Resource Management
in Broadband Multimedia Networks

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DECLARATION

No part of the work referred to in this thesis has been submitted in support of an application for the award of another degree or qualification of this or any other university or other institution of learning.
PUBLICATIONS RELATED TO THE WORK PRESENTED IN THIS THESIS

Seminar Presentations


Papers


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ABSTRACT

This research deals with optimal resource management in an overloaded broadband multimedia network. Optimisation is with respect to user satisfaction, where user satisfaction reflects both the quality of service experienced by connected users and the dissatisfaction of users blocked from access to the network.

The research focuses on Asynchronous Transfer Mode (ATM) networks and the Internet, because these are the dominant emerging broadband networks which present some fundamental unsolved problems, related to the sharing of resources between mixed traffic types. ATM networks use conservative admission control, which protects network resources and ensures a high level of service for those admitted to the network, but results in low network efficiency because of low utilisation of resources due to blocking of many potential users. The Internet does not use admission control, with the result that performance degrades progressively as load increases. This causes frustration among users, and lowers the network efficiency due to high levels of congestion.

We propose an optimisation model for each network (ATM networks and the Internet) which is intended to represent the distribution and consumption of key network resources by different traffic types. The model is aimed at maximising performance such that users admitted to the network are offered no less than some minimum acceptable level of quality of service (QoS). The solution is a set of traffic flow rates on each path which results in maximising an objective function value (revenue based on network operator interest or throughput based on customer interest) for a given network configuration with given user demand. As an example using the ATM network model, we illustrate the application of the model to an ATM network carrying both connection oriented and connectionless traffic. We explore the optimal response to a link failure which in turn causes node overload. As an example using the Internet model, we consider an overloaded network with link bottlenecks and an overloaded Web server, and explore the effect of transferring some server capacity to a mirror site and a proxy server.
For real-time traffic control, the optimisation model is used to assign quotas for bandwidth or connections to selected paths. A control algorithm is implemented to provide maximum performance by admitting requests within the quotas which are obtained from the optimisation model. In an ATM network simulation, the algorithm is used to manage the virtual path (VP) pool in a network which suffers a link failure. A comparison is made between fixed virtual path management (FVPM) and dynamic virtual path management (DVPM), comparing the revenue achieved by each. This illustrates how DVPM adapts the VP pool in a robust fashion to achieve maximum revenue in the face of a link failure. However, the transient response suggests that benefit could be obtained using non-steady-state solutions. The model is extended by taking network state and traffic parameters into account to control changes in the VP pool to recognise limits to the rate at which traffic can be moved (through the natural birth-death processes). This scheme is called state dependent virtual path management (SDVPM). Performance evaluation of the new model shows that SDVPM achieves higher revenue than DVPM when the network suffers a link failure that requires a major change to the VP pool. In an Internet simulation, two algorithms are compared for control of access to a proxy server and a set of primary servers. An algorithm based on optimal flow solutions provides substantially better network performance than a localised heuristic algorithm. In each simulation case (ATM and Internet examples), the performance using a control system based on the steady state optimum flow model is close to the ideal optimal result.
CHAPTER 1
INTRODUCTION

This research deals with the optimal management of resources in overloaded broadband networks. The work focuses on two types of network; ATM (Asynchronous Transfer Mode) networks and the Internet. These networks appear at first sight to have very different objectives, and these different objectives are used to clarify suitable goals for an optimisation model. Separate models are explored initially for ATM and the Internet, and ultimately it is possible to compare the nature and outcome of these separate models.

ATM has emerged as the transport standard for the Broadband Integrated Services Digital Network (B-ISDN), which has been proposed by the International Telecommunication Union (ITU) to provide seamless and efficient transport for mixed service types [CCI92], [ITU95] and [ITU97]. Thus ATM is designed expressly to meet the needs of mixed service types. ATM networks use connection admission control (CAC) to limit access to the network, such that appropriate quality of service (QoS) can be achieved for those connections admitted to the network. The problems posed by CAC and multiple QoS requirements are complex and have not been fully solved. For this reason, the weakness of ATM networks in situations of overload is that, in managing resources to ensure quality of service, the network will not use those resources fully, and hence will not achieve good performance.

In the context of ATM the meaning of good performance in this research is taken to be achievement of high throughput (expressed either as number of connections or as revenue) subject to satisfying the QoS requirements for all connected users.

The Internet has evolved into a global multimedia network since its origins 30 years ago. The World Wide Web (WWW) has led to an explosion of demand and of new and exciting services, but this very growth in demand has led to poor quality of service as the load increases. This highlights the problem with the traditional philosophy of the
Internet; in allowing open access to resources, quality of service may not be acceptable and throughput may be low when the network is overloaded.

Because of its fundamental open philosophy, there are many “players” involved in management and service delivery for the Internet. Thus in exploring optimisation of the Internet, a necessary question is: “for whom should we optimise?”. The choice made in this work is to optimise with respect to “user satisfaction”, where user satisfaction is intended to reflect both the quality of service experienced by connected users and the dissatisfaction of users blocked from access to the network. In an overloaded network this objective becomes one of maximising overall network throughput subject to satisfying some minimum QoS requirement.

Although ATM and the Internet appear to have such different philosophies, both networks ultimately must try to meet the same kind of need, and it is argued that the same kind of optimisation objective should be used for both kinds of network. In this research, the optimisation goal for both ATM and the Internet is to maximise throughput subject to satisfying the QoS requirement of all connected users.
CHAPTER 2
TOWARD BROADBAND MULTIMEDIA NETWORKS

2.1 Introduction

For the past 15 years, telecommunications carriers have been seeking to build a single unified network that will support diverse services such as data communication, voice, telephony, video conferencing, and TV broadcast. The first solution was to develop the Integrated Services Digital Network (ISDN) that can support voice and data at 64 kbit/s. The advent of new multimedia data services where data now incorporates various text fonts, graphic drawings, photographs and now video, has meant that ISDN has insufficient bandwidth for new services and insufficient flexibility of bandwidth allocation for bursty traffic. In response, the telecommunication carriers began to develop the Broadband ISDN (B-ISDN) model for a broadband multimedia network. Asynchronous Transfer Mode (ATM) emerged as the proposed transport network for the future.

The network of the telecommunications carriers has been paralleled by the development of the Internet. The Internet was initially developed for numeric and plain text data traffic, but has been steadily evolving to support image and video services. Thus the Internet is also seeking to become a broadband network, carrying mixed traffic types, and ultimately delivering services with a wide range of performance requirements.

Broadband multimedia networks still present some fundamental unsolved problems, related to the sharing of resources between mixed traffic types. Connection Admission Control and Routing go to the heart of the problem of maintaining network performance under overload conditions. Connection Admission Control seeks to predict what connections can be admitted to the network so that the network has just sufficient resources to give the required level of service to the admitted connections. Routing seeks to select paths for the admitted connections to make optimal use of the network resources. The special difficulty presented by these problems in broadband networks is due to the wide range of objectives for mixed traffic types.
This research focuses on ATM networks and the Internet, because these are the dominant emerging broadband networks. The Internet incorporates some embedded ATM networks, and these are likely to increase over time, so although ATM and the Internet technologies have emerged from different backgrounds, they face many problems in common. Researchers and developers are attempting to address the unsolved problems, and new initiatives, such as the resource ReSerVation Protocol (RSVP) for the Internet (as in [ZHA93a], [ZHA93b] and [BRA97]), are able to take advantage of the capabilities of ATM to improve the features of the Internet [WRO97] and [TER99]. For example, classical Internet Protocol (IP) over asynchronous transfer mode (ATM) has been deployed in [LAU94] and with RSVP signalling in [BER96].

The original philosophies behind ATM networks and the Internet are in marked contrast with each other. ATM networks ensure a high level of service by blocking some requests. Admission control [JAM92] can be used to protect network resources and guarantee quality of service (QoS), but this in turn can cause low network efficiency because blocking of potential users can cause low utilisation of resources. On the other hand, the Internet aims to offer service to anyone who requests access, with the result that performance degrades progressively as load increases. This causes frustration among users, and lowers the network efficiency due to high levels of congestion.

ATM networks and the Internet also use different approaches to routing, based on a different philosophy regarding the relative costs of bandwidth and switch processing power. ATM uses a connection-oriented, cell-based approach while the Internet uses a connectionless packet-based approach.

This chapter provides an overview of the developments in ATM networks and the Internet, and is intended to draw out fundamental unsolved problems and suggest possible keys to approaching these problems.
2.2 Nature of ATM Networks

The goal of ATM networks is to support multi-services in an efficient and seamless fashion. The traffic for any service type is organised as a connection-oriented stream of small fixed size cells.

The ATM standard specifies two types of connections – Virtual Path Connections (VPCs) and Virtual Channel Connections (VCCs). A VPC is a point to point logical connection, which consists of a bundle of VCCs. ATM cells are transported on VCCs. The idea of grouping a number of connections (VCCs) and managing them as a Virtual Path (VP) is defined in [ATM94] [PRY93].

The VP concept is motivated to reduce setup and switching costs of VCCs, which are established on demand (or per connection), by using existing VPCs. Setting up a VCC and routing of cells along that VCC involves only the VPC terminator nodes. The VPC transit nodes are not involved in VCC setup. The process of admitting a VCC can be handled in a short time because the more complex process of setting up the VPC can be performed in advance.

The VP concept also reduces network control cost by grouping many connections into a single unit (VPC). This reduces the scale of the VCC management problem, while at the same time still allowing for elegant control methods. For example dynamic resource management can provide adaptability to varying traffic and to network failures. Priority control can be implemented by segregating traffic with different QoS requirements.

2.2.1 Connection admission control and virtual path management

Connection admission control (CAC) is defined as a standard feature of ATM networks to ensure QoS for accepted connections. CAC deals with the important decision of whether accepting a new connection will degrade the QoS of the existing connections [HAB97]. The fundamental trade-off in CAC is between causing low network performance by rejecting too many potential connections, and, on the other hand causing user dissatisfaction by accepting too many connections and hence not delivering the required QoS.
Availability of VPC capacity from end to end is the indicator for CAC to make the decision whether or not to accept a new connection. Based on the traffic parameters, the controller will compute the VPC capacity that should be allocated to the connection. If the capacity is available, then the connection is accepted; otherwise it is rejected [HAB97].

The key to achieving high network efficiency in an ATM network is the management of the VP pool [FRI96] [BUR90] [BUR91]. The number of VCCs able to be carried in the network depends on the effectiveness of the VP pool. Thus the management of the VP pool is one of the keys determining the throughput or revenue available from the network.

The issue of virtual path management is an active area of research related to achieving an effective CAC suitable for broadband networks. For example there are many papers related to virtual path management in ATM networks, in journals such as "IEEE Journal of Selected Areas in Communications" and the "IEEE Network and Communications Magazines", and in conferences such as IEEE ICC’93–97, INFOCOM’93–97 and GLOBECOM’93–97.

In [GEL97], the authors discuss the broad issue of CAC and resource allocation in high-speed networks, focusing on ATM technology. It is maintained that despite the considerable amount of high-quality work carried out in this area, the debate surrounding these issues is not yet resolved.

The three major kinds of resource management considered in the literature are bandwidth, buffer and processing management. In this thesis the three kinds of resource are effectively reduced to bandwidth and processing, based on an argument to do with time scale, and the notion of “effective bandwidth”. The approach used applies to a time scale long compared with queuing delays. This means that it is relevant to bandwidth management and processing management, but only indirectly to buffer management. The notion of “effective bandwidth” includes consideration of bandwidth and buffer
capacity together, because it is the bandwidth required to support a stream of traffic with given properties, given level of associated buffer resource and achieving some given QoS. It is assumed that there is some appropriate lower level buffer management system operating (such as that of [PAR99]). For multiple traffic types the notion of effective bandwidth can be extended as in [BER98].

