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Performance Evaluation of Data Communication Protocols
- Example of a Case Study on X.25 -

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ABSTRACT

This paper deals with a performance evaluation of data communication protocols, example of a case study on CCITT Recommendation X.25.
The queuing analysis of the whole system is based on decomposition. The total system is subdivided into two submodels, one which takes the window flow control of one explicit virtual circuit into consideration and one submodel which takes multiplexing as well as demultiplexing functions and, therefore, the influence of the other handled virtual circuits into account. Both submodels are analyzed using the method of mean value analysis.
The decomposition as well as both submodels are explained and some results are given for the following system characteristics:

- throughput of information for each of the virtual circuits
- mean delay time of data packets.

1. INTRODUCTION

The CCITT Recommendation X.25 defines a local interface between an intelligent terminal or a host and the network.
This paper deals with the performance evaluation of X.25.
The approach is based on decomposition of the whole system into two submodels and on the method of mean value analysis exerted on those submodels. With the help of this kind of performance evaluation of CCITT X.25, as an example of a complex data communication protocol, results can be obtained as throughput and mean transfer time.

2. CCITT RECOMMENDATION X.25

In this part a brief review of the main features of CCITT X.25 as far as necessary for modelling will be given. For further details the reader is referred to /1/ as well as /2,3/.

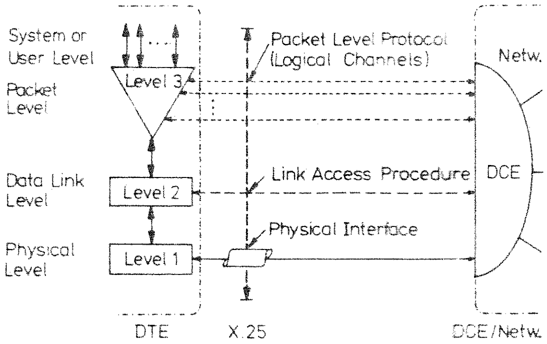

Fig.1: Structure of the X.25 interface

2.1 Structure of CCITT X.25

X.25 is structured in three distinct and independent levels (see Fig.1).
Each level of X.25 uses the functions offered by the next lower level.
X.25 defines rules, the so-called protocols, how information between correspondent levels in the DTE and the DCE have to be exchanged.

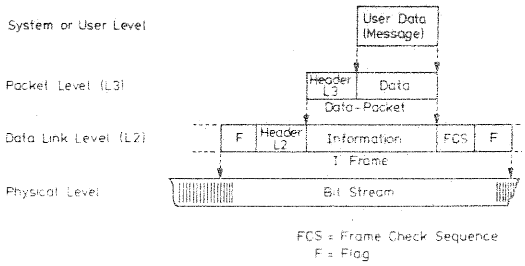

Fig.2: Transfer of information through the levels

Fig.2 shows the transfer of information through the levels in that each level accepts the information from the higher level and adds a header (header L2, header L3) and a trailer (FCS) before passing the so completed block to the next lower level.
A summary of the main tasks of the three levels is as follows:

- level 1: this level, usually called physical level, specifies electrical and physical characteristics of the interface.
- level 2: this level, the so-called link level, specifies a link access procedure (LAP) for converting the error-prone physical link into a relatively error-free one. This LAP corresponds to the Balanced Class of HDLC procedures.

- level 3: this is the highest level of X.25, the packet level. It defines the rules how user-data of the higher levels is to be encapsulated into packets. It also performs a concentrator function in that it multiplexes a number of so-called logical channels onto the physical link. Furthermore, each logical channel has its own and independent data-control exerted on the flow of packets.

2.2 Window Flow Control Mechanism

The use of sequence numbers at level 2 is primarily for the error control, whereas the use of sequence numbers at level 3, the so called packet send sequence numbers P(S) and the packet receive sequence numbers P(R) is to control the flow of packets. This is achieved by limiting the number of packets accepted by the network. Therefore, an independent window flow control mechanism is used for each established virtual circuit (VC) and for each direction to prevent VC-congestion. In this context the window size w is defined as the number of unacknowledged packets that a DTE or DCE may have outstanding at any time for a particular virtual circuit. The value of w can range between 1 and 7 (or 1 and 127 if extended numbering, Modulo=128 is used). The mechanism of flow control is as follows: the value of the lower window edge (LWE) is that one of the last received P(R). That one of the upper window edge (UWE) is given by:
$UWE = (LWE + w - 1)\mathrm{mod}8$.
Hence, the allowed range of P(S) which could be used for packets to be transmitted is bounded by the following rule:
$LWE \leq P(S) \leq UWE$.
If the P(S) of the last transmitted packet has already reached the upper window edge a so-called "window stop" occurs, in that the flow of packets stops due to the lack of free values of P(S). The flow of data continues only when a newly received P(R) acknowledges one or more outstanding packets.

