ANALYSIS OF HDLC NORMAL RESPONSE MODE WITH FULL-DUPLEX TRANSMISSION - A NEW CALCULATION METHOD AND SIMULATION

Raith, T., Truong, H.L. +)

Institute of Switching and Data Technics, University of Stuttgart
Fed. Rep. of Germany

ABSTRACT

The paper deals with the analytical performance evaluation of data links operating under the procedure HDLC (High Level Data Link Control) in Normal Response Mode (NRM) and full-duplex transmission between two stations. It is assumed that both stations are saturated, i.e. the stations have always messages to be transferred. Then, the attainable throughput is the most suitable measure of performance being dependent on the main system parameters as modulus value of the window-mechanism, link propagation delay, transmission rate, message length, and bit error probability. The throughput analysis is based on the notion of a "virtual transmission time" which was successfully applied to the performance analysis of HDLC links (see Ref./1, 2/). The analytic solution has been extensively checked against simulations and found to be in excellent agreement. Practical implications of the analysis results are summarized in the conclusion of the paper.

1. INTRODUCTION

Data communication protocols are needed for the control of serial data transmission over unreliable links. The International Standardization Organization (ISO) has standardized the majority of these procedures under the name HDLC (High Level Data Link Control), see Ref./7, 8/.

HDLC allows a wide flexibility over various parameters, e.g.

- class and mode of the procedure
- number and type of the stations
- link configuration and operation
- error recovery.

This paper deals with the analytical performance evaluation of HDLC, Unbalanced Class of Procedures. The kind of operation we investigate is Normal Response Mode (NRM). This mode is based on the master-slave principle using two types of stations, primary and secondary.

We restrict our consideration to a point-to-point link and full-duplex operation. To recover errors two different mechanisms are considered: Checkpoint Retransmission (P/F-Bit Recovery) and Reject Recovery.

HDLC has been extensively studied in the recent literature, see /1-5/. In /1-4/ the half-duplex operation (only one station has messages to be transmitted) has been considered mostly. The case of full-duplex operation is treated in /5/ by means of simulation. The analysis of the full-duplex operation case is more difficult and will be considered here.

2. MAIN FEATURES OF HDLC-NRM

In this section we briefly review some features and characteristics of the procedure class Normal Response Mode. We confine our descriptions to views that are important for our throughput analysis. The reader who is not familiar with the details of Normal Response Mode is referred to the HDLC documents, see Ref./7, 8/.

2.1 The Data Link Model

For the throughput analysis we need a data link model as shown in Fig.1.

It consists of one primary station and one secondary station interconnected by a point-to-point link with full-duplex transmission operating in HDLC-NRM.

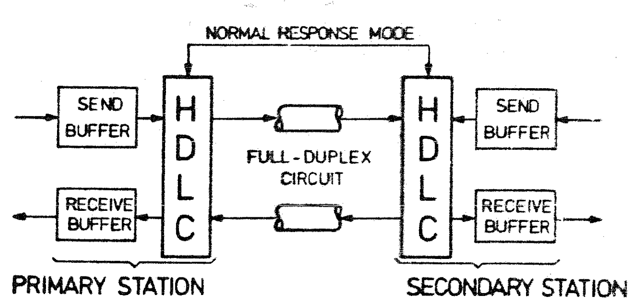

Fig.1 The data link model

+) H.L. Truong is now with Standard Elektrik Lorenz AG, Stuttgart, Fed. Rep. of Germany

It is assumed that both stations are saturated, i.e. stations have always messages to transmit. Then, the maximum throughput as the most suitable measure of performance is evaluated.

2.2 The Information Transfer Phase

A data message which has been transmitted from primary to secondary or vice versa consists of one HDLC frame. Frames which carry information are denoted as information frames (I-Frames), whereas supervisory frames (S-Frames) are used to control operations.

I-frames are sequentially numbered by a send sequence number N(S) ranging from 0 up to M-1, where M denotes the modulus value. Similarly, acknowledgments are signalled by a receive sequence number N(R) which is piggybacked on I-frames in the reverse direction.