The task of CAC is critical. Its role is to ensure that the total admitted load is within the resources of the system. For example in [SUT99] there is discussion of flow control, but in assuming the existence of enough elasticity to allow buffering, there is really an assumption of some overall load limiting mechanism, so that “flow control” will work without violating reasonable constraints on buffer utilisation (say at the network edge). “Flow control” is seen in this thesis as a medium term measure – effective only if the demand over a period greater than buffer capacity is bounded. These assumptions are taken into account in the notion of “effective bandwidth”, which makes a set of assumptions about QoS and buffer size and their relationship to the traffic models.

Processing management is also related to CAC, which must ensure that the flows admitted into the network fall within the processing capacity of the network nodes. A notion equivalent to “effective bandwidth” is also needed for processing demand. The “effective processing load” should define the processing resource required to adequately support a stream of connection requests, making allowance for the statistical behaviour of those requests – the random traffic mix, and any buffering etc included in the processor. This is really the use of a coarse grained model (as in [GUE99]) for the processing of connections/packets.

2.2.2 Virtual path management

Research work in VP management can be classified into three main categories.

- VPC capacity allocation - dealing with bandwidth allocation for VPCs.
- VPC configuration - dealing with the management of VPC topology.
- VP pool management – dealing with both the configuration of VPCs and VPC capacity allocation.
2.2.2.1 VPC capacity allocation

A great deal of research work is related to bandwidth allocation for VPCs. In [OHT92], a dynamic bandwidth allocation scheme based on the VP concept is proposed to reduce the normalised processing load. If the VP bandwidth is not enough for a new VCC, a request for bandwidth increase is generated; if the VP bandwidth exceeds the demand, a request for bandwidth decrease is generated.

In [WU95], the authors propose and analyse an adaptive bandwidth allocation scheme to select an appropriate step size for each VPC. The bandwidth demand factor is proposed as a trigger to reflect the expected bandwidth requirements and traffic conditions. In [XIA94] Infinitesimal Perturbation Analysis, a technique which estimates the gradients of the functions in discrete event dynamic systems by passively observing the system, is used in dynamic bandwidth allocation to estimate delay sensitivities under general traffic patterns.

With respect to different methods for the allocation of the bandwidth of an outgoing link, alternative CAC strategies are examined and compared in [BOL97]. Their approach is in the context of service separation, where traffic sources are grouped into classes, homogeneous in terms of performance requirements and statistical characteristics, which share the bandwidth of a link according to some specified policy.

In [SHI94], resource allocation methods are categorised, and static and dynamic allocation strategies are compared with emphasis on bandwidth allocation. Dynamic allocation uses actual traffic behaviour, while static allocation uses only the reference traffic condition given a priori. Examples of dynamic allocation strategies are available bit rate flow control, dynamic connection admission control, and dynamic VPC bandwidth control. Dynamic resource allocation is shown to be promising for situations where the reference model is unclear.
2.2.2.2 VPC configuration
Considerably less work has been reported on network configuration from the VPC perspective. In [GER95], the authors present the problem of dynamically adjusting the layout of VPCs, in response to the changing needs of the network users. In [AHN94], a heuristic approach is used to design VPC layout. The guidelines for the design of robust VPC layouts and the efficient establishment of VCCs are also presented. In [LEE97], reconfiguration in the situation of unreliable links is examined.

2.2.2.3 VP pool management
Some published work focuses on the problem of VPC configuration and VPC capacity allocation at the same time. Most of this work is formulated as some kind of an optimisation problem.

For example, the minimisation of average queuing delay is considered by Gerla et al.[GER89], Mitra et al.[MIT93] and Xiao et al.[XIA94]. The minimisation of average blocking probability is considered by Gopal et al.[GOP91]. Lee et al.[LEE93] formulate an optimisation problem to minimise the total cell loss rate. Hui et al.[HUI91] formulate optimisation problems for the path layer that minimise the usage of physical links, subject to satisfying grade of service (GoS) requirements.

In Kim [KIM95], the author considers the trade-off between increased capacity costs and reduced control costs. An optimisation problem is formulated to minimise a cost function (link buffer and control cost), subject to constraints on QoS and GoS. In [PIT97], evolutionary programming is used for VPC bandwidth allocation. In [LAZ95], a game theoretic model is employed for the fairness problem in allocating capacity for VPC in a non-cooperative network.

In [BER97], the authors examine how dynamic reconfiguration in single-service networks can be used to achieve an optimal match between offered traffic and link capacities. In [AIU97], the authors propose a bandwidth management framework for ATM based B-ISDN. The bandwidth management framework consists of a network
model and a bandwidth allocation strategy. The network considered is a partitioning of core and edge networks.

2.2.3 Proposed solution

The problem of VPC configuration and VPC capacity allocation are related and interdependent. To achieve cost-effective resource management (e.g. high network efficiency, maximum revenue etc.), both problems must be solved together. For example, we cannot achieve the highest network efficiency if we do not know how much capacity should be allocated for the VPC overlay network. We also cannot allocate suitable capacity to VPCs if we do not know the structure of the VPC overlay network. The approach of solving the VPC topology and its capacity at the same time is used by [FRI96], where modifications are periodically made based on anticipated traffic conditions, and also in facilitating recovery from component failure.

The problem of finding a suitable VPC topology and VPC capacity is complex. The number of possible VPC topologies grows exponentially with the network size. A wide range of VPC capacity allocations is possible, ranging from zero (no VPC) up to the number of VCCs which fully utilise the link capacity. It has been found that most of the techniques have high computational complexity [FRI96].

In this research, an ATM network is approached in a systematic way. The major network resources are identified for an overload situation. A network model is proposed for optimisation with respect to user satisfaction. The model solves for an optimal set of traffic flows. A technique is illustrated for using this optimal solution as a basis for CAC, through real-time management of the VP pool.

2.3 Nature of the Internet

2.3.1 The Internet and the problem of poor performance

The Internet is the world’s biggest network of networks and continues to grow, apparently without limit. ARPANET was established with only 4 connected computers in 1969 under the sponsorship of the Advanced Research Projects Agency of the US
The present Internet encompasses about 50,000 networks and over 5 million computers [CER96], and growth is exponential, doubling each year.

The expansion of the Internet is rapid in both traffic volume and variety of applications. In June 1997, Walnut Creek CDROM’s popular FTP server, wcarchive.cdrom.com, sent out more than 4 tera-bytes of files to over a million people [GRE97]. Some of the companies running major “search engines” on the Internet serve over 4 million HTTP requests per day [FIL97].

One of the big technical challenges for an Internet Service Provider (ISP) is scaling their services in the face of rapid growth in traffic volume. For example, wcarchive [GRE97] started life in 1993 using an Intel 486/66 with 64MB RAM, a 3GB disk drive, connected by a 1.5Mbps T1 line and with a user limit of 150. Wcarchive now uses a 200MHz Pentium Pro, with 512MB RAM, 139GB disk space, connected via 100Mbps fast Ethernet and can serve more than 2,000 simultaneous users. If the demand continues to grow at 100% per year as it has up to now, then by the year 2000 wcarchive will need to have 1 terabyte of disk space and handle more than 12,000 users.

![Figure 2.1: The growth of wcarchive.](image_url)
There has been rapid growth in the variety of Internet applications. Traditional Internet applications are text based applications such as telnet, e-mail and file transfer. Since the World Wide Web (Web) was created at CERN, a physics laboratory in Geneva, Switzerland, Hyper Text Transmission Protocol (HTTP) has been used to transmit Web pages over the Internet. HTTP allows the Internet to be used as an interactive multimedia worldwide network [NAR96], [HAN96], [HAR95] and [MUI95]. Users can “travel” from one Web page to another or select from protocols such as file transfer protocol (FTP), telnet, or gopher by simply clicking on hypertext links in the Web page.

A wide variety of traffic types can be carried over the Internet. For example a Web page can deliver a variety of audiovisual material such as text, pictures, sound, music, voice, animations, video, Internet telephony, video conferencing and multi-player games. These services generate a wide variety of traffic types, and have widely differing QoS requirements. Some of these services are handled badly by the present Internet, giving inadequate quality of service (QoS).

The network is likely to remain chronically overloaded, which means that most applications will often suffer from excessive response times. When response times are excessive, many users abandon their requests, thus contributing to the amount of unproductive traffic in the network, and the consequent unproductive use of resources. The problems of throughput and QoS in the Internet have attracted substantial attention from the research community. For example the Internet features significantly in major international conferences on communication such as ICC, GLOBECOM, and INFOCOM. Specific conferences on Internet issues have been set up to accelerate its development, such as the Internet Society Networking Conference (INET) and the International World Wide Web Conference (IW3C). The Internet Engineering Task Force (IETF) is an open international community of network designers, operators, vendors, and researchers, formed to make technical and other contributions to the design and evolution of the Internet and its technologies [IETF].
2.3.2 Proposed solutions to the problem

A fundamental issue in Internet management is the policy to be applied if user demand exceeds the network resources. In this thesis it is assumed that the ideal policy is to limit access to achieve the maximum number of satisfied users. Figure 2.3 shows the general effect of access policy on network performance, when the network resources are fixed and user demand varies.

![Diagram showing the effect of access policy on network performance](image)

**Present network resources**

**Excessive Demand**

**Limited access policy**

**Unlimited access policy**

Figure 2.2: Effect of access policy on number of satisfied users in an overloaded network.

If all connection requests are accepted when the demand exceeds the network resources, QoS cannot be satisfied for all users (“Unlimited access policy” Figure 2.3). There are two reasons for this.

1. If there is open access such that the resources per user are not enough to meet the minimum QoS requirements per user, then, if the resources are distributed equally, all users will be dissatisfied.

2. If the policy is to allow open access to all users, then during periods of overload, it is common for users to become frustrated and to disconnect during a transaction. Terminating in the middle of a transaction results in unproductive traffic in the
network. Congestion leads to early termination of transfers, retransmission attempts, further congestion and so on, and eventually to congestion collapse. This increases the traffic in the network, but does not give rise to user satisfaction. As a result, all users suffer reduced QoS due to unnecessary congestion in the network.

If the network could provide some minimum bandwidth guarantee to those users given access, the overall performance (number of satisfied users) would be improved, even though some requests for access would need to be refused [BRA94] ("Limited access policy" Figure 2.3).

If connections are limited then, in principle, the QoS can be protected for those users who are connected. The network efficiency can be optimal provided the forecasts and control are optimal. Some users will not be able to access the network, and thus will receive no service, but the total number of satisfied users can be maximised. A list of features for each situation (unlimited access and limited access) is shown in Table 2.1.

Table 2.1: List of features for unlimited access and limited access.

<table>
<thead>
<tr>
<th>Unlimited Access (all connections accepted)</th>
<th>Limited Access (connections are limited)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- QoS unsatisfactory</td>
<td>- QoS satisfactory (for those connected)</td>
</tr>
<tr>
<td>- Some dissatisfied users will disconnect (self-regulation)</td>
<td>- Efficiency should be high (if forecasts &amp; control are accurate [optimal])</td>
</tr>
<tr>
<td>- Efficiency may be low (due to congestion)</td>
<td>- Some (unconnected) users will receive no service</td>
</tr>
</tbody>
</table>
To control the QoS in the Internet, RSVP has been proposed by IETF [BRA94]. RSVP uses the connection-oriented concept where all of the packets for a given connection use the same route. This allows appropriate resource reservation on that route. RSVP has been designed to give flexible control over multi service resources [ZHA93a] and [ZHA93b]. Applications can obtain predictable quality of service on an end-to-end basis [YAV96].

The optimal use of network resources is not trivial, and has been addressed by researchers since before the era of broadband multi-service networks. For example, a linear programming model has been proposed for the purpose of traffic management in a circuit switch network [COW87], [WAR88a]. The model also has been trialled on the real Australian network, as shown in [WAR88b]. In [BER97], the authors use a nonlinear programming model to dynamically configure a single-service broadband network.

