
tx_packet, x bytes	536 + x*156	
rcv_packet, x bytes	540 + x*160	

In the following text, [0] denotes the message queue of the highest priority, [1] denotes the queue of a lesser priority. A Dispatcher cycle includes the getmsg() call.

	action	time (μs)	message queue after action
Initiating side			
	...`tx(SABME)`$_1$		[0] PH_DATA_REQUEST
			[1] 2 x DL_ESTABLISH_REQUEST
start T200$_1$:	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] 2 x DL_ESTABLISH_REQUEST
	Dispatcher cycle	2237	
	`dlestreq_4()`	2600	[0] PH_DATA_REQUEST
			[1] DL_ESTABLISH_REQUEST
start T200$_2$:	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] DL_ESTABLISH_REQUEST
	Dispatcher cycle	2237	
	`dlestreq_4()`	2600	[0] PH_DATA_REQUEST
			[1] -
start T200$_3$:	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] -
Responding side			
	Assume all three SABME's are received in sequence. This will affect the response times in a negatively: they increase slightly. Assume further that all message queues are empty.		
	...receive 3 bytes (interrupt)	1000	[0] PH_DATA_INDICATION
			[1] -
	...receive 3 bytes (interrupt)	1000	[0] 2 x PH_DATA_INDICATION
			[1] -
	...receive 3 bytes (interrupt)	1000	[0] 3 x PH_DATA_INDICATION
			[1] -
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0] 2 x PH_DATA_INDICATION
			[1] SABME$_1$
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0] PH_DATA_INDICATION
			[1] SABME$_1$, SABME$_2$
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0]
			[1] SABME$_1$, SABME$_2$, SABME$_3$
	Dispatcher cycle	2237	
	`sabme_4()`	3387	[0] PH_DATA_REQUEST
			[1] SABME$_2$, SABME$_3$
	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] SABME$_2$, SABME$_3$
	Dispatcher cycle	2237	
	`sabme_4()`	3387	[0] PH_DATA_REQUEST
			[1] SABME$_3$
	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] SABME$_3$
	Dispatcher cycle	2237	
	`sabme_4()`	3387	[0] PH_DATA_REQUEST
			[1] -
	Dispatcher cycle	2237	
	`tx_packet(3 bytes)`	1004	[0] -
			[1] -

	action	time (μs)	message queue after action
Initiating side			
	Assume initiating party starts receiving UA responses, in sequence. Again, this assumption increases the response times.		
	...receive 3 bytes (interrupt)	1000	[0] PH_DATA_INDICATION [1] -
	...receive 3 bytes (interrupt)	1000	[0] 2 x PH_DATA_INDICATION [1] -
	...receive 3 bytes (interrupt)	1000	[0] 3 x PH_DATA_INDICATION [1] -
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0] 2 x PH_DATA_INDICATION [1] UA$_1$
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0] PH_DATA_INDICATION [1] UA$_1$, UA$_2$
	Dispatcher cycle	2237	
	`rcv_packet(3 bytes)`	1600	[0] [1] UA$_1$, UA$_2$, UA$_3$
	Dispatcher cycle	2237	
Stoptimer T200$_1$	`ua_5`	2600	[0] - [1] UA$_2$, UA$_3$
	Dispatcher cycle	2237	
Stoptimer T200$_2$	`ua_5`	2600	[0] - [1] UA$_3$
	Dispatcher cycle	2237	
Stoptimer T200$_3$	`ua_5`	2600	[0] - [1] -

It is now possible to calculate the response times (i.e. the time between each `tx(SABME)`$_i$ and receiving a UA$_i$. The results are listed in table 6.2. Although these results are inaccurate, an important conclusion may be drawn from them: the implementation is able to handle bursts of short packets. A burst consists of at most 3 packets, since there are only three data link layer entities. After transmitting a packet, each entity will await a response.

TABLE 6.2: Response times of three consecutive data link layer setup procedures (estimation).

entity	response time
1	76.3 ms
2	73.0 ms
3	70.0 ms

Another interesting analysis concerns information transfer. In this case, three data link layer entities transmit an information frame of maximum size. Again, the analysis is done by summing up all data link layer actions. Transmitting a frame is considered to take 16.5 ms, which is calculated from the D-channel transmission speed. I will not include the complete analysis but only the results. The results show that all three transmitted I_frames are responded in one second. The minimal response time was shown to be greater than 0.6 s. Theoretically, the implementation of the data link layer should function properly. When layer three functions are added and activated, response times should not increase, because layer 3 is assigned a lower priority than layer 2, including the TRANSMISSION process.

