

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

Department of Defense. 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.

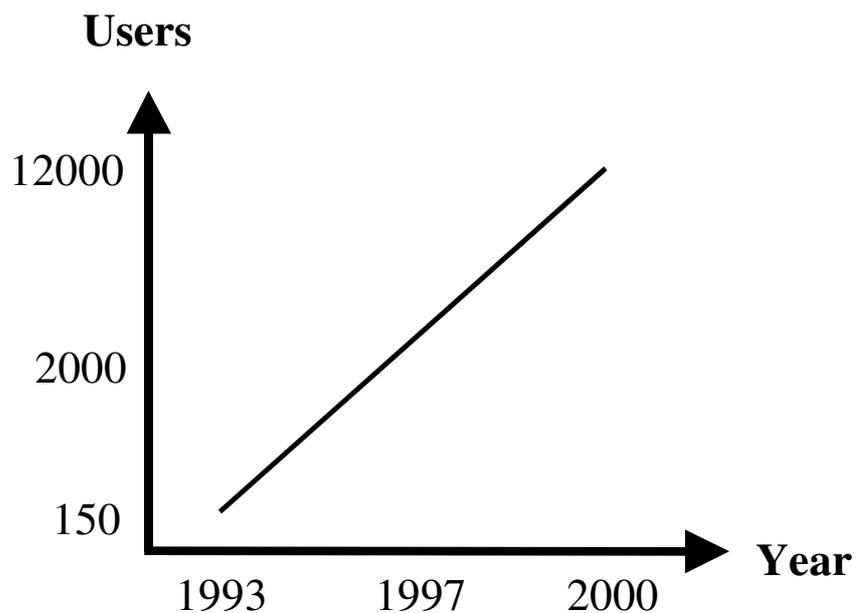


Figure 2.1: The growth of `wcarchive`.

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.

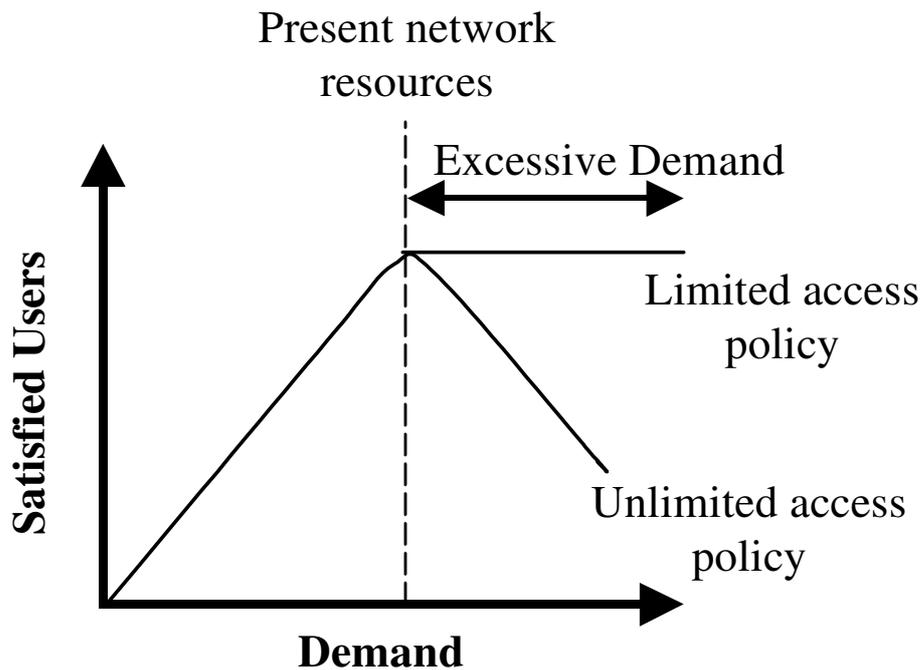


Figure 2.2: Effect of access policy on number of satisfied users in an overloaded network.

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.

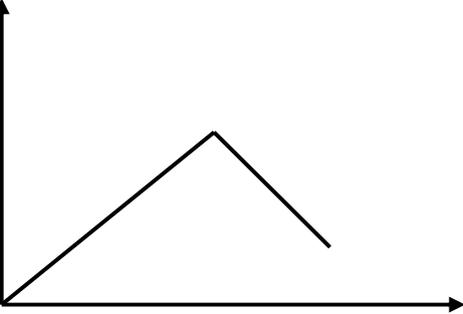
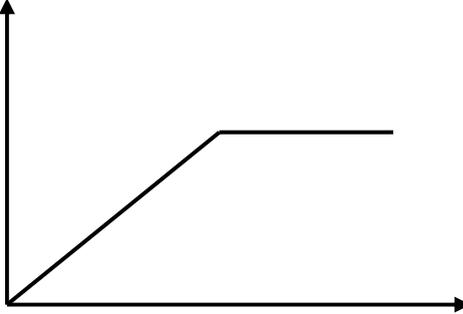
1. If there is open access such that the resources per user are not enough to meet the minimum QoS requirements per user, then, if the resources are distributed equally, all users will be dissatisfied.
2. If the policy is to allow open access to all users, then during periods of overload, it is common 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.