If any such model is applied to the Internet, the issue of complexity must be considered. The Internet (the network of networks) is a large and complex network. The number of routes increases exponentially with the number of network elements (routers, links and servers), and the number of elements in the Internet is large and growing. The complexity of the problem is also increased when many kinds of traffic are involved in a network. The Internet has the capability to carry a very wide variety of traffic types, each with its own traffic characteristics, and performance requirements.

To manage the network in real-time, the optimisation problem must be solvable in real-time, so the problem must be simplified somehow. In [WAR88a] and [WAR88b], the circuit switched network model is simplified to allow real-time solution by considering only the top hierarchy of the network. Fast solution algorithms have been developed for real-time traffic management applications in [LAM91]. In [LIU97], the authors propose the idea of partitioning the network into core and edge networks to contain the size of their model. In this thesis it is assumed that partitioning can be used to contain the complexity of the problem to a level where real-time solution is feasible.
2.4 Conclusions

ATM networks and the Internet are well known and are both assumed to have a role in the future of broadband networks. The literature regarding both networks has been reviewed to provide a background to the problem of optimising network performance.

Although both networks are based on quite different philosophies, they face a common set of unsolved problems related to the sharing of resources between mixed traffic types.

ATM has been designed to meet multi-service QoS requirements. CAC has an important role in controlling access to the network and allowing the protection of QoS. VPC spare capacity from end to end has an important role in the CAC decision-making process, by indicating whether there is enough resource available to meet the needs of the additional service.

On the other hand, the Internet has not been designed to address multi-service QoS requirements. Free access to resources leads to unacceptable mean delay for all users whenever there is excess demand. RSVP has been proposed by IETF to address the requirements of delay sensitive traffic, however the problem of optimal resource allocation has not yet been solved.

Thus this research aims to address a set of unsolved problems that applies to both ATM networks and the Internet. It proposes a strategy for optimal operation of both networks. Whether considering ATM networks or the Internet, control of access to the network is essential to achieving optimal network operation. Some form of optimisation model, which provides an optimal set of accepted connections, offers a basis for improving the network performance, where the optimisation objective is to maximise network throughput while satisfying the QoS requirement.
CHAPTER 3
DEVELOPMENT OF AN OPTIMISATION MODEL FOR ASYNCHRONOUS TRANSFER MODE (ATM) NETWORKS

3.1 Introduction

In this chapter, we propose a linear programming model to represent the problem of traffic control in an overloaded broadband network. The objective of the model is to determine an optimal set of traffic flows in the network. The model is developed first by using a graphical tool to represent the traffic flows in a network and their relationship with network resources, and then by expressing the relationships as a Linear Program problem.

Traffic management has been a major problem in telecommunication networks for many years since well before the era of broadband multi-service networks. Because of the connection-oriented nature of ATM networks, we can draw on the large body of circuit switched network knowledge to help address the problem of managing the performance of ATM networks.

The problem of managing traffic in overloaded networks has been discussed extensively in the context of circuit-switched networks. For example dynamic routing designs have been described as feedforward systems in [ASH81a], [ASH81b] and [ASH83], and adaptive systems in [NAR77], [SZY79a], [SZY79b], [GAR80], [CAM83], [SZY85], [OTT85], [ADD85], [CAR88], [CAR89], [MAS89], [KRI89], [REG90] and [FIL85]. Several models that have been used include static multi-commodity flow, dynamic flow, diffusion models, Markov decision processes, queuing theory models, learning automata and simulation. An overview of the models used is described in [FIL85] and dynamic routing systems are surveyed and classified in [BEL85].

Dimensioning of overloaded networks using linear programming models has been studied in [GUE83] and also in [COW87] for demand servicing. In [COW87] and [WAR88a], the authors present a linear programming model for maximising revenue in circuit-switched networks. The linear programming model described in [WAR88a], has
been trialed successfully in the Australian network [MCM88] and [WAR88b]. The trial network comprised about twenty exchanges which formed the top level of the hierarchy of the Australian network, and three international switching centres.

In broadband networks the problem of traffic management becomes much more difficult, because broadband networks involve issues of loss and delay and multiple QoS measures, as well as those of blocking and routing. To address the difficult issue of resource allocation in mixed traffic networks, the concept of “effective bandwidth” (e.g. [SAF95], [LEE95] and [DZI95]) is used to characterise the service rate required by a VCC. By using the concept of effective bandwidth, we simplify the traffic representation. We can represent traffic flow in the network as being steady and deterministic, and this allows us to use a steady state deterministic optimisation model. Similarly the concept of “effective processing load” is used to characterise the node processing rate required at the switch associated with groups of VCCs.

The notion of “effective bandwidth” arises from queuing theory models, and allows stochastic-loss-network (generalised-Erlang) models to be used for resource allocation. This leads to the opportunity to use the LP model, and hence make the large scale network problem tractable. Alternatives to using the LP model include game theory and pricing theory. For example [YAM99] uses game theory to develop a distributed dynamic routing scheme. That scheme does not claim to produce global optimality, but rather is a fully decentralised scheme. The aim of the LP model used here is to explore issues of global optimality.

3.2 Graphical Representation of Network Traffic and Resources
In this section, the intention is to develop a graphical representation of network resources, to help illustrate the relationships between streams of connection events (such as accepted and rejected connection attempts) and the resources with which these streams are associated (such as the processing power associated with routing decisions, or the bandwidth associated with accepted connections).
This approach draws on the work of [WAR88a] for circuit-switch networks, but is revisited here in the context of broadband networks. The graphics represent the traffic flow and help us to understand the characteristics of the system.

![Diagram of broadband network elements](image)

**Figure 3.1: Graphical representation of broadband network elements.** (X, Y refer to connection rates). (a) Summer: Y = X₁ + X₂. (b) Splitter: Y₁ + Y₂ = X. (c) Routing and Flow Control: Y = X. (d) Rate and State Limiters: Y = X, Y ≤ Y_{max}.

The function blocks are as follows:

- The summing element in Figure 3.1: (a) is used to represent summation between convergent streams. Its function is represented by the flow equation Y = X₁ + X₂. X refers to the connection rates of the input streams and Y refers to the connection rate of the output stream.

- The splitting element in Figure 3.1: (b) is used to represent the division of a single stream into divergent streams. It is assumed that flow conservation applies, so Y₁ + Y₂ = X. The “control parameter” might represent some property of the network environment (such as the probability that a congested sub-net will accept a
connection request originating from another sub-net), or it might represent a required control action (such as CAC action required to limit a flow of accepted connections).

- The routing and flow control system box in Figure 3.1: (c) is used to represent any kind of routing and flow control algorithm in the network. Its function is to assist any stream which has been admitted into the network to pass through the network to the destination. We assume all input streams admitted into routing and flow control systems will pass through the network. Thus the function is represented by the flow equation \( Y = X \).

- The rate and state limiter in Figure 3.1: (d) is used to represent a limitation of flow in the network due to a resource availability limit. We assume again that all input streams admitted to this set of resources pass through these resources, so flow conservation applies, and \( Y = X \). However the resource limit sets a constraint on flow so that \( Y \leq Y_{\text{max}} \). The mechanism for enforcing that constraint on input \( X \) will normally be associated with a splitting element. In assuming that all of the input stream passes through to the output, we also assume that some control mechanism (such as CAC) or physical behaviour mechanism (such as blocking due to non-availability of channels) is available to ensure that the resource is protected from excess demand.

Each node in the network is modelled approximately as a rate limiter. This means that it will accept all offered connection attempts provided the rate of these attempts is below a fixed limit. If the node is offered a higher connection rate than its maximum limit, selective control will be applied to some of the streams of offered connection attempts. The controls (to be devised elsewhere) must always ensure that the rate of acceptance of connection attempts does not exceed the rate limit of the node. This rate limit is based on the performance of the processor at the interface to the ATM network.

Each link is modelled approximately as a state limiter. Connection attempts can be accepted until link occupancy reaches its limiting value. Once the limiting value is reached, some of the incoming connection attempts must be selectively
blocked. The limiting value represents the assignable bandwidth of a link which is protected from excessive overload by appropriate network management action.

These symbols are combined to represent a broadband network as illustrated in Figure 3.2. The notion of “connection intents” is introduced in [WAR88a] in the context of circuit switched networks. It is intended to represent the newly arising demand from the user population, whereas “repeat attempts” represents requests for connection left over from earlier intents that were unsuccessful. The “connection attempts” are the sum of all attempts seen by the network interface, comprising not only new “intents” but also old “repeat attempts”.

In the context of ATM networks it seems useful to retain the notion of “intents” and “repeat attempts”. This can represent effects such as multiple connection requests from computer-based equipment, or for repeated connection attempts by human users of services. It should be noted that the flows of “intents”, “repeat attempts” and “abandoned connections” will usually occur in some queueing system within the equipment or sub-net which generates the flow of “connection attempts” to the ATM network interface.

Some connection attempts are rejected by admission control at the network edge. The rest are accepted for connection to the network. It is assumed that accepted connections pass through the network to the destination with the assistance of the routing and flow control systems. There is provision in the model for connection attempts to be successfully routed to the destination, but then not accepted (“not answered”) at the destination. Possible causes of non-acceptance at the destination might be non-availability or congestion of the destination object. Both rejected and not answered connections are classed as unsuccessful connections which may result either in repeated connection attempts to the network or else be abandoned.

Although the flow of “accepted connections” through the resource elements is shown as if it is one coherent stream, in fact there is a different demand for resources (such as
bandwidth) due to “successful” connection requests and “unanswered” requests. “Unanswered” requests carry control information plus the data stream through the connection. This issue is addressed by permitting different traffic parameters for “successful” and “unanswered” streams.

![Figure 3.2: Broadband Network Connection Flow Diagram for LP Model.](image)

### 3.3 Model Implementation

In this section, mathematical relationships are developed around the structure suggested in Figure 3.2. We develop relationships for the flow, link and node constraints, and for an objective function.

In our model, all links and nodes are modelled as saturating devices. That is, a link is assumed to have a fixed upper limit to the bit rate it can process, while a node is assumed to have a fixed upper limit to the rate of connection requests it can process. The objective function proposed is a linear combination of the independent variables. The formulation is similar to that used by Lambert [LAM91]. The answer-seizure ratio (ASR) associated with each source-destination pair is modelled as a simple known
probability. The repeat attempt probabilities for various streams of unsuccessful attempts are modeled as if they are known values.

The model is expressed as a Linear Programming problem:

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 all flows (divided into traffic types, source-destination pairs, and alternative paths through the network) and one variable for each equality constraint. Elsewhere in the text, these extra variables 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 coefficients showing the demand of each stream for network resources, termed the “technological” matrix.
- \( b \) is the column vector associated with the constraints on offered traffic and network resources.

The following notation is used in developing the LP model:

- \( n \) is the number of nodes in the network.
- \( l \) is the number of links in the network.
- \( r_{i,j} \) is the number of virtual paths defined for accepted connections from origin \( i \) toward destination \( j \).
- \( t \) is the type of traffic associated with a particular connection. Different types will have different parameter values, such as holding time, ASR, etc. An indication of some possible assignments of traffic type \( t \) is given below.
  - \( voice \) traffic type voice.
  - \( data \) traffic type data.
video traffic type video.

In general, there must be sufficient categories to identify all traffic aggregations with significantly different parameter descriptors. The problem of grouping traffic streams into types is somewhat similar to grouping traffic streams into Virtual Paths based on similar behaviours and similar QoS requirements.

