

CHAPTER 5

STATE DEPENDENT VIRTUAL PATH MANAGEMENT IN ATM NETWORKS

5.1 Introduction

The steady state deterministic LP model is useful as a basis for finding an optimal VPC pool, as shown in chapter 4. However, the basic steady state model has limitations in the case of large traffic fluctuations or major network failures because it determines an optimal VP pool for the new steady state, but does not solve for optimum transient behaviour. Although the steady state solution should be broadly relevant, there are constraints on how rapidly traffic can be moved from one resource to another, so the model should take some account of the existing state of the network. Existing connections normally can only release resources as the number of connections declines through natural completions. Resources, such as bandwidth, that relate to the number of existing connections, can only be released at the lower limit of the birth-death process. This lower limit applies when no new connections are being accepted. Similarly there is a limit to the rate at which connections can occupy newly available resources. This is the upper limit of the birth-death process, with all available connection attempts being accepted. These two constraints should be included in the optimisation model if possible.

A dynamic optimisation model was explored, based on maximising the objective function over a control interval much less than the transient time, but this proved to have poor steady state performance when tested by event-by-event simulation. This dynamic optimisation model was not explored further. To address both the transient and steady state performance requirements, an approach is proposed which is intended to retain the “sense of direction” of the steady state solution but keep within constraints based on the maximum feasible rate of change of state. This traffic optimisation model is called the State Dependent Virtual Path Management model (SDVPM).

The SDVPM model solves for optimal VPC topology and VPC capacity assignment based on the current state of the network (VCCs) and a forward estimate of the traffic

parameters. This is a steady state deterministic model, but with additional constraints which represent the feasible upper and lower limits to the change of VCCs in each control interval. We assume that the state of the network is known, the expected rate of incoming traffic is known, and that the upper and lower limits to VCC capacity are determined by the mean birth and death process of a Markov model as shown in appendix I.

5.2 Improvement of Virtual Path Management Model

The model proposed here is a further development of the VP management model of chapter 4. The model is as proposed for steady state optimisation, but with additional constraints on the rate of change of state.

The following notation is used:

$r_{i,j}$ is the number of routes allowed for VPC from origin i toward destination j .

$h_{i,j}^t$ is the VCC holding time for traffic type t from origin i to destination j .

$b_{i,j}^t$ is the effective bandwidth demand per VCC for traffic type t from origin i to destination j .

$v_{i,j,k}^t$ is the VPC capacity for traffic type t from origin i to destination j along route k for $k = 1, 2, \dots, r_{i,j}$.

$v_{i,j,\bullet}^{t-att}$ is the bandwidth of requests for VCC attempts for traffic type t from origin i to destination j for all the paths. It is the predicted value of future demand.

$\phi_{t,i,j,k}^e$ is the indicator variable which takes the value 1 if the stream of attempts for traffic type t from origin i to destination j via VPC k must pass through the link identified by e .

S^e is the state limit of the link identified by e .

$t_{i,j}^t$ is the tariff rate (in dollars per unit of time) charged for a VCC for traffic type t from origin i to destination j .

$\bar{n}_{i,j}^t(T)$ is the mean number of VCCs for traffic type t at time T from origin i to destination j .

$n_{i,j}^0$ is the number of connections in progress at management time from origin i to destination j .

5.2.1 Flow constraint

The flow constraint is as for chapter 4. The flow of offered traffic is a constraint in the sense that accepted VCCs can never exceed offered VCCs. It can be form as

$$\sum_{k=1}^{r_{i,j}} v_{i,j,k}^t \leq v_{i,j,\bullet}^{t-att} \quad (5.1)$$

5.2.2 Link constraint

The link constraint is as for chapter 4. Each link is considered as a state limiter which can accept traffic until its average bandwidth demand reaches the capacity of the link. It can be form as

$$\sum_{t,i,j,k} \phi_{t,i,j,k}^{l(v)} v_{i,j,k}^t \leq S^{l(v)} \quad (5.2)$$

5.2.3 Node constraint

The node constraint is as for chapter 4. For every rate limiter (node), there is an inequality constraint on the rate of connection arrivals, for all traffic types of the form

$$\frac{1}{h_{i,j}^t b_{i,j}^t} \sum_{t,i,j,k} \phi_{t,i,j,k}^{n(u)} v_{i,j,k}^t \leq R^{n(u)} \quad (5.3)$$

5.2.4 Virtual connection state constraint implementation

In this section, we propose new constraints on the rate of change in VPC capacities. The new constraint equations have been classified into upper and lower bounds on VPC capacities.

5.2.4.1 Upper bound

The upper bound constraint represents the upper limit on the VPC capacity that can feasibly be occupied during the next VPC management interval, based on the current state of the network and the incoming rate of connection attempts for that VPC.

From the birth-death process in appendix I, the mean number of VCCs at the next management time t^+ from origin i to destination j is

$$\bar{n}_{i,j}^t(t^+) = x_{i,j,\bullet}^{t-att} h_{i,j}^t + (n_{i,j}^0 - x_{i,j,\bullet}^{t-att} h_{i,j}^t) e^{\frac{-t^+}{h_{i,j}^t}} \quad (5.4)$$

where it is assumed that all $x_{i,j,\bullet}^{t-att}$ attempts are admitted. $x_{i,j,\bullet}^{t-att}$ can be derived from the LP model variable $v_{i,j,\bullet}^{t-att}$ by

$$x_{i,j,\bullet}^{t-att} = \frac{1}{h_{i,j}^t b_{i,j}^t} v_{i,j,\bullet}^{t-att} \quad (5.5)$$

The upper bound constraint on VPC capacity is

$$\sum_{k=1}^{r_{i,j}} v_{i,j,k}^t \leq \bar{n}_{i,j}^t(t^+) b_{i,j}^t \quad (5.6)$$

5.2.4.2 Lower bound

The lower bound constraint represents the lower limit on VPC capacity that can feasible be occupied at the end of the next VPC management interval, based on the current state of the network. This constraint is intended to ensure that capacity is not allocated elsewhere if it will still be occupied by connections yet to be released by natural terminations.

The lower limit on VPC capacity can be found from (5.4) based on blocking of all new connection attempts. The lower bound constraint is

$$v_{i,j,k}^t \geq \bar{n}_{i,j}^t(t^+) b_{i,j}^t, x_{i,j,\bullet}^{t-att} = 0 \quad (5.7)$$

5.2.5 Objective function implementation

The objective function is of the same form as used in chapter 4

$$f = \sum_{t,i,j,k} (\alpha_1 \frac{t_{i,j}^t}{b_{i,j}^t} v_{i,j,k}^t + \alpha_2 \frac{1}{h_{i,j}^t b_{i,j}^t} v_{i,j,k}^t) \quad (5.8)$$

Where the two terms in the summation represent the rate of revenue and the rate of accepted VCCs. The weighting coefficients are as follows:

α_1 is the weighting coefficient for revenue. It is a dimensionless quantity.

α_2 is the weighting coefficient for accepted VCCs. It is expressed in units of number of VCCs.

5.2.6 Summary of state dependent virtual path management (SDVPM) model

The SDVPM model can now be written as:

Maximise

$$f = cv \quad (5.9)$$

Subject to

$$Av\{\leq, \geq\}^* b \quad (5.10)$$

* Designates either \leq or \geq .

$$v \geq 0 \quad (5.11)$$

where:

f is the objective function value which is to be maximised.

c is the row vector of cost coefficients, as determined by the choice of weighting coefficients in the objective function.

v is the column vector of independent variables ($v_{i,j,k}^t$ for $k = 1, \dots, r_{i,j}$).

A is the matrix of coefficients representing network connectivity and the traffic parameters, such as average hold times and effective bandwidth per VCC; termed the “technological” matrix.

b is the column vector of right hand side terms, associated with the constraints on offered traffic, network resources and network state.

It can be seen that equation (5.9) is the abbreviated form of the objective function as defined in equation (5.8). Equation (5.10) is the abbreviated form of the flow, link and node constraints as defined in equations (5.1), (5.2), (5.3), (5.6) and (5.7) respectively.

5.3 Performance Evaluation of State Dependent Virtual Path Management Model

In this section, we assess the performance of state dependent virtual path management (SDVPM) during a major transient period. A comparison of the transient performance between the two models (DVPM model in chapter 4 and SDVPM in section 5.2) shows that SDVPM adapts the VP pool in a robust fashion to achieve a high level of network utilisation and revenue during the transient period following the link failure.

5.3.1 Sample problem

The network configurations, traffic parameters and control mechanisms are as chosen in chapter 4 except that the SDVPM optimisation model is used for updating the VP pool. Again the case of a major link failure is used to evaluate the transient performance after the failure (see Figure 5.1). The link capacity between node n3 and gateway g of the network is set from 155 Mbit/sec to 0 Mbit/sec at 100 sec to represent the loss of the link.

Tariff rate and mean VCC attempt rate are shown again in Table 5.1. As before the tariff rate for interstate connections is twice that on local connections. The arrival process of VCC attempts is represented as a Poisson process. Each VCC requires an effective bandwidth of 50 kbit/sec. The average VCC holding time is 180 sec with negative exponential distribution.

In the simulation, the routing algorithm and VP pool update time have been chosen to be the same as in chapter 4. The routing method is to route a VCC on a direct VPC. If a VCC cannot be routed on a direct VPC, it will be blocked. If there is more than one direct VPC, the preferred VPC is that with less physical links. The VP pool is updated every 1/3 of a mean holding time (60 sec).

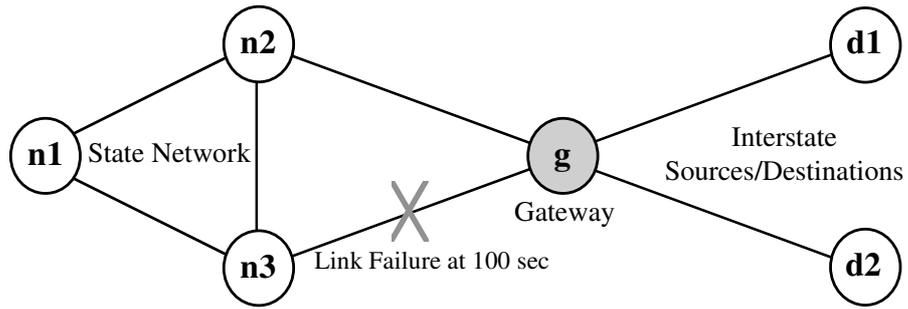


Figure 5.1: Sample 6 Node Network.

Table 5.1: Tariff Rate and VCC Attempt Rate.

Origin	Destination	Tariff (\$/Mbit)	VCC attempt (/sec)
N1	n2	0.01	13
N1	n3	0.01	13
N2	n3	0.01	13
N1	d1	0.02	4
N1	d2	0.02	4
N2	d1	0.02	5
N3	d2	0.02	5

5.3.2 Sample results

We are interested in the effect of the network control scheme on revenue during the transient following the link failure shown in Figure 5.1. For evaluation purposes, the transient period of the network is taken to be one mean holding time (180 sec) from the first VP pool update following the network failure (120 sec – 300 sec). The revenue over this time is converted to a mean event-by-event revenue rate during the transient period for each scheme (DVPM and SDVPM). This is then compared with the mean steady state revenue forecast by the LP solution for the network after failure.