3. MODELLING

Base for the performance evaluation of the CCITT-Interface X.25 is a detailed queuing model (see Fig.3) which takes the three levels and their individual procedures in the DTE and in the DCE into account.
Fig.3 shows the structure of the queuing model. It consists of two stations, the DTE and the DCE, connected by a full-duplex circuit. This FDX-line represents the physical level, characterized by the transmission rate and the one-way propagation delay. The link level in the DTE as well as in the DCE consists of a link access procedure control (LAP-control) and two queues, the transmit and receive buffers (TB,RB). The transmit and receive buffers serve as internal interface of level 2 and 3. At last there exist some other modules which represent level 3. These components handle up to n virtual circuits (VC). Each VC has its own VC-procedure control (VCPC) with main tasks as:

- packetizing and depacketizing of messages
- controlling of the flow of information for the appropriate VC by P(S) and P(R) numbers according to the window flow control mechanism.

The MDM-controllers perform the asynchronous time division multiplex and demultiplex functions by scheduling the n VC-procedure controllers and directing the packets to the transmit buffers of level 2. Vice versa, packets waiting in the receive buffers of level 2 are lead to that VC-procedure control belonging to the appropriate VC of the packet.

4. ANALYSIS

This chapter deals with the performance evaluation only of the packet level. The author wishes to emphasize that level 2 has been sufficiently analyzed, see /4,5,6/. The outcomes of those studies can easily be taken into account as adapted parameters of the transmission rate or propagation delay.

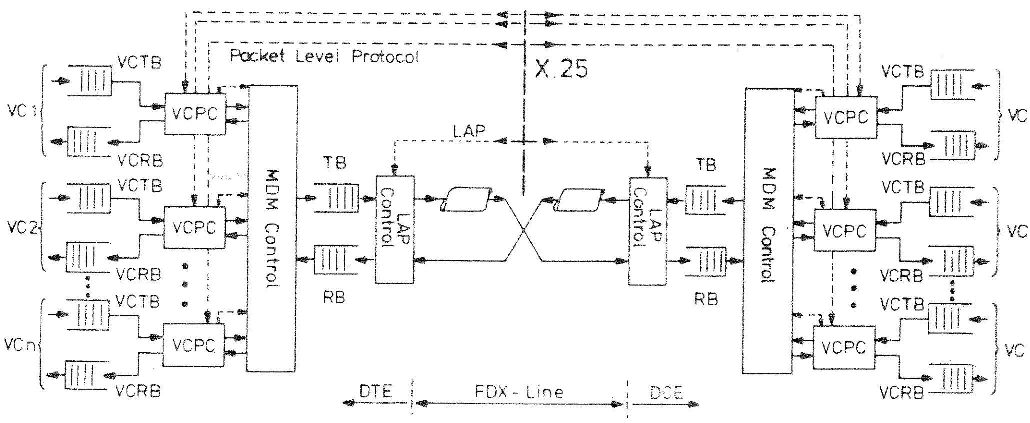

Fig.3: Detailed queuing model of X.25

4.1 Decomposition

Due to the complexity of the whole queuing system the analysis is based on decomposition.
In a first step the whole model as shown in Fig.3 will be modified in such a manner that only one explicit virtual circuit together with its own and individual flow control mechanism is regarded. The influence of the other virtual circuits as well as of the lower levels will form a so-called transit network, which is replaced by one transit queue for each direction with a queue-dependent server whose rate is $\gamma(x)$, the throughput of the transit network with x packets in transit, see Fig.4 .

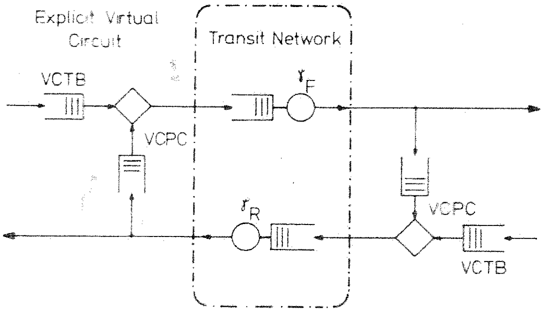

Fig.4: Modified queuing model of X.25

4.2 Transit network

In this section the rate function $\gamma(x)$ is solved using mean value analysis with regard to the assumption of saturated load of the transit network for all possible window assignments.