\( d \) is the disposition which may be any one of the following:

- **in** first attempts or connection intents.
- **att** connection attempts to the network, whether first attempts or repeat attempts.
- **acc** accepted connections or connection attempts admitted to the network.
- **suc** successful connections.
- **na** routed connection requests which are not accepted (“not answered”) at the destination, although fully routed through the network.
- **rej** connection attempts rejected by control action at the network edge.
- **unsuc** unsuccessful connections, whether “not answered” by the destination or rejected by control action.
- **rep** the proportion of unsuccessful connection attempts which are repeated.
- **abd** abandoned connection attempts are unsuccessful connection attempts which are not repeated.

\( x_{i,j,k}^{t-d} \) is the rate of flow of connection attempts from origin \( i \) to destination \( j \) of traffic type \( t \) with disposition \( d \) along virtual path \( k \) for \( k = 1, 2, \ldots, r_{i,j} \). A dummy virtual path is defined for \( k = 0 \) to accommodate the connection attempts which are rejected by control action at the input to the network.

\( p_{i,j}^{t} \) is the ASR probability. It is the conditional probability of an accepted connection from origin \( i \) to destination \( j \) for traffic type \( t \) being answered. Thus, the average holding time for accepted connections for traffic type \( t \) is given by:

\[
p_{i,j}^{t} h_{i,j}^{t-acc} + (1 - p_{i,j}^{t}) h_{i,j}^{t-na}
\]

\( q_{i,j}^{t} \) is the probability of an unsuccessful connection from origin \( i \) to destination \( j \) for traffic type \( t \) being repeated.

\( h_{i,j}^{t-d} \) is the holding time of \( d \) for source type \( t \) from origin \( i \) to destination \( j \).
$b_{i,j}^{t-d}$ is the effective bandwidth\(^1\) demand per connection of $d$ for traffic type $t$ from origin $i$ to destination $j$.

For summation over origins, destinations, or virtual paths, dot notation is used; for example:

- $x_{i,j}^{video-in}$ is the rate of arrival of connection intents from origin $i$ toward destination $j$ of video type, for all virtual paths from $i$ to $j$.
- $x_{i,*}^{data-unsuc}$ is the rate of unsuccessful connection attempts from origin $i$ of data type, for all virtual paths from $i$ to all destinations.
- $b_{i,*}^{voice-na}$ is the effective bandwidth demand per connection of not answered connections for voice type traffic from origin $i$ to all destination.
- $\phi_{i,j,k}^{t}$ 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 virtual path $k$ must pass through the network element (node or link) identified by $e$.
- $S^{e}$ is the state limit of the link identified by $e$.
- $R^{e}$ is the rate limit of the node identified by $e$.
- $t_{i,j}^{t}$ is the tariff rate (in dollars per unit of time) charged for a successful connection from origin $i$ to destination $j$ for traffic type $t$.

Using the above notation, the connection flow diagram in Figure 3.2. can be developed further by adding mathematical relationships as show in Figure 3.3.

\(^1\) The “effective bandwidth” is an estimate of the service-rate required by a connection that takes into account the gains from multiplexing whilst satisfying network QoS constraints.
3.3.1 Flow constraint implementation

From Figure 3.3, it can be seen that

$$x_{i,j}^{t-in} + \sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-rep} = x_{i,j}^{t-att} = \sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-acc} + x_{i,j}^{t-rej}$$  \hspace{1cm} (3.2)

and

$$\sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-na} = (1 - p_{i,j}) \sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-acc}$$  \hspace{1cm} (3.3)

From the diagram

$$x_{i,j}^{t-rep} = q_{i,j} x_{i,j}^{t-unsuc}$$  \hspace{1cm} (3.4)

and

$$x_{i,j}^{t-unsuc} = x_{i,j}^{t-rej} + \sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-na}$$  \hspace{1cm} (3.5)

Therefore

$$x_{i,j}^{t-rep} = q_{i,j} (x_{i,j}^{t-rej} + \sum_{k=1}^{r_{ij}} x_{i,j,k}^{t-na})$$  \hspace{1cm} (3.6)
From equation (3.2), (3.3) and (3.6), the flow constraint is

\[
(1 - q'_{i,j})(1 - p'_{i,j}) \sum_{k=1}^{n_f} x_{i,j,k}^{t-acc} + (1 - q'_{i,j})x_{i,j}^{t-rej} = x_{i,j}^{t-in} \quad (3.7)
\]

The reject flow \(x_{i,j}^{t-rej}\) can be related directly to the idea of slack variables in LP models. Equation (3.7) can be converted to the form where the slack variable is \(x_{i,j}^{t-rej}\) be simple rescaling.

\[
\frac{1 - q'_{i,j}(1 - p'_{i,j})}{1 - q'_{i,j}} \sum_{k=1}^{n_f} x_{i,j,k}^{t-acc} + x_{i,j}^{t-rej} = \frac{1}{1 - q'_{i,j}} x_{i,j}^{t-in} \quad (3.8)
\]

An example is given for three traffic types; voice, data and video, each with different repeat probability, ASR probability, and connection intent rate. The flow constraints will be in the form of three groups of equations as follows:

\[
\frac{1 - q_{i,j}^{\text{voice}} (1 - p_{i,j}^{\text{voice}})}{1 - q_{i,j}^{\text{voice}}} \sum_{k=1}^{n_f} x_{i,j,k}^{\text{voice-acc}} + x_{i,j}^{\text{voice-rej}} = \frac{1}{1 - q_{i,j}^{\text{voice}}} x_{i,j}^{\text{voice-in}}
\]

\[
\frac{1 - q_{i,j}^{\text{data}} (1 - p_{i,j}^{\text{data}})}{1 - q_{i,j}^{\text{data}}} \sum_{k=1}^{n_f} x_{i,j,k}^{\text{data-acc}} + x_{i,j}^{\text{data-rej}} = \frac{1}{1 - q_{i,j}^{\text{data}}} x_{i,j}^{\text{data-in}}
\]

\[
\frac{1 - q_{i,j}^{\text{video}} (1 - p_{i,j}^{\text{video}})}{1 - q_{i,j}^{\text{video}}} \sum_{k=1}^{n_f} x_{i,j,k}^{\text{video-acc}} + x_{i,j}^{\text{video-rej}} = \frac{1}{1 - q_{i,j}^{\text{video}}} x_{i,j}^{\text{video-in}}
\]

### 3.3.2 Link constraint implementation

For every state limiter of link \(v (l(v))\), there is an inequality constraint on the bandwidth of connections in progress for all traffic types of the form

\[
\sum_{l(v), j, k} \phi_{i,j,k}^{l(v)} \left( x_{i,j,k}^{t-suc} h_{i,j}^{t-suc} b_{i,j}^{t-suc} + x_{i,j,k}^{t-na} h_{i,j}^{t-na} b_{i,j}^{t-na} \right) \leq S^{l(v)} \quad (3.9)
\]

It should be noted that equation (3.9) uses a deterministic limit to represent two kinds of stochastic behaviour. Firstly, as mentioned in the footnote on page 24, the notion of ‘effective bandwidth’ is used to represent the service rate required to handle the stochastic bit rate for a given connection. Secondly a high link occupancy is assumed to be feasible. That is, equation (3.9) assumes that the effective bandwidth of any one connection is small relative to total link bandwidth, and/or that the rate of offered traffic
is much greater than the link capacity (that is that there is a substantial overload). This allows a deterministic approximation to be applied to a stochastic process.

From the diagram in Figure 3.3

\[ x_{i,j,k}^{t-suc} = p_{i,j}^{t} \sum_{k=1}^{T_{i,j}} x_{i,j,k}^{t-acc} \quad (3.10) \]

From equation (3.3) and (3.10), equation (3.9) becomes

\[ \sum_{l(v)} \phi_{l(v)}^{t(v)} \left( p_{i,j}^{t} h_{i,j}^{t-suc} b_{i,j}^{t-suc} + (1 - p_{i,j}^{t}) h_{i,j}^{t-na} b_{i,j}^{t-na} \right) x_{i,j,k}^{t-acc} \leq S_{l(v)}^{t} \quad (3.11) \]

By addition of a slack variable for link \( v \) (\( x_{l(v)}^{v} \)), equation (3.11) can be converted to equality form

\[ \sum_{l(v)} \phi_{l(v)}^{t(v)} \left( p_{i,j}^{t} h_{i,j}^{t-suc} b_{i,j}^{t-suc} + (1 - p_{i,j}^{t}) h_{i,j}^{t-na} b_{i,j}^{t-na} \right) x_{i,j,k}^{t-acc} + x_{l(v)}^{v} = S_{l(v)}^{t} \quad (3.12) \]

where \( x_{l(v)}^{v} \) represents unused link capacity

An example is given for three traffic types; voice, data and video, each with different traffic parameters, transmitted on a link. The link constraint will be in the form of

\[ \sum_{l(v)} \phi_{l(v)}^{t(v)} \left( p_{i,j}^{t} h_{i,j}^{t-suc} b_{i,j}^{t-suc} + (1 - p_{i,j}^{t}) h_{i,j}^{t-na} b_{i,j}^{t-na} \right) \]

By addition the slack for node \( u \) (\( x_{n(u)}^{u} \)), the equality form of node constraint in equation (3.14) is

### 3.3.3 Node constraint implementation

For every rate limiter of node \( u \) (\( n(u) \)), there is an inequality constraint on the rate of connections arrivals for all traffic type of the form

\[ \sum_{l(u)} \phi_{l(u)}^{n(u)} x_{i,j,k}^{t-acc} \leq R_{n(u)}^{u} \quad (3.13) \]

By addition the slack for node \( u \) (\( x_{n(u)}^{u} \)), the equality form of node constraint in equation (3.14) is
An example is given for three traffic types; voice, data and video, all using node $u$. The node constraint will be in the form of

\[
\sum_{i,j,k} \phi_{i,j,k}^{n(u)} x_{i,j,k}^{t} + x_{u}^{n(u)} = R^{n(u)}
\] (3.14)

### 3.3.4 Objective function implementation

The management of buffer, bandwidth and processor is really a multi-objective function optimisation problem (as discussed in [AND98]). This is handled here by optimising instead for a single objective function that is a linear combination of bandwidth and processing utilisation. Buffer management is assumed to be a more fine grained problem that is taken into account within the notions of “effective bandwidth” and “effective processor load”.

We wish to provide a range of options for optimisation objective, allowing the objective to be expressed either from the viewpoint of the network operator or the network user. The network operator’s interest is assumed to be maximising revenue, whereas the user’s interest is assumed to be either maximising accepted connection rate or minimising rejected rate. The objective function is divided into 3 terms and a weighting coefficient is used in each term to allow any selected weighting of each interest. The objective function is of the form

\[
f = \sum_{i,j,k} \alpha_1^t h_{i,j}^{t-acc} x_{i,j,k}^{t-acc} + \alpha_2^t x_{i,j,k}^{t-acc} + \alpha_3^t x_{i,j,k}^{t-rej}
\] (3.15)

Where the three terms in the summation represent the rate of revenue, the rate of fully routed connection attempts, and the rate of rejected attempts. The weighting coefficients are as follows:

- $\alpha_1^t$ is the (positive) coefficient for revenue of source type $t$. It is a dimensionless quantity.
- $\alpha_2^t$ is the (positive) coefficient for fully routed connection attempts of source type $t$.

It is expressed in units of dollars per routed attempt.
\( \alpha' \) is the (negative) coefficient for rejected connection attempts of source type \( t \). It is expressed in units of dollars per rejected attempt.