When the above two situations were put into practice, the results were different. Starting three data link layer connections was no problem. After a few minutes however, one by one the data link connections were released. The reason for this has yet to be discovered[1]. The error might be found in buffer/queue management, although in some cases a SNIC interrupt remained unserviced, thus suggesting the error to be found in the interrupt handler. The reason why the error has not been found is the fact that every error situation showed a different probable cause.

Summary

A tiny set of tests has been done on the software. The results are encouraging, but not perfect. Transmission of large packets is still a problem, an essential one when looked at from layer 3, since layer 3 makes use of this facility. Two brief performance tests revealed that the implementation can very well fullfill the timing restrictions imposed by LAP D. Unfortunately, a practice run with the protocol analyzer revealed a serious error. The software is not capable of maintaining a data link connection for a long period of time. It is therefore far from ready to be used by layer 3, let alone ready to enable development of ISDN services. The only conclusion that can be made is that the software should be tested exhaustively.

[1]One of the problems causing the data link connection has been found. It concerns an action of layer 2 management after a collision of commands. This action is to send an ID_VERIFY_REQUEST to the NT. The test configuration however, does not provide any NT services. The request remains unanswered, causing layer 2 management to remove the TEI value of the data link in question. I have disabled this managemement reaction, as the data link layer entities are capable of resolving this collision by themselves.

Chapter 7

Conclusions

The Keyword during the continuation of the ISDN project should be: Testing. A much overlooked and underestimated factor. Where previous students working on the project declared a piece of work "tested and functional", I have encountered the opposite. Many errors, not discussed in the previous chapters, could have been detected if each function was tested individually. This can be done using a debugger and evaluating the function's results. Much to my dismay, testing is something I have not been able to pursue to the maximum extent.

Those parts I did test showed mixed results. Although the various parts of the software seem to function, it is not yet possible for layer 3 to access an error free transmission channel. Likewise, maximum rate performance is still out of the question. The reason for this can be ascribed to difficulties in the transmitter process of layer 2, and to the lack of testing (and correcting any errors) of LAP D. In order to find the errors, I suggest improving an important tool: the protocol analyzer. More parts of the software (status of relevant variables) should be observable. A facility through which test patterns (preferably NET3) can be applied to LAP D would greatly aid conformance testing. These improvements should always be evaluated as to the pressure they cause on the timing requirements and restrictions of the protocol.

When the layer 2 software can at last be "released", the time comes to test layer 3. Testing layer 3 in a similar configuration as used for layer 2 is not possible. The layer 3 protocol specification (Q.931) is not symmetrical for TE and ET. Lemmens [7] suggests using CEPT Recommendation T/S 46-30 as a solution, to enable testing of layer 3 in an end-to-end situation with two terminals. One should always carry in mind how the protocols are defined (for TE or NT) and the configuration in which one wants to apply them.

Bibliography

[1] Michael Abrash. *Zen of Assembly Language Volume I, Knowledge.* Assembly Language Programming Series. Scott, Foresman and Company, London, 1990.

[2] J.J.P.H. Beijnsberger. Hardware en software debugging van het ISDN terminal board. Graduation Report EB276, Eindhoven University of Technology - Digital System Group, Eindhoven, October 1990.

[3] T. Boyce, T. Grenier, R.L. Probert, and H. Ural. Formalization of ISDN LAP D for conformance testing. In *Proceedings of the Eigth Annual Joint Conference of the IEEE Computer and Communications Societies, Technology: Emerging or Converging?*, volume 1, Ottawa, Ont., Canada, 1989.

[4] O.B.P. Rikkert de Koe. *OSI-protocollen lagen 1 tm/4: een inleiding tot een beschrijving van de OSI-standaarden.* Kluwer Technische Boeken, Deventer, 1990.

[5] Dicenet. *Design and Prospects for the ISDN.* Artech House, Inc., London, 1987.

[6] Mitel Documentation. *Microelectronics Data Book*, issue 6 edition, Canada 1988.

[7] R.J.M. Lemmens. Implementatie van het ISDN laag 3 signaleringsprotocol voor het D-kanaal. Graduation Report EB308, Eindhoven University of Technology - Digital System Group, Eindhoven, June 1991.

[8] H. Oudelaar. Implementation of a CCITT Protocol on an ISDN Terminal Board. Graduation Report EB222, Eindhoven University of Technology - Digital System Group, Eindhoven, December 1989.