 <p style="text-align: center;">unlimited access (all connections accepted)</p>	 <p style="text-align: center;">limited access (connections are limited)</p>
<ul style="list-style-type: none"> • QoS unsatisfactory • Some dissatisfied users will disconnect (self-regulation) • Efficiency may be low (due to congestion) 	<ul style="list-style-type: none"> • QoS satisfactory (for those connected) • Efficiency should be high (if forecasts & control are accurate [optimal]) • Some (unconnected) users will receive no service

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.

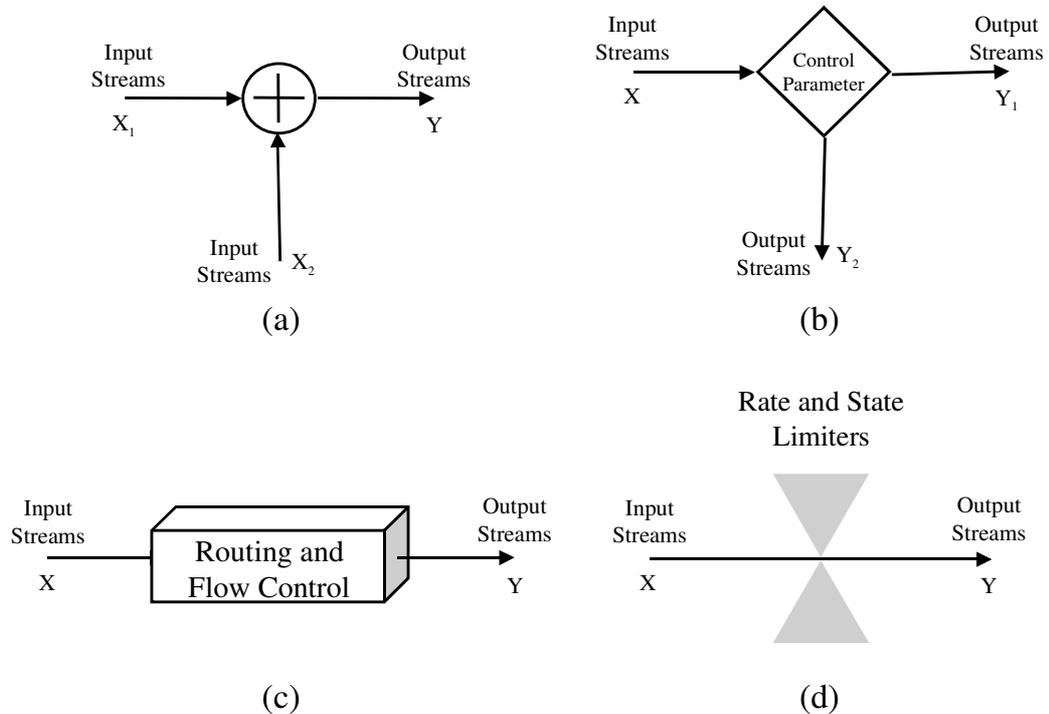


Figure 3.1: Graphical representation of broadband network elements. (X , Y refer to connection rates). (a) Summer: $Y = X_1 + X_2$. (b) Splitter: $Y_1 + Y_2 = X$.
(c) Routing and Flow Control: $Y = X$.
(d) Rate and State Limiters: $Y=X$, $Y \leq Y_{\max}$.

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 $Y = X_1 + X_2$. 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 $Y_1 + Y_2 = X$. 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 $Y \leq Y_{\max}$. 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.