Supervisory frames are used to acknowledge correctly received I-frames by their receive sequence number N(R) (RR = receive ready frame) or requesting a retransmission (REJ = reject frame) in case a frame is received in error. Both frame types may carry a Poll/Final bit (P/F-bit). We restrict the problem to the case where the P/F-bit takes effect only on S-frames. If a station has M-1 unacknowledged I-frames outstanding simultaneously (window limitation), it has to stop transmission and has to wait for an acknowledgment. In NRM, the secondary cannot transmit further frames until a command (S-frame) is received from the primary with the P-bit set to 1. After the last frame of the response, the secondary has to transmit a S-frame with the F-bit set to 1. For further transmission the secondary has to wait for the next P-bit from the primary. Upon reception of this P-bit, the secondary is enabled to continue sending. The secondary is assumed to be polled by the primary as often as possible. Thus, the secondary has the opportunity to transmit frames at the earliest instant.

As an example, the diagram in Fig.2 shows the principal operation between a primary and a secondary station across the data link. The operation is controlled by supervisory frames, P/F-bits, and the send and receive sequence numbers N(S) and N(R), respectively.

As demonstrated by the example of Fig.2, the transmission capacity of the channel may not be fully used due to the limitation of the Modulo-mechanism and due to frame errors. A disturbed frame has to be repeated as soon as possible. The station which indicates the transmission error first starts the recovery by transmitting a reject frame. Retransmitted and repeatedly disturbed frames cannot be repeated by REJ-recovery for reasons of possible ambiguities. Then, a transmission error has to be resolved by checkpointing (P/F-recovery). For our considerations we assume that the transmission of supervisory frames is error-free. Therefore, timeout recovery needs not be considered.

2.3 Summary of Model Assumptions

The paper aims at the calculation of the channel throughput which is a complex function of the parameters: modulus value, link propagation delay, processing delay, channel transmission rate, message length and bit error probability.

Throughout this paper we adopt the following restrictions and assumptions:

- stations are saturated
- messages are of constant length
- P/F-bit only takes effect on S-frames
- S-frames are always correctly transmitted
- primary time-out state is not considered

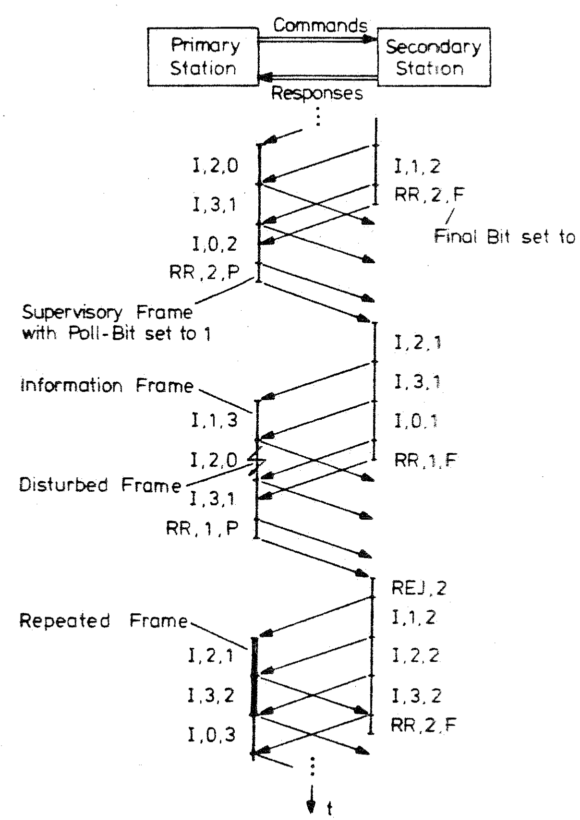

Fig.2 Point-to-point link, full duplex operation
Modulo = 4, constant frame length
I,N(S), N(R): Information frame
RR,N(R), P/F: Supervisory frame
N(S): Send sequence number
N(R): Receive sequence number
P/F: Poll/Final-bit

3. ANALYSIS

In this section the principal way to calculate the maximum information throughput of a NRM controlled data link is summarized. To keep the paper straightforward, some derivations of analytical expressions are stated in the appendix.

3.1 Principle of Throughput Analysis

The throughput analysis is based on the concept of the "virtual transmission time". This new concept allows to present performance measures in explicit and easily computable expressions. Furthermore, it is a quantity comprising not only the real transmission times of a message but also the waiting times for acknowlegments and the duration of error recovery actions.

For the analytic throughput calculation, several transmission cases have been distinguished systematically:

a) Throughput degradation due to window limitation, see Fig.2
b) Throughput degradation due to one or several consecutive frame errors.