The ideal steady state revenue after the failure is 122.37 \$/sec. During the transient period, using SDVPM to manage the VP pool, the network provides a mean revenue rate of 111.65 \$/sec or 91.24% of the ideal steady state revenue. DVPM provides a mean revenue rate of 108.39 \$/sec or 88.58% as shown in Table 5.2. The loss of revenue

over the transient period is thus 8.76% for SDVPM and 11.42% for DVPM, relative to the optimal steady state.

Table 5.2: The mean event-by-event revenue rate.

	Event-by-Event Revenue Rate (\$/sec)
At steady state	122.37 (100%)
SDVPM*	111.65 (91.24%)
DVPM*	108.39 (88.58%)

* during transient period.

5.3.3 Main features

The transient behaviour of revenue is shown in Figure 5.2 for the DVPM and SDVPM schemes. For each the ideal revenue, based on the latest LP solution, is shown together with the event-by-event revenue rate. As can be seen from the graphs, when the network loses the link at 100 sec, all of the connections on the lost link are assumed terminated, and so have an immediate effect on the ideal revenue rate and the event-by-event revenue rate. When the VP pool is re-solved at 120 sec, both DVPM and SDVPM reallocate VP pool capacity in search of higher revenue rate from the damaged network. As shown shortly after the network failure, the ideal revenue rate of DVPM is higher than SDVPM. However the VP pool for DVPM results in lower event-by-event revenue rate than that for SDVPM. This is because the DVPM model provides a new VP pool based on a new steady state solution, but the network needs time to recover resources from connections already in progress.

DVPM suddenly tries to remove capacity from some VPCs and fill this capacity with new connections from preferred traffic streams, but these resources are not available for use by new connections until the previous connections have been released. On the other hand SDVPM gradually removes capacity from non-favoured VPCs and transfers it to favoured VPCs based on the rate of terminating and incoming of VCCs.

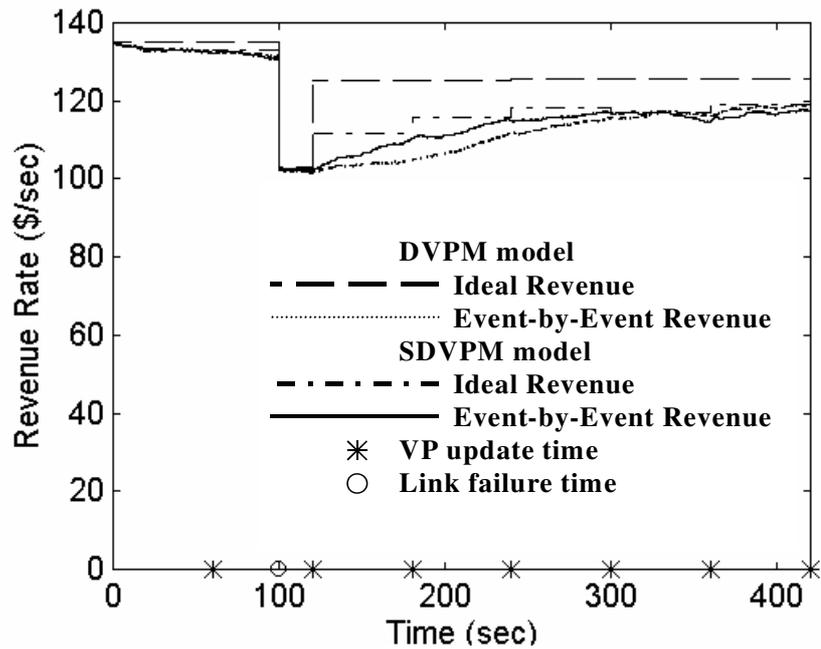


Figure 5.2: Ideal and Event-by-Event Revenue Rate from DVPM and SDVPM models.

Figures 5.3 and 5.4 show how SDVPM manages this gradual transfer of capacity, referring to particular streams of traffic within the network. Figure 5.3:(a and c) and Figure 5.4:(a and c) show bandwidth allocation and mean blocking rate for non-favoured streams (from node n1 to node n2 and from node n2 to node n3). When compared with the DVPM model (Figure 4.2:(a and c) and Figure 4.3:(a and c)), it can be seen that the mean blocking rate with DVPM is much higher for stream n2 to n3 than with SDVPM after the link failure. This is because DVPM completely shuts off incoming VCCs from n2 to n3 after the network failure on the assumption that extra capacity is required for connections from n3 to d2. SDVPM more gradually blocks the incoming VCCs on non-favoured paths so that capacity is released only at the rate at which it can be used productively by a favoured path.

Figure 5.3:(d, e, f and g) and Figure 5.4:(d, e, f and g) show bandwidth allocation and mean blocking rate on favoured traffic streams (node n1 to node d1, node n1 to node d2, node n2 to node d1 and node n3 to node d2) for the SDVPM model. The mean blocking rate and bandwidth usage are very similar to DVPM because SDVPM appropriately increases VPC capacity to support incoming VCCs before the next management time.

As can be seen, although SDVPM carefully rations excess bandwidth allocation on favoured paths (n3 to d2) this does not lead to increased blocking relative to DVPM. The careful rationing of SDVPM does succeed in reducing the blocking rate for non-favoured paths (because these paths are able to continue to accept connections which are blocked under DVPM). As a result, total revenue increases during the transient period under SDVPM. With both SDVPM and DVPM, revenue is equally high when the network is stable.

5.4. CONCLUSIONS

The SDVPM model has been proposed for optimal real-time management of the VP pool in an ATM network. The model is a modification of a steady state deterministic model which takes current network state and traffic parameters into an account to determine the optimal traffic flow for the next control period. This set of optimal flows can be used for VP pool management, to control CAC and routing in a simple and effective manner. The simulation example shows that both the DVPM model and SDVPM model provide sophisticated management of the VP pool in response to a network failure. SDVPM achieves higher revenue during the transient period by matching the movement of VPC capacity to the maximum rate at which traffic can be moved to new paths. The result shows that SDVPM can provide elegant and robust management of the VP pool in the face of major disturbances such as failure of a link.

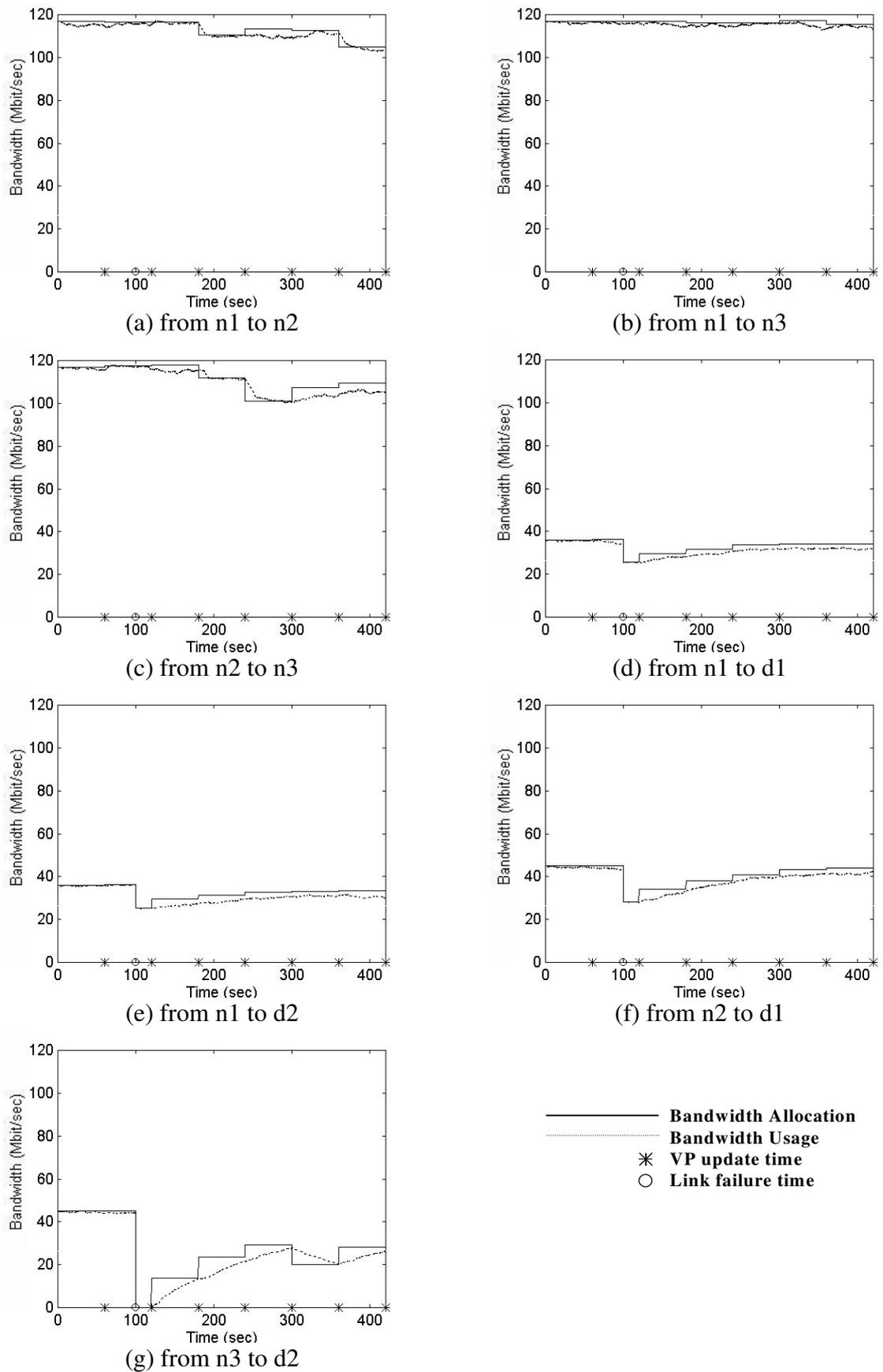
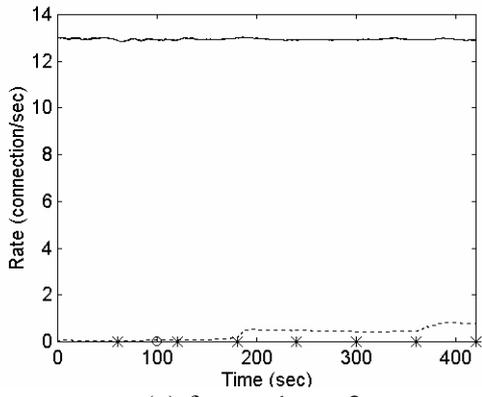
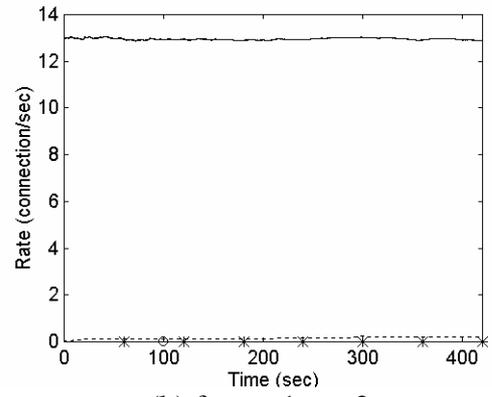


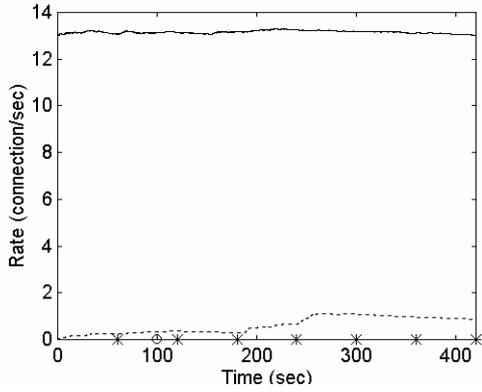
Figure 5.3: Total Bandwidth Allocation and Total Bandwidth Usage from SDVPM.