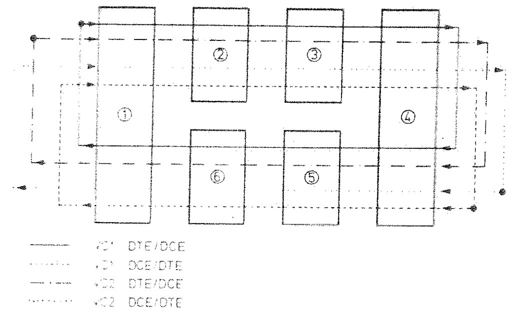

Fig.5: Transit network

The transit network could be discribed as a network with many closed chains, two chains for each virtual circuit: one for the direction DTE/DCE and due to a full-duplex connection one for the direction DCE/DTE.
Fig.5 shows an example of a closed multichain network for two virtual circuits. It consists of six servers with appropriate waiting queues:

- server 1: this server represents the L3-processing time for multi-/demultiplexing and for packetizing and depacketizing in the DTE.
- server 2: this server stands for transmission of data packets and supervisory packets for the direction DTE/DCE.
- server 3: this server models the propagation delays in level 2 as well as on the physical channel for the direction DTE/DCE.
- server 4: this server is the DCE-equivalent of server 1.
- server 5: this server represents the same functions as server 2 but for direction DCE/DTE.
- server 6: propagation delays for direction DCE/DTE.

The transfer of a test data-packet through one closed chain, with regard to data transmission in direction DTE/DCE, is as follows: the test data-packet starts its transfer in the VC-procedure control and in the MDM-control, represented by server 1 with service time ts. After that it will be lead to level 2 where it waits until transmission. The transmission time of that test packet will be:
tidp = length of data-packet / tr.rate.
This will be done by server 2. After that the packet will be delayed by the propagation delays, modeled by server 3. After waiting in the RB of level 2 in the DCE the packet will be treated by level 3, represented by server 4 with service time tr.
After that the data-packet will be acknowledged due to its error-free transmission. This means that the data-packet will be virtually converted into a smaller supervisory packet. This fact manifests itself in that the closed chain occupies again server 4 with service time ts. Then this supervisory packet will be transmitted by server 5 in the backward direction DCE/DTE with
tisp = lgth. of superv.packet / tr.rate
and delayed by server 6 due to the propagation delays. After reception in the DTE with service time tr in server 1 this supervisory packet leads to the transfer of a new data-packet. Two interesting aspects can easily be shown with the help of Fig.5 as well as with regarding the flow of data mentioned above:

- the number of packets in transit, this means data-packets in forward direction as well as supervisory packets in backward direction will be constant to the value of the window assignments
- the influence of the virtual circuits on each other is taken into consideration by the fact that allways more than one chain are visiting the several servers.

Base for the solution of this complex closed multichain network is /7/.
Due to the lack of space only necessary notations as well as important equations shall be outlined.

Notations:

$R(i)$: set of chains visiting queue i

$Q(r)$: set of queues in chain r

N : number of queues

R : number of chains

λ^r : throughput of chain r

τ_i^r : mean service time of a chain r customer in queue i (as mentioned above in the description of the closed multichain network)

t_i^r : mean time a chain r customer spends in queue i between successive visits to a marked queue

n_i^r : mean number of chain r customers at queue i

k^r : population size of chain r

ε_i^r : measure how one new chain r customer added to the system is distributed over the individual queues.

With the help of these notations the following equations are valid:

$$t_i^r = \tau_i^r \cdot (1 + n_i - \varepsilon_i^r) \qquad (1)$$

$$\lambda^r = k^r / \sum_{i \in Q(r)} t_i^r \qquad (2)$$

$$n_i = \sum_{j \in R(i)} \lambda^j \cdot t_i^j \qquad (3)$$

This nonlinear system of equations can be solved by a simple iteration method, starting with initial values for n_i and λ^r, $(i=1,..,N;\ r=1,..,R)$ and then iterating through (1) to (3) in a cyclic fashion until convergence is observed.
A heuristic method to obtain ε_i^r in each step of the iteration is as follows:

$$\varepsilon_i^r = \hat{n}_i^r(k^r) - \hat{n}_i^r(k^r-1) \qquad (4)$$

Suppose that $\hat{n}_i^r(k^r)$, $(i=1,..,N)$, are the mean queue sizes of a single chain queueing problem, see /7/, with population k^r and with:

$$\hat{\tau}_i^r = \tau_i^r / (1 + \lambda^r \cdot \tau_i^r - \sum_{j \in R(i)} \lambda^j \cdot \tau_i^j) \qquad (5)$$

