MODELLING AND ANALYSIS OF COMPUTER NETWORKS - DECOMPOSITION TECHNIQUES, TRANSIENT ANALYSIS AND PROTOCOL IMPLICATIONS

Paul J. Kuehn
Institute of Switching and Data Technics
University of Stuttgart
Stuttgart, FRG

Packet switching data networks are introduced in many countries to meet the increasing demands in computer and data communications. For planning and operation of such networks efficient performance evaluation tools are needed. This paper reviews some basic traffic models and performance evaluation tools. The organisation of the paper follows the logical structure of communication networks focusing primarily on the link, network, and transport level.

1. INTRODUCTION

During the recent 15 years, great effords have been made in modelling and performance evaluation of verious aspects of packet switching networks. Most of them have been of basic research nature by modelling complex protocol mechanisms or queuing network traffics and exploring particular effects as throughput degradations and transfer delays. However, most of these models describe only a very limited part of the entire problem as, e.g., a particular link control mechanism, a single buffer, or some global network behavior. The interaction of such effects is generally too complex for an analytical study.

To get a sound insight into models of a more complex structure simulation is used intensively. However, simulation is also limited with respect to model complexity and computer run times for highly parameterized models. Therefore it has primarily been used either for singular case studies or for validation purposes of approximate analytical approaches.

In a recent paper by M. Reiser [1] , an excellent introduction has been given to the various problems and methods for the performance evaluation of data communication systems. Some of the basic models will also be highlighted here combined with some new studies on transfer delays and transient behavior of congestion control mechanisms.

The paper is organised as follows: Sections 2,3, and 4 are devoted to modelling aspects on the link, network, and transport level. In Section 5 we address some methods for the performance analysis. Because of the limited space, we will outline the basic approach only; for a sound discussion we refer to specialized papers and work reports.

2. LINK LEVEL CONTROL MODELS

Link level control comprises all functions related to a safe transmission of information units between two adjacent control units of one transmission section. We will refer to two typical problems: multiplexing and window flow control.

2.1. Multiplexing

Multiplexers are used when several peripheral units share one common transmission media. Multiplexing can be implemented by various techniques:

(1) synchronous multiplexing for conversion of SDM-channels to TDM-channels

(2) asynchronous (statistical) multiplexing of data, which come from different sources and which are intermediately stored within one buffer

(3) asynchronous multiplexing of data of different sources and spacially separated buffers.

Case (1) usually does not cause any traffic problem. Case (2) leads to a finite capacity GI/G/1 queuing system, which has been solved by several authors for various special cases, see W.W. Chu [2] . Case (3) requires a special protocol to control the access rights of the various sources. Two basic traffic models are illustrated in Fig. 1.

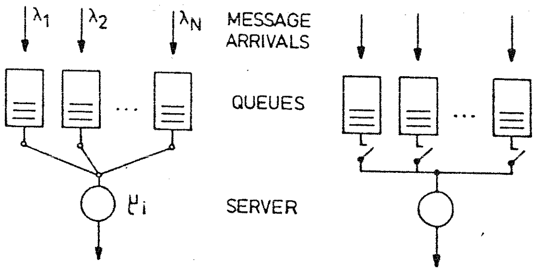

Fig. 1. Basic multiplexer models
λ_i arrival rate for messages of queue i
μ_i service rate for queue i

The model at the left hand side of Fig. 1 can be used when the access control is given to a source (station) immediately after the preceeding transmission, possibly including some overhead time for control depending on the protocol mechanism.

Int. Conference on Communications (ICC '84), Amsterdam, May 14-17, 1984.
Paper 41.6, Session 41 "Tools for Evaluating Computer Network Performance"

Typical protocol mechanisms are:

centralized control:	Polling
decentralized control:	Token passing Carrier sensing.

a) Polling

A centralized station grants the access right in a cyclic manner. The basic sequence of signals exchanged between the polled station and the centralized control station is

REQUEST TO SEND ⟶
RESPONSE ⟵

Polling mechanisms have extensively been analyzed in the past [3-6] . The polling model has also been extended with respect to half- and full-duplex transmission with a handshake-protocol for the error control [7] , to the inclusion of prioritized service [8] , or to multiple servers [9] .

b) Token passing and Carrier Sensing

The token passing protocol is a distributed version of the polling protocol. It has been analyzed especially in connection with the access to ring or bus media within local area networks, see [10] . Carrier sensing, especially with collision detecting (CSMA-CD) is another basic access mechanism within local area networks. The bus arbitration bases on sensing of the media activity; in case of a collision, a random resolution technique is usually applied [11] . There exist several protocols which extend the basic CSMA-CD mechanism to reduce succeeding collisions [12] .