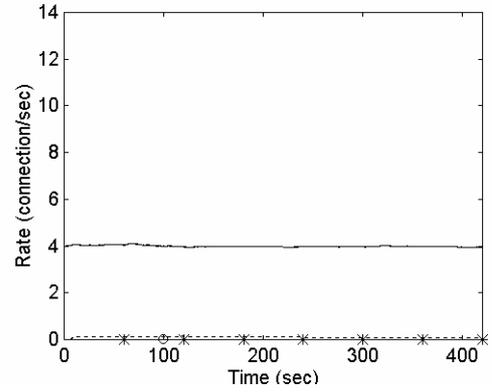
(a) from n1 to n2



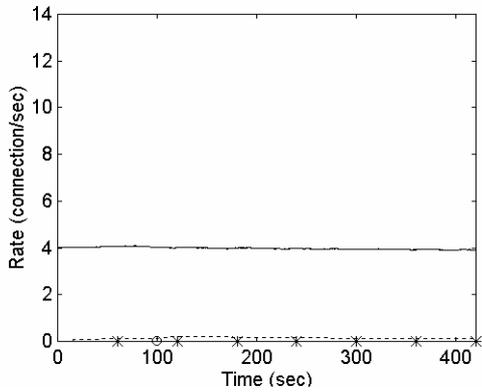
(b) from n1 to n3



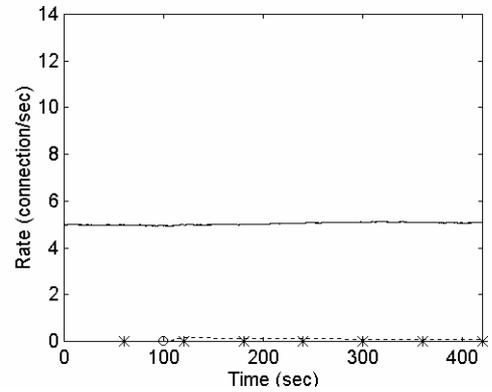
(c) from n2 to n3



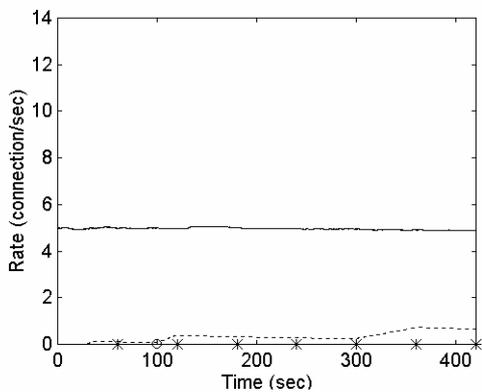
(d) from n1 to d1



(e) from n1 to d2



(f) from n2 to d1



(g) from n3 to d2

— Mean Offered Rate
 - - - Mean Blocking Rate
 * VP update time
 ○ Link failure time

Figure 5.4: Mean Offered Rate and Mean Blocking Rate from SDVPM.

CHAPTER 6

DEVELOPMENT OF AN OPTIMISATION MODEL FOR THE INTERNET

6.1 Introduction

The original intention of this research was to explore the idea of optimising traffic management resource utilisation in ATM networks and the Internet. The unexpected/surprising outcome is the proposition that ATM networks and the Internet can usefully be viewed in a very similar fashion, based on an approach originally proposed for circuit-switched network. Although this is initially unexpected (because of the different philosophies of ATM networks and the Internet), it is not unreasonable, since these two (ATM and Internet) must coexist, and ultimately share the same objectives of handling an unlimited range of services in a competent and efficient fashion.

Inevitably, if similar models/approaches are being proposed for supposedly unlike networks, there appear initially to be some major inconsistencies between the two types of network, and it appears improbably that a uniform model can apply to both. The work undertaken here attempts to address and resolve these inconsistencies.

6.1.1 Connection-oriented versus connectionless networks

Connection-oriented and connectionless traffic and resource management systems would appear to require different models, but if connectionless traffic is viewed as being connections with very short holding time, then techniques that are suitable for managing connection-oriented networks can be applied also to connectionless traffic (of course with some implications regarding the amount of processing resources required relative to connection-oriented networks). The following example shows that the overlap between connection-oriented and connectionless networks. Connectionless traffic might originate as TCP/IP datagrams, but then be carried in one part of its journey over an ATM network. In the ATM network, each datagram will appear as a burst of cells, each handled as a connection with short holding time.

6.1.2 TCP/IP versus resource reservation for QoS guarantees

TCP/IP flow control appears at first sight to be at odds with resource-reserved QoS-guaranteed streams. A reasonable visualisation is that TCP/IP traffic will “fill the gaps” after the needs of QoS guaranteed streams have been met. It appears at first sight to be a nonsense to propose that TCP/IP traffic should be modelled and controlled (or managed) in the same way as QoS guaranteed traffic. But Pitsillides [PIT93] [PIT94a] [PIT94b] and Hu [HU94] [HU95a] [HU95b] have demonstrated that delay-tolerant traffic (e.g. TCP/IP traffic) can operate with high efficiency and low cell loss together with delay sensitive traffic. The delay-tolerant traffic is essentially manipulated so that the aggregate of delay-sensitive and delay-tolerant traffic is smoothed. This smoothing relies largely on reactive feedback control. This view is consistent with a traffic and resource management scheme that

- (a) reserves resources for QoS guaranteed traffic (e.g. using RSVP in a connection-oriented, CAC protected fashion) and
- (b) reserves resources (albeit at lower priority level) for delay-tolerant traffic such that some minimum performance criterion is met (where the accuracy of this minimum performance achievement is determined by the accuracy of CAC forecasts – a soft guarantee)

6.1.3 For whom should we optimise?

The Internet involves a loosely integrated community of service providers, who operate on a competitive/cooperative basis. In seeking to optimise the Internet, should we use a game theoretic approach, and if so how can we model all the significant players? The approach used here is to take the viewpoint of the user population, and seek to optimise user satisfaction. Optimal resource management then means the management of given network resources to maximise the network performance from the perspective of the user community. This maximum performance can be measured either in terms of throughput or of revenue since, for a given tariff structure, maximising throughput also maximises the revenue transferred from the user to the community of service providers.

Most research work (e.g. [LEE93], [LIA94] and [KOR95c]) has principally focused on the problem of improving performance from the designer’s viewpoint, but our problem

statement is as follow: We wish to maximise network (Internet) performance with guaranteed QoS by solving for the optimum connection rate of a given network with given user demand. In the case of some traditional TCP/IP delay-tolerant services, the QoS guarantee we have in mind may simply reduce to a minimum acceptable mean bandwidth for the service to be satisfactory to the user.

6.1.4 A model for Web browsing

For Web browsing users, the task of the network is to connect users to services. Our model for traffic flows is shown in Figure 6.1. The language used is that there is a demand by users for services, but Figure 6.1 shows that there is a small amount of request traffic from user to service and a large amount of information flow back from service to user. The user requested traffic is assumed to represent a small amount of load in the network when compared with the backward traffic stream of the service. In this work “source” is the originator of user requests. “Destination” is the location of the service. The backward traffic streams comprising the service are treated as having known characteristics and known minimum bandwidth requirements.

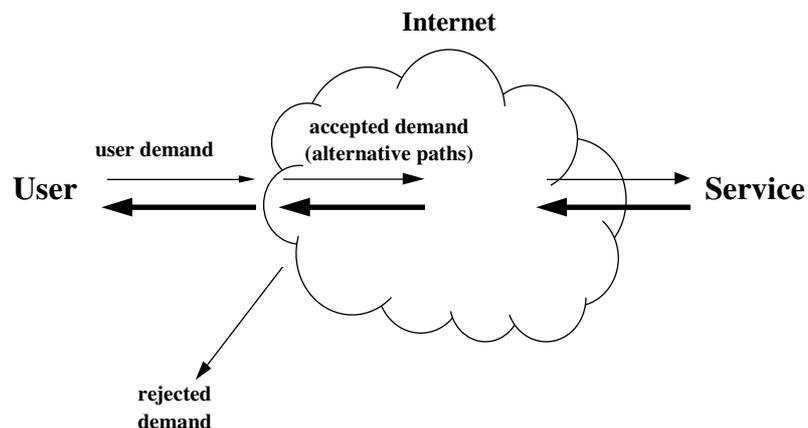


Figure 6.1: Traffic Flow.

We consider a network topology as show in Figure 6.2. The network consists of users connected to the network resources (link, router and server). Network resources provide users with access to services. A service is located on a machine, called a server.

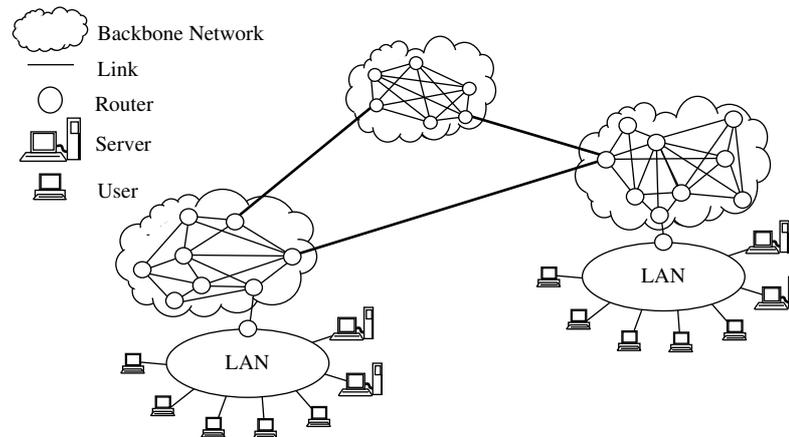


Figure 6.2: Network Topology: (logical or physical).

The nature of the scarcity associated with various network resources is shown in Table 6.1.

Table 6.1: Network Resources.

TYPE OF RESOURCE	NATURE OF SCARCITY
Link (link capacity)	Transmission bit rate
Router (processing rate)	Datagram processing rate
Server (processing rate)	Number of connections

For Web browsing, we classify the servers into three kinds as follows:

- Primary server – a Web server that is the master source for the service.
- Mirror site - a Web site that contains a copy of a service available from a primary server.
- Proxy server – a Web server that offers local caching of recently requested services for a group of users.

The detailed concept of these servers can be found in appendix II.

6.1.5 A model for resource-reserved services and QoS guarantees

The problem of allocating key network resources to different traffic types is a difficult problem to solve. Different traffic types have a complex range of source behaviours and QoS requirements.