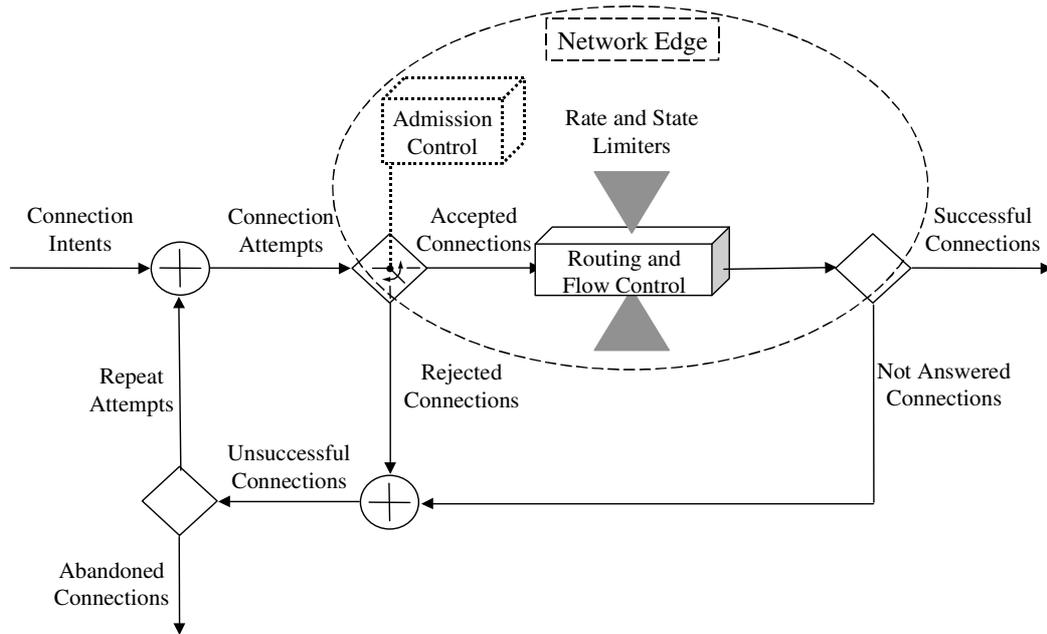


Figure 3.2: Broadband Network Connection Flow Diagram for LP Model.

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 $k = 1, 2, \dots, r_{i,j}$. 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:

$$p_{i,j}^t h_{i,j}^{t-suc} + (1 - p_{i,j}^t) h_{i,j}^{t-na} \quad (3.1)$$

$q_{i,j}^t$ 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 bandwidth¹ 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:

$x_{i,j,\bullet}^{video-in}$ 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 .

$x_{i,\bullet,\bullet}^{data-unsuc}$ is the rate of unsuccessful connection attempts from origin i of data type, for all virtual paths from i to all destinations.

$b_{i,\bullet}^{voice-na}$ is the effective bandwidth demand per connection of not answered connections for voice type traffic from origin i to all destination.

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

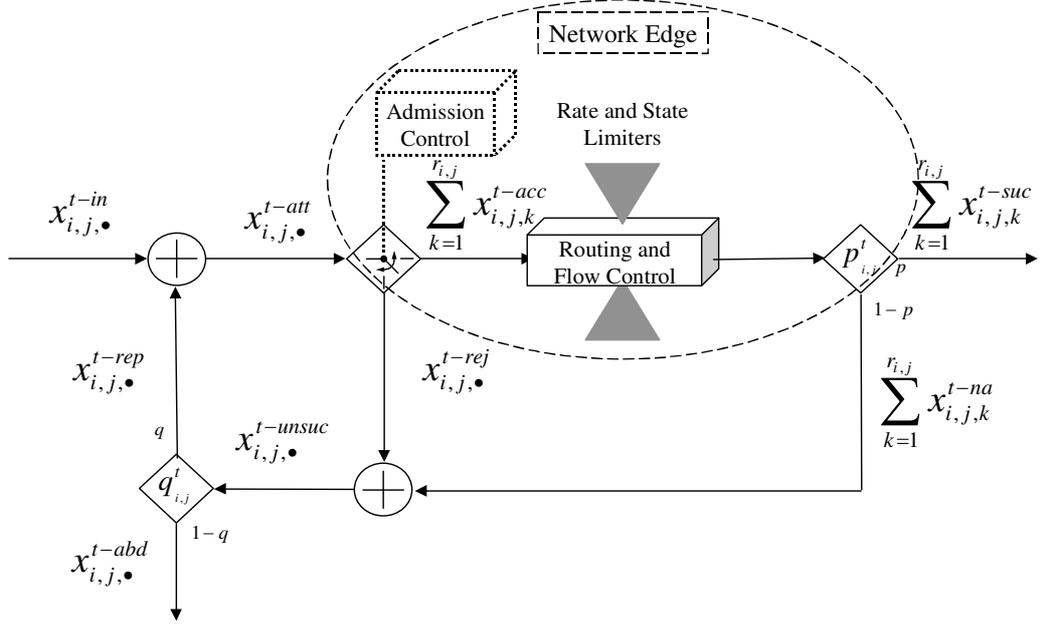


Figure 3.3: Broadband Network Connection Flow Diagram for LP Model (showing mathematical relationships).

