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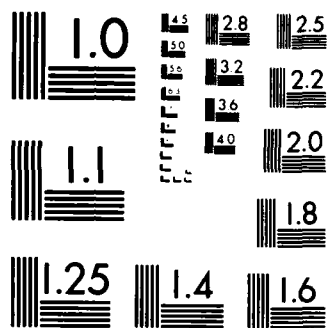
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ROYAL SIGNALS & RADAR
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SYSTEM DYNAMICS AND NETWORK CONTROL

Author: T E G King

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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 3755

Title: System Dynamics and Network Control
 Author: T E G King
 Date: July 1984

SUMMARY

The difficulties involved in the evaluation of the performance of adaptive controls in communications networks are discussed. Current analytical tools are assessed and the System Dynamics technique is described.

The application of System Dynamics to the investigation of various network controls is discussed and results are given for some simple examples, including nodal congestion control, sliding window flow controls, and adaptive routing.

Finally, the relevance of System Dynamics to the simulation of large realistic networks is examined and conclusions are presented.

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1. INTRODUCTION

The fundamental concept inherent in the design of packet-switched networks is the principle of resource sharing, the resources being the switch buffers and the line capacities. Packets associated with different source-destination pairs must traverse the network whilst sharing the network resources: without network controls such uncoordinated resource sharing will lead to conflict and congestion [1].

Flow and congestion controls can be implemented at various levels. At both the switch-switch and end-to-end levels, sliding window flow control can be used to limit the total number of unacknowledged packets. The routing control governs the flow of packets at the subnet level; it may be static (fixed) or respond to the state of the network in an adaptive way. Moreover this control may be centralised (so that decisions are made at a single location and are subsequently disseminated throughout the network), isolated (i.e. each switch independently makes routing decisions without reference to information from other switches), or distributed (where switches exchange routing information). A distributed adaptive routing algorithm is the appropriate choice for a network which experiences changes in topology.

Flow control is conventionally defined to be the means by which the sender is prevented from sending data at a rate that is too fast for the receiver. Congestion control is concerned with the problems that may occur at individual switches and acts to prevent the saturation of switches by too many packets. This control may be exerted on a global basis (e.g. isarithmic control, in which the total number of packets within the subnet is limited) or at the switch level, where excess packets may be discarded or choke packets [1] may be sent back to the source host that is causing the congestion in order to reduce its traffic generation rate.

Analytical techniques for the performance evaluation of network controls have not been totally successful. Performance characteristics such as mean throughput and delay have been obtained for static controls (e.g. standard window flow control and static routing algorithms) by means of queueing theory [2]. Unfortunately queueing theory is not useful in those cases where the network is not at equilibrium, where adaptive controls are implemented, or where constraints such as finite storage invalidate the assumption of statistical independence of packet queues.

Investigations have been initiated into the performance evaluation of adaptive routing [3-11], using either control theory or finite Markov chain models. These methods can be applied only to very simple networks and have not enjoyed the same success in dealing with adaptive control and transient behaviour as queueing theory has had in evaluating static control in networks at equilibrium.

In these circumstances it is not surprising that simulation is the preferred technique for the evaluation of adaptive control [12,13]. Nevertheless simulation also possesses disadvantages. The level of detail for the model must be chosen carefully: the important characteristics of the system must be incorporated, yet the model must not be so complex that the simulation takes too long to run. Another disadvantage of a complex model is that it is in general difficult to

interpret the behaviour of the system: if the system is too complicated to understand, then it is unlikely that a detailed simulation would provide fresh insight.

It is therefore desirable to devise a modelling technique which attempts to provide both insight and a wide range of applicability. This Paper advocates the methodology of System Dynamics as suitable for this purpose. A description of System Dynamics is given in the following Chapter.

2. THE SYSTEM DYNAMICS TECHNIQUE

As an excellent text on System Dynamics already exists [14], the following description will be limited to those aspects which are directly relevant to the modelling of communication networks.

System Dynamics is mostly concerned with the dynamical response of closed-loop systems to outside influences. A closed-loop (or feedback) system is characterised by the ability to modify its input in response to its output according to some policy or decision rule: an example of this is a production-inventory system, where the production rate is set according to the rate of depletion of the inventory.

Such feedback loops cause dynamic behaviour which is not necessarily beneficial for the system. The object of a System Dynamics study is to explain the dynamic behaviour in terms of the structure and decision rules of the system and to suggest changes to the structure and rules which result in improvements to the behaviour. In particular the system should be able to deal effectively with any variations in the input; i.e. its policies should be robust.

A generalised feedback loop is shown in fig 1.

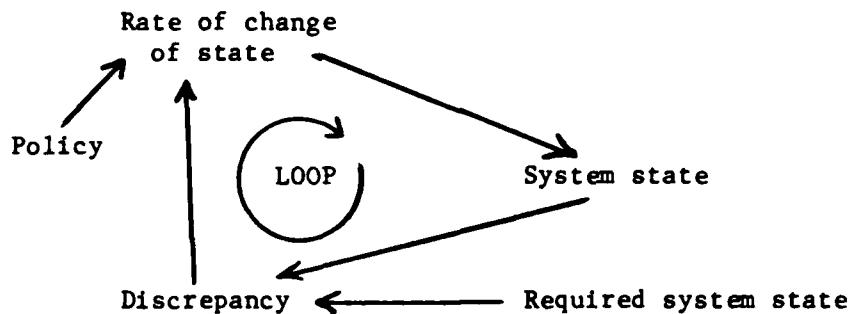


Fig 1 : A generalised feedback loop

The state variables and rates of change of state are known in System Dynamics terminology as LEVELS and RATES respectively. A complicated rate may be expressed in terms of AUXILIARY VARIABLES which are functions of the levels. A POLICY is a rule for modifying a rate in order to achieve a target level. It affects the rate of change of state, which in turn is integrated to produce a level. This level is compared with a desired level and the rate is then adjusted in accordance with the policy and discrepancy, and so on.

The first step in a System Dynamics study is to construct an INFLUENCE DIAGRAM. This lists the system variables and rates thought to be relevant and depicts the influences operating between these entities. It is possible to analyse some systems in a qualitative but useful way

with the aid of the influence diagram. The influence diagram possesses two useful properties; it yields an easily understandable representation of the system and it can be extended in a logical manner to develop more complex models of the system. Some examples of influence diagrams for various aspects of network control will be given in this Paper.

The final stage is to develop a numerical model of the system from the influence diagram. The simulation package DYSMAP [14] is of considerable value at this point, as it facilitates a fast error-free development of this part of the model. The applicability of DYSMAP to the modelling of networks is discussed in Chapter 5.

3. SYSTEM DYNAMICS AND COMMUNICATION NETWORKS

3.1 Introduction

The System Dynamics technique and the DYSMAP software package were originally developed as tools for the investigation of the management of socio-economic systems: such systems contain many interacting nonlinear feedback loops which render the systems intractable to analytical control-theoretical methods. The analytical performance evaluation of network controls is inhibited for the same reason. End-to-end window flow control provides an illustrative example of this type of control. The feedback occurs because the allowed rate of input traffic for a particular source-destination pair depends on the amount of traffic for that pair that is already in the subnet. The control is nonlinear because there is a sharp cutoff at the maximum window size for the amount of this traffic in the subnet, and the feedback loops interact because the packets for different source-destination pairs must share the common resources of the subnet.