Resource ReSerVation Protocol (RSVP) [ZHA93a] [ZHA93b] seeks to address the problem of allowing the appropriate resources to be reserved to meet the needs of each connection. To reserve resources along the path, the router has to understand the demands that are currently being made on its assets and connection admission control (CAC) can be applied [JAM92]. If sufficient capacity remains in the network, a reservation for that capacity can be put in place. If insufficient capacity remains, the CAC will be refused but the traffic could be still be forwarded with no guarantee on QoS.

Because RSVP provides a minimum bandwidth guarantee for end-to-end connections and focuses on the connection-level, the concept of effective bandwidth can be used to simplify the wide range of QoS requirements of multi-traffic types.

6.1.6 A unified model for Web browsing and QoS guaranteed services

It is argued above that, whether considering “best effort” (e.g. Web browsing or TCP/IP) services, or QoS guaranteed services (e.g. services using RSVP), the model requirements are remarkably similar. Each needs some form of CAC. Each needs some minimum level of resource allocation. We go on to use an argument based on the concept of effective bandwidth, and we assume that accepted connections can be carried with guaranteed QoS, provided that the required bandwidth resources are allocated. A linear programming model can then be used to model the Internet resource allocation problem. We assume that any connection admitted to the network will not be rejected within the network, so that end-to-end transmission will occur without unacceptable congestion or loss. It is assumed that the network will not admit any connection that would be interrupted before completion (due to congestion or loss). Such connections we assume would be rejected by using CAC or other protective controls at the network edge. Using the effective bandwidth concept allows us to model flows in the network as

if they were steady state deterministic flows. A type of multicommodity flow problem can then be used to represent the behaviour of the Internet.

In addition to the bandwidth considerations above, our model needs to allow for the other kinds of resource constraints listed in table 6.1 (router processing rate (datagram rate) and server processing rate (connection rate)).

6.2 Model Implementation

The model is similar to that for broadband multimedia networks in chapter 3, but expressed here in terms of Internet resources. The key resources are modelled approximately as saturating devices. The capacity of key network resources is included in the constraints of the model. The problem is to maximise an objective function which allows a choice of weighting between revenue based on connection time and connection rate. Weighting coefficients are provided to allow a selected balance between two performance measures.

The proposed model considers four types of constraint:

- Link capacity (bandwidth)
- Router capacity (datagram processing rate)
- Server capacity (number of connections)
- User demand (which is a limited resource in the sense that accepted demand can never exceed offered demand from users)

Once any resource limit is reached, it is assumed that the resource will be protected by appropriate network management action. The network management action assumed here is “preventive” such as selective blocking of new connections by the CAC, but might also be “reactive” such as negotiated source rate adaptation.

The model is expressed as a Linear Programming model:

Maximise

$$f = cx$$

Subject to

$$Ax = b$$

$$x \geq 0$$

where

f is the objective function value which is to be maximised.

c is the row vector of cost coefficients in the objective function.

x is the column vector of independent variables including the flows along all permitted paths and one variable for each equality constraint. Elsewhere in the text, these are referred to as “slack” variables, reflecting their origin in a conversion from the $Ax \leq b$ form to $Ax = b$ form.

A is the matrix of constraint’s coefficients, termed the “technological” matrix.

b is the column vector, associated with the right hand side constraints.

The following notation is used:

n is the number of routers in the network.

l is the number of links in the network.

s is the number of servers in the network.

$r_{i,j}$ is the number of paths permitted for connection attempts from user i toward service j .

$x_{i,j,k}^{t-acc}$ is the rate of accepted connection attempts for data type t from user i to service j along path k for $k = 1, 2, \dots, r_{i,j}$; it is expressed in units of connections per second.

$x_{i,j}^{t-att}$ is the user attempt rate for traffic type t from user i toward service j ; it is expressed in units of connections per second.

$b_{i,j}^t$ is the minimum acceptable mean bit rate for a connection of data type t from user i to service j ; it is expressed in units of Mbit per second.

$h_{i,j}^t$ is the connection holding time for data type t from user i to service j ; it is expressed in units of second.

$c_{i,j}^t$ is the mean size of datagrams transmitted from user i to service j for data type t ; it is expressed in units of Mbit.

L^e is the capacity limit of the link identified by e ; it is expressed in units of Mbit per second.

R^e is the processing limit of the router identified by e ; it is expressed in units of datagrams per second.

S^e is the processing limit of the server which provides the service identified by e ; it is expressed in units of number of simultaneous user connections.

$\phi_{i,i,j,k}^e$ is the indicator variable which takes the value 1 if the stream of traffic type t from user i to service j via path k affects the network element (link, router or server) identified by e .

$t_{i,j}^t$ is the tariff rate charged per connection time for a successful connection from user i to service j for data type t ; it is expressed in units of dollars per second.

$d_{i,j}^t$ is the tariff rate charged per Mbit for transmitting data type t from user i to service j ; it is expressed in units of dollars per Mbit.

6.2.1 User demand constraint implementation

The user demand constraint limits the traffic flow available to the network. It is not possible for the traffic flow in the network to be greater than the offered demand. In other words, the summation of traffic from user i to service j for all paths cannot be greater than the user offered traffic from i to j for each traffic type t .

$$\sum_{k=1}^{r_{i,j}} x_{i,j,k}^{t-acc} \leq x_{i,j,\bullet}^{t-att} \quad (6.1)$$

This can be converted to equality form by adding a slack variable for user demand from user i to service j ($x_{i,j}^{t-rej}$). The slack variable, $x_{i,j}^{t-rej}$, is the rate of rejected attempts for traffic type t from user i toward service j , for all paths from i to j .

$$\sum_{k=1}^{r_{i,j}} x_{i,j,k}^{t-acc} + x_{i,j}^{t-rej} = x_{i,j,\bullet}^{t-att} \quad (6.2)$$

6.2.2 Link constraint implementation

Each link is modelled as a simple state limiter, which can accept traffic until its average bandwidth demand reaches the capacity of the link. The summation of all the traffic flow cannot be greater than the capacity of the link. The total bandwidth depends on the bandwidth per connection, connection holding time between the user and service, and

the connection acceptance rate. For each link, an inequality constraint on the bandwidth of connections in progress for all traffic types is of the form:

$$\sum_{t,i,j,k}^{l(v)} \phi_{t,i,j,k}^{l(v)} h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t-acc} \leq L^{l(v)} \quad (6.3)$$

This can be converted to equality form by adding a slack variable for link v ($x^{l(v)}$). The slack variable $x^{l(v)}$ represents the available capacity for each link.

$$\sum_{t,i,j,k}^{l(v)} \phi_{t,i,j,k}^{l(v)} h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t-acc} + x^{l(v)} = L^{l(v)} \quad (6.4)$$

6.2.3 Router constraint implementation

Each router in the network is modelled as a rate limiter. This rate limit is based on the processing power required to control the routing of datagrams. It is assumed that the router will process all datagram arrivals provided the rate of these arrivals is below a specified limit. The solution assigns an appropriate router workload to each router along the path for each component of traffic flow in the network. For each router, an inequality constraint on the processing of datagram arrivals for all traffic types can be expressed as:

$$\sum_{t,i,j,k}^{n(u)} \phi_{t,i,j,k}^{n(u)} \frac{h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t-acc}}{c_{i,j}^t} \leq R^{n(u)} \quad (6.5)$$

This can be converted to equality form by adding a slack variable for node u ($x^{n(u)}$). The slack variable $x^{n(u)}$ represents the available capacity for each node.

$$\sum_{t,i,j,k}^{n(u)} \phi_{t,i,j,k}^{n(u)} \frac{h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t-acc}}{c_{i,j}^t} + x^{n(u)} = R^{n(u)} \quad (6.6)$$

6.2.4 Server constraint implementation

Each server is modelled as a state limiter, which can accept connections to a service up to some maximum number of connections. The connection-load is allocated to the destination server providing the service, whether that is a mirror service site or the primary service site. The same service may be available from different servers. For each server, an inequality constraint on connections to service can be expressed as:

$$\sum_{t,i,j,k}^{s(j)} \phi_{t,i,j,k}^{s(j)} h_{i,j}^t x_{i,j,k}^{t-acc} \leq S^{s(j)} \quad (6.7)$$

This can be converted to equality form by adding a slack variable for server j ($x^{s(j)}$). The slack variable $x^{s(j)}$ represents the available capacity for each server.

$$\sum_{t,i,j,k}^{s(j)} \phi_{t,i,j,k}^{s(j)} h_{i,j}^t x_{i,j,k}^{t-acc} + x^{s(j)} = S^{s(j)} \quad (6.8)$$

6.2.5 Objective function implementation

The objective function considered here has two terms which deal with revenue based on connection time and successful connection rate. The objective function uses a weighted linear combination of the independent variables and is of the form

$$f = \sum_{t,i,j,k} (\alpha_1^t t_{i,j}^t h_{i,j}^t x_{i,j,k}^{t-acc} + \alpha_2^t x_{i,j,k}^{t-acc}) \quad (6.9)$$

where f is the objective value which we want to maximize; it is a dimensionless quantity.

The weighting coefficients are as follows:

α_1^t is the coefficient for revenue for connection-based tariff for data type t ; it is expressed in units of seconds per dollar.

α_2^t is the coefficient for successful connection rate for data type t ; it is expressed in units of seconds per connection.

6.2.6 Summary of the Internet model

The Linear Programming model can now be written as:

Maximize

$$f = cx \quad (6.10)$$

Subject to

$$Ax = b \quad (6.11)$$

$$x \geq 0 \quad (6.12)$$

where:

f is the objective function value (e.g. revenue), which is to be maximised.

c is the row vector of cost coefficients, as determined by the choice of weighting coefficients in the expression for the objective function.

x is the column vector of independent variables including flow along alternative paths through network ($x_{i,j,k}^{t-acc}$ for $k = 1, \dots, r_{i,j}$) and one variable for each equality constraint ($x^{l(v)}$, $x^{n(u)}$, $x^{s(j)}$ and $x_{i,j,\bullet}^{t-rej}$). The reject flows $x_{i,j}^{t-rej}$ form a special subset of the slack variables with appropriate scaling.

A is the technological matrix of coefficients representing network connectivity and the traffic parameters, such as holding times, minimum acceptable mean bit rate and mean size of datagrams.

b is the column vector of right hand side terms, associated with the constraints on link capacity, router capacity, server capacity and user demand.

It can be seen that equation (6.10) is the abbreviated form of the objective function as defined in equation (6.9). Equation (6.11) is the abbreviation form of the user demand, link, router and server constraints as defined in equation (6.2), (6.4), (6.6) and (6.8) respectively.

6.3 Application Example

In this section, an Internet application example is presented to show how the model can be applied. The example is intended to show the effect of a mirror site on the performance of the network. The optimal solution of a sample network without mirror site is calculated. Then some of the capacity of the original servers is relocated to a mirror site and the solution is re-calculated to compare the overall performance.

6.3.1 Sample specification and basic solution

In the example, the amount of user demand offered to the network is shown in Table 6.2. The characteristics of user demand traffic are chosen as follows. Mean size of datagrams is 0.01 Mbit. Minimum acceptable mean bit rate for a connection is 0.01 Mbit per second. Connection holding time is 150 second.