The model at the right hand side of Fig. 1 operates on a clocked basis. Intermediately buffered messages are transferred only when the centralized control switches into an I/O-phase, usually upon a periodic clock schedule. This protocol can save on overhead considerably by transferring several messages per clock instant [13,14] .

2.2. Data Links with Window Flow Control

Handshake protocols for error recovery need too much overhead, especially when the propagation delay of the transmission link is high. For this reason, a sliding window protocol is used allowing to proceed to send before an acknowledgement of the preceeding message has arrived. To control this mechanism, both terminal stations of a link use sequence numbers N(S) and N(R) which are incremented cyclically modulo M (M=8 or 128). N(S) indicates the next message (frame) to send where N(R) acknowledges the other station that all frames up to N(R)-1 have been received safely. A station may send as long as its window is opened, the window size W may vary between W=0 and W=M-1 or less.

Besides this sequencing mechanism, the data link protocols feature several other aspects:

- primitives to set-up and take-down a data link connection
- definition of several operational modes as Normal Response Mode (NRM) or Asynchronous Balanced Mode (ABM)
- Recovery mechanisms using checkpointing by poll and final bits (P/F recovery) and time-out.

The performance of a data link, i.e. its maximum throughput and transit delay, depends largely on the data link and protocol parameters as

- transmission speed
- propagation delay
- error probability
- maximum window size
- recovery mechanism

and is subjected to a careful performance analysis. A basic data link model for HDLC-type procedures is shown in Fig. 2.

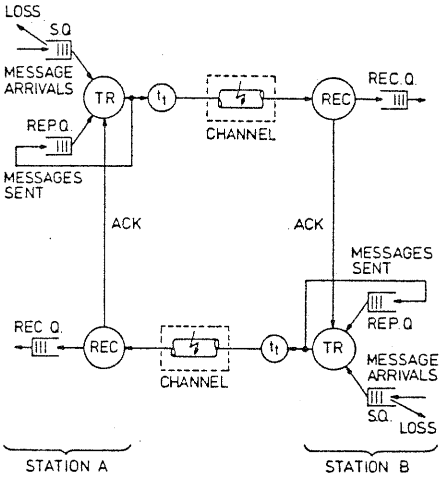

Fig. 2. Link level model for HDLC-ABM

TR	Transmitter
REC	Receiver
S.Q.	Send-Queue
REP.Q.	Repeat-Queue
REC.Q.	Receive-Queue
ACK	Acknowledgement
t_t	Transmission time/frame

Performance results have been obtained by simulations as well as by analytical studies using a concept of "virtual transmission time" [15-17] .Typical results show a throughput maximum for medium sized frame lengths. The throughput degrades for small frame sizes (window limitation) as well as for large frame sizes (frame errors); the maximum may be far less then 100% depending on factors as error probabilities, window size, and recovery mechanism. Fig. 3 shows a typical result of these studies for throughput and delay of an HDLC-ABM data link. The results are especially important for network planning since they indicate the physical link parameter degradation through the protocol.

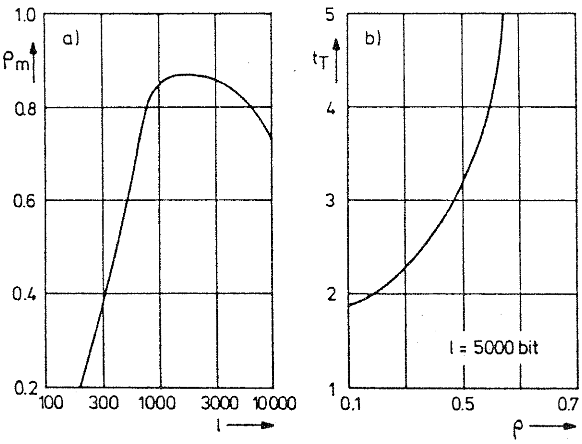

Fig. 3.

a) Maximum channel utilization ρ_m versus message length l in bit

b) Average transfer time t_T versus channel utilization ρ

Parameters :

ABM	Asynchr. Balanced Mode,FDX
constant	message length
t_p=50ms	propagation delay
c=48kbps	transmission rate
p_E=0.00001	bit error probability
M=8	modulus value

3. NETWORK LEVEL CONTROL MODELS

The network level control comprises all functions of the packet level, especially the DTE-DCE network interface and all functions of routing and switching. We will refer to three typical problems: network interface, network node, and congestion control.

3.1 X.25 Network Interface

X.25 of CCITT defines the local interface between a packet-oriented terminal or host (DTE) and the network (DCE). The main features of X.25 are:

- Combination of level 1 (X.21), level 2 (LAP B, similar to HDLC-ABM and level 3
- Multiplexing of several network (level 3) connections ("virtual calls", VC) on one data link between DTE and DCE
- Set-up and take-down of the individual VC's with negotiations on throughput class and window flow control parameters during set-up.