Although System Dynamics was not designed with such a low-level application in mind, it may nevertheless prove to be useful for the evaluation of control methods in communication networks: after all, the network control problem is (as discussed above) fundamentally similar to the problems conventionally addressed by System Dynamics. The first step is to recast network control as a System Dynamics problem.

The building blocks of a System Dynamics model are the levels, rates, and their relations to each other. The obvious choices for the levels of the model are the packet occupancies of the switches: the associated rates will then be the traffic rates along each link. The levels are determined by a simple integration of the rates, but the rates are more difficult to calculate as they depend upon the control policy, line capacities, and levels. If there are N possible destinations in the network, then each switch will be associated with N levels, representing the number of packets currently in that switch which are to be routed to each particular destination.

As it is easier to demonstrate the technique of System Dynamics by presenting a specific example, the following two Sections describe in detail the construction of an influence diagram and numerical model for a simple nodal congestion control scheme.

3.2 The influence diagram

In order to demonstrate the application of System Dynamics and the DYSMAP package to the analysis of network controls, a very simple model of a nodal congestion scheme is now introduced. The simple network of fig 2 consists of a host (i.e. a device that makes use of network services) and a switch. Traffic at a rate RH packets per unit time is required to be transmitted over the subnet via the switch. The switch may exert control over the input that it receives from the host, but the effects of this control are subject to delay. The object of the control

is to limit congestion at the switch so that other users of the switch do not experience a considerable degradation of service. The modified input rate to the switch is denoted by RS and the output traffic rate from the switch is RO . The packet occupancies for the host and switch are LH and LS respectively. All of these quantities are considered to be functions of time.

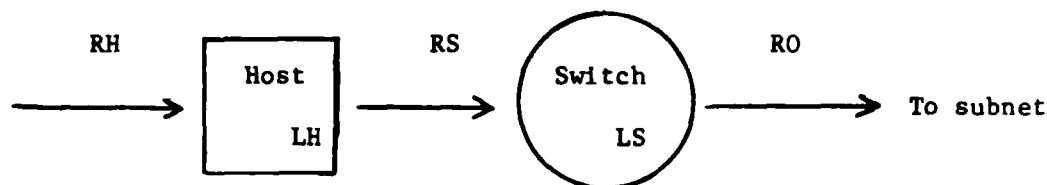


Fig 2 : A simple congestion control model

The influence diagram for this model is shown in fig 3. The structure of this diagram will now be described in detail. The input rate RH is enclosed in a box to show that it is an EXOGENEOUS rate; i.e. it originates from outside the system and is not under the system's control [N.B. this situation is exactly the opposite to that encountered in the usual System Dynamics problem such as a production-inventory system, where the input (i.e. production) rate is under control but the inventory depletion rate (i.e. the output rate) is subject to outside influences]. An arrow with a "+" sign at its head links the input rate RH to the host packet occupancy LH . This notation indicates that the input rate and packet occupancy are related in a positive way - if the input rate increases, then this leads (all other things being equal) to an increase in the packet occupancy, whilst if the rate decreases, then so does the occupancy. Similarly a negative sign indicates that an increase (decrease) in the variable at the tail of the arrow leads to a decrease (increase) in the variable at the head of the arrow.

The actual input rate RS depletes the occupancy LH , but is constrained to be zero if LH is zero: otherwise negative occupancies would occur. The depletion and constraint are represented by the negative and positive arrows respectively of loop A. Loop A is a negative feedback loop (because it contains an odd number of negative arrows [14]), but it is not a control loop: it merely reflects the presence of the physical constraint that LH must not be negative.

The rate RS accumulates to give the packet occupancy LS of the switch. RS is limited by the capacity of the line between the host and the switch. It is constrained to be zero if the occupancy LS is equal to the number of available switch buffers $BMAX$: this physical constraint is represented by loop B.

The switch occupancy LS is depleted by the output rate RO , which is zero whenever LS is zero. This constraint is indicated by loop C. The current packet occupancy is compared with a desired occupancy $DOCC$ and the discrepancy $DISC$ is calculated. The discrepancy is defined to be the number of packets in excess of the desired occupancy: it is zero if the