From equation (3.3) and (3.10), the objective function (3.16) becomes

\[
f = \sum_{i,j,k} \left( \alpha'_{i,j} h_{i,j}^t t_{i,j} p_{i,j}^t + \alpha_{1} x_{i,j,k}^{v-acc} + \alpha_{2} x_{i,j,k}^{v-rej} \right) \]

(3.16)

An example is given for three traffic types; voice, data and video, each with different holding time, tariff rate and ASR probability. The objective function will be in the form of

\[
f = \sum_{i,j,k} \left( \alpha_{i,j}^{voice} h_{i,j}^{voice} t_{i,j}^{voice} p_{i,j}^{voice} + \alpha_{1}^{voice} x_{i,j,k}^{voice-acc} + \alpha_{2}^{voice} x_{i,j,k}^{voice-rej} \right) \]

(3.16a)

\[
f = \sum_{i,j,k} \left( \alpha_{i,j}^{data} h_{i,j}^{data} t_{i,j}^{data} p_{i,j}^{data} + \alpha_{1}^{data} x_{i,j,k}^{data-acc} + \alpha_{2}^{data} x_{i,j,k}^{data-rej} \right) \]

(3.16b)

\[
f = \sum_{i,j,k} \left( \alpha_{i,j}^{video} h_{i,j}^{video} t_{i,j}^{video} p_{i,j}^{video} + \alpha_{1}^{video} x_{i,j,k}^{video-acc} + \alpha_{2}^{video} x_{i,j,k}^{video-rej} \right) \]

(3.16c)

It should be noted that, although revenue is expressed here in terms of a tariff in dollars per unit of connection time, the model structure can readily accommodate a range of different tariff structures.

### 3.3.5 Summary of broadband multimedia model

The Linear Programming model can now be written as:

Maximise

\[
f = cx \]

(3.17)

Subject to

\[
Ax = b \]

(3.18)

\[
x \geq 0 \]

(3.19)

where

- \( f \) is the objective value or part of revenue, which we want to maximise.
- \( c \) 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 flows along alternative paths through network (\( x_{i,j,k}^{v-acc} \) for \( k = 1, ..., r_{i,j} \)) and one variable for each equality.
constraint \((x_{i,j}^{r-rej}, x_{j}^{l(v)}\) and \(x_{n(a)}^{n_u})\). The reject flows \(x_{i,j}^{r-rej}\) 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 repeated probability, ASR probability, average hold times and effective bandwidth per connection.

\(b\) is the column vector of right hand side terms, associated with the constraints on offered traffic, link capacity and node capacity.

It can be seen that equation (3.17) is the abbreviated form of the objective function as defined in equation (3.15). Equation (3.18) is the abbreviated form of the flow, link and node constraints as defined in equations (3.8), (3.12) and (3.14) respectively.

### 3.4 Application Example

In this example, we apply the model to a network carrying two different traffic types, and investigate the effect of a major network (link) failure. The two traffic types are connection-oriented and connectionless. The reason for choosing these types is that they have a very different pattern of resource requirements. The connection-oriented traffic has a relatively low ratio of processing load to bandwidth. The connectionless traffic has a relatively high ratio of processing load to bandwidth, because routing decisions need to be made on a packet-by-packet basis.

The sample network is illustrated in Figure 3.4. The network consists of six nodes with a gateway to represent an interstate network. Three nodes in the network, n1, n2 and n3, represent the top level in the hierarchy of a state network. Two of these state nodes, n2 and n3, are connected to a gateway exchange, g, which provides access to two interstate sources/destinations, d1 and d2.
3.4.1 Sample specification and basic solution

The bandwidth of each link (state limit) is 155 Mbit/sec. The processor speed (rate limit) of nodes, n1, n2, n3, d1 and d2, is 120 call attempts/sec, while the processor speed of the gateway, g, is 250 connection attempts/sec.

Table 3.1: Traffic Parameters for Sample Network.

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Connection Attempt Rate (attempt/sec)</th>
<th>Holding Time (sec)</th>
<th>Bandwidth (Mbit/sec)</th>
<th>Tariff per Connection ($/sec)</th>
<th>Traffic Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>n2</td>
<td>0.02</td>
<td>1000</td>
<td>2</td>
<td>0.01</td>
<td>t1</td>
</tr>
<tr>
<td>n1</td>
<td>n3</td>
<td>0.02</td>
<td>1000</td>
<td>2</td>
<td>0.01</td>
<td>t1</td>
</tr>
<tr>
<td>n2</td>
<td>n3</td>
<td>0.02</td>
<td>1000</td>
<td>2</td>
<td>0.01</td>
<td>t1</td>
</tr>
<tr>
<td>n1</td>
<td>d1</td>
<td>0.01</td>
<td>1000</td>
<td>2</td>
<td>0.02</td>
<td>t1</td>
</tr>
<tr>
<td>n3</td>
<td>d1</td>
<td>0.01</td>
<td>1000</td>
<td>2</td>
<td>0.02</td>
<td>t1</td>
</tr>
<tr>
<td>n1</td>
<td>d2</td>
<td>0.01</td>
<td>1000</td>
<td>2</td>
<td>0.02</td>
<td>t1</td>
</tr>
<tr>
<td>n3</td>
<td>d2</td>
<td>0.01</td>
<td>1000</td>
<td>2</td>
<td>0.02</td>
<td>t1</td>
</tr>
<tr>
<td>n3</td>
<td>d1</td>
<td>75*</td>
<td>0.5</td>
<td>1</td>
<td>0.005</td>
<td>t2</td>
</tr>
<tr>
<td>n1</td>
<td>d2</td>
<td>75*</td>
<td>0.5</td>
<td>1</td>
<td>0.005</td>
<td>t2</td>
</tr>
</tbody>
</table>

* Note: For connectionless traffic the attempt rate is the same as the packet rate, because a packet is considered as a short holding time connection.
Offered traffic conditions are as shown in Table 3.1. Traffic type t1 is connection oriented traffic while type t2 is connectionless packet traffic, which is treated as connections with a very short holding time. The tariff for type t1 traffic on interstate connections is twice that for t1 traffic on local connections. The tariff for type t2 long distance traffic is half that per Mbit of type t1 long distance traffic.

To simplify the problem, the probability of repeated connection attempts, \( q \), is set to 0 and the ASR probability, \( p \), is set to 1. The objective is to maximise revenue so we set the weighting coefficient \( \alpha_1 = 1 \) and \( \alpha_2 = \alpha_3 = 0 \).

For the specified conditions, the LP solution shows that the network can handle all the traffic demand. It does not reject any connections. All nodes and links have spare capacity. The optimal revenue is 1.775 $/sec.

![Sample Network with Link Failure](image)

**Figure 3.5:** Sample Network with Link Failure.

3.4.2 Effect of a link failure

If there is a link failure as shown in Figure 3.5, any long distance traffic must be routed through node 2 to the gateway. If all the traffic from node 3 to d1 and d2 had previously been using the direct link, then there is a potential loss of revenue of 0.3875 $/sec (21.8%). If an attempt is made to reroute all the interstate traffic through node n2, this node becomes overloaded and selective blocking action must be taken to reject some connections. To protect node n2 from overload the optimal solution is to reject 30.10
packets per second of connectionless traffic (t2) from n1 to d2 and n3 to d1. This is 20% of the offered connectionless traffic. This optimal solution results in a loss of revenue of only 0.076 $/sec (4.3%) relative to the original situation with no link failure.

In this example the failure of one type of resource causes an overload in a different type of resource. Even though a link fails, a node resource becomes the bottleneck. There is a marked contrast in the demand for node resources by the connectionless packets and the connection-oriented traffic. The t1 long distance traffic presents a node processing load of 0.01/0.02=0.5 attempts/$, whereas t2 long distance traffic presents a load of 75/0.005=15,000 attempts/$.

3.4.3 Discussion of the sample problem
This example shows how the network should adapt when there is a gross mismatch between the network dimensioning and the offered traffic load. It shows also how the model readily takes into account both bandwidth and processing resource limitations at the same time. In this situation where a bandwidth resource has failed, a heuristic algorithm might easily assume that bandwidth optimisation is required, because it is (assumed) likely that bandwidth resources will form the most critical bottleneck. However a processing resource is ultimately the key scarcity in this example, and the LP solution simply finds the optimum, as it must do according to the problem definition. In general, this scheme will find the optimum admitted traffic volumes and routing choices.

3.5 Conclusions
The broadband multimedia network model proposed can be applied to many aspects of network resource management. It is presented here in terms of a B-ISDN or ATM network. The model includes link bandwidth and node processing constraints, so can be used to explore issues such as different VP management strategies (e.g. connectionless vs. connection oriented transmission) or the changing balance of link and node resource costs due to changes in technology. The network model offers an important tool for the development of resource management schemes. The sample problem gives an interesting example where a link failure causes node overload, and the optimal response
is to apply selective blocking for some of the connectionless traffic. It should be noted that, if the network failure had created a bottleneck at a long distance link, then the optimal solution would have been to selectively block the opposite traffic type, because it yields less revenue per unit of bandwidth.
CHAPTER 4
APPLICATION TO VIRTUAL PATH MANAGEMENT IN ATM NETWORKS

4.1 Introduction

In this chapter, we focus on converting the output of the optimisation model into control action. In the literature, several distinct layers of control have been considered for high performance networks. For example, [HSI91], [DOU92], [ZHA92], [ALT94] and [KOR95d] deal with flow control, [ECO91], [ALT93] and [ORD93] deal with routing, [LAZ95] deal with virtual path bandwidth allocation, and [COC93] deal with pricing.

On a connection level timescale, admission control and routing are the key to maximising network performance. In ATM networks, the management of the VP pool (a group of VPCs) provides an enabling tool for implementing the required admission control and routing [BUR90] [SHI94]. The VP pool establishes a set of permissible routes, and bandwidth allocations that automatically directs the routing and admission controls towards the optimal flow solution.

In this work, we focus on VP pool management, because the VP pool plays an important role in the cost-effective management of access to network resources, and in controlling this access in a way which allows the desired quality of service. The network model of chapter 3 is adapted and simplified to determine the optimal VPC topology and the assignment of capacity to the VPCs. The issue of Virtual Path (VP) management in asynchronous transfer mode (ATM) networks stands out as a major technical area with a number of unsolved problems.

The concept of the VP pool provides a linkage between large scale policy and event-by-event control actions. Admission of a connection to a VCC is an event-by-event activity which requires relatively little processing, because a VCC draws on the available, preset VPCs. On the other hand, creating a VPC requires more processing overhead. The concept of separating the network entities into VPC and VCC allows for adaptation of the VP pool to changing demand for network resources (a high level processing task), while controlling the admission of connections (a low level processing task). The
concept also allows for segregation of traffic according to differing quality of service (QoS) requirements.

Provided we control connection admission to ensure that the effective bandwidth of admitted traffic does not exceed the VP bandwidth, we can assume that traffic admitted to the network has an adequate resource allocation, and so can achieve the required QoS. The linear program (LP) optimal flow solution can be used to determine the optimal VP pool and set of bandwidth allocations. We can then assume that a simple event-by-event admission control based on available VP bandwidth will ensure the required QoS.

We need to consider the problem of allocating appropriate bandwidth to each VPC, where the “appropriate bandwidth” is that expected to carry the desired number of connections. As discussed shortly, we assume that an end-to-end connection requires a single VPC (rather than a series of VPCs forming a multi-hop connection). Then the set of all VPCs will create a fully meshed logical network (sometimes with multiple alternative logical links for a given source-destination pair). So the bandwidth allocation problem reduces to the traditional link dimensioning problem of circuit switched networks.

Since the connection birth-death process is random, the bandwidth allocated to any VPC will need to be somewhat greater than the desired bandwidth of carried traffic. If a Poisson arrival process is assumed, the traditional Erlang loss function could be applied directly to find the capacity allocation to be assigned in order to carry the optimal number of VCCs. Where a small number of VCCs is to be carried, and where the target is to carry almost all the offered traffic, the Erlang loss function requires a marked over-assignment of bandwidth. On the other hand where the target is a large number of VCCs or there is a large excess demand, the assigned bandwidth is little more than the carried bandwidth.