Typical performance questions are related to the influence of the number of VC's, their throughput classes and window flow control parameters on the throughput and delay of the X.25 network interface. Fig.4 shows a detailed model which includes all 3 levels of X.25 . Results on the performance of the X.25 interface have been obtained by simulation as well as by analytic modelling [18,19] .

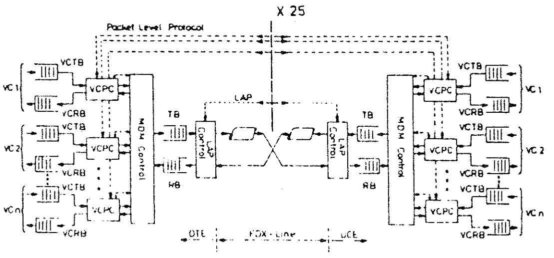

Fig.4. Model of the CCITT X.25 network interface

DTE	data terminal equipment
DCE	data circuit terminating equipment
LAP	Link access procedure
VC	Virtual call or virtual circuit
RB/TB	receive/transmit buffer
VCPC	VC procedure control
MDM	multiplex/demultiplex device

3.2 Network Node

Network nodes perform the routing and switching of packets. Today, they are usually highly modularized according to load and function sharing principles. Fig. 5 shows a model of a typical modern packet switching node. The model includes only level-3-functions; functions of the link level are individually associated to each of the link level controllers; after handling the full set of level-2-functions, packets are transferred to level 3.

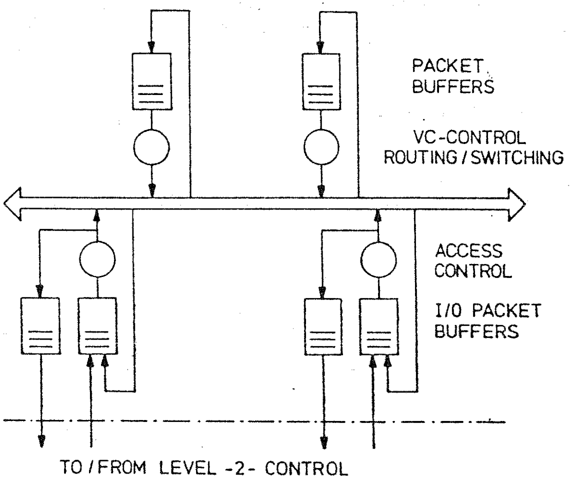

Fig.5. Model of a modular packet switch (level 3)

The model shows two control levels, access control and VC control. Each of the access control processors serves a limited number of terminals or trunks. Received packets are directed to the centralized VC-control processors for routing (VC set-up and datagram packets) or switching

(data packets within an established VC). The processors are interconnected by a high speed bus.
Packets suffer several delays when traversing through the switch:

- waiting in the I/O-packet buffer
- access control and bus transfer
- waiting in the packet buffer
- processing for routing/switching
- transfer to I/O-packet buffers
- forwarding to the particular level-2-control.

Cross-switch delays add to the total transit delays of packets and are therefore subject to analysis. Modular switching nodes can be analyzed by simulation [20] or by analytic decomposition methods [21] .

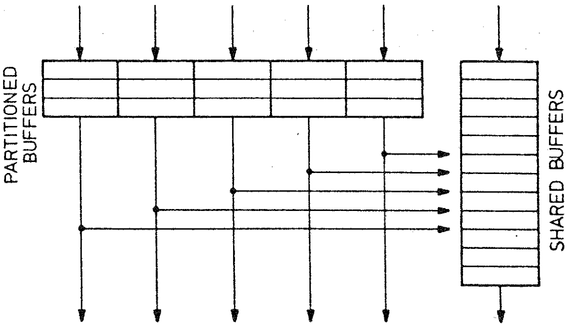

Fig.6. Model of packet buffer management

Within the switch, further details have to be regarded as scheduling of packet processing, intermodule packet transmission, and packet buffer management. The latter problem is indicated in Fig.6. The whole packet buffer space is subdivided into a region for individual buffer arrays which may be dedicated to a particular packet stream (partioned buffers) and another region which can be used for all streams (shared buffers). This management allows an effective protection of low intensive or highly prioritized connections against mass traffic connections; to achieve an effective buffer utilization, the dedicated buffers should be limited to a minimum. A good compromise is to use the overflow principle: packets which cannot be stored momentarily within their dedicated area may compete for a place within the shared buffer area.
Buffer models have been studied in connection with congestion control (protection of transit against originating traffic), with storage engineering within message handling systems, and packet switches as mentioned before [22,23] .