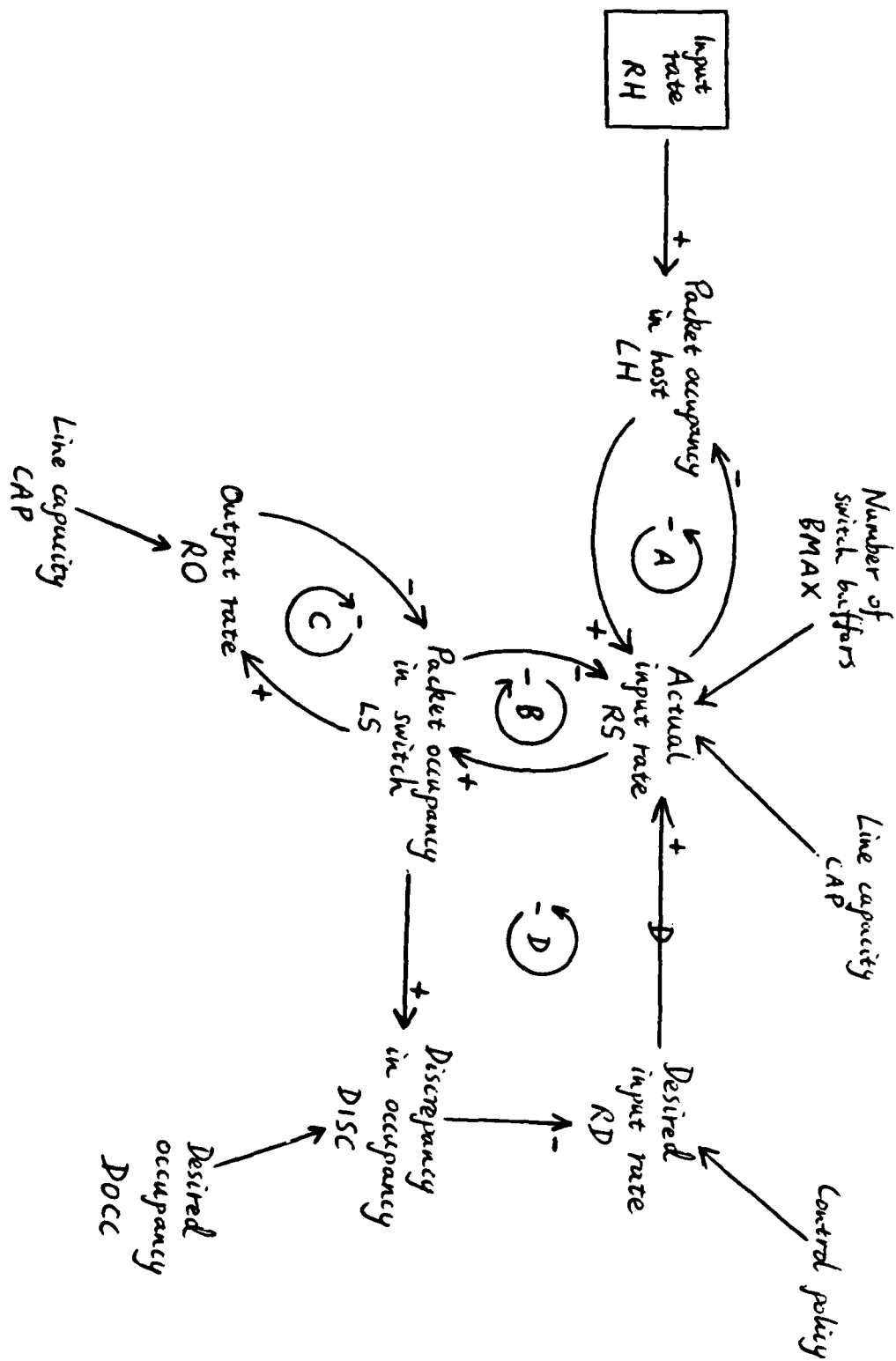


Fig 3 : Influence diagram for congestion control model

occupancy is at or below the desired occupancy. The occupancy and discrepancy are connected by a positive influence line because an increase (decrease) in the occupancy may lead to an increase (decrease) in the discrepancy. The desired input rate RD is determined by a control policy which takes account of the current discrepancy in the occupancy. The control policy should reduce the input traffic rate if the discrepancy increases, so the influence arrow between DISC and RD is given a negative sign.

Finally the desired input rate RD becomes the actual adjusted input rate RS after a delay. This delay arises because (for example) a network information packet must be sent from the switch to the host in order to inform the host of the necessary control action. The delay is denoted by the letter "D" which is drawn through the influence line. This line completes a negative feedback control loop D which creates the dynamic behaviour within the system.

The influence diagram in fig 3 is structurally and definitionally coherent: i.e. the relationships between its variables satisfy the rules laid down in Ref [14]. The most important of these rules are:

- (a) Only an auxiliary variable or a rate may follow a level.
- (b) Only a rate or another auxiliary variable may follow an auxiliary variable.
- (c) Only a level or a delayed rate may follow a rate.

Such rules enforce the development of a correct and consistent model of the system.

LH and LS are obviously levels because they are points of accumulation. RH, RS and RD are rates, and DISC is an auxiliary variable. Auxiliary variables are merely intermediate quantities which occur in the determination of rates (in this case, RD); they are not fundamental system variables. Nevertheless their inclusion yields a clearer picture of the system and for that reason they are allowed within the DYSMAP package.

The influence diagram is reasonably easy to understand but rather more difficult to create. List extension [14] aids the construction process by creating the diagram in an evolutionary way. For example:

- (a) Write down the switch occupancy LS (this being an obvious first step in the modelling of the system).
- (b) Include all quantities that directly affect (or are affected by) LS and draw the relevant influence lines. These quantities are RS, BMAX, RO, and DISC.
- (c) Introduce any additional quantities that influence or are influenced by those given in (b). Thus LH, CAP, RD, BMAX and DOCC are now incorporated into the influence diagram.
- (d) Using the same procedure, the control policy and RH are added to the diagram to produce fig 3.

At this stage the influence diagram contains a feedback control loop and thus represents a dynamical model of the system. It may not necessarily be either a complete or valid model: for example, there may

be factors external to the diagram which affect the input rate RH or the output rate RO and perhaps should be included in the model description. The analyst must decide where to define the boundaries of the model and extend these if the behaviour of the model does not reasonably approximate that of the real system. Such an extension can be accomplished readily within the framework of the influence diagram representation.

3.3 The numerical model

The influence diagram of fig 3 depicts the influences that operate between the model variables but does not indicate the exact manner in which these influences work. A numerical model cannot be constructed until the control policy and detailed workings of the model have been resolved.

The specific control policy to be investigated in this example consists of the following procedure. Whenever the occupancy of the switch attains or exceeds a desired occupancy DOCC, the switch requests the host to cease transmission (by, for example, transmitting a network information packet to the host). When the occupancy drops below DOCC, the switch allows transmission to restart. It is assumed that the switch occupancy is checked at every simulation time instant and that the effect of the control action is always delayed by one time unit. The packets are all assumed to be of the same size and the control traffic and switch processing time are ignored.

The DYSMAP program may now be constructed. The important lines of the DYSMAP data file are explained in full in the following paragraphs. The subscripts J, K and L associated with the level variables refer to three consecutive time instants: the subscripts JK and KL associated with the rate variables refer to the time intervals at which the rates take effect. This notation accords with standard System Dynamics usage [14].

The exogeneous input rate RH will be chosen so as to provide a shock to the system. The DYSMAP equation for RH is thus chosen to be

$$R \text{ RH.KL} = \text{BASE} + \text{PULSE}(\text{HGHT}, \text{PTM}, \text{LENGTH} + 1) \quad (1)$$

The first "R" implies that this equation is a rate equation. The input rate RH is maintained at a constant value BASE until time PTM, when a pulse of height HGHT is injected. The third argument of the PULSE function refers to the interval between pulses and is set to be longer than the length of the simulation so that the effect of a single pulse can be investigated. (The DYSMAP function PULSE generates a series of pulses, but we require only one pulse for this particular example.)

The host packet occupancy LH is fed by RH and depleted by the actual input rate RS to the switch. LH obeys the standard level equation

$$L \text{ LH.K} = \text{LH.J} + \text{DT} * (\text{RH.JK} - \text{RS.JK}) \quad (2)$$

This equation represents a rate integration which yields the level LH. DT is the simulation time increment. The first "L" in the equation informs DYSMAP that this equation concerns a level variable.

The controlled input rate RS depends on five quantities (as shown in the influence diagram) and its formulation is rather complicated. For this reason the auxiliary variables A1 and A2 (not shown in the influence diagram) are employed in the construction of the equation for RS. The calculation of RS involves the following auxiliary equations and rate equation:

$$A \ A1.K = \text{MIN}(\text{CAP}, (\text{BMAX} - \text{LS}.K) / \text{DT}) \quad (3)$$

$$A \ A2.K = \text{MIN}(A1.K, \text{LH}.K / \text{DT}) \quad (4)$$

$$R \ \text{RS}.KL = \text{MIN}(A2.K, \text{DEADTI}(\text{PREV}, \text{RD}.JK, 1)) \quad (5)$$

The first auxiliary variable A1 reflects the constraints on the rate RS imposed by the line capacity and the finite amount of storage available in the switch. In particular the input rate must not be larger than that which can fill the remaining BMAX-LS.K buffers in the next DT time units. The second auxiliary variable A2 acknowledges the constraint placed upon RS by the number of packets LH held in the host: the omission of this constraint would result in the creation of negative packet occupancies! These constraints are physical and thus their effects occur immediately; there is no delay. Finally, the rate equation for RS incorporates the effect of the delayed control action. The DYSMAP function DEADTI creates a 'dead' time (in this case of duration one time unit) before the rate RD takes effect. The net result of equations (3)-(5) is to assign to RS the minimum value allowed by the quantities that influence RS.