In either case, several subcases have to be considered as well. In each of the cases the resulting virtual transmission time is exactly calculated. From this and the special values of the parameters as transmission rate, message length, etc., the useful channel throughput is calculated finally.

3.2 Preliminaries

For the analysis we have to specify some quantities which are useful for the calculation of the virtual transmission time:

l: constant message length - the number of information bits in an I-frame.

l_S: overhead length - 48 bit in the unextended frame format (modulus value = 8) and 56 bit in the extended frame format (modulus value = 128).

t_I: transmission time of an I-frame (v = channel transmission rate):

$$t_I = (l+l_S) / v \qquad (3.1)$$

t_S: transmission time of a S-frame:

$$t_S = l_S / v \qquad (3.2)$$

t_p: constant delay - consisting of processing delay (t_{proc}) and link propagation delay (t_{prop})

$$t_p = t_{proc} + t_{prop} \qquad (3.3)$$

p_F: probability a frame is received in error. p_F is depending on the independent bit error probability p_{Bit}, the message length, and the overhead length

$$p_F = 1-(1-p_{Bit})^{l+l_S} \qquad (3.4)$$

3.3 The Virtual Transmission Time

The virtual transmission time represents the effective channel occupation by one frame including repeated transmissions in case of errors and enforced idle times due to the protocol mechanism. The virtual transmission time is defined in the following way: The virtual transmission time of an I-frame with N(S) = i begins with the start of its transmission provided the I-frame with N(S) = i-1 is received in sequence and without transmission error. It terminates at the end of its transmission at the sending station, provided this transmission of the frame is successful, see Ref./2/.

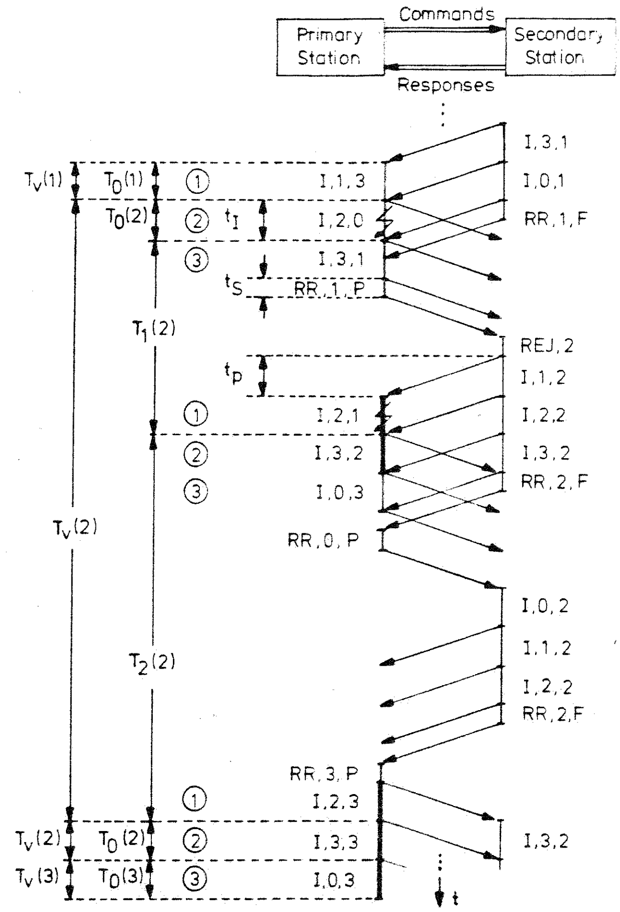

Fig. 3 The virtual transmission time $T_v(s)$ of an I-frame with the position number s, s = 1,2,3; Modulo = 4, ⓢ = Position Number

If the I-frame with N(S) = i cannot be transmitted due to M-1 unacknowledged I-frames, its virtual transmission time is prolonged by the time it has to wait until an acknowledgment of one or more outstanding I-frames is received, see Fig.3. This definition allows to replace the complicated sequence of I- and S-frames from both directions in case of window limitation and in case of one or several consecutive frame errors by an equivalent but much simpler sequence of virtual transmission times.