3.3 Congestion Control

Flow control is used to limit the traffic flow on a particular link (level 2), within a particular VC (level 3), or within a transport connection (level 4). These individual control mechanisms are generally not sufficient to protect a node, a region or the total network against overload. The set of functions controlling the global traffic situation is known as "Congestion Control".
Traffic Congestion may be caused by various effects as:

- statistical fluctuations of packet intensities within the VC's or of VC set-up requests
- break-down of trunk or switch devices
- storage blocking .

Congestion effects usually build up quite quickly and may be drastically amplified through the built-in mechanisms of automatic repetition. To protect the network against useless resource occupation, mechanisms for a fast detection and reaction have to be provided.

Due to the various causes of overload, different kinds of control actions may be applied to meet particular requirements of control range, control speed, selectiveness, fairness, or overhead:

- storage management
  partitioning, reservation and dynamic foreground/background storing
- throttling of VC set-ups or packet emissions within existing VC's by dynamic window adjustments
- dynamic scheduling of packets according to origination/transit /destination traffic
- dynamic routing to detour a congested link or node .

Congestion control phenomenons are nonstationary by their nature, they require therefore a transient analysis. Models for the basic congestion effects and their analysis have been analyzed only recently [24-27]. A detailed discussion on the various problems and their analysis will be included in a forthcoming report [27] .

4. TRANSPORT LEVEL CONTROL MODELS

The transport level comprises all functions related to the end-to-end communication between two user entities through the network. These functions are the set-up and take-down of transport connections, the multiplexing/demultiplexing of several transport connections on one network connection, the splitting/recombination of one transport connection on several network connections, segmenting and reassembling of transport service data units (TSDU) on transport protocol data units(TPDU), the end-to-end flow control and the negotiation on transport service parameters.

4.1 Basic Model

Since the transport service definition has been completed in late 1983, only a few modelling approaches are known so far. Fig.7 shows the basic structure of transport level control models where the network (i.e. all levels 1 to 3) is included as a submodel. The source model should comprise the functions of level 5, i.e. the set-up and take-down requests for network connections and the arrival of TSDU's. The sink model should include details on the arrival buffer area and the acknowledgement signalling.

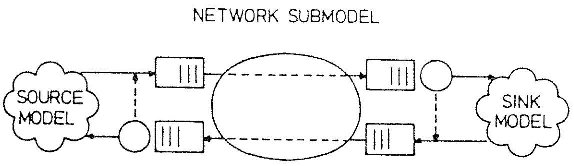

Fig.7. Basic transport level control model

4.2 End-to-End Control Model

A particular model for the end-to-end control through a network is shown in Fig.8 [27] . The source model consists of two Markovian traffic sources with high (λ_1) and low rates (λ_2). The sink model consists of an arrival storage of maximum capacity S buffers and a Markovian server with service rate μ_S. The traffic flow is controlled by two storage levels L1 and L2: Upon an upward crossing of L1 a control message is sent back to the source to switch from high to low traffic; another control message is applied upon downward crossing of L2<L1 to switch the source from low to high traffic. The inherent network delays for the control messages and the data units are lumped together in one "infinite server" stage IS with an arbitrary delay distribution with average $1/\mu_N = d$.

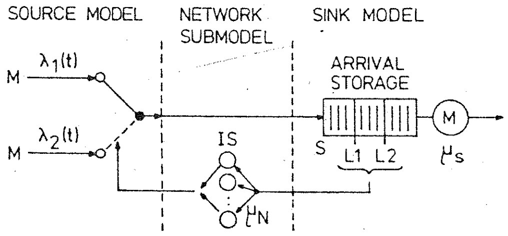

Fig.8. End-to-End Traffic Control Model

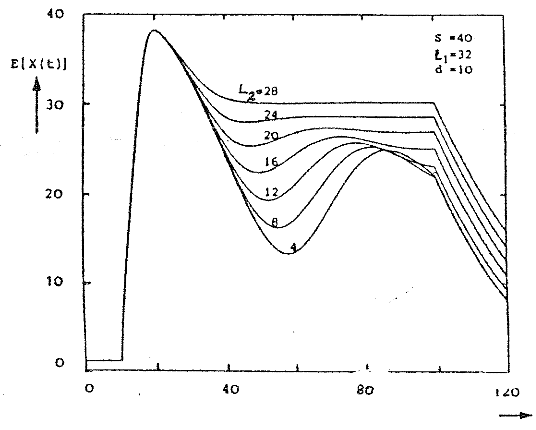

Fig. 9. Control of arrival storage occupancy by a two-level end-to-end control mechanism

Fig.9 shows the transient results of the average number of messages within the sink system E[X(t)] versus time t (all time-related values are normalized to units of the average service time $1/\mu_S$). At time t=10 the input rate λ_1 switches from 0.5 to 6.0 (overload burst of a duration of 90 time units). The throttled arrival rate λ_2 has been set to zero, the arrival storage capacity is S=40 and the average network delay d = 10.