The level equation for LS is similar to that for LH, except that the input and output rates are now RS and RO respectively.

The output rate RO is determined by the number of packets LS held in the switch and is constrained by the line capacity. Thus RO obeys the equation

$$R \ \text{RO}.KL = \text{MIN}(\text{CAP}, \text{LS}.K / \text{DT}) \quad (6)$$

The desired input rate RD is determined by the control policy. As mentioned earlier in this Section, the control stops the host transmission if the desired switch occupancy is exceeded: moreover the effect of the control action is delayed by one time unit. In the formalism of System Dynamics, only rates may be the subject of delays. In this case, unfortunately, the delay occurs to the decision to stop the host transmission, rather than to a rate. Nevertheless the delayed control action can be modelled (albeit rather artificially) by the following equations.

$$A \ \text{DISC}.K = \text{LS}.K - \text{DOCC} \quad (7)$$

$$R \ \text{RD}.KL = \text{CLIP}(0, 1, \text{DISC}.K, 0) * \text{CAP} \quad (8)$$

DISC is an auxiliary variable which is equal to the excess switch occupancy. The function CLIP satisfies

$$\text{CLIP} = 1 \quad \text{if} \quad \text{DISC} \geq 0$$

$$\text{CLIP} = 0 \quad \text{if} \quad \text{DISC} < 0$$

Thus RD is equal to the line capacity if the switch occupancy is less than the desired occupancy, and is equal to zero if the switch

occupancy is greater than or equal to the desired occupancy. RD then makes its presence felt in the RS equation after a delay of one time unit; the effect is to set RS to zero if RD was zero, and to set RS to whatever value it would have taken (i.e. given no control action) if RD was equal to CAP. The effect of the delayed rate RD is therefore the same as the effect of the original delayed control decision. Thus the model still retains the intended behaviour whilst satisfying the requirements of System Dynamics.

The DYSMAP input file for the model is given in fig 4. The first line contains the title and the following "C" lines set the values of constants. The "TP" line initialises a dummy level which is used by the delay function DEADTI in the equation for RS. The rate, level, and auxiliary equations already discussed are included, together with two "N" equations which initialise the model levels. The final lines set the length of the simulation, the length of the time increment, the time interval for the printed output, and the variables to be printed.

The results of the simulation are shown in fig 5. The rates given on each line are those that take effect in the NEXT time interval. The input pulse occurs at time T=2; before this time the system is running smoothly. At T=3 the host packet occupancy LH increases; this results in a traffic input rate to the switch which is equal to the line capacity. At T=4 the switch occupancy rises to 6, thus restricting the rate of traffic RS that can be accommodated in the next time step to 4 packets (as the maximum number of packets in the switch is restricted to BMAX=10). A control decision is made at this stage to request the host to cease transmission. This decision is delayed by one time unit and becomes effective during the interval 5 to 6 in reducing RS to zero.

At T=5 the switch still contains an excessive number of packets and so the rate RS remains at zero during the next interval. The switch occupancy falls to zero for time steps 6 and 7. At T=8 the build-up of packets in the host forces the switch occupancy to exceed the desired level again and permanent oscillatory behaviour of LS sets in, even though the traffic input rate to the host is now constant at 2 packets per time unit. This type of behaviour is wasteful of network resources and is therefore undesirable.

One way of remedying this situation is to find a better control policy. An example of a better policy is one which reacts less sharply to an excess switch occupancy, thus leading to a smoother response.

```

* SIMPLE NODAL CONGESTION CONTROL MODEL
C CAP=6
C BMAX=10
C DOCC=4
C BASE=2
C HGHT=10
C PTM=2
TP PREV=2
R RH.KL=BASE+PULSE(HGHT,PTM,LENGTH+1)
L LH.K=LH.J+DT*(RH.JK-RS.JK)
A A1.K=MIN(CAP,(BMAX-LS.K)/DT)
A A2.K=MIN(A1.K,LH.K/DT)
R RS.KL=MIN(A2.K,DEADTI(PREV,RD.JK,1))
L LS.K=LS.J+DT*(RS.JK-RO.JK)
R RO.KL=MIN(CAP,LS.K/DT)
A DISC.K=LS.K-DOCC
R RD.KL=CLIP(0,1,DISC.K,0)*CAP
N LH=BASE
N LS=BASE
C LENGTH=60
C DT=1
C PRTPER=1
PRINT 1)RH/2)LH/3)RS/4)LS
C PLTPER=1
PLOT RH=R,LS=L
RUN TEST
+
```

Fig 4 : The DYSMAP model input file

SIMPLE NODAL CONGESTION CONTROL MODEL

TIME	RH	LH	RS	LS
00.000E+00	2.0000	2.0000	2.0000	2.0000
1.000	2.0000	2.0000	2.0000	2.0000
2.000	12.000	2.0000	2.0000	2.0000
3.000	2.0000	12.000	6.0000	2.0000
4.000	2.0000	8.0000	4.0000	6.0000
5.000	2.0000	6.0000	00.0000E+00	4.0000
6.000	2.0000	8.0000	00.0000E+00	00.0000E+00
7.000	2.0000	10.000	6.0000	00.0000E+00
8.000	2.0000	6.0000	4.0000	6.0000
9.000	2.0000	4.0000	00.0000E+00	4.0000
10.00	2.0000	6.0000	00.0000E+00	00.0000E+00
11.00	2.0000	8.0000	6.0000	00.0000E+00
12.00	2.0000	4.0000	4.0000	6.0000
13.00	2.0000	2.0000	00.0000E+00	4.0000
14.00	2.0000	4.0000	00.0000E+00	00.0000E+00
15.00	2.0000	6.0000	6.0000	00.0000E+00
16.00	2.0000	2.0000	2.0000	6.0000
17.00	2.0000	2.0000	00.0000E+00	2.0000
18.00	2.0000	4.0000	4.0000	00.0000E+00
19.00	2.0000	2.0000	2.0000	4.0000
20.00	2.0000	2.0000	00.0000E+00	2.0000
21.00	2.0000	4.0000	4.0000	00.0000E+00
22.00	2.0000	2.0000	2.0000	4.0000
23.00	2.0000	2.0000	00.0000E+00	2.0000
24.00	2.0000	4.0000	4.0000	00.0000E+00

Fig 5 : Results of the simulation

4. THE MODELLING OF NETWORK CONTROLS

4.1 Introduction

The investigation by means of System Dynamics of the model described in Chapter 3 was pursued from the initial construction of the model to the final production of numerical results. In the present Chapter - which deals with various aspects of network control - the generation of the numerical simulation is not discussed. The reason for this omission is that this stage is both fairly straightforward and specific to the particular network being modelled. Thus the analysis will be taken only as far as the influence diagram stage, although some indications will be given as to how to derive the rate equations in each case (these being the most difficult system equations to construct).