The example of Fig.3 demonstrates the virtual transmission time from an I-frame with N(S) = 2 transmitted from primary to secondary. In the example the considered I-frame is disturbed twice. Its virtual transmission time starts at the end of the successful transmission of frame I,1,3 and ends at the beginning of the transmission of frame I,3,3. In the example window limitation and frame errors are considered. To understand these and other complicated sequences of I- and S-frames, the virtual transmission time is partitioned into three possible durations, as demonstrated in Fig.3:

T_0, the transmission time of an I-frame corresponds to t_I.
T_1, the duration for the first retransmission if the frame under consideration was disturbed.
T_2, the duration for one more retransmission.

These time durations are depending on the protocol mechanism and the position number s which marks the position of a frame within a sequence of (M-1) transmitted frames as well as on the number of consecutive disturbed frames. In case of window limitation always sequences of M-1 frames are transmitted, see Fig.2,3. Appendix A1 and A2 give analytic expressions of $T_0(s)$, $T_1(s)$ and T_2 for every special case as mentioned above.

The virtual transmission time of a frame which has been disturbed exactly n times before it is received correctly is

$$T_v(s) = T_0(s) + T_1(s) + (n-1)T_2 \qquad (3.5)$$

The probability that the same frame is disturbed n times is geometrically distributed and equal to

$$p_F^n \cdot (1-p_F), \; n = 0,1,2,\ldots \qquad (3.6)$$

Then, the conditional expectation of the virtual transmission time can simply be derived

$$E[T_v(s)] = E[T_0(s)] + p_F \cdot E[T_1(s)] + \frac{p_F^2}{1-p_F} \cdot E[T_2] \qquad (3.7)$$

The probability that a frame gets the position s in a sequence of (M-1) I-frames is determined as follows:

$$\alpha(s) = \begin{cases} \dfrac{p_F(1-p_F)^{M-2}}{1-(1-p_F)^{M-1}} & \text{for } s=1 \\[2ex] \dfrac{p_F(1-p_F)^{s-2}}{1-(1-p_F)^{M-1}} & \text{for } s=2,\ldots,M-1 \end{cases} \qquad (3.8)$$

The derivation of $\alpha(s)$ is treated in appendix A3. By means of the equation (3.7) and (3.8) we get the mean virtual transmission time:

$$E[T_v] = \sum_{s=1}^{M-1} E[T_v(s)] \cdot \alpha(s) \qquad (3.9)$$

3.4 The Throughput

As mentioned in section 2, we calculate the channel throughput for each direction separately and under the assumption that the stations are saturated. The mean time to transmit successfully an I-frame with a message length l corresponds to the expectation of the virtual transmission time derived in Eq.(3.9). Therefore, the maximum information throughput is determined as follows:

$$\text{Throughput} = \frac{1}{E[T_v]} \qquad (3.10)$$

The throughput can be normalized by the transmission rate v. Thus, we get the relative throughput

$$\text{Rel.Throughput} = \frac{1}{E[T_v] \cdot v} \qquad (3.11)$$

For the throughput calculation we have to estimate the expectation of the virtual transmission time and thereby the durations $T_0(s)$, $T_1(s)$ and T_2 for each direction and every special case summarized in section 3.1. The evaluation of these durations is outlined in appendix A1 and A2.

4. RESULTS

In this section typical calculation and throughput results of HDLC-NRM controlled data links are presented as a function of the essential parameters: message length l, processing plus propagation delay t_p, modulus M, transmission rate v and bit error probability p_{Bit}. The presentation of the results is restricted to satellite links with a propagation delay of 350 ms.

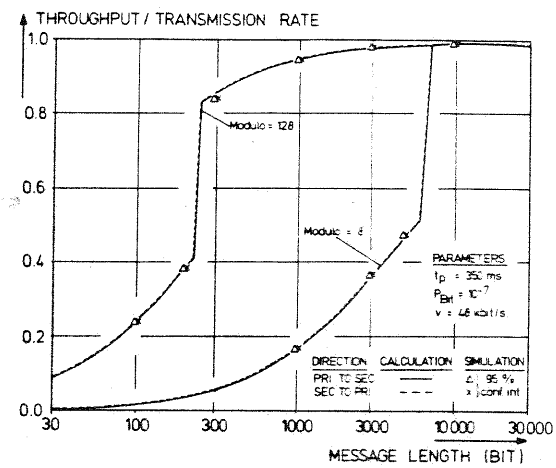

Fig.4 Relative throughput versus message length l (bit error probability 10^{-7})

As demonstrated in Fig.4, window limitation in case of Modulo = 8 appears over a wide range of the message length due to the HDLC protocol mechanism. With a bit error probability of 10^{-7} the channel is nearly fully used by message lengths greater than 10 000 bit, and Modulo = 8.
For the parameter configuration shown in Fig.4 and the modulus value of 128 a better throughput behaviour is obtained.