Without an end-to-end control, E[X(t)] would quickly reach the saturation of about 41 causing heavy losses at the arrival storage which - in turn - would cause a high retransmission rate by the source. Fig. 9 shows how the average occupancy of the arrival storage can be controlled using a two-level control mechanism with L1=32 and various values of L2 from 28 down to 4. If L2 is chosen too small, the system starts oscillating. The overshoot at the beginning is caused by the large network delay and becomes smaller with smaller values of d. Parametric curves like the ones in Fig. 9 allow an optimum sizing of the control parameters to get a maximum throughput at a low rate of retransmissions [27].

5. COMPUTER NETWORK PERFORMANCE ANALYSIS

This section summarizes some analytical performance evaluation methods. We will refer to standard analyses for single queuing systems, separable queuing networks, various decomposition techniques, and transient analyses.

5.1 Standard Analysis Methods

For single queuing systems, a rich repertory of standard methods is known as

- State equation technique for Markovian queues
- Imbedded Markov chain method
- Supplementary variable method
- Mean value analysis on the basis of renewal theory and Little's law
- Lindley's integral method.

These methods are well documented in standard queuing books and performance evaluation books [28, 31].

5.2 Product-Form Queuing Networks

Networks of queues are frequently used to model traffic problems within computers and computer-communication systems. Under certain conditions as

- Markovian interarrival and service times
- General service times in connection with immediate service start at the arrival of a customer at a station (processor sharing, infinite server station, LIFO preemptive resume)
- work conserving routing strategies

the vector state probabilities can be factored as a product of state probabilities of isolated stations (separable queuing networks). Additionally, different classes of customers, state-dependent arrival and service rates, and population size constraints may be allowed [29]. Such networks show some remarkable properties of robustness, local balance, and aggregation of a station's residual network to a single complementary station [33], the so-called Norton's theorem for product-form queuing networks. The problem arises in the numerical evaluation of the state probabilities and derived performance criteria. For closed networks the problem can be reduced to the calculation of the normalizing factor (partition function). The mean-value analysis [30] and efficient computational algorithms [32] enhance this problem greatly.

Product-form networks allow the analysis of a number of application problems as flow control [1], multiprogrammed computer systems with automatic page-I/O [31], or the modelling of arbitrary delays. However, there is a great number of problems where this class of networks does not apply. This is usually the field of approximations.

5.3 Decomposition Techniques

Decomposition is used to reduce the complexity of a queuing network by aggregation or disaggregation.

a) Nearly Decomposable Networks

Exact aggregations are only known for product-form queuing networks [33] and some other special cases. If a network contains parts with a short-term dynamic while the interaction between these parts has long-term dynamics, then these parts will reach an equilibrium after each interaction. Under this assumption, each of the parts may be analyzed in isolation on the condition of their current populations. The global balance for the interaction between the parts of the network allows for the calculation of the state probability distributions [34].

b) Decomposition by Desciption of the Input and Output Traffic as Renewal Processes

In this approach, single stations or subnetworks are analyzed in isolation with respect to their input/output behavior, e.g., by describing the interarrival and interdeparture statistics by renewal point processes or, at least, by their first and second moments represented by the flow rates λ and the coefficients of variation c, see Fig. 10, [35]. In case of open networks, the flow rates follow from a system of linear equations for the conservation of flow for each station. The coefficients of variation can be found from the output processes where in case of networks with feedback an iteration is necessary until consistency is reached. Two basic operations MERGE and SPLIT have to be performed under the hypothesis of renewal point processes. The individual station characteristics as mean queue size and mean flow time are obtained from a GI/G/1 - analysis with respect to two moments only for the arrival and service processes.

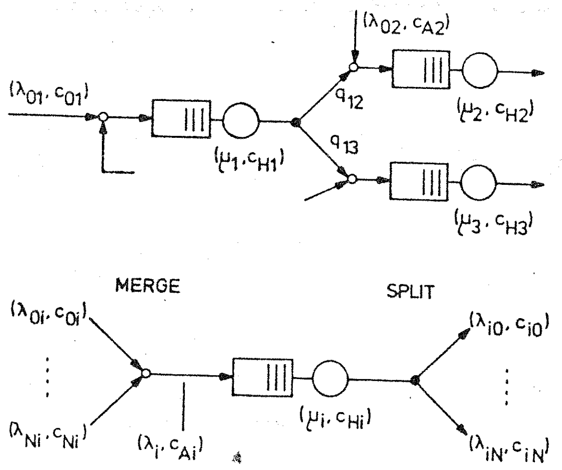

Fig. 10. Decomposition by input/output processes

To characterize the input and output traffic more realistically, the nonrenewal nature has to be considered besides the interarrival and interdeparture statistics. A successful approach is the application of Markov-modulated processes, especially the Switched Poisson-Process [38].