In event-by-event connection admissions, there must be some form of routing algorithm to identify which VPC should be used to carry a VCC. In the literature on routing in ATM networks, it is common to use a similar idea to the routing algorithms in circuit
switch networks, by considering the VPC as a link. These algorithms route a VCC on a
direct VPC as first choice. If the VCC cannot be routed on a direct VPC then an
alternative multi-hop VPC path is chosen. The idea of using alternative multi-hop VPC
paths is less efficient than using direct VPC paths. The lower the number of VPCs
required for a VCC, the lower the corresponding overall data transmission cost (or
specifically switching cost) [AHN94]. Hadama et al.[HAD94] introduce the concepts of
VP bandwidth control and the VP group into ATM transport networks to realise the
direct VP configuration in a very efficient manner.

In this work, we choose to route VCCs on direct VPCs only. If a VCC cannot be routed
on a direct VPC, the VCC must be blocked. In the case of multiple alternative direct
VPCs, our heuristic for the preferred direct VPC is the direct VPC which contours the
least physical links because we assume that this conserves physical resources to offer
flexibility for future optimal VPC reallocation.

4.2 Modification of the Broadband Multimedia Model

The model of chapter 3 solves for an optimal accepted connection rate to the network.
To use the model in a VP management application, it is convenient to view the solution
in terms of bandwidth rather than connection rate. The problem then is to find the
bandwidth that must be assigned to each VPC in order to carry the bandwidth indicated
by the LP solution. Here the bandwidth required for a connection is taken to be its
effective bandwidth, so that a simple allowance is made for statistical multiplexing gain.
The following steps are required to determine VPC allocated bandwidth:

- From the target for VPC carried bandwidth, find the target for the number of carried
  VCCs.
- From the target for carried VCCs find the required number of allocated VCCs. To
  allow for a target of \( t \) carried VCCs, the required \( N \) allocated VCCs can be found
  using the Erlang loss function (shown in recursive form here).
Where \( E_N(n) \) is the Grade of Service\(^1\) (Blocking Probability). It is the probability that all \( N \) allocated VCCs will be in use at any given moment for an offered traffic of \( n \) VCCs. It is based on analysis of a random traffic model, assuming that statistical equilibrium has been reached.

\( N \) is the required number of allocated VCCs in order to carry the target of \( t \) VCCs where \( t = n(1-E_N(n)) \).

- From the required number of allocated VCCs, find the required VPC bandwidth allocation.

In this section, we present a slightly modified and simplified model for determining the optimal VPC carried bandwidth in the network. The model is modified to find bandwidth rather than connection rate, so that the solution is in familiar terms for VPC resource allocation. To simplify the model, ASR probability \( p'_{i,j} \) is assumed to be 1 and repeat attempt probability \( q'_{i,j} \) is assumed to be 0. The model is expressed in the form of LP model as follow:

Maximise

\[
 f = cv
\]

Subject to

\[
 Av \leq b
\]

\[
 v \geq 0
\]

where

- \( f \) is the objective function value which is to be maximised.
- \( c \) is the row vector of cost coefficients in the objective function.

---

\(^1\) Grade of service (the fraction of call attempts which fail) is used as to express how well the network meets the demand for attempts. The grade of service may range from 0 to 1, with 0 being perfect, and 1 meaning that no traffic is carried at all. For offered traffic of \( A \) Erlang and carried traffic of \( n \) Erlang the grade of service (or Blocking Probability) is \( B = \frac{A-n}{A} \).
\( v \) is the column vector of independent variables (effective bandwidth of traffic carried on VPCs).
\( A \) is the technological matrix of coefficients representing network connectivity and the traffic parameters.
\( b \) is the column vector of constraints.

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 carried bandwidth for traffic type \( t \) from origin \( i \) to destination \( j \) along route \( k \) for \( k = 1, 2, \ldots, r_{i,j} \).

Where
\[
v_{i,j,k}^t = h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t,acc}
\]
and
\[
x_{i,j,k}^{t,acc}
\]
is the rate of accepted connections from origin \( i \) to destination \( j \) of traffic type \( t \) along virtual path \( k \) for \( k = 1, 2, \ldots, r_{i,j} \).
\( v_{i,j,k}^{t,att} \) 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.
\( \phi_{i,j,k}^t \) is the indicator variable which takes the value 1 if the VPC for traffic type \( t \) from origin \( i \) to destination \( j \) via route \( k \) passes through the network element 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 \( j \).

From equation (4.3), the model in chapter 3 can be modified as follow:
4.2.1 Modification of flow constraint

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

\[ \sum_{k=1}^{r_{i,j}} v_{i,j,k}^t \leq v_{i,j,*}^{t-\text{at}} \]  

(4.4)

4.2.2 Modification of link constraint

Links are modelled approximately as saturating devices, and traffic streams are treated as having known effective bandwidth. A simple state limiter is applied in the sense of each link can accept traffic until its average bandwidth demand reaches the capacity of the link. For every state limiter (link), there is an inequality constraint on the bandwidth of VCCs in progress of the form

\[ \sum_{l=v}^{l^{(v)}} \phi_{i,j,k}^{l(v)} v_{i,j,k}^t \leq S^{l(v)} \]  

(4.5)

4.2.3 Modification of node constraint

For every rate limiter (node), there is an inequality constraint on the rate of connections arrivals for all traffic type of the form

\[ \frac{1}{h_{i,j} b_{i,j}} \sum_{l^{(u)}} n^{(u)} \phi_{i,j,k}^{l^{(u)}} v_{i,j,k}^t \leq R^{n^{(u)}} \]  

(4.6)

4.2.4 Modification of objective function

The objective function is of the form

\[ f = \sum_{t,s,j,k} \left( \alpha_1 \frac{f_{i,j}^t}{b_{i,j}^t} v_{i,j,k}^t + \alpha_2 \frac{1}{h_{i,j} b_{i,j}^t} v_{i,j,k}^t \right) \]  

(4.7)

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

\( \alpha_1 \) is the weighting coefficient for revenue. It is a dimensionless quantity.

\( \alpha_2 \) is the weighting coefficient for accepted VCCs. It is expressed in units of number of VCC.
4.3 Development of DVPM Traffic Management System

In this section, simulation is used to evaluate examples of real-time traffic management using the LP model to manage the VP pool. The control policy is to accept a new VCC connection if its bandwidth is less than the difference between VPC allocated bandwidth and already connected total VCC bandwidth. Routing is performed automatically when the VCC is admitted to a VPC, since the VPC defines a particular route. Two schemes of VP management are illustrated - fixed virtual path management (FVPM) and dynamic virtual path management (DVPM). FVPM updates the VP pool only at the beginning of the simulation based on the known mean VCC attempt rates and the initial network topology. DVPM updates the VP pool at a regular control period based on the mean observed traffic during that period, and the current network topology (allowing for failure and recovery of network elements).

In the simulation throughout this work, we assume for simplicity the network has high capacity links and there is a large number of VCCs for each VPC, so that the Erlang loss correction is regarded as negligible. Thus the upper limit on VPC carried bandwidth is assumed to be equal to VPC allocated bandwidth.

The case of a major link failure is used to illustrate how FVPM and DVPM respond to major disturbances, and how closely the revenue for FVPM and DVPM approach the optimal revenue, before and after the failure. The simulation illustrates the effect of losing all the VPCs on the failed link. DVPM generates a revised VP pool while FVPM does not.

Consideration needs to be given to the appropriate choice of control period. In the literature on dynamic VP reallocation, there has been discussion about the VPC reallocation time. Burgin [BUR90] argues that less than a second is required to transmit the monitoring information to the controller, perform the reallocation calculations, and redistribute the new allocations, and that this rapid updating should increase stability and reduce response time of the network. Unlike Burgin, Shioda [SHI94] maintains that the lower limit of the control cycle should be on the order of the longest average VCC holding time, due to the amount of time required for the system to stabilise and for accurate call blocking estimates to be made after a reallocation.
Although, there are no exact solutions to the problem of VPC reallocation time, the model should certainly be re-solved whenever the current VP pool is not performing well. In this simulation, we reallocate a new set of VPCs on a fixed, repetitive time of 1/3 of the mean holding time of the traffic.

4.3.1 Sample problem

The network illustrated in Figure 4.1 is used in the simulation. The network configuration is the same as that in chapter 3. The network consists of six nodes with node g representing an interstate gateway. Three of the nodes, n1, n2 and n3, represent the top level in the hierarchy of a state network. Two of these state nodes, n2 and n3, are connected to a gateway exchange, g, which provides access to two interstate destinations, d1 and d2. Every link in the network has a bandwidth capacity (state limit) of 155 Mbit/sec.

![Figure 4.1: Sample 6 Node Network.](image)

Tariff rate and mean VCC attempt rate are shown in Table 4.1. The tariff rate for interstate connections is twice that on local connections (because interstate connections request more resources than the state connections). The attempt rate of traffic in the state network is such that almost the full capacity is used, however, the state network is still able to carry the interstate traffic from node n1. In case of no failure, the network should be able to carry all connection attempts. However, when the link fails between node n3 and node g, the state network is overloaded. It is possible to reroute interstate traffic.
from node n3 via the state network, and the model should adjust the VP pool to handle this situation.

In the simulation, we use a Poisson arrival process for new VCCs requests. The mean holding time of VCCs is chosen to be 180 sec with negative exponential distribution. 50 kbit/sec is chosen as the effective bandwidth for each VCC (because that is close to the basic rate of ISDN) The control update period is 60 sec.

Table 4.1: Tariff Rate and VCC Attempt Rate.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination</th>
<th>Tariff ($/Mbit)</th>
<th>VCC attempt (/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>n2</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>n1</td>
<td>n3</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>n2</td>
<td>n3</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>n1</td>
<td>d1</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>n1</td>
<td>d2</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>n2</td>
<td>d1</td>
<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>n3</td>
<td>d2</td>
<td>0.02</td>
<td>5</td>
</tr>
</tbody>
</table>

4.3.2 Sample results

We are interested in the effect of link failure on network performance with different control alternatives. As a basis for comparison we use the optimal revenue (calculated from the LP model) available from the network with no link failure (135.00 $/sec). For the link failure situation, there are two cases.

1. Using the same VP pool as the normal network. In this case the optimal revenue (calculated from the LP model) is 102.67 $/sec (24% reduction relative to the normal network).

2. Using a new VP pool, which is optimal for the network with link failure. In this case the optimal revenue (again from the LP model) is 125.40 $/sec (7% reduction relative to the normal network).

Thus without dynamic VP pool management we ideally expect a revenue loss of 24% due to link failure, whereas with dynamic VP pool management we ideally expect only 7% loss (after the initial transient).
Table 4.2: Revenue Comparisons.

<table>
<thead>
<tr>
<th>Network Condition</th>
<th>Optimal Revenue* ($/sec)</th>
<th>Simulation Revenue** ($/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fixed VP pool (FVPM)</td>
<td>fixed VP pool (FVPM)</td>
</tr>
<tr>
<td></td>
<td>dynamic VP pool (DVPM)</td>
<td>dynamic VP pool (DVPM)</td>
</tr>
<tr>
<td>Normal Network</td>
<td>135.00 (100%)</td>
<td>132.52 (98.16%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>132.59 (98.21%)</td>
</tr>
<tr>
<td>Network With Failed Link</td>
<td>102.67 (76.05%)</td>
<td>101.26 (75.01%)</td>
</tr>
<tr>
<td></td>
<td>125.40 (92.89%)</td>
<td>122.37 (90.64%)</td>
</tr>
</tbody>
</table>

* Direct computation from LP model.
** Average revenue from simulation run.

Note: For the “normal network”, this is the revenue averaged over a long run with no link failure.

For the network with failure, this is the revenue averaged over a long run, after allowing time for the link failure transient to settle.