3.3.1 Flow constraint implementation

From Figure 3.3, it can be seen that

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

and

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

From the diagram

$$x_{i,j,\bullet}^{t-rep} = q_{i,j}^t x_{i,j,\bullet}^{t-unsuc} \quad (3.4)$$

and

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

Therefore

$$x_{i,j,\bullet}^{t-rep} = q_{i,j}^t \left(x_{i,j,\bullet}^{t-rej} + \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{t-na} \right) \quad (3.6)$$

From equation (3.2), (3.3) and (3.6), the flow constraint is

$$(1 - q_{i,j}^t (1 - p_{i,j}^t)) \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{t-acc} + (1 - q_{i,j}^t) x_{i,j,\bullet}^{t-rej} = x_{i,j,\bullet}^{t-in} \quad (3.7)$$

The reject flow ($x_{i,j,\bullet}^{t-rej}$) 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 $x_{i,j,\bullet}^{t-rej}$ be simple rescaling.

$$\frac{1 - q_{i,j}^t (1 - p_{i,j}^t)}{1 - q_{i,j}^t} \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{t-acc} + x_{i,j,\bullet}^{t-rej} = \frac{1}{1 - q_{i,j}^t} x_{i,j,\bullet}^{t-in} \quad (3.8)$$

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:

$$\begin{aligned} \frac{1 - q_{i,j}^{voice} (1 - p_{i,j}^{voice})}{1 - q_{i,j}^{voice}} \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{voice-acc} + x_{i,j,\bullet}^{voice-rej} &= \frac{1}{1 - q_{i,j}^{voice}} x_{i,j,\bullet}^{voice-in} \\ \frac{1 - q_{i,j}^{data} (1 - p_{i,j}^{data})}{1 - q_{i,j}^{data}} \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{data-acc} + x_{i,j,\bullet}^{data-rej} &= \frac{1}{1 - q_{i,j}^{data}} x_{i,j,\bullet}^{data-in} \\ \frac{1 - q_{i,j}^{video} (1 - p_{i,j}^{video})}{1 - q_{i,j}^{video}} \sum_{k=1}^{r_{i,j}} x_{i,j,k}^{video-acc} + x_{i,j,\bullet}^{video-rej} &= \frac{1}{1 - q_{i,j}^{video}} x_{i,j,\bullet}^{video-in} \end{aligned}$$

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

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

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

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

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

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

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

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

where $x^{l(v)}$ 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

$$\begin{aligned} & \sum_{i,j,k}^{l(v)} \phi_{i,j,k}^{l(v)} \left(p_{i,j}^{voice} h_{i,j}^{voice-suc} b_{i,j}^{voice-suc} + (1 - p_{i,j}^{voice}) h_{i,j}^{voice-na} b_{i,j}^{voice-na} \right) x_{i,j,k}^{voice-acc} + \\ & \sum_{i,j,k}^{l(v)} \phi_{i,j,k}^{l(v)} \left(p_{i,j}^{data} h_{i,j}^{data-suc} b_{i,j}^{data-suc} + (1 - p_{i,j}^{data}) h_{i,j}^{data-na} b_{i,j}^{data-na} \right) x_{i,j,k}^{data-acc} + \\ & \sum_{i,j,k}^{l(v)} \phi_{i,j,k}^{l(v)} \left(p_{i,j}^{video} h_{i,j}^{video-suc} b_{i,j}^{video-suc} + (1 - p_{i,j}^{video}) h_{i,j}^{video-na} b_{i,j}^{video-na} \right) x_{i,j,k}^{video-acc} + \\ & + x^{l(v)} = S^{l(v)} \end{aligned}$$

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

$$\sum_{t,i,j,k}^{n(u)} \phi_{t,i,j,k}^{n(u)} x_{i,j,k}^{t-acc} \leq R^{n(u)} \quad (3.13)$$

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

$$\sum_{t,i,j,k}^{n(u)} \phi_{t,i,j,k}^{n(u)} x_{i,j,k}^{t-acc} + x^{n(u)} = R^{n(u)} \quad (3.14)$$

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

$$\sum_{i,j,k}^{n(u)} \phi_{i,j,k}^{n(u)} x_{i,j,k}^{voice-acc} + \sum_{i,j,k}^{n(u)} \phi_{i,j,k}^{n(u)} x_{i,j,k}^{data-acc} + \sum_{i,j,k}^{n(u)} \phi_{i,j,k}^{n(u)} x_{i,j,k}^{video-acc} + x^{n(u)} = R^{n(u)}$$

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

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

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:

α_1^t is the (positive) coefficient for revenue of source type t . It is a dimensionless quantity.

α_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.