Each type of network control will be considered in isolation from the others for reasons of clarity. The modelling of several types of control within a single network is described in Chapter 5.

The effect on switch occupancy of network control traffic is ignored in this Chapter. Although in principle there are no difficulties involved in the incorporation of control traffic into the model, its omission is justified on the grounds of clarity.

4.2 Nodal congestion control

The simplest nodal congestion control requires the node to discard any packets in excess of a certain number. The control policy used for the illustrative example in Chapter 3 differs from this method in that the actual occupancy of the node was allowed to exceed the desired maximum; i.e. excess packets were not discarded.

Consider the simple partial network of fig 6. It contains two switches 1 and 2 which are transmitting packets via a third switch.

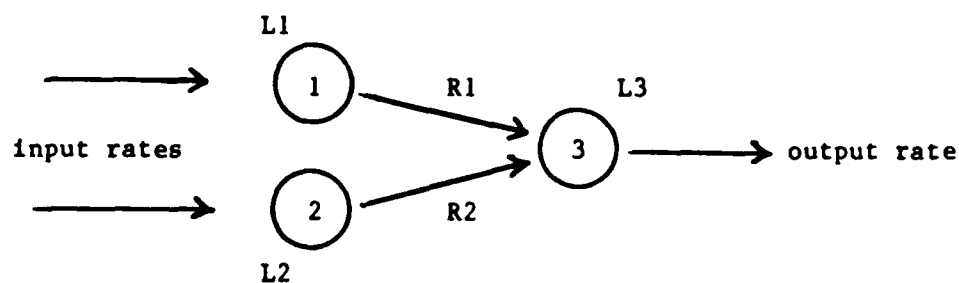


Fig 6 : Partial network for congestion control model

In a realistic network, switches 1 and 2 would of course also be

exercising congestion control. The effects of this are ignored here: the purpose of this Section is to determine the influences directly associated with the control exerted at switch 3.

The influence diagram for the above model is given in fig 7. L_1 , L_2 and L_3 are the occupancies at switches 1,2,3 respectively. The constraints of level positivity, line capacity and finite switch storage have been omitted in order to emphasise the control loops.

The question arises as to whether a decision to discard excess packets in fact constitutes a feedback process. It is a feedback process if the usual time-out and retransmission procedure is implemented at the data-link-control level: the discarding of extra packets then implies that switches 1 and 2 must retransmit these packets. The result is an effective reduction of the rates R_1 and R_2 which is brought about by the control decision at switch 3. This is an important observation which also plays a part in the approximate modelling of the data-link-control protocol, as will be discussed in Section 5.3.

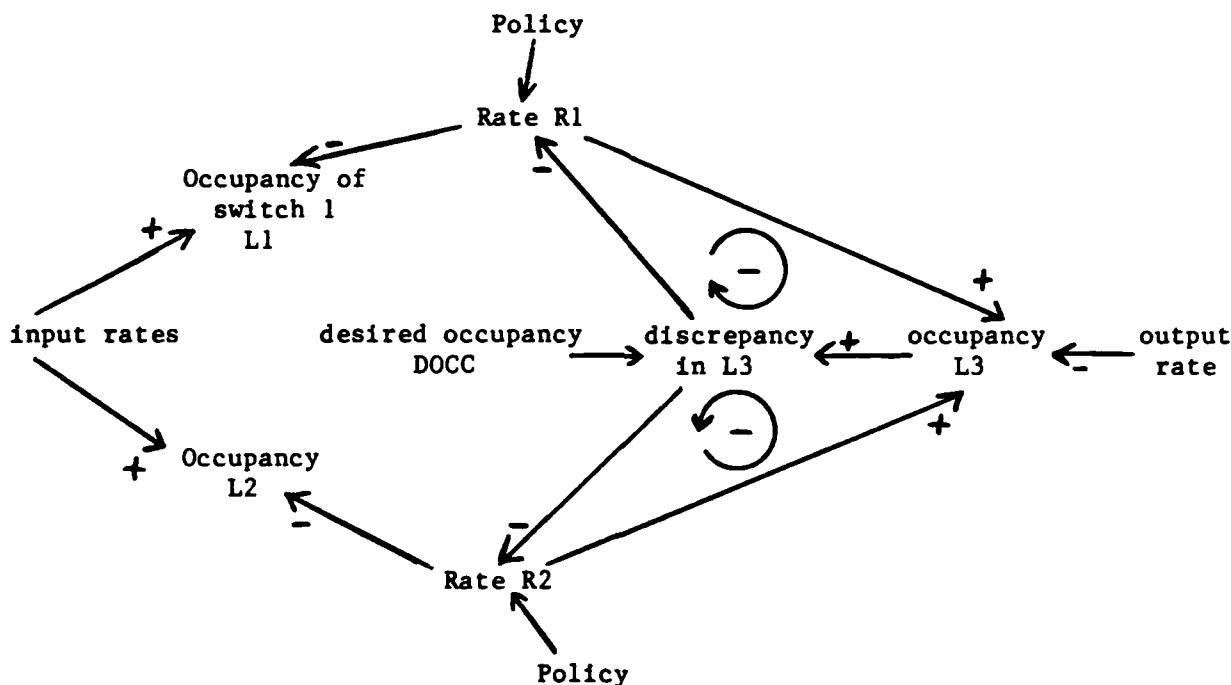


Fig 7 : Influence diagram for nodal congestion control

Finally, the rate equations are similar to those which reflect the presence of finite switch storage, as given in Section 3.3. The rates must not exceed values which would result in excess switch occupancies during the next time interval.

4.3 Window flow control

End-to-end window flow control limits the amount of unacknowledged network traffic associated with each source-destination pair. The influence diagram for this type of control is given in fig 8.

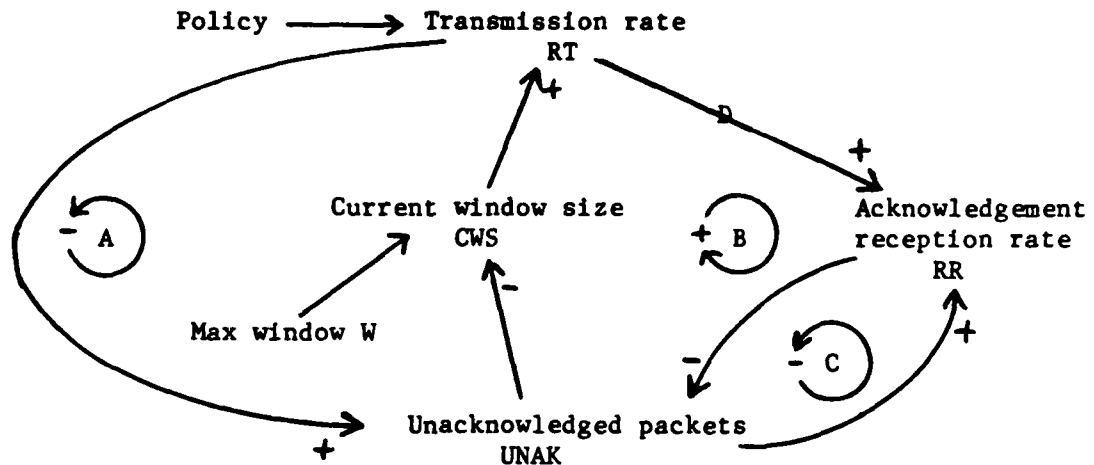


Fig 8 : Influence diagram for window flow control

Loop A is the primary feedback control loop. An increase in the rate of transmission results in a corresponding increase in the number of unacknowledged packets. This decreases the current window size and the transmission rate is then reduced.