Using discrete event simulation, we explore the performance of the two VP pool management schemes - fixed virtual path management (FVPM) and dynamic virtual path management (DVPM), and can compare this performance with the ideal revenue from the LP model.

For FVPM,
- With no link failure we achieve mean revenue of 132.52 $/sec or 98.16% of the ideal revenue. The scarce resources in the network are link n1-n2 and link n1-n3. There is competition between national traffic (low tariff) and international traffic (higher tariff). As a result there is blocking of some national traffic from n1 to n2 and from n1 to n3. This faithfully reflects the bandwidth allocations to the VP pool based on the LP solution.
- When there is a link failure, all the VPCs which use link n3-g are lost. As a result, revenue drops to 101.26 $/sec. This revenue is very close to (1.37% below) that computed for FVPM from the LP model.
For DVPM,

- With no link failure the mean revenue is 132.59 $/sec or 98.21% of the optimal revenue. This performance is virtually identical to that for DVPM, suggesting that, when the arrival process for connection attempts stationary, it makes little difference to performance whether the LP model is driven by the true mean rate parameter values from the simulator random number generator, or from samples taken at the control period.

- When there is a link failure, the mean revenue after the transient is 122.37 $/sec. This revenue is very close to (2.42% below) that computed for DVPM from the LP model.

Following link failure there is a transient whose general form is shown in Figure 4.2 to Figure 4.4. Firstly there is a delay until the next routine update of the VP pool (although in the real network, a new VP pool calculation could be triggered immediately the link failure is detected). Then there is a progressive transfer of load as connections terminate on some VPCs and are accepted on others.

In this simulation, initially all the VPC allocated bandwidth is lost from n3 to d2 (Figure 4.2:(g)) and some of VPC allocated bandwidth is lost from n1 to d1, n1 to d2 and n2 to d1 (Figure 4.2:(d), (e) and (f)). When the VP pool is updated, the VPC allocated bandwidth for low cost traffic using link n2-n3 is reduced to provide for higher tariff traffic from n3 to d1, routed via link n2-n3 (Figure 4.2:(c)). The effect of this on blocking can be seen in Figure 4.3:(c) as an increase in mean blocking rate from n2 to n3. As this transfer of load takes place the network adjusts gradually to a new steady state.

Figure 4.4 shows the ideal LP model revenue ideally available from the VP pool and the revenue actually generated by the simulated traffic. As can be seen the scheme modifies the VP pool at the first control update (120 sec) after the link failure (100 sec) but the network takes some time to transfer connections to the new VPCs, and restore revenue towards its ideal optimum value.

**4.4 Conclusions**
A simple control technique is proposed to manage the traffic flow in an ATM network by using the real-time LP model to modify the VP pool for the network. The model automatically generates a set of VP path and bandwidth allocations which maximise the objective function value of the LP model. The model proposed can be used for multiple traffic types by segregating each traffic type into separate VPCs. In the simulation example given, the system responds to a link failure by reducing the VPC allocated bandwidth allocated for low tariff traffic so that the capacity can be optimally reallocated to high tariff traffic. It is found that in all cases tested the simulation revenue with the proposed control system is close to the optimal revenue determined by the LP solution (within 2.42%). A comparison between DVPM and FVPM shows that the performance of DVPM is close to that of FVPM when the network topology and mean traffic remain steady, but that DVPM is much more robust than FVPM in the case of a network failure.
Figure 4.2: Total Bandwidth Allocation and Total Bandwidth Usage.
(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

Figure 4.3: Mean Offered Rate and Mean Blocking Rate.
Figure 4.4: Ideal Revenue Rate & Event-by-Event Revenue Rate.
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 \( j \).
- \( h'_{i,j} \) is the VCC holding time for traffic type \( t \) from origin \( i \) to destination \( j \).
- \( b'_{i,j} \) is the effective bandwidth demand per VCC for traffic type \( t \) from origin \( i \) to destination \( j \).
- \( v'_{i,j,k} \) is the VPC capacity for traffic type \( t \) from origin \( i \) to destination \( j \) along route \( k \) for \( k = 1, 2, \ldots, r_{i,j} \).
- \( v'_{i,j} \) 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.
- \( \phi_{i,j,k} \) 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 \( e \).
- \( t'_{i,j} \) is the tariff rate (in dollars per unit of time) charged for a VCC for traffic type \( t \) from origin \( i \) to destination \( j \).
- \( n_{i,j}(T) \) is the mean number of VCCs for traffic type \( t \) at time \( T \) 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

$$\sum_{k=1}^{t_{i,j}} v_{i,j,k}^l \leq v_{i,j}^{\text{init}}$$  \hspace{1cm} (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

$$\sum_{i,j,k} \phi_{i,j,k}^{(v)} v_{i,j,k}^l \leq S_{(v)}$$  \hspace{1cm} (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

$$\frac{1}{h_{i,j} b_{i,j}^l} \sum_{i,j,k} \phi_{i,j,k}^{(n)} v_{i,j,k}^l \leq R_{(n)}$$  \hspace{1cm} (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

$$\bar{\pi}_{i,j}(t^*) = x_{i,j}^{t-att}h_{i,j} + (n_{i,j}^0 - x_{i,j}^{t-att}h_{i,j})e^{-r^*}$$  \hspace{1cm} (5.4)

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

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

The upper bound constraint on VPC capacity is

$$\sum_{k=1}^{r_{i,j}} v_{i,j,k}^t \leq \bar{\pi}_{i,j}(t^*)b_{i,j}^t$$ \hspace{1cm} (5.6)

5.2.4.2 Lower bound
The lower bound constraint represents the lower limit on VPC capacity that can feasibly 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

$$v_{i,j,k}^t \geq \bar{\pi}_{i,j}(t^*)b_{i,j}^t, x_{i,j}^{t-att} = 0$$ \hspace{1cm} (5.7)

5.2.5 Objective function implementation
The objective function is of the same form as used in chapter 4.
\[ f = \sum_{i,j,k} \left( \alpha_1 \frac{t_{i,j,k}}{b_{i,j}} v_{i,j,k} + \alpha_2 \frac{1}{h_{i,j} b_{i,j}} v_{i,j,k} \right) \]  \hfill (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:

\( \alpha_1 \) is the weighting coefficient for revenue. It is a dimensionless quantity.

\( \alpha_2 \) 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

\[ f = cv \]  \hfill (5.9)

Subject to

\[ A v \{ \leq, \geq \} b \]  \hfill (5.10)

* Designates either \( \leq \) or \( \geq \).

\[ v \geq 0 \]  \hfill (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 (\( v_{i,j,k} \) for \( k = 1, \ldots, n_{i,j} \)).

\( A \) 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.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination</th>
<th>Tariff ($/Mbit)</th>
<th>VCC attempt (/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>n2</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>N1</td>
<td>n3</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>N2</td>
<td>n3</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>N1</td>
<td>d1</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>N1</td>
<td>d2</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>N2</td>
<td>d1</td>
<td>0.02</td>
<td>5</td>
</tr>
<tr>
<td>N3</td>
<td>d2</td>
<td>0.02</td>
<td>5</td>
</tr>
</tbody>
</table>

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.
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.
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.](image)

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

<table>
<thead>
<tr>
<th>TYPE OF RESOURCE</th>
<th>NATURE OF SCARCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link (link capacity)</td>
<td>Transmission bit rate</td>
</tr>
<tr>
<td>Router (processing rate)</td>
<td>Datagram processing rate</td>
</tr>
<tr>
<td>Server (processing rate)</td>
<td>Number of connections</td>
</tr>
</tbody>
</table>

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

\[ Ax = b \]
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.

\( r_{ij} \) is the number of paths permitted for connection attempts from user \( i \) toward service \( j \).

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

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

\( b_{ij}^{\text{br}} \) 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.

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

\( c_{i,j}^{\text{c}} \) 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.
\( R \) is the processing limit of the router identified by \( e \); it is expressed in units of datagrams per second.

\( S \) 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.

\( \phi_{i,j,k} \) 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 \( e \).

\( t_{i,j} \) 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.

\( d_{i,j} \) 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 \( t \).

\[
\sum_{k=1}^{n_{i,j}} x_{i,j,k}^{t-acc} \leq x_{i,j}^{t-att}
\]

(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 \( j \).

\[
\sum_{k=1}^{n_{i,j}} x_{i,j,k}^{t-acc} + x_{i,j}^{t-rej} = x_{i,j}^{t-att}
\]

(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:

$$\sum_{t,i,j,k} \phi^{(v)}_{t,i,j,k} h^t_{i,j} b^t_{i,j} x^{acc}_{t,i,j,k} \leq L^{(v)}$$  \hspace{1cm} (6.3)

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

$$\sum_{t,i,j,k} \phi^{(v)}_{t,i,j,k} h^t_{i,j} b^t_{i,j} x^{acc}_{t,i,j,k} + x^{(v)} = L^{(v)}$$  \hspace{1cm} (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:

$$\sum_{t,i,j,k} \phi^{(u)}_{t,i,j,k} h^t_{i,j} b^t_{i,j} x^{acc}_{t,i,j,k} \leq R^{(u)}$$  \hspace{1cm} (6.5)

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

$$\sum_{t,i,j,k} \phi^{(u)}_{t,i,j,k} h^t_{i,j} b^t_{i,j} x^{acc}_{t,i,j,k} + x^{(u)} = R^{(u)}$$  \hspace{1cm} (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:

$$\sum_{t,i,j,k} \phi^{(j)}_{t,i,j,k} h^t_{i,j} x^{acc}_{t,i,j,k} \leq S^{(j)}$$  \hspace{1cm} (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.
\[
\sum_{t,i,j,k} \phi_{t,i,j,k} h_{i,t} x^{t,acc}_{i,j,k} + x^{s(j)} = S^{s(j)}
\] (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
\[
f = \sum_{t,i,j,k} (\alpha^t_{t,i,j} h_{i,t} x^{t,acc}_{i,j,k} + \alpha^2_{i,j,k} x^{r,acc}_{i,j,k})
\] (6.9)

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

The weighting coefficients are as follows:
- \( \alpha^t_1 \) is the coefficient for revenue for connection-based tariff for data type \( t \); it is expressed in units of seconds per dollar.
- \( \alpha^t_2 \) 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
\[
f = cx
\] (6.10)

Subject to
\[
Ax = b
\] (6.11)
\[
x \geq 0
\] (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 ($x_{i,j,k}^{\text{acc}}$ for $k = 1,...,r_{i,j}$) and one variable for each equality constraint ($x^{l(v)}, x^{u(a)}, x^{u(f)}$ and $x_{i,j}^{r rej}$). The reject flows $x_{i,j}^{r rej}$ 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.

<table>
<thead>
<tr>
<th>User from router</th>
<th>Service</th>
<th>Attempt rate (connection/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R3</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R4</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R5</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R1</td>
<td>B</td>
<td>8</td>
</tr>
<tr>
<td>R3</td>
<td>B</td>
<td>8</td>
</tr>
</tbody>
</table>

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.

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.

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-time\(^1\) 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 the 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.

<table>
<thead>
<tr>
<th>User from router</th>
<th>Service</th>
<th>Attempt rate (connection/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
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</tr>
<tr>
<td>R3</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R4</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R5</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>R1</td>
<td>B</td>
<td>10</td>
</tr>
<tr>
<td>R3</td>
<td>B</td>
<td>10</td>
</tr>
<tr>
<td>R1</td>
<td>C</td>
<td>20</td>
</tr>
</tbody>
</table>

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.
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.