Table 6.2: Offered user demand.

User from router	Service	Attempt rate (connection/sec)
R1	A	10
R3	A	10
R4	A	10
R5	A	10
R1	B	8
R3	B	8

The configuration of the sample network is illustrated in Figure 6.3. The network consists of six nodes, of which R1, R2 and R3 form the top level in the hierarchy of a national network 1 and the other three, R4, R5 and R6 form the top level in the hierarchy of a national network 2. Router R3 represents a gateway of national network 1 which provides access to a gateway of national network 2, R4, through an international link.

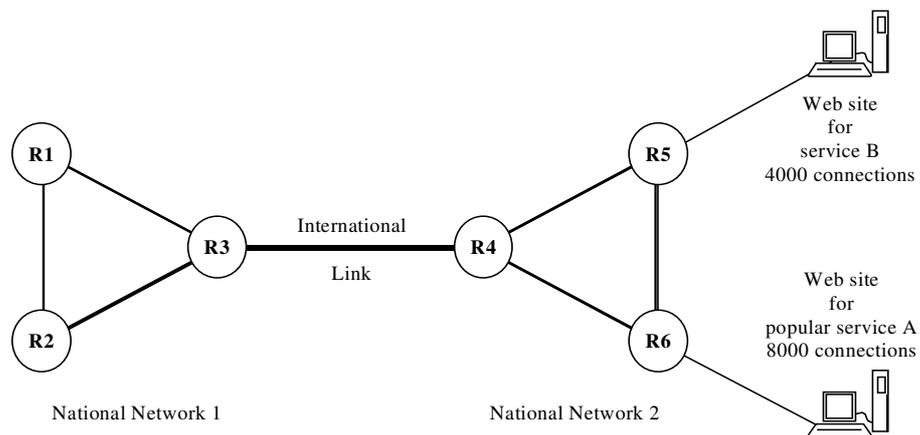


Figure 6.3: Sample network.

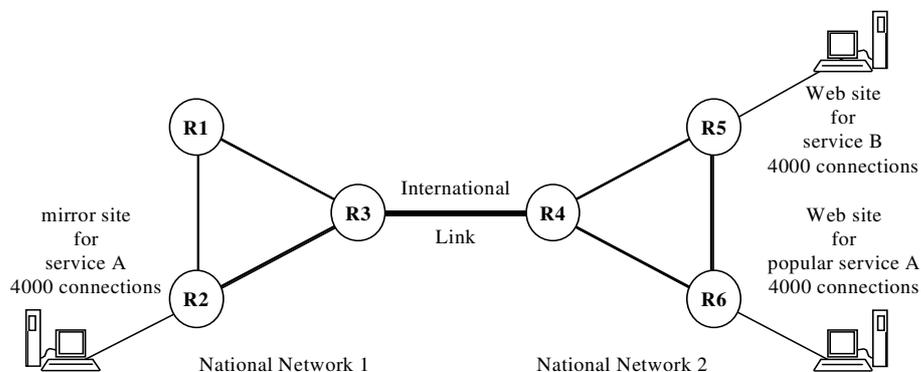
A server which provides a popular service A is connected to router R6, while the server which provides another (less popular) service B is connected to router R5. The server capacity is set high enough to meet the total demand on the services. The servers have

capacity of 8000 and 4000 simultaneous connections for service A and service B respectively.

The processor speed of the gateways and routers is also set high enough to meet the total user demand. The processor speed of gateways R3 and R4 is set to 9000 datagrams per second, while the processor speed of routers R1, R2, R5 and R6 is set to 4500 datagrams per second.

Each link has a bandwidth capacity of 20 Mbit per second. The national link capacity is sufficient to meet the user demand but the international link capacity is not sufficient to meet the user demand.

From the optimal revenue result, it is found that 40.5% of user demand must be rejected. Only 59.5% of user demand can be satisfied. Part of the user demand for both service A and service B must be rejected. The limiting resource is the international link.



Finger 6.4: Sample network with mirror site.

6.3.2 Effect of transferring server capacity to a mirror site

In this modified example, some of the server capacity for service A at router R6 (4000 connections) is transferred to a mirror site at router R2 in the national network 1. Each of the servers now has a capacity of 4000 simultaneous connections. From the optimal revenue result, it is found that only 4.8% of user demand must be rejected. More user demand is satisfied because users in the national network 1 can access service A by domestic resources. However, the international link still overloads because it cannot

meet the demand for service B. The example shows how the benefit of the mirror site can be evaluated.

It should be noted that the model can just as readily handle more complex problems such as those with mixed traffic types which have profiles of demand for network resources. Such problems quickly become too difficult for intuitive solutions.

6.4 Conclusions

In this chapter, an Internet model is proposed, to represent the consumption and distribution of the key network resources. The objective of the model is to optimise the use of scarce resources by appropriately controlling access to the network. From the model, an optimal set of connection acceptance rates can be solved for a given demand and fixed network topology. To demonstrate how the model can be used with a network, a simple example is given. The example shows the effect of transferring some of the server capacity to a mirror site. The result confirms that a mirror site can significantly increase the network throughput relative to adding equivalent capacity to the primary server site.

CHAPTER 7

APPLICATION TO INTERNET TRAFFIC MANAGEMENT

7.1 Introduction

Although at present the bulk of Internet users have unrestricted access to the network, this cannot continue if the Internet is to offer some minimum level of acceptable QoS to those connected, and if the network is to be efficient as discussed in chapter 2. The purpose of this chapter is to consider the application of the LP optimal flow solution to real-time¹ connection admission control, such that the Internet resources are used optimally. Just as the Internet community must ultimately adopt some form of access restriction, also it seems natural that a connection-oriented philosophy could be adopted. Already RSVP is consistent with this mindset, so in this chapter we imagine that all traffic of concern to us is handled using a philosophy similar to that of RSVP. The general resource management requirement for any Internet service is similar in the sense that access must be restricted and the appropriate resources must be available to support the minimum required QoS. RSVP aims to allow protection of QoS by reserving adequate resources to meet the performance requirements of connected users. Using RSVP the Internet is transformed into a connection-oriented network. This then offers interesting possibilities for traffic control where the optimal number of connections in progress can be calculated from the Internet model.

The Internet is a vast network, and since the number of possible paths grows exponentially with the network size, centralised global optimisation is bound to be infeasible. To manage Internet traffic and resources in real-time, the network needs to be partitioned in some way to put a bound on complexity. Provided that a connection-oriented network is of satisfactory complexity, it has been shown that real-time solution of the LP optimisation model is feasible [LAM91]. With the workstation computing power available at that time, a 30 node fully mesh network with 2-hop chains could be

¹ The meaning intended for “real-time” here is that the LP model is solved repeatedly in real-time, and that the real-time solution is used for network control. “Real-time” here is not intended to refer to delay-sensitive applications and the buffer management control algorithms that deal with delay-sensitive packets. Buffer management is taken to be a lower level task which is made feasible by the connection admission control measures used in this chapter.

solved within 8 minutes, and a 12 node network in a few seconds. With moderate levels of subnet complexity, it is considered feasible to generate real-time optimal solutions on timescales of a few seconds to a few minutes.

7.2 Optimal Revenue Example

To illustrate the operation of the LP optimisation model on an Internet network, the model network chosen is one which can include a proxy server. The idea is to set up a network problem with enough complexity so that the optimal solution is not trivial, and would not necessarily be found by a simple heuristic algorithm for connection and routing.

The objective of this section is to consider the impact of a proxy server on network performance. Optimal revenue is calculated by (by direct computation from LP model) using the sample network of chapter 6, but this time using a proxy server. The optimal revenue is to be used to provide a performance target for real-time proxy management. In real-time operation with random traffic arrival, a good control mechanism should ideally provide revenue close to the optimal revenue.

We are interested in the effect of including a proxy server in the network. The example is intended to show that the optimal revenue is higher if some server capacity is located at a proxy server. A sample network is considered without a proxy server and the optimal revenue is calculated. Then part of the primary server capacity is transferred to a proxy server and the optimal revenue is re-calculated to compare the performance.

7.2.1 Sample network without proxy server

We present a sample problem using a similar network topology to that of chapter 6. There is a slight change in server configuration as illustrated in Figure 7.1. Web sites providing services A, B, and C are connected to router R6, router R5, and router R4 respectively. We assume that service C is a real-time service so that it cannot be cached on a proxy server.

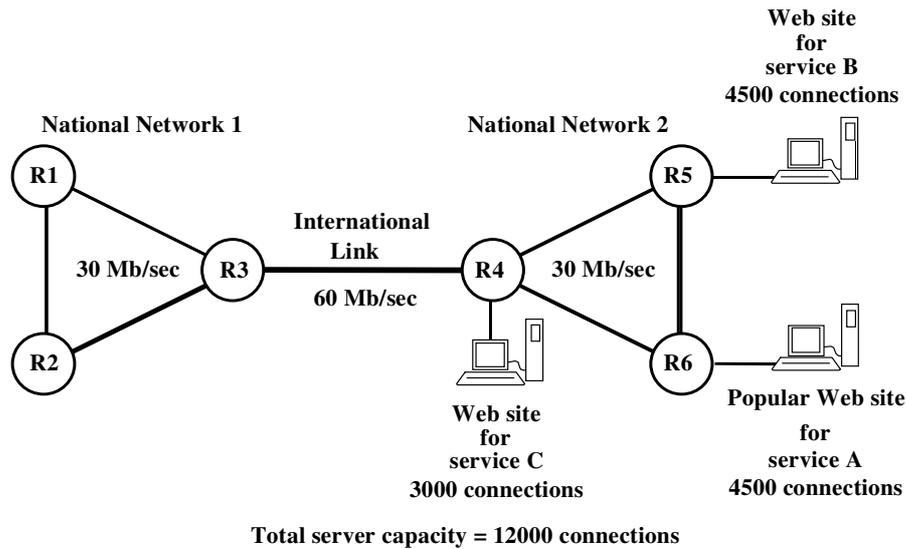


Figure 7.1: Sample network.

The link capacities are also modified to suit the example. Now each national link has a bandwidth of 30 Mbit per second while the international link has a bandwidth of 60 Mbit per second. The international link capacity will limit some traffic flow but there is adequate capacity on the national links.

The processor speed of the gateways is set high enough to cause no limitation in the example; the processor speed of routers R3 and R4, is 9000 datagrams per second, while that of routers R1, R2, R5 and R6, is 4500 datagrams per second.

The server capacity for service A and B is set at 4500 simultaneous connections. The server capacity for service A is insufficient for the user demand because service A is intended to represent a popular service. On the other hand, the server capacity for service B is more than enough because it is intended to represent a less popular service. The server capacity for real-time service C is set to 3000 simultaneous connections which is sufficient to meet the user demand.

The user demand for services is shown in Table 7.1. The characteristics of user demand traffic chosen are as follows. Mean size of datagrams is 0.01 Mbit. Minimum acceptable mean bit rate for a connection is 0.01 Mbit per second. Connection holding time is 150 second. Tariff rate used in the objective function is 0.01 dollars per second.

Table 7.1: Offered user demand.