α'_3 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

$$f = \sum_{t,i,j,k} (\alpha_1^t h_{i,j}^{t-suc} t_{i,j}^t p_{i,j}^t + \alpha_2^t) x_{i,j,k}^{t-acc} + \alpha_3^t x_{i,j,\bullet}^{t-rej} \quad (3.16)$$

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

$$f = \sum_{i,j,k} \left(\alpha_1^{voice} h_{i,j}^{voice-aso} t_{i,j}^{voice} p_{i,j}^{voice} + \alpha_2^{voice} \right) x_{i,j,k}^{voice-acc} + \alpha_3^{voice} x_{i,j,\bullet}^{voice-rej} + \left(\alpha_1^{data} h_{i,j}^{data-aso} t_{i,j}^{data} p_{i,j}^{data} + \alpha_2^{data} \right) x_{i,j,k}^{data-acc} + \alpha_3^{data} x_{i,j,\bullet}^{data-rej} + \left(\alpha_1^{video} h_{i,j}^{video-aso} t_{i,j}^{video} p_{i,j}^{video} + \alpha_2^{video} \right) x_{i,j,k}^{video-acc} + \alpha_3^{video} x_{i,j,\bullet}^{video-rej}$$

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

$$f = cx \quad (3.17)$$

Subject to

$$Ax = b \quad (3.18)$$

$$x \geq 0 \quad (3.19)$$

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 ($x_{i,j,k}^{t-acc}$ for $k = 1, \dots, r_{i,j}$) and one variable for each equality

constraint $(x_{i,j,\bullet}^{t-rej}, x^{l(v)}$ and $x^{n(u)}$). The reject flows $x_{i,j,\bullet}^{t-rej}$ form a special subset of the slack variables with appropriate scaling.

- A* is the technological matrix of coefficients representing network connectivity and the traffic parameters, such as 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.

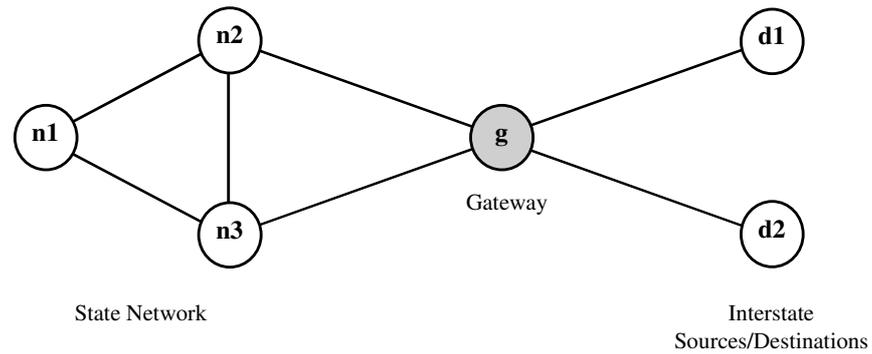


Figure 3.4: Sample 6 Node Network with Gateway.

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.

Source	Destination	Connection Attempt Rate (attempt/sec)	Holding Time (sec)	Bandwidth (Mbit/sec)	Tariff per Connection (\$/sec)	Traffic Type
n1	n2	0.02	1000	2	0.01	t1
n1	n3	0.02	1000	2	0.01	t1
n2	n3	0.02	1000	2	0.01	t1
n1	d1	0.01	1000	2	0.02	t1
n3	d1	0.01	1000	2	0.02	t1
n1	d2	0.01	1000	2	0.02	t1
n3	d2	0.01	1000	2	0.02	t1
n3	d1	75*	0.5	1	0.005	t2
n1	d2	75*	0.5	1	0.005	t2

* 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.

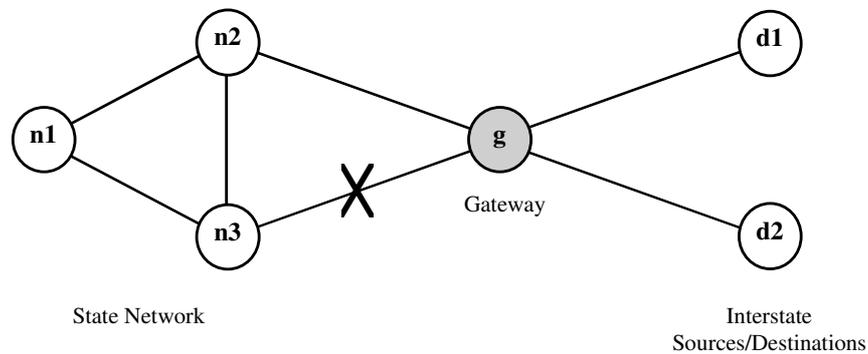


Figure 3.5: Sample Network with Link Failure.