<table>
<thead>
<tr>
<th>SCHEME 0</th>
<th>SCHEME 1</th>
<th>SCHEME 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Solution</td>
<td>Heuristic Solution</td>
<td>“Optimal” Solution</td>
</tr>
<tr>
<td>1. Connect all local requests to proxy.</td>
<td>1. Connect to proxy if there are enough resources to provide satisfactory delay.</td>
<td>Use the solution from the optimisation model to control traffic flow.</td>
</tr>
<tr>
<td>Effect:</td>
<td>2. Otherwise connect to primary if there are enough resources to provide satisfactory delay.</td>
<td>1. Connect if there is capacity available to the service.</td>
</tr>
<tr>
<td>• Unpredictable delay.</td>
<td>3. Otherwise block</td>
<td>2. Otherwise block</td>
</tr>
<tr>
<td>• Some users abandon attempt.</td>
<td>Effect:</td>
<td>Effect:</td>
</tr>
<tr>
<td>• Unproductive traffic wastes resources.</td>
<td>• Acceptable delay</td>
<td>• Acceptable delay</td>
</tr>
<tr>
<td></td>
<td>• Some users have to be blocked</td>
<td>• Some users have to be blocked</td>
</tr>
<tr>
<td></td>
<td>• Efficiency should be high</td>
<td>• Efficiency should be high</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th></th>
<th>SCHEME 1</th>
<th>SCHEME 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heuristic Solution</td>
<td>“Optimal” Solution</td>
</tr>
<tr>
<td>Event-by-Event Revenue *</td>
<td>101.61(84.68%)</td>
<td>118.97(99.14%)</td>
</tr>
<tr>
<td>Optimal Revenue **</td>
<td>120.00(100%)</td>
<td></td>
</tr>
</tbody>
</table>

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

Figure 7.3: LP Result & Simulated Bandwidth Usage.
Figure 7.4: Mean Offered Rate and Mean Blocking Rate.
Figure 7.5: Total LP Result & Total Simulated Bandwidth Usage for Each Service.
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, vice, 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.
APPENDIX I

BIRTH-DEATH PROCESS

The problem is to find the number of VCCs occupying a system as a function of time, subject to various initial conditions. To approach the problem with some chance of deriving simple formulas, some simplifying assumptions must be made.

Assume VCCs arrive for each origin-destination pair according to a Poisson process with parameter $\lambda$ whose units are the number of VCCs per second, and that the probability of a new VCC arriving in the interval $[t, t+\Delta t)$ is independent of $t$. If $\Delta t$ is small then we could expect that the probability of a new VCC arriving in $[t, t+\Delta t)$ is $\lambda \Delta t$.

Assume connection holding times are independent and exponentially distributed with mean $h$ and units of second. Assume also that the probability that a VCC in progress will terminate in the interval $[t, t+\Delta t)$ is also independent of $t$. For small $\Delta t$, the probability that a VCC in progress will terminate is $\frac{\Delta t}{h}$.

Suppose there are $N_0$ VCCs in the VPC at time $t = 0$. Let $p_t(n)$ be the probability that there will be $n$ VCCs in the VPC at time $t > 0$. We can derive a set of equations for the evolution of these probabilities with time.

Probability of $n$ calls at $t + \Delta t = \text{Probability of } n \text{ calls at } t \times \text{Probability that no VCCs terminate in } [t, t+\Delta t) \text{ and that no new VCCs arrive} + \text{Probability of } n+1 \text{ VCCs at } t \times \text{Probability that one VCC terminate in } [t, t+\Delta t) \text{ and that no new VCCs arrive} + \text{Probability of } n-1 \text{ VCCs at } t \times \text{Probability that no VCCs terminate in } [t, t+\Delta t) \text{ and that one new VCC arrives} + \text{Probability of compound events which are second or higher order in } \Delta t$
Let $X$ show a new VCC arrival.
Let $X_m$ show $m$ new VCCs arriving in the interval $[t, t + \Delta t)$.
Let $Y$ show a VCC termination.
Let $Y_n$ show $n$ VCCs terminate in the interval $[t, t + \Delta t)$.

This can be expressed as
\[
P_{t+\Delta t} (n) = P_t(n)P_{t+\Delta t}(X_0 | n)P_{t+\Delta t}(Y_0 | n) + P_t(n+1)P_{t+\Delta t}(X_0 | n+1)P_{t+\Delta t}(Y_0 | n+1) + P_t(n-1)P_{t+\Delta t}(X_0 | n-1)P_{t+\Delta t}(Y_0 | n-1) + O(\Delta t^2)
\]

Since $P(X_m | n) = \binom{n}{m} P(X)^m (1-P(X))^{n-m}, P(X) = \lambda \Delta t, P(Y) = \frac{\Delta t}{h}$

This reduces to
\[
P_{t+\Delta t} (n) = P_t(n)(1 - \frac{\Delta t}{h})^n (1 - \lambda \Delta t) + P_t(n+1)(n+1) \frac{\Delta t}{h} (1 - \frac{\Delta t}{h})^n (1 - \lambda \Delta t)
\]
\[
+ P_t(n-1)(1 - \frac{\Delta t}{h})^{n-1} \lambda \Delta t + O(\Delta t^2)
\]

reducing to first order terms in $\Delta t$
\[
P_{t+\Delta t} (n) = P_t(n)(1 - \frac{n}{h} + \lambda \Delta t) + P_t(n+1)(n+1) \frac{\Delta t}{h} P_t(n+1) + \lambda P_t(n-1) \lambda + O(\Delta t^2)
\]

and for small $\Delta t$, we can find the derivative of $P_t(n)$
\[
\frac{dP_t(n)}{dt} = -\left(\frac{n}{h} + \lambda\right) P_t(n) + \frac{(n+1)}{h} P_t(n+1) + \lambda P_t(n-1) \lambda + O(\Delta t^2)
\]
The Mean Value of the Number of VCCs

In principle it should be possible to calculate all the $P_t(n)$ but for our purposes it may be sufficient to calculate the mean of the number of VCCs in the system.

The mean is defined as the expectation of the number of VCCs

$$\bar{n}(t) = \sum_{n=0}^{\infty} nP_t(n) \quad (A.2)$$

Using A.1 and A.2 together

$$\frac{d\bar{n}}{dt} = \sum_{n=0}^{\infty} n \frac{dP_t(n)}{dt} = -\sum_{n=0}^{\infty} n \left( \frac{n}{h} + \lambda \right) P_t(n) + \frac{1}{h} \sum_{n=0}^{\infty} n(n+1)P_t(n+1) + \lambda \sum_{n=0}^{\infty} nP_t(n-1) \quad (A.3)$$

or, after some manipulation

$$\frac{d\bar{n}}{dt} = \frac{1}{h} \left[ \sum_{n=0}^{\infty} n^2 P_t(n) - \sum_{n=0}^{\infty} n(n+1)^2 P_t(n+1) \right] - \frac{1}{h} \sum_{n=0}^{\infty} n(n+1)P_t(n+1)$$

$$+ \lambda \left[ \sum_{n=0}^{\infty} (n-1)P_t(n-1) - \sum_{n=0}^{\infty} nP_t(n) \right] + \lambda \sum_{n=0}^{\infty} P_t(n-1)$$

Now $P_t(n) = 0$ if $n < 0$, and we shall assume that $P_t(n) \rightarrow 0$ as $n \rightarrow \infty$ fast enough to ensure convergence of any of the summations in equation (A.3); with these assumptions it is possible to simplify the RHS of (A.3). In fact the terms in square brackets become zero and the two remaining summations are equal to the mean and to 1 respectively.

Thus

$$\frac{d\bar{n}}{dt} = -\frac{1}{h} \sum_{n=0}^{\infty} (n+1)P_t(n+1) + \lambda \sum_{n=0}^{\infty} P_t(n-1)$$

$$- \frac{1}{h} \sum_{n=1}^{\infty} nP_t(n) + \lambda \sum_{n=1}^{\infty} P_t(n)$$

$$- \frac{1}{h} \sum_{n=0}^{\infty} nP_t(n) + \lambda \sum_{n=0}^{\infty} P_t(n)$$

and hence
This is the main result, and could be derived heuristically in a couple of lines.

**Solution for Mean of Number of VCCs**

The solution of (A.4) for initial condition $\pi(0) = N_0$ is well known:

$$\bar{\pi}(t) = \lambda h + (N_0 - \lambda h)e^{-\lambda t}$$  \hspace{1cm} (A.5)
APPENDIX II
MIRROR SITE AND PROXY SERVER CONCEPT

Mirror sites and proxy servers both have the potential to improve the use of network resources and to reduce latency times in response to requests.

![Diagram showing the relationship between a Primary Server, Mirror Site and Proxy Server.](image)

Figure AII.1: The relationship between a Primary Server, Mirror Site and Proxy Server.

AII.1 Mirror Site Concept

A mirror site is a Web site that contains a copy of service available from a primary server. Usually, the mirror site has exactly the same service as the primary server. The difference is only in the location of the sites. The value of the mirror site concept is in reducing congestion by distributing traffic to other network resources [KON97]. The mirror site concept also has the potential to reduce the time required to access services. This is an important factor in the quality of service provided by the WWW [BOL96].

The mirror site concept is usually explained in terms of connecting users in one geographical area to the local mirror site but the problem of optimising the use of the set of mirror sites and primary server is more complex. It is not guaranteed that the mirror site in the same geographical area as the user will provide the optimal use of resources.
A particular mirror site can become overloaded if there is heavy demand from the local user community.

The common implementation works like this when a user makes a request to the primary server: the primary server usually provides a list of its mirror sites, but users cannot tell which mirror site can be accessed with the least congestion.

Those who deploy WWW servers have a growing interest in understanding the geographic dispersion of access patterns. The work in [LAM96] draws on a large body of techniques for visualization of network data in the geographic domain. The work is rooted in information visualization [FAI88] and statistical graphics [CLE88] with emphasis on interactive exploration. Other examples include Becker et al’s [BEC95] techniques for displaying communication traffic, and Cox’s [COX92] animation of NSFNet traffic. Both show network connections by drawing links between nodes and show inbound traffic by assigning traffic volume to a range of colors.

Mirror sites have the potential to improve network efficiency, but we cannot gain the maximum benefit without some form of traffic control to distribute load properly among the sites.

### 4.2 Proxy Server Concept

The proxy server offers local caching of recently requested services for a group of users. Measurements have shown that the caching proxy can significantly reduce network load [ABR95].

The concept of a proxy cache is that user requests for service go to a local server instead of directly to the primary server. The local server fetches a copy of the service, saves it on disk and forwards it to the user. Subsequent requests from other users of the proxy cache are provided with the saved copy.

A proxy server requires proper dimensioning to meet its load requirements. In [BOL96], the authors discuss a design to avoid server overload. Server performance can be
optimised by carefully dimensioning the server (so that it has enough resources such as CPU power and disk space to handle expected requests) and the network (so that it has enough resources such as bandwidth and buffers to transport requests and replies), and by using mechanisms such as caching to minimise the resource requirements of user requests.

Issues in caching management include matters such as data replacement with limited disk capacity [ROB90] [SEL88], keeping the data in cache up-to-date [WOR94], etc.

Real time service which request some level of minimum acceptable resources cannot be cached. The trend of web applications is toward real-time services such as Internet chat, Internet phone, real audio, real video, etc.
APPENDIX III
NOTE ON SIMULATION PROGRAM

All of the computed results and simulations in the research are prepared on MATLAB for Windows Version 4.2c.1. MATLAB is a product of the MathWorks, Inc. We use the module LP supplied with the MATLAB optimisation toolbox to solve the Linear Programming model. The simulation programs are grouped into 4 major parts as follow:

- Fixed Virtual Path Management (FVPM) (chapter 4)
- Dynamic Virtual Path Management (FVPM) (chapter 4)
- State Dependent Virtual Path Management (SDVPM) (chapter 5)
- Performance evaluation in the Internet (chapter 7)

The code can be made available by contacting the author or Laboratory for Telecommunication Research, School of Biomedical Science and Electrical Engineering, Swinburne University of Technology.
BIBLIOGRAPHY


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