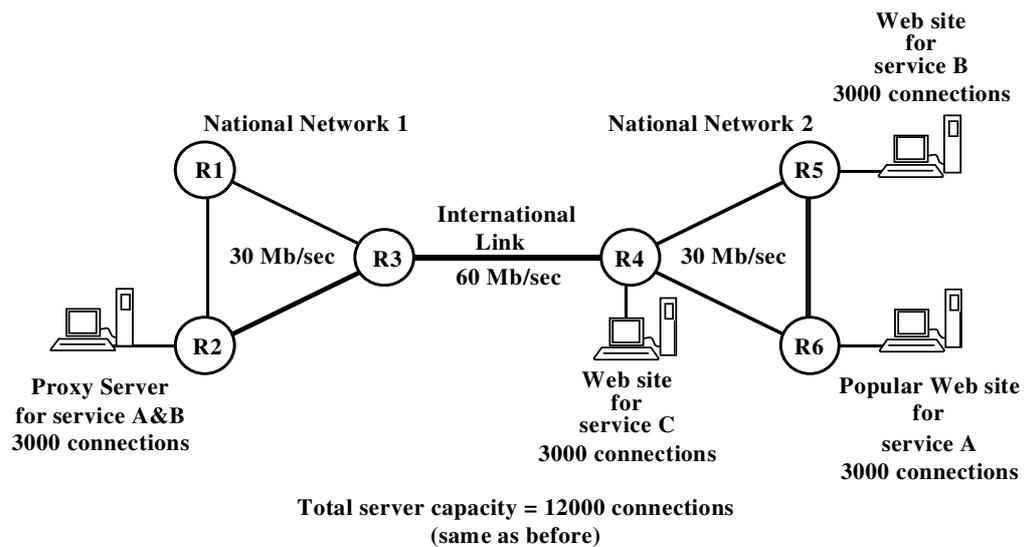
User from router	Service	Attempt rate (connection/sec)
R1	A	10
R3	A	10
R4	A	10
R5	A	10
R1	B	10
R3	B	10
R1	C	20

The optimal revenue available from the network, is 90 dollar per second. It is found that 75% of user demand is satisfied. Part of the demand of users is rejected from router R1 and R3 to service A, due to server overload and the limited capacity of the international link. Part of the demand of users is rejected to service B and C due to the limited capacity of the international link.

In this example, all the traffic types have identical profiles of resource demands and identical tariff rates, so optimal revenue is achieved by any traffic distribution which keeps the international link full and the Web site for service A fully utilised. That is, the international connections to service A could be reduced, and those to service B and C correspondingly increased.

7.2.2 Effect of substituting a proxy server

In this section, a proxy server is setup in the network as shown in Figure 7.2. The proxy server is capable of providing service A and B from national router R2. The total installed server capacity is kept at 12000 connections as before, by reducing server capacity at router R5 and R6 to 3000 connections and transferring this capacity (3000 connections) to the proxy server.



Finger 7.2: Sample network with proxy server.

From the model solution, the network can satisfy 100 % of user demand, giving optimal revenue of 120 dollar per second. Those users not previously able to access the popular service A due to server overload and the limited capacity of the international link now can access service A via the proxy server. Because the proxy offers service A and B, it releases domestic traffic from the international link, and makes this available for the uncachable service (service C in this case). The proxy server does not have sufficient capacity to meet all the domestic demand for service A and B, so some of this traffic still uses the international link.

The model solution offers guidance on what services to cache. Considering the solution in detail, although the proxy server can provide service A and service B, in this case it is sufficient to provide service A only to maximise revenue. The proxy would be required to offer service B if there were more user demand for service B. Service B would need to be more popular to warrant caching in the proxy server to make the most efficient use of resources. It consumes unnecessary resources to cache an unpopular service.

7.3 Implementation of Real-Time Traffic Control

A simulation of real-time network control is illustrated to evaluate the performance using the optimal solution to influence traffic management. The control of an overloaded proxy is an interesting example to demonstrate the potential for improved

performance. The network control must select which server (either primary or proxy server) to use to achieve high network throughput and satisfy QoS requirement.

When a request is directed to the proxy, if the requested service is not available in the proxy cache, the proxy server has to fetch a copy of service from the primary server to deliver to the user. The proxy then keeps the copy for the next user who requests the same service. In a heavily loaded network, the resources required for the first request from a user could be considered a small proportion of the total load on the network when compared with all requests from users to that service. Therefore we assume that the proxy server in the network always has a copy of the requested service.

The normal proxy setup is to connect all local requests through the proxy server. This has the potential disadvantage that during proxy server overload, the response time may be longer than that which would occur if some requests were routed directly to the primary server rather than being routed to the proxy.

A heuristic approach to improve the response time might be to follow these three steps (see scheme 1, Table 7.2); first, connect to the proxy server if there are enough resources on the proxy server to provide acceptable delay; second, connect the request to the primary server if there are enough resources on the primary server and the intervening network to provide acceptable delay; third, block the request. In this case all users who are connected receive delay guarantee services. However some of users will be blocked from accessing the network. This provides a form of connection admission control to avoid the situation where users are not satisfied and create inefficiency of resource utilisation by abandoning partly completed requests.

We evaluate the performance of the heuristic approach (scheme 1) and an optimal approach (scheme 2) which uses the solution from the model to control traffic flow in the network. The solution from the model provides a set of traffic capacities on each path, which maximises objective function value. In scheme 2, the requests are connected to the service if the service is reachable using available resources (according to the model). In the case of scheme 2, the service may be accessed from any server able to

offer that service. This will be determined by the optimisation model. Otherwise the request must be blocked. A summary of each scheme is shown in Table 7.2.

Table 7.2: Different Control Algorithms for Proxy System.

SCHEME 0 Current Solution	SCHEME 1 Heuristic Solution	SCHEME 2 “Optimal” Solution
<p>1. Connect all local requests to proxy.</p> <p><i>Effect:</i></p> <ul style="list-style-type: none"> • Unpredictable delay. • Some users abandon attempt. • Unproductive traffic wastes resources. 	<p>1. Connect to proxy if there are enough resources to provide satisfactory delay.</p> <p>2. Otherwise connect to primary if there are enough resources to provide satisfactory delay.</p> <p>3. Otherwise block</p> <p><i>Effect:</i></p> <ul style="list-style-type: none"> • Acceptable delay • Some users have to be blocked • Efficiency should be high 	<p>Use the solution from the optimisation model to control traffic flow.</p> <p>1. Connect if there is capacity available to the service.</p> <p>2. Otherwise block</p> <p><i>Effect:</i></p> <ul style="list-style-type: none"> • Acceptable delay • Some users have to be blocked • Efficiency should be high

7.3.1 Sample problem

In this section, the network illustrated in Figure 7.2 is used to demonstrate how the model can be used to manage the network in real-time. The network resources and traffic characteristics are as describe in section 7.3 so the network should be able to meet all the user demand.

For simulation purposes a random traffic model is required. In the Internet traffic has fractal behaviour properties [ADD95], [LIK95], [RYU96] and [JI99], and there is no generally accepted precise model for traffic sources. For this simulation a simple Poisson arrival process is used, with a constant mean request rate over the simulation

period. The mean request rate is as shown in Table 7.1. Connection holding time has a mean of 150 second with negative exponential distribution.

As in section 4.3, the Erlang loss correction is regarded as negligible, so the number of connections available for traffic is made equal to the number of connections to be carried, according to the optimal solution.

Connection requests in national network 2 use a similar strategy to scheme 1, but with requests going firstly to the local (primary) server and secondly to the remote (proxy) server.

The initial condition for scheme 1 uses the steady state of a preliminary simulation run using the scheme 1 control algorithm. The simulation is then run for 100 sec using scheme 1 and then switched to scheme 2 for 320 second. The total simulation run is for 420 second.

7.3.2 Sample results

The optimal revenue according to the LP model is 120 dollar per second as found in section 7.2.2. Based on the simulation results (see Table 7.3), the revenue using scheme 1 is only 101.61 dollar per second or 84.68% of the optimal revenue. Using scheme 2 the revenue is 118.97 dollar per second or 99.14% of optimal revenue.

Table 7.3: The revenue at steady state.

	SCHEME 1 Heuristic Solution	SCHEME 2 “Optimal” Solution
Event-by-Event Revenue *	101.61(84.68%)	118.97(99.14%)
Optimal Revenue **	120.00(100%)	

* Average revenue from simulation run.

** Direct computation from LP model.

7.3.3 Main features

Scheme 2 shows a substantial increase in throughput when compared with scheme 1. The principal difference between scheme 1 and scheme 2 is that scheme 1 uses a decentralised algorithm while scheme 2 uses a global optimisation solution to guide the control system. Observations about the behaviour of each scheme are as follows:

- Scheme 1 (operates over the period 0 sec - 100 sec)

In national network 1, the proxy server sees mostly the streams of user request from R1 and R3 to service A and service B. These requests have equal probability of success, so the bandwidth usage is approximately equal (7 Mbit/sec) in each case. Because the total demand for service A and B in national network 1 exceeds the proxy server capacity the excess demand is forwarded via the international link towards the primary servers for service A and service B.

From Figure 7.3:(a), about 7 Mbit/sec of link resource is used initially for demand from R1 to the proxy server (first choice) for service A and about 4 Mbit/sec for R1 to the primary server (second choice).

From Figure 7.3:(b), as in Figure 7.3:(a) about 7 Mbit/sec of link resource is used initially for demand from R3 to the proxy server (first choice) for service A, and about 5 Mbit/sec for R1 to the primary server (second choice). The success rate for connection attempts to the primary server for service A from R3 (Figure 7.3:(b)) is higher than from R1 (Figure 7.3:(a)) because the link between R1 and R3 creates a bottleneck for traffic from R1. At the R1-R3 link, there is competition for access to three services (A, B and C) from R1 to national network 2.

From Figure 7.3:(e), as in Figure 7.3:(a and b) about 7 Mbit/sec of link resource is used for demand from R1 to the proxy (first choice) for service B, and about 6 Mbit/sec for R1 to the primary server. The success rate for connection attempts to the primary server for service B (Figure 7.3:(e)) is higher than that for service A (Figure 7.3:(a)) because the primary server for service A is saturated but the primary server for service B is not.

Figure 7.3:(f) is similar to Figure 7.3:(e) but the success rate to the primary server is higher because as before, the link between R1 and R3 creates a bottleneck for traffic from R1.

From Figure 7.3:(c and d), about 11 Mbit/sec of link resource is used for demand from R4 and R5 to the primary server (first choice). About 2 Mbit/sec is connected to the proxy server (second choice). The proxy is already overloaded due to the demand for service A and service B from R1 and R3, so the success rate is low for requests from national network 2 to the proxy server.

From Figure 7.3:(g), almost all the demand for service C is successful. Some limiting occurs because national network 1 is very close to overload.

- Scheme 2 (operates over the period 100 sec – 420 sec)

The increase in throughput using control scheme 2 is because all the demand for service B is forwarded to the primary server. This leaves the proxy server with enough capacity to meet the user demand for the service A from R1 and R3. The demand on link R1-R3 and primary server for service A are reduced.

Figure 7.3:(a and b) shows that with scheme 2 a transfer of bandwidth occurs from the primary server to the proxy server for requests from R1 and R3 to service A, because the primary server capacity is all required to meet the demand for service A from national network 2.