[9] CCITT Recommendations Q.920-Q.921. Digital Subscriber Signalling System No. 1 (DSS 1), Data Link Layer, User-Network Management. In *Documents of the 9th Plenary Assembly, Melbourne, 14-25 Nov. 1988*, Geneva, 1989. Blue Book, Fascicle VI.10.

[10] Technical Recommendations Application Committee. European Telecommunication Standard 3: Approval requirements for terminal equipment to connect to integrated services digital network (ISDN) using ISDN basic access, part 1: layers 1 and 2 aspects. Technical report, CEPT, CEPT Liaison Office, Seilerstrasse 22, CH-3008 Bern, 1988.

[11] A.S. Tanenbaum. *Computer Networks.* Prentice-Hall International, Inc., London, second edition, 1989.

[12] S. van de Kuilen. Software ontwikkeling rond de Mitel ISDN Express Card. Graduation Report EB266, Eindhoven University of Technology - Digital System Group, Eindhoven, August 1990.

[13] D.F. van Egmond. *Software manual of the ISDN project - december 1991*, December 1991.

[14] P.J.G. Weterman. Design and Building of an ISDN Terminal Board. Graduation Report EB200, Eindhoven University of Technology -Digital System Group, Eindhoven, August 1989.

Appendix A

SNIC registers and access functions

A.1 Address map

TABLE A.1: Description of the SNIC registers.

	Address	Write	Read
A	0xb00	Master Control Register	verify
S	0xb01	ST-BUS Control Register	verify
Y	0xb02	HDLC Control Register 1	verify
N	0xb03	HDLC Control Register 2	HDLC Status Register
C	0xb04	HDLC Interrupt Mask Register	HDLC Interrupt Status Register
	0xb05	HDLC Tx FIFO	HDLC Rx FIFO
	0xb06	HDLC Address Byte #1 Register	verify
	0xb07	HDLC Address Byte #2 Register	verify
S	0xb08	C-channel register	DSTi C-channel
Y	0xb09	DSTo C-channel	C-channel Status Register
N	0xb0a	S-Bus Tx D-channel	DSTi D-channel
C	0xb0b	DSTo D-channel	S-Bus Rx D-channel
	0xb0c	S-bus Tx B1-channel	DSTi B1-channel
	0xb0d	DSTo B1-channel	S-Bus Rx B1-channel
	0xb0e	S-Bus Tx B2-channel	DSTi B2-channel
	0xb0f	DSTo B2-channel	S-bus Rx B2-channel

A.2 Implemented access functions

Relevant implemented access functions (and structures) are:

```
struct Dscstruc
{
   ...
   address   xmtnext;  /*  Address of next transmit byte */
   address   rcvfree;  /*  Address of next free location */
   ...
}

Dscstruc DscRam;

/* read one byte from the RxFIFO */
   #define readRFIFO() *DscRam->rcvfree++ = inportb(0xb05)
/* enable the receiver */
   #define enable_REN() outportb(0xb02, (inportb(0xb02) | 0x48))
/* clear the receiver */
   void resetRFIFO(void)

/* mark next byte in TxFIFO as last byte in packet */
   #define tag_eop() outportb(0xb03, 1)
/* abort packet after next byte */
   #define tag_fa() outportb(0xb03, 2)
/* write a byte to the TxFIFO */
   #define writeTFIFO() outportb(0xb05, *DscRam->xmtnext++)
/* disable the transmitter */
   #define disable_TEN()  outportb(0xb02, (inportb(0xb02) & 0x7F))
/* enable the transmitter */
   #define enable_TEN() outportb(0xb02, (inportb(0xb02) | 0x80))
/* clear the transmitter */
   void resetTFIFO(void)

/* check for activity on the S-bus */
   #define lineact() (inportb(0xb09) & 0x60)

/* read the status of the FIFO's */
   int far readstat(void)

/* read the interrupt register */
   #define rd_ireg()  inportb(0xb04)
```

Initializations necessary to link the SNIC to the software:

```
/* Program SNIC to generate IRQ signal */
   outportb(0xb00, (inportb(0xb00) | 0x04));
   /* Note that selection with B2 of Master Control Register is as follows:
      B2 = 0 selects NDA function
      B2 = 1 selects IRQ function.
      (MITEL Databook p4-67 has been proven wrong on this,
      with the use of a logic analyzer) */

/* enable INT 15, generated by IRQ from SNIC */
   outportb(0x21, (inportb(0x21) & 0x7F ));

/* redirect INT 15 to user SNIC interrupt service routine */
```

```
   oldvec0F = getvect(15);
   setvect(15, Sisr);

/* set direction of D-channel port to microprocessor port */
   outportb(0xb02, 0x58);

/* enable SNIC interrupts */
   outportb(0xb04, 0x7f);
```

Appendix B

LAP D formats

TABLE B.1: Format of layer 2 frames.