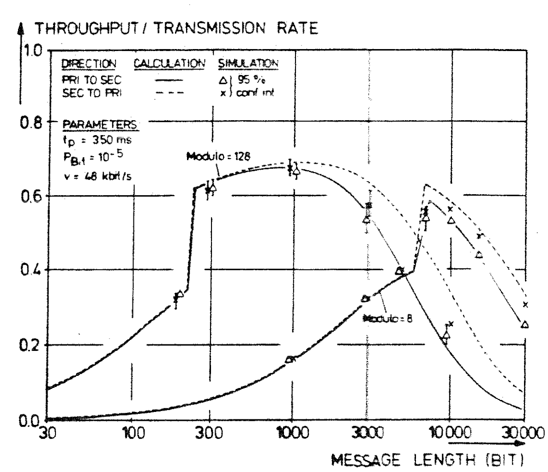

Fig.5 Relative throughput versus message length l (bit error probability 10^{-5})

Fig.5 shows that for a bit error probability of 10^{-5} and message lengths of 10 000 bit the attainable throughput for modulo = 8 is much better than modulo = 128. Therefore, an increase of modulo does not always enforce an increase of throughput, because the recovery actions (P/F-recovery) need more time in case of a higher modulus value. As the graph in Fig.5 demonstrates the throughput behaviour of both directions is different as a cause of the master function of the primary station. Retransmitted and again disturbed frames of the primary need more time to recover than disturbed frames transmitted from the secondary, i.e. the time duration T_2 of the direction from primary to secondary is much longer than T_2 of the other direction.

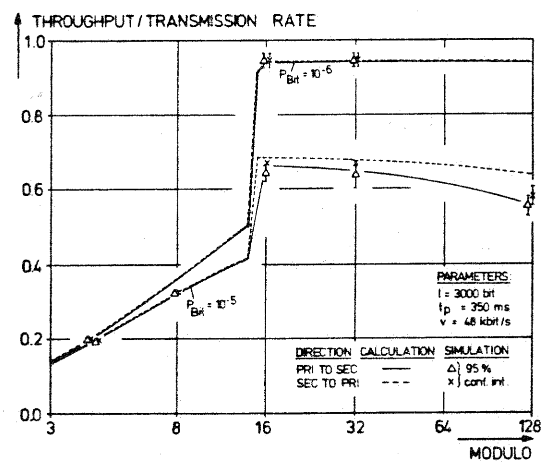

Fig.6 Relative throughput versus modulus value

Fig.6 represents the relative throughput versus the modulus value. We observe a strong dependence of the throughput on the error probability: at first, the enforced idle times can be reduced by increasing modulo. After reaching a maximum, the throughput cannot further be increased by the modulus value anymore; on the contrary, a further increase of modulo also increases the probability of retransmission of undisturbed frames in case of error and, thus, throughput drops again. This drop becomes the more effective the higher the error probability. Finally, Fig.7 demonstrates that for the parameters assigned therein, as well as for propagation delays up to 50 ms (terrestrial links) modulo = 8 is the suitable value, whereas for propagation delays greater than 50 ms (satellite links) modulo = 128 provides a better throughput behaviour.

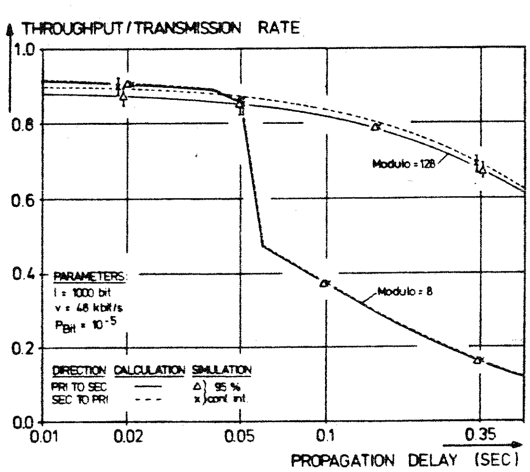

Fig.7 Relative throughput versus propagation delay

CONCLUSION

In the paper an analytic solution of full duplex and HDLC-NRM controlled data links has been presented. The solution offers insights in parametric dependences of the throughput on the most important channel and protocol characteristics. By means of a detailed consideration of the various principal cases of the information exchange, including transmission errors and proper retransmissions, the maximum throughput is found by a fast and accurate evaluation for HDLC-NRM controlled data links.