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 (t_2) from n_1 to d_2 and n_3 to d_1 . 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 t_1 long distance traffic presents a node processing load of $0.01/0.02=0.5$ attempts/\$, whereas t_2 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).

$$E_N(n) = \frac{nE_{N-1}(n)}{N + nE_{N-1}(n)} \quad (4.1)$$

$$E_0(n) = 1 \quad (4.2)$$

Where $E_N(n)$ is the Grade of Service¹ (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 $p_{i,j}^t$ is assumed to be 1 and repeat attempt probability $q_{i,j}^t$ 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 $k = 1, 2, \dots, r_{i,j}$.

Where

$$v_{i,j,k}^t = h_{i,j}^t b_{i,j}^t x_{i,j,k}^{t-acc} \quad (4.3)$$

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 $k = 1, 2, \dots, r_{i,j}$.

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

$\phi_{i,i,j,k}^e$ 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

$$\sum_{k=1}^{r_{i,j}} v_{i,j,k}^t \leq v_{i,j,\bullet}^{t-att} \quad (4.4)$$

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

$$\sum_{t,i,j,k}^{l(v)} \phi_{t,i,j,k}^{l(v)} v_{i,j,k}^t \leq S^{l(v)} \quad (4.5)$$

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

$$\frac{1}{h_{i,j}^t b_{i,j}^t} \sum_{t,i,j,k}^{n(u)} \phi_{t,i,j,k}^{n(u)} v_{i,j,k}^t \leq R^{n(u)} \quad (4.6)$$

4.2.4 Modification of objective function

The objective function is of the form

$$f = \sum_{t,i,j,k} \left(\alpha_1^t \frac{t_{i,j}^t}{b_{i,j}^t} v_{i,j,k}^t + \alpha_2^t \frac{1}{h_{i,j}^t b_{i,j}^t} v_{i,j,k}^t \right) \quad (4.7)$$

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

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

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

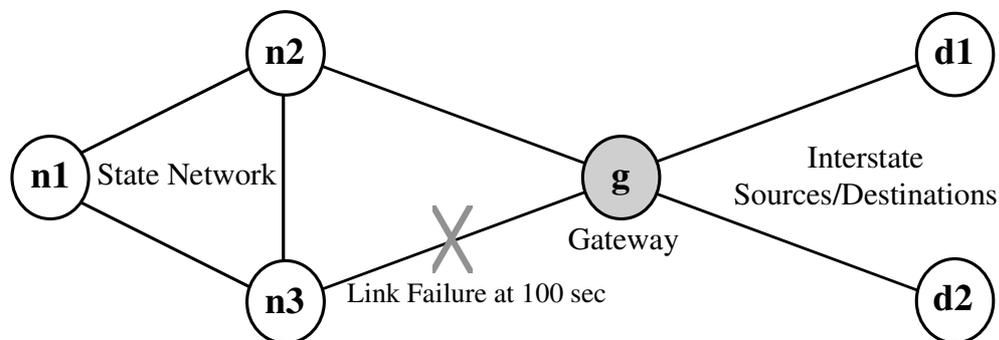


Figure 4.1: Sample 6 Node Network.

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.

Origin	Destination	Tariff (\$/Mbit)	VCC attempt (/sec)
n1	n2	0.01	13
n1	n3	0.01	13
n2	n3	0.01	13
n1	d1	0.02	4
n1	d2	0.02	4
n2	d1	0.02	5
n3	d2	0.02	5

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.

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

* 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.