Octet	Contents		
1	Opening Flag 0 1 1 1 1 1 1 0		
2	SAPI	C/R	0
3	TEI		1
4(5)	Control Field		
6	Information Field		
N-2, N-1	Frame Check Sequence		
N	Closing Flag 0 1 1 1 1 1 1 0		

TABLE B.2: Command/Response bit definition.

Command/Response	direction	C/R value
Command	network $\Longrightarrow$ user	1
	user $\Longrightarrow$ network	0
Response	network $\Longrightarrow$ user	0
	user $\Longrightarrow$ network	1

TABLE B.3: SAPI definitions.

SAPI value	Related layer 3 or management entity
0	Call control procedures
1	Packet mode communication conforming to Q.931
16	Packet mode communication conforming to X.25 layer 3
63	Layer 2 Management procedures
Others	Reserved

TABLE B.4: TEI definitions.

TEI value	User type
0-63	Non-automatic TEI assignment user equipment
64-127	Automatic TEI assignment user equipment
127	Broadcast TEI

TABLE B.5: Commands and responses.

			ENCODING								
Type frame	Frame	C/R	1	2	3	4	5	6	7	8	Octet
Information transfer	I	C	0	N(S)							4
			P/F	N(R)							5
Supervisory	RR	C/R	1	0	0	0	0	0	0	0	4
			P/F	N(R)							5
	RNR	C/R	1	0	1	0	0	0	0	0	4
			P/F	N(R)							5
	REJ	C/R	1	0	0	1	0	0	0	0	4
			P/F	N(R)							5
Unnumbered	SABME	C	0	1	1	P/F	1	1	1	1	4
	DM	R	0	0	0	P/F	1	1	1	1	4
	UI	C	0	0	0	P/F	0	0	1	1	4
	DISC	C	0	1	0	P/F	0	0	1	1	4
	UA	R	0	1	1	P/F	0	0	1	1	4
	FRMR	R	1	0	0	P/F	0	1	1	1	4
	XID	C/R	1	0	1	P/F	1	1	1	1	4

TABLE B.6: Use of P/F bit.

Frame	P/F function
Command	Poll; P=1 solicits a response from the peer
Response	Final; F=1 indicates answer to a poll

TABLE B.7: Management message structure.

8 7 6 5 4 3 2	1	
Management Entity Identifier		1
Reference Number		2,3
Message Type		4
Action Indicator	E	5

TABLE B.8: Codes for messages concering TEI management procedures.

Message name	Management entity identifier	Reference number Ri	Message type	Action indicator Ai
Identity request (user to network)	0x0F	0–65535	0x01	Ai=127, any TEI value acceptable
Identity assigned (network to user)	0x0F	0–65535	0x02	Ai=64-126, assigned TEI value

Identity denied (network to user)	0x0F	0–65535	0x03	Ai=64-126, denied TEI value
				Ai=127, no TEI value available

Identity check request (network to user)	0x0F	Not used (coded 0)	0x04	Ai=127, check all TEI values Ai=0-126, TEI value to be checked
Identity check response (user to network)	0x0F	0–65535	0x05	Ai=0-126, TEI value in use
Identity remove (network to user)	0x0F	Not used (coded 0)	0x06	Ai=127, request for removal of all TEI values Ai=0-126, TEI value to be removed
Identity verify (user to network)	0x0F	Not used (coded 0)	0x07	Ai=0-126, TEI value to be checked

Appendix C

LAP D parameters

TABLE C.1: List of used LAP D parameters.

Parameter	Value	Description
T200	1 s	Default value for timer T200 at the end of which transmission of a frame may be initiated according to the procedures described in Q.921 (5.6). T200 must be greater then the maximum time between transmission of command frames and the reception of their corresponding response or acknowledgement frames.
T201	T200	Minimum time between retransmission of TEI Identity check messages
T202	2 s	Minimum time between retransmission of TEI Identity request messages
T203	10 s	Maximum time allowed without frames being exchanged
N200	3	Maximum number of retransmission of a frame, system parameter
N201	260	Maximum number of octets in an information field
N202	3	Maximum number of transmissions of a TEI Identity request message
k	1	Size of sliding window in case of basic access signalling services
k	3	Size of sliding window in case of basic access packet services

(declared in file DECLARE.I)