Finally, a practical implication of the analysis will be discussed. For the optimization of the useful channel throughput a rule of thumb can be recommended to facilitate the selection of the optimum data link parameters. With this rough estimation we are able to determine two limits of the message length interval l_{min} and l_{max} ensuring that the maximum of the throughput calculation is within these limits:

$$l_{min} = \frac{v \cdot 2t_p}{M-3} \; ; \; l_{max} = \frac{1}{p_{Bit}} \cdot \sqrt{\frac{0.2}{3M-4}}$$

In the rough calculation the probability a frame is received in error was restricted by 10 per cent. With this rule of thumb it is possible to check and to modify the parameters in such a way that the data link is operating in the optimum range of the throughput. As an example, for the graph of Fig.5 we find 270 bit < l < 2300 bit for M = 128 and 6720 bit < l < 10 000 bit for M = 8. As shown by this example, the message lengths may vary between these limitations and need not necessarily be constant as assumed for the analysis. If the interval obtained by l_{min} and l_{max} does not cover the desired message lengths the modulus value may be chosen appropriately to meet the requirements.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Prof.(em.) Dr.-Ing. Dr.-Ing.E.h. A. Lotze and Prof. Dr.-Ing. P. Kuehn, Head of the Institute of Switching and Data Technics, University of Stuttgart, for supporting this work.

APPENDIX

A1) Evaluation of T_0, T_1 and T_2 (Errors permitted in Direction Primary to Secondary).

Case (1a) - Transmission with Window Limitation

Even in case of no frame errors and window limitation, the parameter $2t_p > (M-3)t_I$. (1)

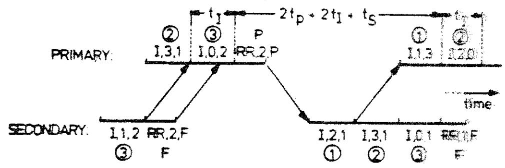

Fig.8 Window limitation without frame errors, Modulo = 4, $t_I/t_p = 1$

In the diagram the sequence numbers are replaced by the position numbers. As shown in Fig.8

$$T_0(s) = \begin{cases} 2t_I + 2t_p + t_S & s = 1 \\ t_I & s = 2,3,\dots,M-1. \end{cases} \quad (2)$$

To find $T_1(s)$ two subcases within case (1a) have to be distinguished:

- In a sequence of M-1 frames one or more consecutive frames are disturbed. It is demanded that the frame with the position number M-1 is correctly transmitted, then, REJ-recovery is possible.

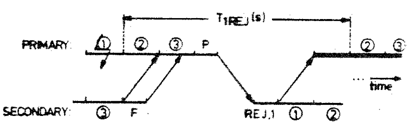

Fig.9a Window limitation, frames repeated by REJ-recovery, Modulo = 4, $t_I/t_p = 1$

Consequently, the solution of this subcase is

$$T_{1REJ}(s) = (M-s)t_I + 2t_p + 2t_S \quad (s \neq M-1). \quad (3)$$

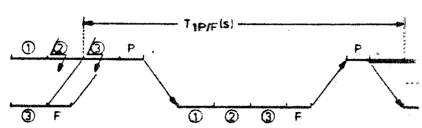

Fig.9b Window limitation, frames repeated by P/F-recovery, Modulo = 4, $t_I/t_p = 1$

- In the second subcase the disturbed frames have to be recovered with P/F-recovery. Thus,

$$T_{1P/F}(s) = [2(M-1) - s + 1]\cdot t_I + 2t_p + 3t_S . \quad (4)$$

Both subcases and their probabilities $1-p_F^{M-1-s}$ and p_F^{M-1-s}, respectively result into

$$T_1(s) = (M-s)t_I + 2t_p + 2t_S + p_F^{M-1-s}\cdot[(M-1)t_I + t_S] . \quad (5)$$

By similar reasoning results for T_2 can be derived which happen to be independent of the position number s. In the worst case we have

$$T_2 = 2(M-1)t_I + 4t_p + 4t_S. \quad (6)$$

Case (1b) - Window Limitation Enforced by Errors

In this case, the parameters obey: $2t_p \leq (M-3)t_I$. (7)

Furthermore, the probability that a frame gets the position s in the sequence of transmitted frames is equally probable and need not be considered in this case.