Figure 7.3:(c and d) shows the increase of bandwidth usage to the primary server for R4 and R5 requests to service A. This increase occurs because there is now no competition from national network 1. The capacity of primary server for service A can meet the demand from national network 2.

Figure 7.3:(e and f) shows a transfer of bandwidth from the proxy server to the primary server for requests from R1 and R3 to service B because the capacity of the primary server and the R1-R3 link are sufficient. This is because the demand for service A from R1 is now connected directly to the proxy server, and does not need to use link R1-R3.

Figure 7.3:(g) shows all the demand to service C can be carried within the capacity of link R1-R3, link R1-R2-R3 and the international link.

The event-by-event revenue provided by scheme 2 is approximately 20% higher than that provided by scheme 1 as shown in Figure 7.7. This is mostly because the total bandwidth usage for service A is increased as shown in Figure 7.5: (a).

7.4 Conclusions

In this chapter the Internet model is applied to a network which includes proxy server capacity. A sample computation shows that replacing some primary server capacity with proxy server capacity allows a significant increase in network throughput and consequent improvement in user satisfaction. However, the optimal throughput is not achieved unless an appropriate control algorithm is used at the proxy server. The example shows that the LP model could be used as a guide for the best choice of services to hold in the cache in order to make effective use of overall network resources. Performance evaluation shows that the best way to manage the network is to use some kind of optimisation model. It also illustrates that the model could be used for real-time network management.

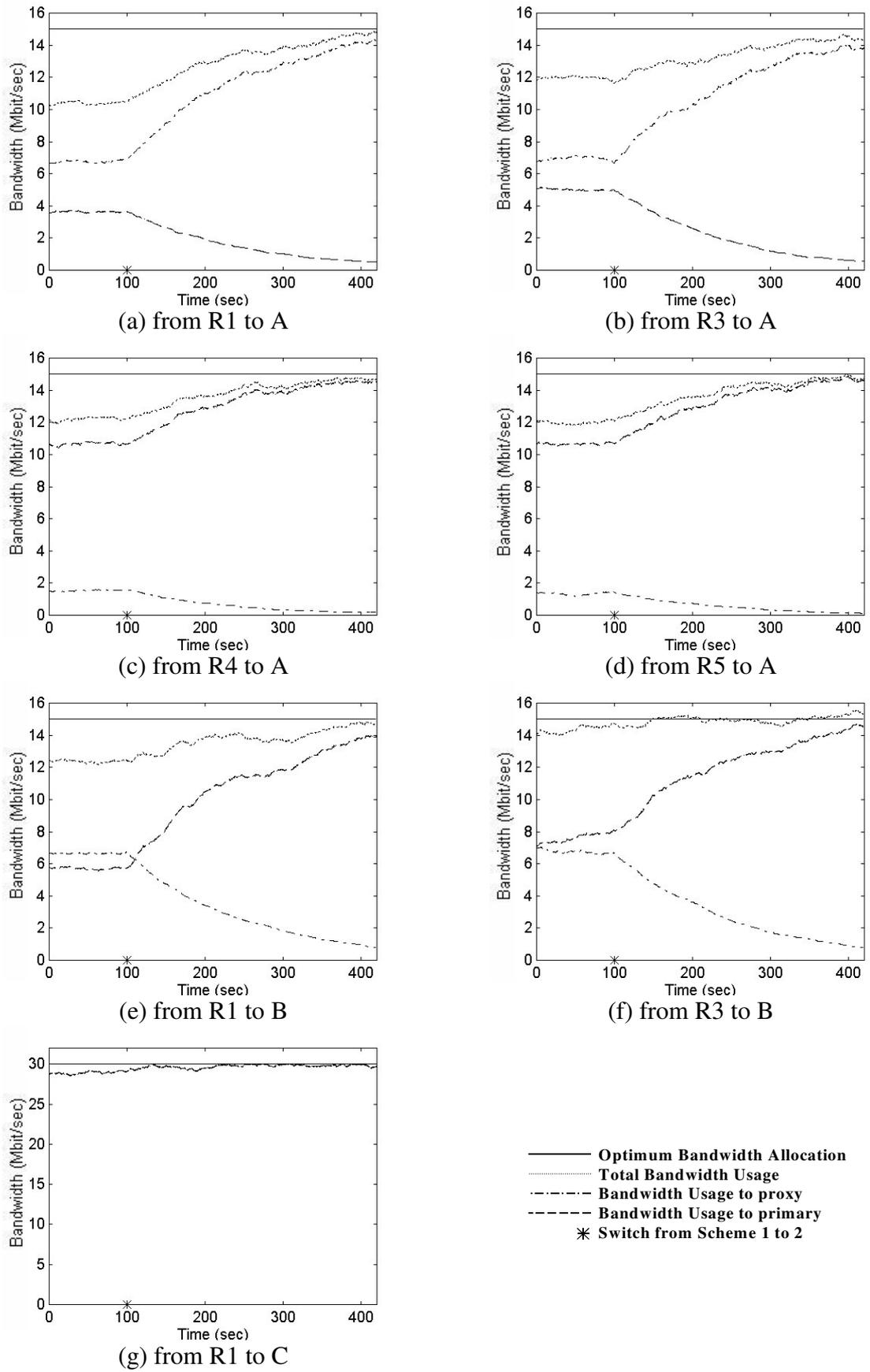
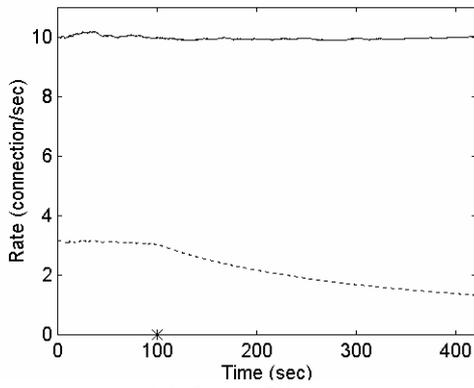
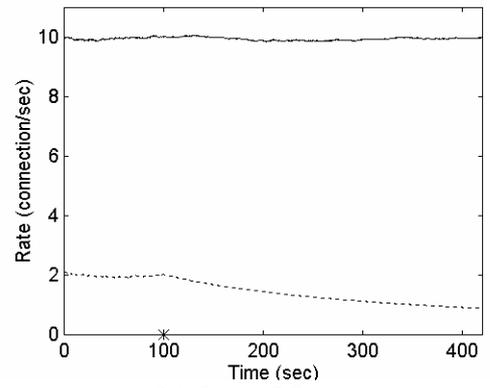


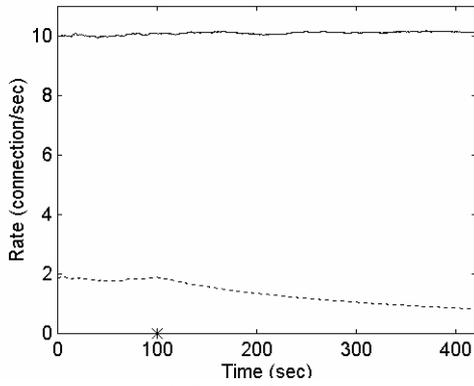
Figure 7.3: LP Result & Simulated Bandwidth Usage.



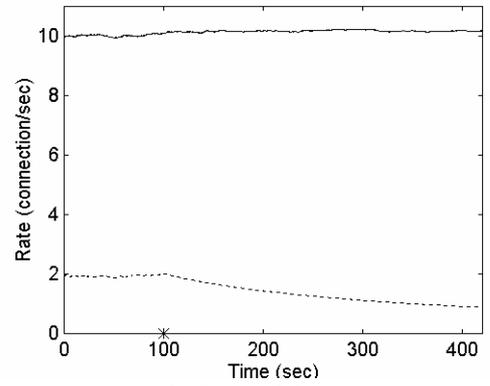
(a) from R1 to A



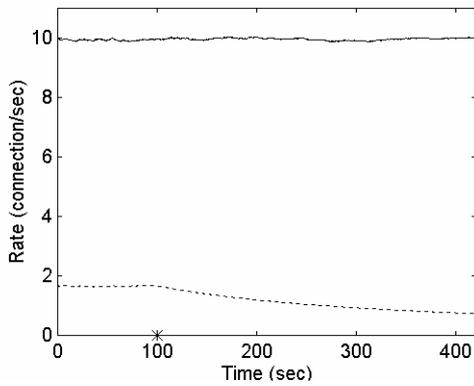
(b) from R3 to A



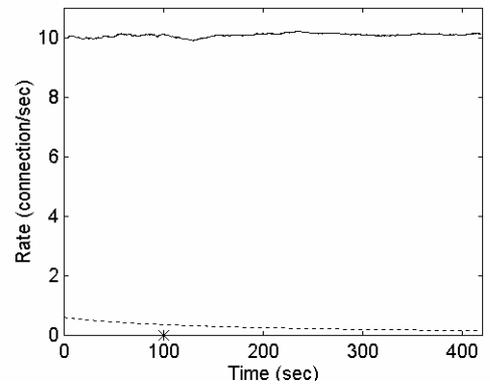
(c) from R4 to A



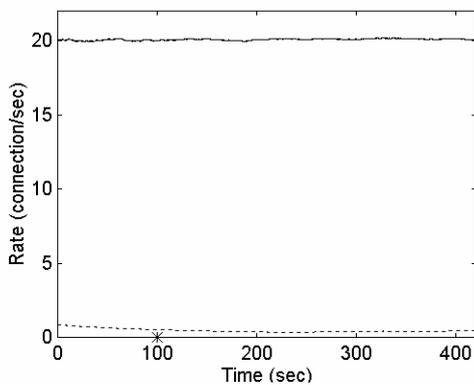
(d) from R5 to A



(e) from R1 to B



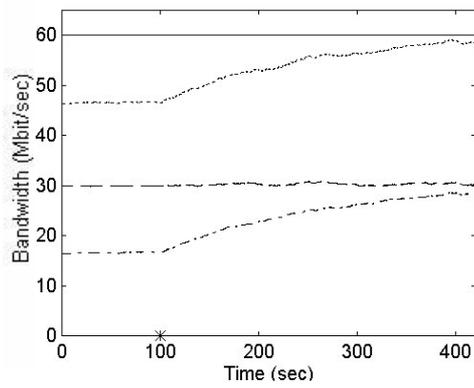
(f) from R3 to B



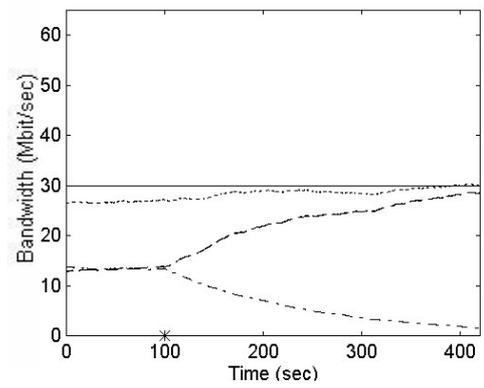
(g) from R1 to C

— Mean Connection Attempt Rate
 Mean Blocking Rate
 * Switch from Scheme 1 to 2

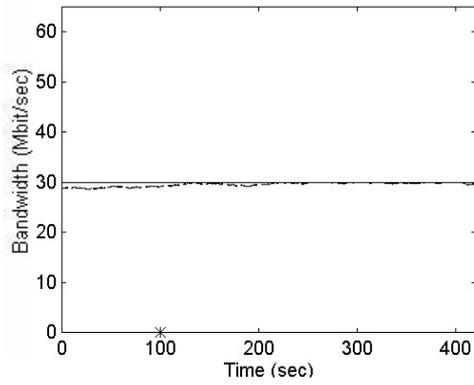
Figure 7.4: Mean Offered Rate and Mean Blocking Rate.