With respect to the fact that k^r, $(r=1,..,R)$, holds for the packets in transit which may not exceed the window size w and that all chains are symmetrically parameterized it follows:

$$\lambda^r = \lambda^r(k^r) = \lambda(k), \quad (r=1,..,R;\ k^r=k=1,..,w) \qquad (6)$$

The solution of the rate function $\gamma(x)$ is now given by

$$\gamma_F(x) = \gamma_R(x) = \gamma(x) \qquad (7)$$

$$\gamma(x) = \lambda(k=x), \quad (x=k=1,..,w). \qquad (8)$$

4.3 Explicit virtual circuit

With the help of this submodel portrayed in Fig.6 the admission delays onto a virtual circuit with window flow-control mechanism are derived, see /8/.

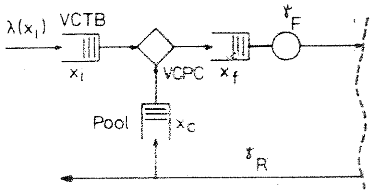

Fig.6: Explicit virtual circuit

The explicit virtual circuit with its sliding window can be described as follows: a pool of w credits is kept by the sending equipment of the virtual circuit. As a message enters the VCTB it obtains a permit if there are any credits available and is dispatched. One credit is removed from the pool. If no credit is available, the message waits. As messages arrive with throughput rate γ_F in forward direction at the destination equipment acknowledgements are returned with γ_R to the sender via the backward direction, as mentioned above in section 4.2 . As acknowledgements arrive at the source credits are returned to the send pool with this rate γ_R . Evidently, the total number of messages and credits (or acknowledgements) is at all times fixed to w.
With the following notations

w : window size

x_i : number of messages waiting for permits; $x_i = 0,1,...,N$

x_f : number of messages in transit in forward direction; $x_f = 0,1,...,w$

$x_c = w - x_f$: number of credits; $x_c = 0,1,...,w$

$\lambda(x_i)$: state dependent arrival rate of messages

γ : throughput of the explicit virtual circuit

and considerations :

i) $x_i \geqslant 0$ if $x_c = 0$
ii) $x_i = 0$ if $x_c \geqslant 0$
iii) $\lambda(x_i) = 0$ if $x_i = N$
iv) $\gamma_R(x_f,x_c) = \gamma_F(x_f,x_c)$

it follows:

$p(x_i,x_f,x_c)$: state propabilities of the explicit VC

$$\bar{x}_f = w - \sum_{\text{all states}} (w - x_f) \cdot p(x_i,x_f,x_c) \qquad (9)$$

$$\bar{x}_i = \sum_{\text{all states}} x_i \cdot p(x_i,x_f,x_c) \qquad (10)$$

Performance characteristics are then given by:

throughput:

$$\gamma = \sum \lambda(x_i)\cdot p(x_i,x_f,x_c) \qquad (11)$$

admission delay:

$$\bar{d}_A = \bar{x}_i / \gamma \qquad (12)$$

transfer delay:

$$\bar{d}_T = \bar{x}_f / \gamma \qquad (13)$$

mean transfer time:

$$\tau = \bar{d}_A + \bar{d}_T \qquad (14)$$

5. RESULTS

This chapter deals with the derived results which allow a determination of performance characteristics of CCITT X.25 such as: maximum throughput and mean transfer time. All results are compared with those obtained by simulation in which the queuing model as shown in Fig.3 as well as the rules recommended in X.25 are implemented in full detail. The evaluation of the simulation results is given in /9/.
It should be notified that for all figures in this chapter the following global parameters are valid:

transmission rate v = 48 000 bit/s
total propag. delay t_p = 50 ms
L3-processing delay $t_s = t_r$ = 1 ms

5.1 Maximum throughput

As a first interesting performance characteristic the study on the maximum throughput is presented.