c) Hierarchical Decomposition

This technique uses the basic idea of aggragation. Subnetworks are defined and described by some simpler network or - if possible - by a single service station with sate-dependent service times. The aggregated system generates a flow-equivalent traffic rather than an interarrival time-equivalent traffic, see Fig. 11. Repeated application of this method bottom-up allows the successive reduction of the network complexity.

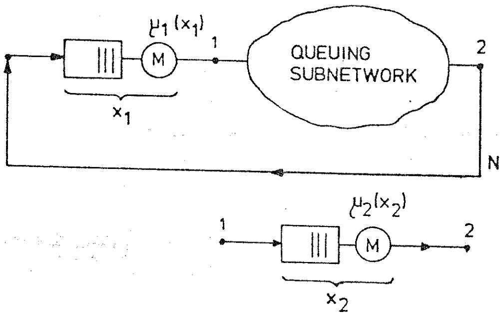

Fig. 11. Hierarchical decomposition by aggregation

Examples of this technique have been reported for computer system analysis [43], admission delay calculations in compter networks with flow control [36], and end-to-end protocols [1]. This technique is also the key to the analysis of multi-level computer networks: The link-level model has to be replaced by a simpler flow- and delay-equivalent dual-server model on the basis of "virtual transmission times" which include all effects of the link-level protocol, see [15]. This aggregated system is now inserted into the network-level model. Within the network-level model, the network nodes have to be aggregated in a single server with a MERGE-operation at the input and a SPLIT-operation at the output representing the sharing of the node switch and routing, respectively. On the basis of this aggregated network-level network, network and transport connections may be defined with their individual flow-control mechanisms.

d) Decomposition by Customer Classes

This decomposition is applied to priority queuing networks. Each of the priority stations is equivalently decomposed into as many single-class stations as the number of priority classes indicates. The influence of the other classes on a particular class is considered in a state-dependent service rate. Thus, the P-class network is decomposed into P one-class networks; these networks can be analyzed by the usual queuing network algorithms [37].

5.4 Transient Analyses

Transient analysis techniques are used in case of nonstationary traffic flows and overload control. They are also necessary for the analysis of the d.f. of "life-time" functions as network delays or busy periods.

a) Nonstationary Traffic

Nonstationary traffic can be characterized by a time-dependent arrival rate $\lambda(t)$. In case of Markovian systems, the set of Kolmogorov-forward differential equations has to be solved instead of the set of linear equations for equilibrium. An analytic solution requires the set of eigenvalues; this method is limited to models with a small number of states. For larger state spaces numerical methods like the Runge-Kutta-method have to be applied [27].

b) Life-Time Processes

Waiting times, transit flow times and busy periods are of finite lengths and can generally be considered as "life-times". Whereas the average of these times can always be obtained from a state probability analysis and Little's law[28], the distribution function requires a life-time process analysis.

Network life-time distributions have been studied only recently as cycle time distributions within closed tandem queuing networks or overtake-free structures of networks [39 - 41]. Unfortunately, the combinatorial approaches used in these cases cannot be applied to networks with overtaking of customers as in case of feedback-type networks with alternate paths or queue disciplines other than FIFO. The method of first passage time analysis, however, allows for quite general networks including overtaking, arbitrary queue disciplines and state-dependent service rates [42]. The principle of this method is outlined in Fig. 12. We define a set S of "life-states". A customer enters this set at the beginning of the life-time process. The life-time lasts on as long as the customer stays in S continuously. The life-states and their transitions have to be constructed such, that all other customers who may influence the life-time of the considered one are represented. The life-time may terminate from each of the states in S in general as, e.g., by completing a cycle time or termination of a busy period of a server. Then, the considered customer enters the taboo set H of "absorbing states".

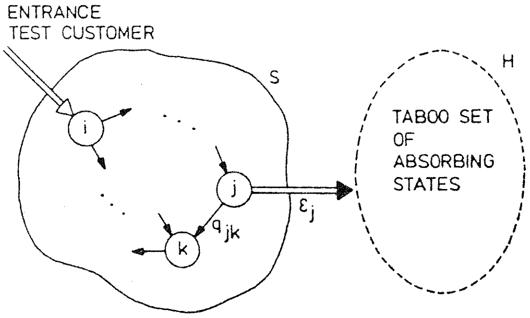

Fig. 12. Life-time process analysis

The life-time process can be described by a set of Kolmogorov-backward differential equations for conditional life-time d.f.'s. Alternatively, from this set of equations simpler sets of linear equations for the ordinary moments of the conditional life-times can be derived. The set of differential equations may be solved numerically by eigenvalues or by the Runge-Kutta method. The ordinary moments follow from the linear moment equations which have to be solved recursively for the orders k=1,2,... The life-time moments can be used to approximate the distribution functions of the conditional life-times.