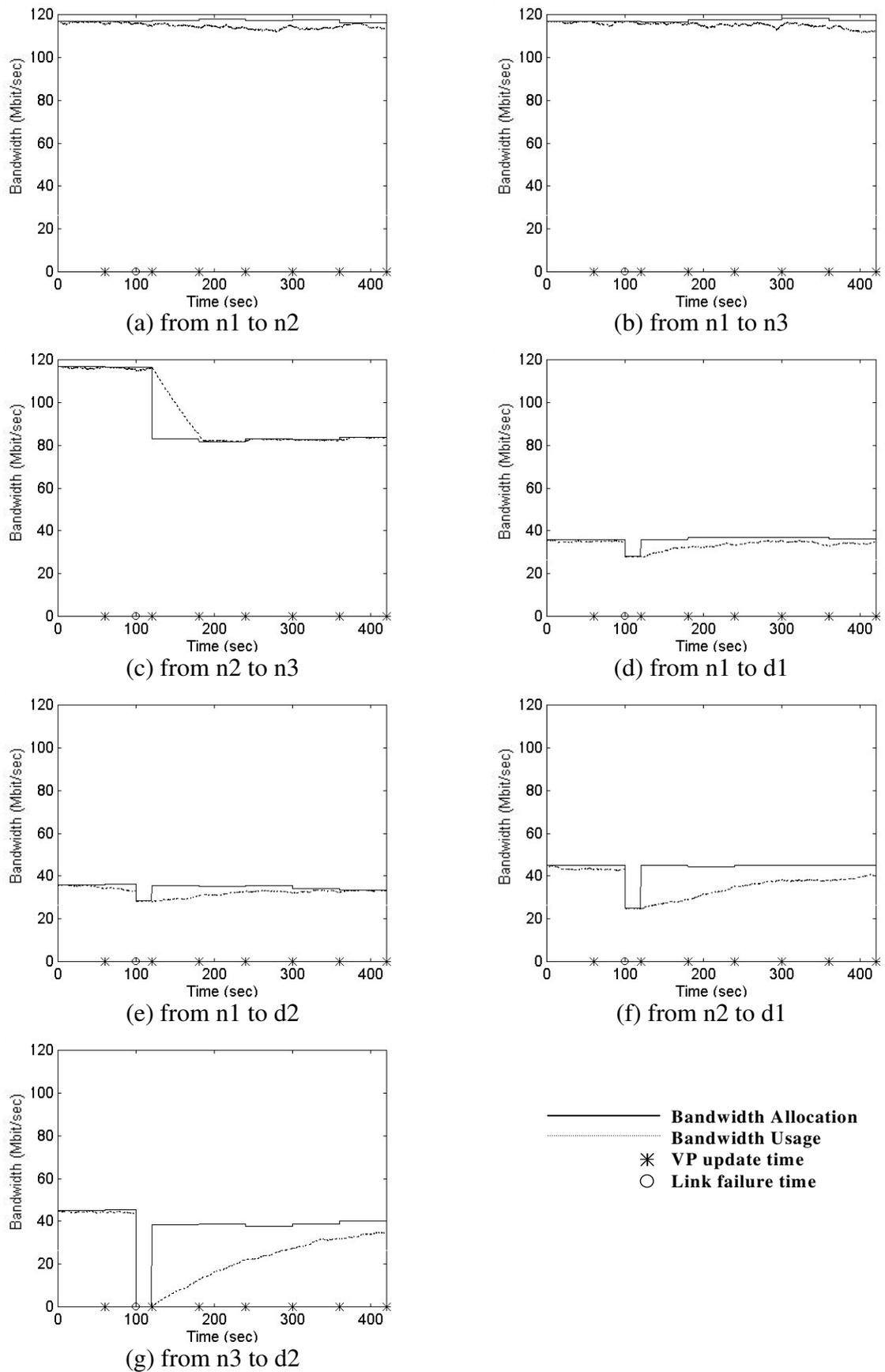
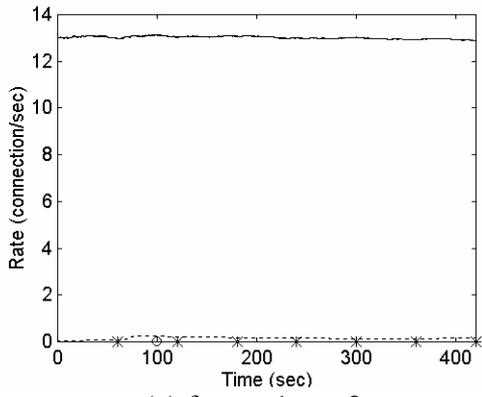
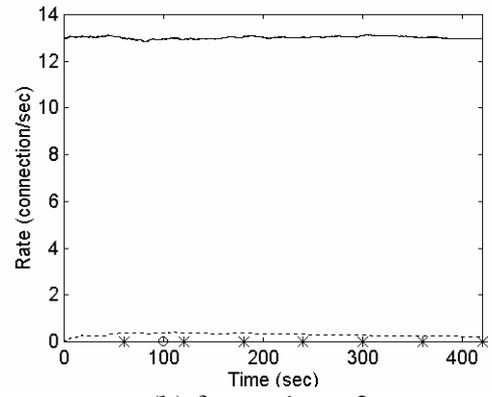


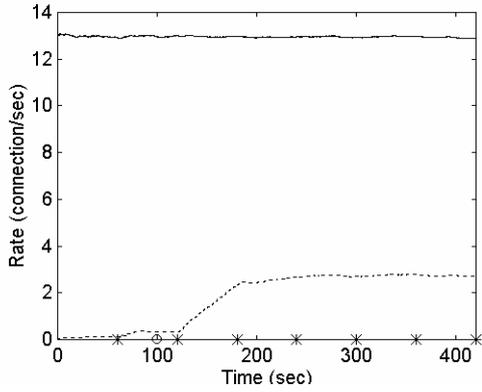
Figure 4.2: Total Bandwidth Allocation and Total Bandwidth Usage.