The duration T_0 corresponds to the transmission time of an I-frame t_I, therefore $T_0 = t_I$. (8)

To determine the duration T_1 two subcases have to be distinguished:

- After one frame is received in error, both stations stop their transmission (window limitation) and have to start error recovery. Then, t_p is bounded by $(M-3)t_I - t_S < 2t_p \leq (M-3)t_I$. (9)

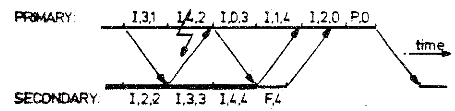

Fig.10 Window limitation enforced by frame errors Modulo = 5; $t_I/t_p = 1$

On condition that the last transmitted frame of the primary - in this example I,2,0 - is either disturbed or error-free, the durations T_{1REJ} and $T_{1P/F}$ are evaluated as in the previous case. Thus,

$$T_1 = (M-1)t_I + 2t_p + 2t_S + p_F^{M-2}\cdot[(M-1)t_I + t_S] . \quad (10)$$

- The primary is able to transmit its S-frame earlier, i.e. before I-frame I,1,0. Then, $2t_p \leq (M-3)t_I - t_S$. (11)

There exist three possibilities for T_1:

$$T_1^{*} = (M-2)t_I + 2t_p + 2t_S \quad (12)$$

with the probability: $1-p_F^{M-3}$

$$T_1^{**} = (M-1)t_I + 2t_p + 2t_S \quad (13)$$

with the probability: $(1-p_F)p_F^{M-3}$

$$T_1^{***} = (2M-3)t_I + 2t_p + 3t_S \quad (14)$$

with the probability: p_F^{M-2}

If $2t_p \ll (M-3)t_I - t_S$ then it can be assumed that window limitation is appearing after k consecutive disturbed I-frames.

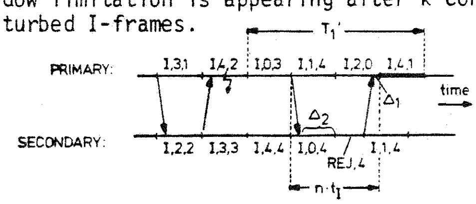

Fig.11 Error recovery without window limitation Modulo = 5, $t_I/t_p = 6$

When only one I-frame is disturbed the duration T_1 is determined by (see Fig.11):

$$T_1' = (n+3)t_I - w\cdot t_I, \quad (15)$$

where

$$w = \frac{\Delta_2}{t_I} = \frac{nt_I - 2(t_p + t_S)}{t_I} \; ; \; n = \left\lfloor \frac{2t_p + t_S}{t_I} \right\rfloor + 1. \quad (16)$$

($\lfloor\,\rfloor$ corresponds to the entire function)

To find the solution for T_1 in this subcase, we find from Fig.12 for the current window size x:

$$x < M - \frac{2t_p + t_S}{t_I} = \left\lfloor M - \frac{2t_p + t_S}{t_I} \right\rfloor \quad (17)$$

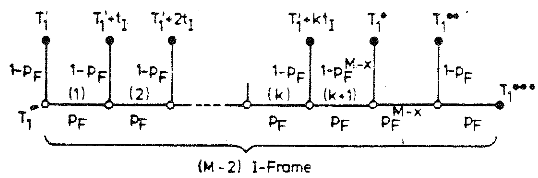

Fig.12 Solution-graph of T_1

Furthermore, the value of k is

$$k = x - 4, \text{ thereby } k \in \{-1,0,1,2,\ldots\} \ . \tag{18}$$

Hence, in this subcase T_1 is given by

$$T_1 = p_F^{k+1}(1-p_F^{M-x})T_1^* + (1-p_F)p_F^{M-3}T_1^{**} + p_F^{M-2}\cdot T_1^{***} + (1-p_F^{k+1})T_1' + t_I \frac{p_F(1-p_F^{k+1})-(k+1)p_F^{k+1}(1-p_F)}{1-p_F} \ . \tag{19}$$

The determination of T_2 in case (1b) is found in the same way as case (1a):

$$T_2 = (3M-4)t_I + 4t_S + 2t_p \ . \tag{20}$$

A2) Evaluation of T_0, T_1, T_2 (Errors Permitted from Secondary to Primary)

Case (2a) - Transmission with Window Limitation

For this case $T_0(s)$, $T_1(s)$ and T_2 are found in analogy to appendix A1, case (1a). Therefore, $T_0(s)$ corresponds to Eq.(2) and

$$T_1(s) = (M-s)t_I + 2t_p + 2t_S, \tag{21}$$

$$T_2 = M \cdot t_I + 2t_p + t_S \ . \tag{22}$$

Case (2b) - Window Limitation Enforced by Errors

The solution of T_0 corresponds to the transmission time of an I-frame t_I, therefore, $T_0 = t_I$.