The transmitted packets are received at the destination after a network transit delay and acknowledgements are sent to the transmitter. The acknowledgements are received by the transmitter after a further delay and the current window size is increased. This process is represented by loop B in the influence diagram. B is a positive feedback loop: an increase in the transmission rate eventually results in an increase in the acknowledgement reception rate. This implies an increase in the current window size, allowing the transmission rate to grow, and so on.

This behaviour does not of course remain unchecked: the transmission rate may (indirectly) have a positive influence on the current window size via loop B, but it also exerts a direct negative influence via loop A. A further factor which restrains the positive feedback behaviour of loop B is the physical constraint that the reception rate must be zero if there are no outstanding unacknowledged packets. This constraint is represented by loop C.

The formulation of the DYSMAP equations for the system rates and levels is straightforward apart from the case of the acknowledgement reception rate. The delay associated with the influence line from the transmission rate to the acknowledgement reception rate will of course

depend upon the current (and past) state of the subnet, which has not been modelled here. (Incidentally it is undesirable for the acknowledgement traffic to be modelled explicitly in what is intended to be a high-level network simulation: it may be sufficient to introduce a delay which depends in a simple way on the network state.)

Assuming the rate RR to be given (and ignoring other constraints such as line capacities, etc.), the rates and levels are given by the following equations.

$$L \text{ UNAK.K} = \text{UNAK.J} + DT * (RT.JK - RR.JK) \quad (9)$$

$$A \text{ CWS.K} = W - \text{UNAK.K} \quad (10)$$

$$R \text{ RT.KL} = \text{CWS.K} / DT \quad (11)$$

The effect of these equations is to curtail transmission if the current window size is zero, and to allow the transmitter to fill the available window during the next time interval DT if the current window size is greater than zero. (For clarity, these equations do not reflect the presence of constraints such as line capacity, finite switch storage, and the possible unavailability of traffic to be transmitted.)

4.4 Network access flow control

An intuitively obvious method for the avoidance of congestion is to restrict the acceptance of new traffic into the network until the amount of traffic already in the network has been reduced to an acceptable level. A buffer management scheme has been proposed [1] for those subnet switches that are directly connected to hosts. New input traffic may occupy only a certain fraction of the number of buffers in these switches, whereas traffic in transit across the network may occupy any or all of the buffers without restriction. The scheme therefore restricts entry of new traffic into the network whenever the network is congested.

The influence diagram is shown in fig 9.

The level LT is of course subject to rates extraneous to the influence diagram depicted in fig 9. The auxiliary variable LA and rate RI are determined by the equations

$$A \text{ LA.K} = \text{MIN}(NI, BMAX - LI.K - LT.K) \quad (12)$$

$$R \text{ RI.KL} = \text{LA.K} / DT \quad (13)$$

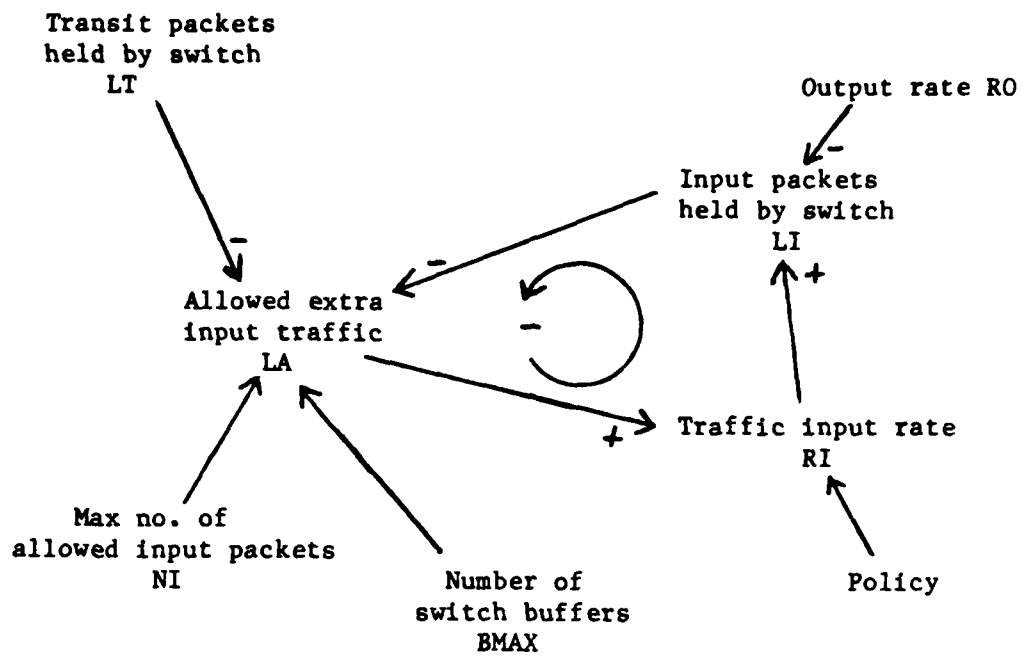


Fig 9 : Influence diagram for network access flow control

4.5 Distributed adaptive routing

In cases where there may be considerable fluctuations in the distribution of traffic to the network, a distributed adaptive routing algorithm is appropriate [1]. A simple example of this type of routing algorithm requires that each switch maintains a "distance table" D of distances (with respect to some metric such as total queue length) from the switch to each destination via each neighbour of the switch. Each switch i is able to measure directly the distance $d(i,l)$ from i to each neighbour l .

If the distance from switch i to destination k via a neighbouring switch l is denoted by $D_i(k,l)$, then the minimum distance $M_i(k)$ from i to k is obviously given by

$$M_i(k) = \min_l D_i(k,l) \quad (14)$$

where the minimum is taken over all neighbours l of switch i . Periodically, each switch i transmits to its neighbours its own table of estimated minimum distances and updates its own distance table according to the equation

$$D_i(k,l) = d(i,l) + M_l(k) \quad (k \neq i) \quad (15)$$

The new minimum distances may now be calculated, and so on.

It is immediately apparent that the modelling of this type of network control within the framework of the DYSMAP simulation language involves the construction of a large number of auxiliary equations for the various distances. A serious drawback of DYSMAP is that no provision is made for modelling of the system variables in array form or for the implementation of program loops. Thus routing algorithms cannot be represented compactly in the DYSMAP input file for large networks. Further discussion of these points may be found in Chapter 5.