In case of extended networks with large state sets, aggregation techniques may be used again to reduce the complexity, see Fig. 11. However, the flow-equivalence of an aggregated station preserves the average life-time only; to approximate the higher moments accurately, an augmented aggregation technique has to be used which counts for the variability of the transit time of a test customer entering the aggregated subsystem.

CONCLUSION

In this paper various queuing models for computer networks have been reviewed describing traffic problems within the communications protocol levels 1-4. Besides some fundamental analytical performance analysis methods, hierarchical decomposition techniques are adequate to analyze global models which include several protocol levels. Additional to the usual equilibrium state analysis, nonstationary traffic problems are important in cases of dynamic overload control or in case of finite life-times. Some examples have been given demonstrating the implications protocols may burden on resource useability. These results may be applied for optimum sizing of network resources, adjustment of protocol parameters and computer network planning.

REFERENCES

[1] Reiser,M.: Performance Evaluation of Data Communication Systems. Proc. IEEE, Vol. 70, No.2 (1982), pp. 171-196 .

[2] Chu,W.W.: Buffer Behavior for Poisson Arrivals and Multiple Synchronous Constant Outputs. IEEE Transact. on Comp., Vol.C-19 (1970), pp. 530-534.

[3] Hashida,O., Ohara,K.: Line Accomodation Capacity of a Communication Control Unit. Review of the Electr. Commun. Laboratories, NTT Publ. Corp. 20(1972), pp. 231-239.

[4] Cooper,R.B., Murray,G.: Queues Served in Cyclic Order. BSTJ, Vol.48(1969), pp. 675-689.

[5] Konheim, A.G., Meister,B.: Service in a Loop System. J. ACM, Vol.19(1972), pp. 92-108.

[6] Kuehn,P.J.: Multiqueue Systems with Nonexhaustive Cyclic Service. BSTJ, Vol.58 (1979), pp. 671-698.

[7] Kuehn,P.J.: Performance of ARQ-Protocols for HDX-Transmission in Hierarchical Polling Systems. Int. Journ. Performance Evaluation, Vol.1(1981), pp. 19-30.

[8] Manfield,D.R.: Analysis of a Polling System with Priorities. IEEE Globecom-Conference (1982).

[9] Morris,R.J.T., Wang,Y.T,: Some Results for Multi-Queue Systems with Multiple Cyclic Servers. 2nd. Conf. on Performance of Computer-Communication Systems, Zürich (1984). North-Holland, pp. 245-258.

[10] Bux,W.: Local Area Subnetworks: A Performance Comparison. IEEE Transact. on Commun. Vol.COM-29(1981), pp. 1465-1473.

[11] Tobagi,F.A. Hunt,V.B.: Performance Analysis of Carrier Sense Multiple Access with Collision Detection.Computer Networks, Vol.4(1980), pp. 245-259.

[12] Kiesel,W.M., Kuehn,P.J.: A New CSMA-CD Protocol for Local Area Networks with Dynamic Priorities and Low Collision Probability. IEEE Journ. on Selected Areas in Comm., Vol.SAC-1(1983), pp. 869-876.

[13] Langenbach-Belz,M.: Sampled Queuing Systems. Proc. Symp. on Comp.-Comm. Networks and Teletraffic, New York (1972). Polytechn. Press of the PIB, XXII (1972), pp. 157-176.

[14] Jans,H.: Queuing Systems with Clocked Operation and Priorities. Proc. 10th Int. Teletraffic Congress, Montreal (1983), paper 4.4.A-4.

[15] Bux,W., Kümmerle,K., Truong,H.L.: Balanced HDLC-Procedures: A Performance Analysis. IEEE Transact. on Common., Vol.COM-28 (1980), pp. 1889-1898.

[16] Bux,W., Kümmerle,K., Truong,H.L.: Data Link-Control Performance: Results Comparing HDLC Operational Modes. Comp. Networks, Vol.6(1982), pp. 37-51.

[17] Goeldner, E.-H., Truong,H.L.: A Simulation Study of HDLC-ABM with Selective and Nonselective Reject. Proc. 10th Int. Teletraffic Congress, Montreal (1983), paper 3.4-5.