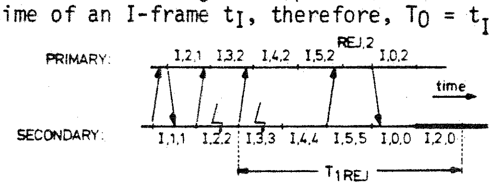

Fig.13a REJ-recovery without window limitation, Modulo = 6, t_I/t_p = 6

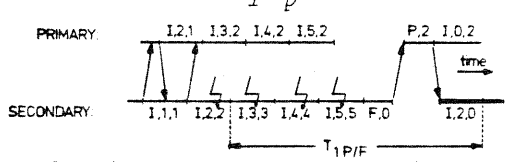

Fig.13b P/F-recovery with window limitation, Modulo = 6, t_I/t_p = 6

As Fig.13a and 13b demonstrate there exist two possible time durations for T_1:

$$T_{1P/F} = (M-1)t_I + 2(t_p + t_S). \tag{23}$$

$$T_{1REJ}(y) = y \cdot t_I + (n+3)t_I - w \cdot t_I. \tag{24}$$

The calculation of n and w was shown in A1,Eq.(16). In Eq.(24), y corresponds to the number of disturbed frames which follow the considered frame, $0 < y < L-1$. Furthermore, L is determined by

$$L = \left\lfloor (M-2) - \frac{2t_p + t_S}{t_I} \right\rfloor + 1 \ . \tag{25}$$

With Eq.(23) and Eq.(24) and the corresponding probabilities we have

$$T_1 = p_F^L \cdot T_{1P/F} + \sum_{y=0}^{L-1} p_F^y (1-p_F) \cdot T_{1REJ}(y). \tag{26}$$

The duration T_2 agrees with Eq.(23); therefore $T_2 = T_{1P/F}$.

A3) Derivation of $\alpha(s)$

The process that an I-frame occupies the current position s can be described by a discrete-time Markov chain, see Ref./6/. With all position numbers s, $(1 \leq s < M-1)$, and the probability that a frame is either received correctly or in error, a state transition diagram can be found, see Fig.14.

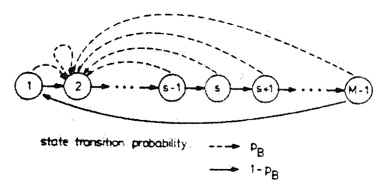

Fig.14 Position number state transition diagram

From this state transition diagram we find by standard methods Eq.(3.8).

REFERENCES

/1/ Truong,H.L., On the Performance of HDLC-Controlled Data Links. 33rd Report on Studies in Congestion Theory. Inst.of Switching and Data Technics, Univ. of Stuttgart, 1982.

/2/ Bux,W., Truong,H.L., High Level Data Link Control Traffic Considerations. Proc. of the 9th Internat. Teletraffic Congress, Vol.2, Session 44, Torremolinos, 1979.

/3/ Traynham,K.C., Steen,R.F., Data Link Control and Contemporary Data Links. IBM Techn. Report TR 29.0168, June 1977.

/4/ Kaul,A., Performance of High Level Data Link Control in Satellite Communications. COMSAT Techn. Review, Vol.8, No.1, Spring, 1978.

/5/ Bux,W., Kuemmerle,K., Truong,H.L., Data Link Control Performance: Results Comparing HDLC Operational Modes. Computer Networks 6 (1982) pp.37-51

/6/ Kleinrock,L., Queueing Systems. Vol.1: Theory. John Wiley & Sons, New York, 1975.

/7/ Data Communication - High Level Data Link Control Proc. - Frame Structure. International Standard ISO 3309, 1976.

/8/ Data Communication - High Level Data Link Control Proc. - Elements of Procedure (Independent Numbering). International Standard ISO 4335, 1976.