We thus restrict this Section to a consideration of the simple partial network of fig 10.

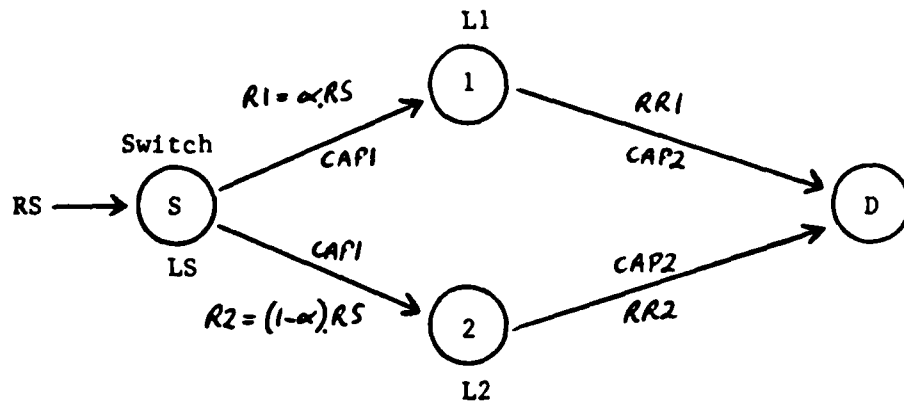


Fig 10 : A simple routing model

The switch S is fed by traffic of rate RS which is intended for a single destination D: the traffic may be routed via switches 1 or 2. The lines connected to switch S and switch D are of capacities CAP1 and CAP2 respectively, with $CAP1 > CAP2$. The routing decision depends upon the switch occupancies L1 and L2. The influence diagram is given in fig 11.

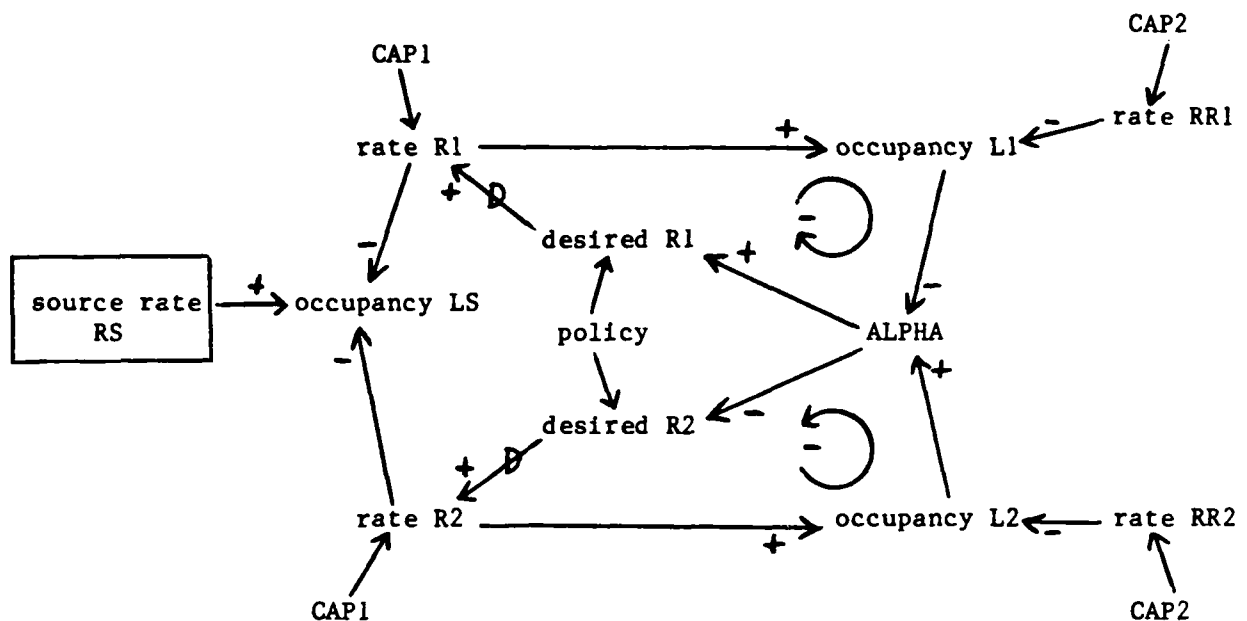


Fig 11 : Influence diagram for routing algorithm

The auxiliary variable α determines the routing. Note that the rules for influence diagram structure [14] do not permit rate-dependent rate equations (apart from the special case of a delay) such as $R1.KL = \alpha.K.RS.KL$. Thus an intermediary level LS is introduced between the rate RS and the rates R1, R2.

A standard routing policy consists of setting α to 0 whenever $L1 > L2$ and setting α to 1 otherwise. Because of the delay between the choice of routing decision and the effect of that decision, oscillatory behaviour occurs in the traffic routing, as may be seen if the appropriate DYSMAP model is constructed. The auxiliary variable α may be modelled by the equation

$$A \text{ } \alpha.K = \text{CLIP}(0, 1, L2.K, L1.K) \quad (16)$$

5. SIMULATION OF LARGE NETWORKS

5.1 Introduction

The material covered in the previous Chapter indicates that it may be possible to construct a simulation of a large network by incorporating the various aspects of network control described in that Chapter into a single model. A simulation so formed would be a high-level (i.e. ISO layer 3) description containing no explicit modelling of the data-link-control protocol; nevertheless it should be of considerable value in assessing the performance (both static and dynamic) of network controls whilst avoiding the complications associated with a conventional network simulation.

Influence diagrams provide an excellent representation of the relationships and control flows between the system variables and give a clear basis for the development of a simulation model. The construction of a single influence diagram for a complete network is however neither necessary nor desirable. It is unnecessary because the different controls are adequately described by separate diagrams, and it is undesirable because the influence diagram would be so convoluted as to be useless. The remainder of this Chapter describes how to create a simulation of a complete network.

5.2 Levels and rates

The first step in constructing the System Dynamics model is to decide which network quantities define the levels and rates. The levels (i.e. the occupancies of each switch) must be labelled by the current switch and the final destination. If the routing algorithm relies upon an estimate of output queue lengths, then the levels may need to be labelled also by the next switch to which the packets are to be routed in order for the output queues to be defined. If window or access flow controls are implemented, then the levels must in addition be labelled by the source. The internal rates deplete the levels and transfer their contents to the levels associated with neighbouring switches: thus the internal rates require the same labels as the levels, plus a label for the next switch if one has not already been included.

The levels and rates are thus naturally represented as arrays with arguments equivalent to the labels already mentioned. The simulation language DYSMAP unfortunately does not allow this.

The following variables are defined:

- $L_i^j.K$ - Occupancy of switch i at time K by packets destined for host j
- $E_i^j.JK$ - Exogeneous input rate at switch i during interval JK of traffic destined for host j
- $R_{ik}^j.JK$ - Internal rate directed from switch i to neighbouring switch k during interval JK of traffic destined for host j

The label for the source has been omitted as it plays no important part in the following discussion.