(a) Service A



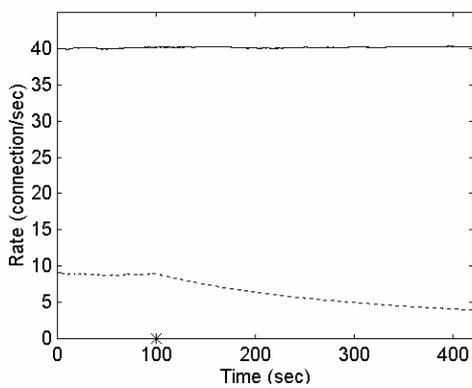
(b) Service B



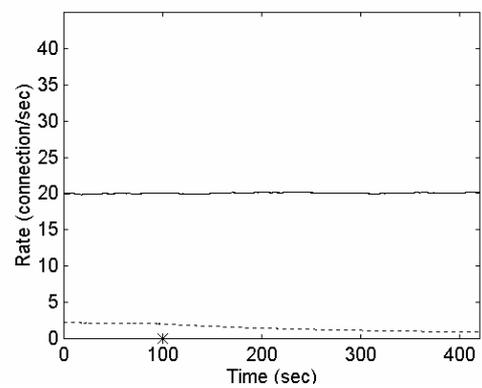
(c) Service C

— Optimum Bandwidth Allocation
 Total Bandwidth Usage
 -.-.- Bandwidth Usage to proxy
 - - - Bandwidth Usage to primary
 * Switch from Scheme 1 to 2

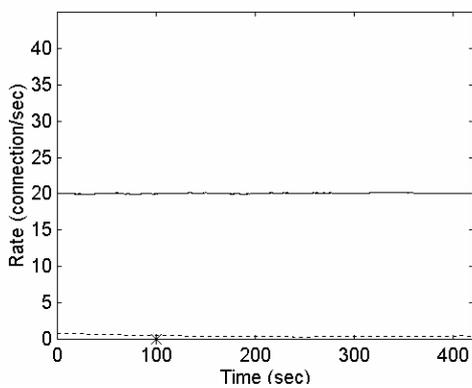
Figure 7.5: Total LP Result & Total Simulated Bandwidth Usage for Each Service.



(a) Service A



(b) Service B



(c) Service C

— Mean Connection Attempt Rate
 Mean Blocking Rate
 * Switch from Scheme 1 to 2

Figure 7.6: Total Mean Offered Rate & Total Mean Blocking Rate for Each Service.

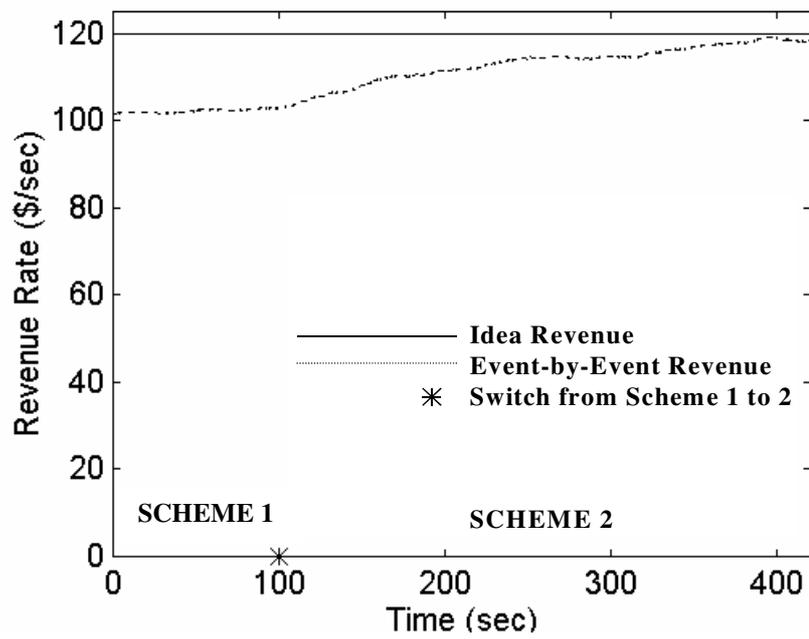


Figure 7.7: Optimum Revenue Rate & Event-by-Event Revenue Rate.

CHAPTER 8

CONCLUSIONS

8.1 Summary of Conclusions

In this research, we focus on the problem of how to control an overloaded network to give maximum throughput subject to providing satisfactory quality of service for those connected. The networks considered in this work are ATM networks and the Internet because there are key networks of the future and because they need to be able to interwork to meet a common objective. Both these networks pose some important unsolved problems. For ATM networks the problem of efficient resource management has not been solved. For the Internet the problem of acceptable QoS has not been solved. In ATM networks, it is argued here that using an optimisation model as a basis for virtual path management offers the opportunity to achieve high performance resource management. To control the quality of service in the Internet, it is argued that some form of connection admission control must be introduced (for most, if not all traffic) together with some method of managing routing. In this work the notation of centralised optimisation is explored, using a connection-oriented model for resource allocation in real-time. The proposed solution in the case of both ATM and Internet networks is to use an optimal traffic flow solution from an optimisation model to guide the network control system.

A broadband multimedia network model is proposed in the context of ATM networks in chapter 3. The model considers the flow of traffic through the network, and its impact on network resources of various types (link bandwidth and node processing capacity). The solution is a set of traffic flow rates which maximise the objective value. The sample problem gives an example where an ATM network carrying both connectionless and connection-oriented traffic suffers a major link failure. In the particular case studied, the link failure causes a node overload, and the optimal response is to apply selective blocking for some of the connectionless traffic. The connectionless traffic is chosen for blocking in this case because it generates less revenue per unit of node processing demand than connection-oriented traffic.

In chapter 4, the ATM network model of chapter 3 is used as the basis for real-time management of the VP pool (a set of VPCs and their capacities). This VP pool is in turn used for the event-by-event control of CAC and routing. A comparison is made between fixed virtual path management (FVPM) and dynamic virtual path management (DVPM). The robustness of the DVPM scheme relative to the FVPM scheme is demonstrated in the situation of a major link failure. The model is further developed to improve its transient behaviour in chapter 5. State dependent virtual path management (SDVPM) takes into account the current state of the network and incoming traffic parameters so that feasibility constraints can be placed on the rate of change of the VP pool. To demonstrate the capability of the SDVPM model a comparison is made with the DVPM scheme. SDVPM achieves higher revenue after a network failure by containing control action to match the reachability limits of the network state. This demonstrates that, for optimal transient performance, control adjustments to the VP pool in an ATM network should be made smoothly, such that they fall within the dynamic feasibility range of network traffic.

An optimisation model for the Internet is established in chapter 6 to find the optimal connection acceptance rate, such that connected users are offered no less than some minimum acceptable level of response. The model considers the Internet from the user's viewpoint, and seeks to optimise the connection of users to services. The key network resources considered are links, routers and servers. The solution optimally distributes the workload among those resources. An example is given where a mirror site added to the system significantly increases the network throughput relative to adding equivalent capacity to the primary server site.

The Internet model of chapter 6 is modified in chapter 7 to find the optimal number of connected users for use in real-time traffic/resource management. In a proxy system, the model can offer an optimal choice of items to be caches. An application example to real-time Internet traffic management demonstrates the potential benefit of using a real-time optimisation model to manage Internet traffic/resources. The example illustrates some general optimisation principles. For example if a proxy server is overloaded, the connections to each service should be properly distributed among the proxy and the

primary server and mirror sites for that service. The example using a proxy server shows that a significant increase in network throughput can be achieved by using an appropriate control mechanism to select which connections should be directed to the various alternative sources of each service.

8.2 Original Contributions

In general, the original contribution of this research is in the exploration of appropriate optimisation objectives and mechanisms for overloaded broadband networks, and in arriving at a unified model that provides for similar outcomes in both ATM and Internet networks. The research focuses on optimal management of resources in these networks. The optimisation goal for both kinds of network is to maximise throughput subject to satisfying the QoS requirement of all connected users.

In the development of the optimisation model, a number of original concept and techniques are employed; there are listed below.

- The optimisation objective of maximising network throughput subject to satisfying the QoS requirement of all connected users is proposed as a valid objective in order to maximise “user satisfaction”. It is argued that this is relevant not only to ATM networks, but also to the Internet, even though Internet service provision involves a diverse range of entrepreneurial players.
- A steady state deterministic model in the form of linear programming problem is proposed to optimise traffic flows in an ATM network with link and node constraints. The solution of the model is a set of connection rates for each path in the network. This set of connection rates represents an optimal use of network resources.
- The use of the LP model as a basis for real-time management of resources via the virtual path (VP) pool is proposed. The LP solution provides a real-time dynamic set of VPC routes and VPC capacities which guarantee the optimum objective function value. The VPC capacity allocation takes account of the stochastic nature of connection request arrivals. A simple control mechanism is used to implement CAC and routing.

- The idea of using a steady state deterministic model with additional reachability constraints to limit the rate of change of the VP pool to match traffic movement constraints is proposed. The constraint takes the carried connections and birth-death processes into account. The model is called State Dependent Virtual Path Management (SDVPM).
- The idea of Connection Admission Control for the Internet is not new, but it is proposed here as being necessary for most if not all Internet services in order to maximise user satisfaction and avoid poor performance in overload situations.
- A modified linear programming model is proposed to represent the distribution and consumption of key network resources in the Internet (link, router and server) by different traffic types. The objective function and constraints in the model aim to maximise performance provided that users are offered no less than some minimum acceptable level of response. The solution from the model is a set of connection rates for each path in the network.
- A connection-oriented control model is proposed for the Internet, and applied to a proxy server control problem to demonstrate its potential benefits.

8.3 Suggestions for Future Work

Some unresolved issues that warrant further work are as follows:

- The issue of traffic estimation (connection request rates and mean properties) for Internet traffic is more complex than explored here. This issue together with appropriate aggregation of streams may influence the effectiveness of the approach.
- The extreme point solutions produced by LP models are not necessarily the most appropriate. They raise issues of fairness and robustness. It is possible that interior point methods may help to resolve these issues.
- Solution time is an issue. The LP model must be solved within some constrained time for use in real-time resource management and control. This requires exploration of fast solution algorithms and methods for partitioning global networks into limited sub-nets.
- Investigate the effect of different traffic types on the control system performance. This raises issues such as:
 - The effect of holding time on transient response.

- The competition between traffic types with different bandwidth requirement (eg. video, voice, data).
- The issue of upgrading network resources, or the facility location problem is a side issue of this work which could be explored. By solving the dual LP problem we can find the resources which place a limit on network performance.