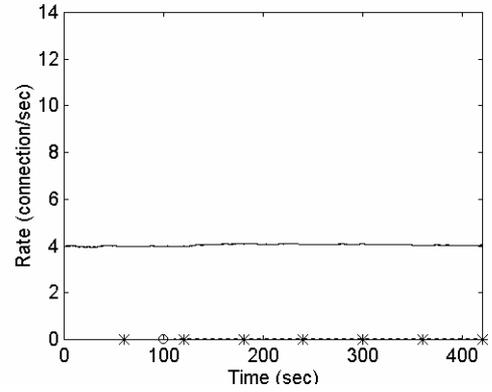
(a) from n1 to n2



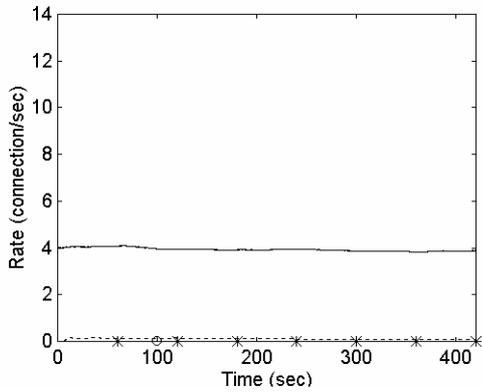
(b) from n1 to n3



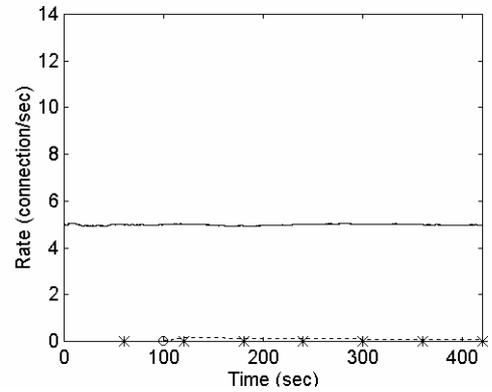
(c) from n2 to n3



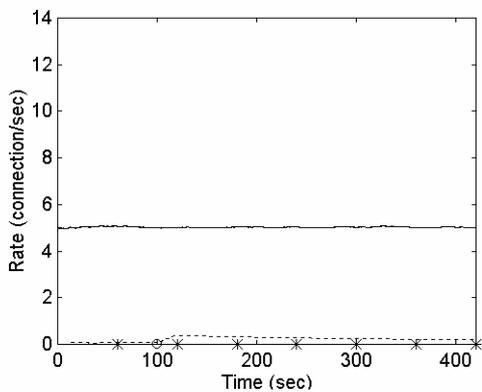
(d) from n1 to d1



(e) from n1 to d2



(f) from n2 to d1



(g) from n3 to d2

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

Figure 4.3: Mean Offered Rate and Mean Blocking Rate.

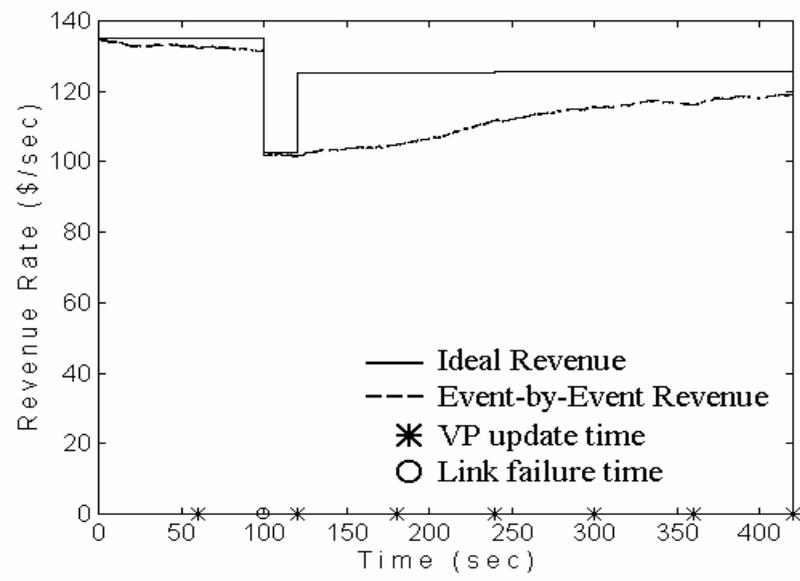


Figure 4.4: Ideal Revenue Rate & Event-by-Event Revenue Rate.