[18] Dieterle,W.: A Simulation Study of CCITT X.25: Throughput Classes and Window Flow Control. Proc. 10th Int. Teletraffic Congress, Montreal (1983), paper 3.3-6.

[19] Dieterle,W.: Performance Evaluation of Data Communication Protocols- Example of a Case Study on X.25. Int. Conf. on Computer-Communication, Sydney (Nov.1984).

[20] Bux,W., Kuehn,P., Kümmerle,K.: Throughput Considerations in a Multi- Processor Packet Switching Node. IEEE Transact. on Comm. Vol.COM-27(1979), pp. 745-750.

[21] Kuehn,P.J.: Analysis of Switching System Control Structures by Decomposition. 9th Int. Teletraffic Congress, Torremolinos (1979), paper 51-4.

[22] Irland,M.I.: Buffer Management in a Packet Switch. IEEE Transact. on Comm., Vol.COM-26(1978), pp. 328-337.

[23] Kaufman , J.S.: Blocking in a Shared Resource Environment. IEEE Transact. on Comm., Col.COM-29(1981), pp. 1474-1481.

[24] Majithia,J.C., et al: Experiments in Congestion Control Techniques. Conf. on Flow Control in Computer Networks, Paris (1979). North-Holland, pp. 211-234.

[25] Gerla,M., Kleinrock,L.: Flow Control: A Comparative Survey. IEEE Transact. on Comm., Vol.COM-28(1980), pp. 553-574.

[26] Davies,M.E., Pehlert,W.K.: Evaluation of No.1 PSS Congestion Control Strategies. Proc. 2nd Conf. on Performance of Computer-Communication Systems, Zürich (1984). North- Holland, pp. 449-461 .

[27] Van As,H.R.: Modelling and Analysis of Congestion Control Mechanisms in Packet Switching Networks. 38th Rep. on Studies in Congestion Theory, Univ. of Stuttgart (1984). ISBN 3- 922 403-48-4.

[28] Kleinrock,L.: Queuing Systems, Vol.I and II, J.Wiley, New York (1975,1976).

[29] Baskett,F. et al: Open, Closed and Mixed Networks of Queues with Different Classes of Customers. J.ACM, Vol.22(1975), pp. 248-260.

[30] Reiser,M., Lavenberg,S.S.: Mean-Value Analysis of Closed Multichain Queuing Networks. J. ACM, Vol.27 (1980), pp. 313-322.

[31] Lavenberg,S.S. (Ed.): Computer Performance Modeling Handbook, Academic Press, New York (1983).

[32] Reiser,M., Kobayashi,H.: Queuing Networks with Multiple Closed Chains: Theory and Computational Algorithms. IBM J.Res. Develop., Vol.19(1975), pp. 282-294.

[33] Chandy,K.M., Herzog,U., Woo,I.: Parametric Analysis of Queuing Networks. IBM J.Res. Develop., Vol.19(1975), pp. 36-42.

[34] Courtois,P.J.: Decomposability: Queuing and Computer System Applications. Academic Press, New York (1977).

[35] Kuehn,P.J.: Approximate Analysis of General Queuing Networks by Decomposition. IEEE Transact. on Comm., Vol.COM-27(1979), pp. 113-126.

[36] Reiser,M.: Admission Delays on Virtual Routes with Window Flow Control. Proc. Conf. on Performance of Data Comm. Systems and Their Applications, Paris (1981). North-Holland, pp. 67-76.

[37] Schmitt,W.: Traffic Analysis of Queuing Networks with Priorities. 39th Rep. on Studies in Congestion Theory, Univ. Stuttgart (1984). ISBN 3- 922 403-49-2.

[38] Tran-Gia,P.: A Renewal Approximation for the Generalized Switched Poisson Process. Proc. Int. Workshop on Appl. Math. and Perf./Reliab. Models of Comp./Comm. Systems, Pisa (1983), pp. 127-139.

[39] Wong.J.W.: Distribution of End-to-End Delay in Message Switched Networks. Computer Networks, Vol.3(1978), pp. 44-49.

[40] Chow,We-Min: The Cycle Time Distribution of Exponential Cyclic Queues. J.ACM, Vol.27 (1980), pp. 281-286.

[41] Daduna,H.: Passage Times for Overtake-Free Paths in Gordon-Newell Networks. Adv. Appl. Prob., Vol.14(1982) , pp. 672-686.

[42] Kuehn,P.J.: Analysis of Busy Periods and Response Times in Queuing Networks by the Method of First Passage Times. Proc. Performance '83, North Holland (1983), pp. 437-455.

[43] Lazowsky, E.D. et al.: Quantitative System Performance - Computer System Analysis Using Queuing Network Models. Prentice-Hall, Inc., Englewood Cliffs, N.J. (1984).