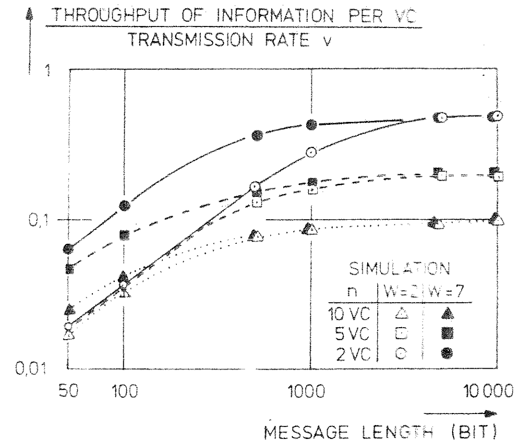

Fig.7: Throughput efficiency vs message length

As it easily can be seen the curves obtained by analysis are in a very good accordance with the simulation results. This effect is due to the fact that the main assumption for the analysis of the transit network, the saturated load for all window assignments, is accomplished over the whole range of message lengths.

5.2 Mean transfer time

Further important performance results are the outcomes for the mean transfer time.

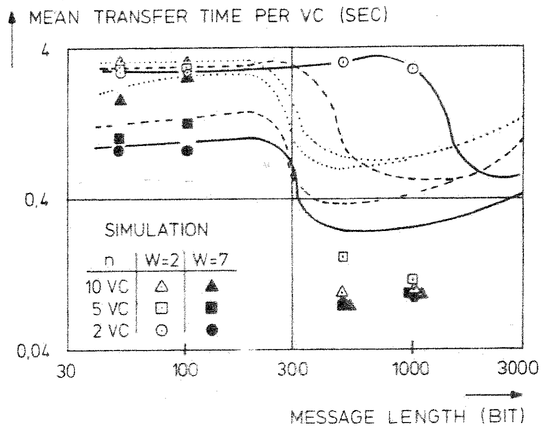

Fig.8: Mean transfer time vs message length

In Fig.8 the mean transfer time is depicted as a function of the message length l, number n of virtual circuits and window size w for a constant offered load ρ = 0.6 , with

$$\rho = l\cdot n\cdot\lambda / v \qquad (15)$$

The analytical results show a good conformity to those obtained by simulation in ranges of message lengths l, in which the mean number of messages waiting for credits is always ≥ 1.
This means that the transit network is always saturated, the assumption mentioned in chapter 4.2 .
For greater message lengths l there is no conformity between analytic and simulation results due to the violation of the assumptions to which the analysis of the transit network is valid.
The analysis of the transit network takes into account that each closed chain has x data-/supervisory packets in transit, whereas in case of nonsaturated load only a few virtual circuits have x packets in transit at the same time.
This means that the analysis takes too much packets in transit into consideration, resulting in higher transit times as in reality.
Further results of the mean transfer time are given in Fig.9.
Contrary to Fig.8 the message length is held constant at 1000 bit.

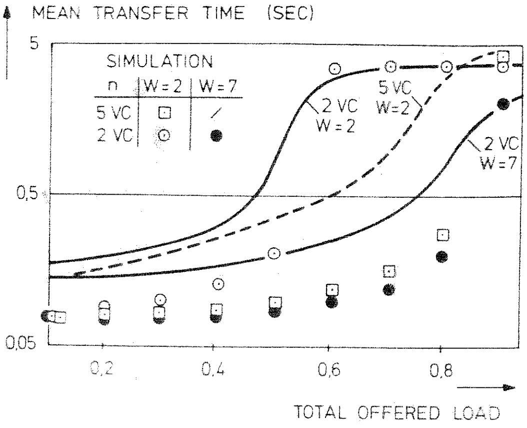

Fig.9: Mean transfer time vs total offered load

The curves obtained by analysis show the principal behavior as those of the simulation. Deviations base on the fact that the analysis of the transit network takes twice the propagation delay into account whereas the mean transfer time of a packet over the interface includes only one propagation delay.
Additionally the assumption of a saturated load to the transit network is not always fullfilled which results in such deviations.

6. CONCLUSION AND OUTLOOK

The main contribution of this paper is the performance evaluation of a complex data communication protocol, example of a case study on X.25, by the method of decomposition.
A detailed queuing network representing the CCITT-interface X.25 has been decomposed into two submodels which could be analyzed independently and separatly by mean value analysis.
The solution of the total system is done by composing the results of those two submodels.
Some exemplary results have been shown and explained which underline the conformity to appropriate simulation results in wide ranges of given parameters in which the assumptions made in chapter 4.2 and 4.3 are valid.
Furthermore the infirmities of the method have been outlined, resulting in deviations between analytic and simulation results due to the violation of those assumptions.
Improvements which take the population size of the virtual circuits as a function of the total offered load into consideration for avoiding these infirmities are still on study /10/.
Nevertheless tendencies, maxima and minima of performance criteria as well as the influence of window flow control can be determined in a simple manner with the help of this analysis method.

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