The general equation for the levels $L_i^j.K$ is given by

$$L_i^j.K = L_i^j.J + DT*(E_i^j.JK - \sum_k R_{ik}^j.JK + \sum_l R_{li}^j.JK) \quad (17)$$

where the above equation applies for all switches i and all destinations j : k and l index the nearest neighbours of switch i . This equation merely reflects the conservation of traffic flow: the amount of traffic accumulated by a switch in any time interval is equal to the amount of exogeneous traffic that arrives, plus the traffic that has been transmitted from neighbouring switches, minus the traffic that has been sent from switch i to its neighbouring switches.

The determination of the rates is of course far more difficult. The rates depend upon the levels via the following constraints:

- (a) The rates into and out of any switch i in the next time interval JK must be such that the levels at time K associated with that switch satisfy

$$0 \leq \sum_j L_i^j.K \leq BMAX \quad \text{for all switches } i$$

i.e. the total number of packets in any switch must be non-negative and less than or equal to the maximum number of buffers in the switch.

- (b) The total traffic rate along any line (i,k) (i.e. the directed line from switch i to switch k) may not exceed the capacity of that line, i.e.

$$\sum_j R_{ik}^j.KL \leq CAP_{(i,k)} \quad \text{for all lines } (i,k)$$

- (c) The total traffic sent from any switch i to its neighbours k during interval KL may not exceed what is stored in switch i at time K , i.e.

$$\sum_{j,k} R_{ik}^j.KL \leq L_i^j.K / DT \quad \text{for all switches } i \text{ and destinations } j.$$

DT is the simulation time increment. The above constraint ensures that no level becomes negative in value.

- (d) Conditions (a),(b) and (c) are physical constraints. In addition to these, the rates are subject to constraints arising from the network controls, as described in the previous Chapter.

A realistic approach to the determination of the rates for a simple 'network' such as that described in Chapter 3 would be to let the rates take the maximum values allowed by the constraints. For a meshed network the calculation is more difficult, as the value assigned to any one rate may affect the allowed values for the other rates (for example, if there is a finite switch storage constraint). The next Section discusses this problem.

5.3 Rates and data-link control

This Report has not so far explicitly described the modelling of the data-link-control (DLC) protocol involved in the transfer of packets from a switch to its neighbours. The present Section investigates how this can be done.

Consider the situation shown in fig 12. Switch A must send 15 packets to switch B, which has room for only 10 packets because all of its other buffers are already occupied. A standard DLC protocol would permit all 15 packets to be sent from A within the next time interval (assuming the window flow control and line capacity permit it). Switch B would acknowledge ten of these packets and discard the other five. Switch A would thus have to retain the unacknowledged packets, and so the effective traffic rate during that interval would be 10 packets per time interval.

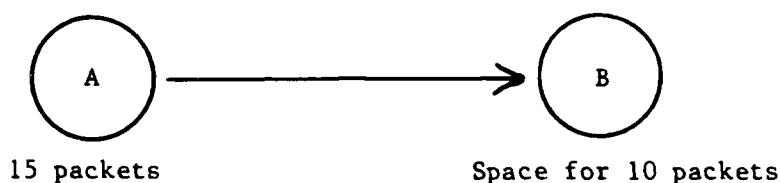


Fig 12 : Data-link-control protocol

This method for assigning the rates was used in Chapters 3 and 4. Such an approach effectively averages out the short-term fluctuations in the traffic arising from the effect of the DLC protocol and replaces this effect by a smooth transfer of traffic over each time interval; the length DT of the simulation time interval must of course be chosen carefully. This approximation for layer 2 of the ISO model results in a considerable simplification of the simulation.

A meshed network (or in fact any network more complex than the simple two-switch 'network' of fig 12) poses a more difficult problem. If switch B of fig 12 is connected to a third switch, then packets may leave B for this switch during the next time interval. This releases space for yet more packets from A during that interval, so in fact more than 10 packets may be sent from A. A further difficulty arises if this situation occurs in a directed circular path consisting of switches A, B and C, for example. An effective rate from A to B cannot be calculated unless we know how much space will be available in B. To find this, we must know what the effective rate is from B to C, but this can only be calculated if the available space in C is known. Unfortunately the space in C cannot be found until the effective rate from C to A is known; this requires a knowledge of the space in A. The space in A cannot be estimated until the rate from A to B is known, but this is what we wished to evaluate in the first place! Similar problems will occur in any meshed network.

Such cyclic dependencies can only be resolved by an iterative procedure which roughly models the effect of the DLC protocol by sharing the switch buffers equally between the traffic from neighbouring

switches. Thus the determination of the allowed rates rests upon the solution of a set of simultaneous equations with nonlinear constraints, for which an efficient iterative algorithm is required. The scope of the present Paper precludes further discussion of this point.

5.4 The DYSMAP simulation package

The DYSMAP software provided by the University of Bradford [14] is ideal for modelling simple partial networks or describing communication systems at a high level (i.e. where the subnet is approximated by a single entity - rather than modelled as a network of individual switches - as part of a larger command and control system, for example). Unfortunately it is less useful for the detailed simulation of a network as described in this Paper because no provision is made within DYSMAP for the utilisation of arrays and program loops. It is possible to devise an input program which converts a network specification (e.g. its topology, line capacities, etc.) into a set of DYSMAP statements, but the absence of arrays and loops necessitates the construction of a very large DYSMAP input file containing many levels and auxiliary variables.

A more realistic approach is to write the simulation program directly, whilst adhering strongly to the System Dynamics methodology. Thus the model must obey the following rules: levels affect rates (possibly via auxiliaries) but do not affect other levels, whilst rates integrate into levels and cannot affect other rates except where mediated by delays. These rules of course constitute the requirements for a correctly-structured influence diagram.

6. CONCLUSIONS

This Paper has advanced a claim that the methodology of System Dynamics constitutes a sound basis for the description and simulation of various network controls at a level which is non-trivial yet easily understandable. The aid provided by influence diagrams in the representation of influences and control flows is invaluable in the construction of a high-level network simulation.

The important concept of approximating the DLC protocol (i.e. ISO layer 2) by a simple algorithm which is not concerned with the identities of individual packets should be instrumental in reducing the complexity of the network simulation to a manageable level. Apart from being desirable for its own sake, such simplicity implies that the simulation may be readily incorporated into a higher-level network management model.

It is not practicable to develop a simulation of a large meshed network using the DYSMAP software package because the DYSMAP simulation language is too limited. Nevertheless a useful simulation can be constructed from scratch in a consistent and accurate manner if the basic techniques of System Dynamics are adopted.

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Abstract The difficulties involved in the evaluation of the performance of adaptive controls in communications networks are discussed. Current analytical tools are assessed and the System Dynamics technique is described. The application of System Dynamics to the investigation of various network controls is discussed and results are given for some simple examples, including nodal congestion control, sliding window flow controls, and adaptive routing. Finally, the relevance of System Dynamics to the simulation of large realistic networks is examined and conclusions are presented.				

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