Abstract

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RESOURCES ALLOCATION AND PRICING FOR QOS MANAGEMENT IN COMPUTER NETWORKS.
(Under the direction of Douglas S. Reeves)

Computer networks must accommodate a wide variety of applications, ranging from simple file transfer programs to complex multimedia applications. Many of these applications require certain Quality of Service (QoS) guarantees for their proper operation. QoS guarantees include bounds on the packet delay, delay variation and loss rate. These guarantees can be provided through the allocation of network resources such as, processor time, buffer space and link bandwidth. Properly allocating network resources remains a challenging problem due to the number of users, diversity of network applications and the finite supply of resources. Furthermore, these resources are expected to have costs associated with their usage (amount and renegotiation). Given this environment, two important resource allocation issues are addressed in this thesis. First, methods are needed to reduce the amount of resources and renegotiations required to provide a desired QoS (thereby reducing the cost and increasing the utilization). Second, network administrators are interested in allocating and managing resources to all users in an efficient and fair manner.

Determining an efficient amount of network resources that will result in a desired QoS is difficult for certain sources, due to their unpredictable behavior and limited a priori source information. Such applications include the transmission of, MPEG-compressed video, live video and interactive multimedia. In this thesis, an allocation method called Dynamic Search Algorithm (DSA+) is introduced. DSA+ is an on-line algorithm that dynamically adjusts the resource allocation based upon the measured QoS. Advantages of DSA+ include efficient use of resources, few renegotiations, reasonable implementation cost, and stringent QoS control. The ability of DSA+ to allocate bandwidth to meet a desired cell loss probability is investigated and analyzed via simulation using generated (MMBP) and actual MPEG-compressed videos. Advantages of DSA+ over other allocation methods,
the robustness to initial parameter selection and the ability to allocate for multiple hop
collections are presented.

Network managers seek to allocate resources, to all users, in an efficient and fair
manner. In this thesis, microeconomic-based allocation techniques are introduced that
model the network as an economy, consisting of separate and independent competitive mar-
kets. In these markets, switches price their link bandwidth based on supply and demand,
and users purchase bandwidth to maximize their individual QoS. Two different types of
markets are used to allocate resources: the spot market and the reservation market. The
reservation market provides users the advantage of bandwidth ownership over a period of
time, while the bandwidth sold in the spot market has the advantage of immediate availabil-
ity (no reservation overhead). These decentralized state-less allocation methods can pro-
vide efficient and fair allocations of bandwidth as well as guarantees of resource availability.
Proofs of important microeconomic and standard computer network measures of fairness are
presented, as well as price stability. The performance of these resource allocation methods
are also investigated and analyzed using simulations with various network configurations
and actual MPEG-compressed videos. Results indicate that these microeconomic-based re-
source allocation methods achieve high utilization, optimal allocations and provide better
QoS than other allocation techniques.
RESOURCE ALLOCATION AND PRICING FOR QOS MANAGEMENT IN COMPUTER NETWORKS

by

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ERRIN WESLEY FULP
To my wife, my parents and my brother
Biography

Errin W. Fulp earned his BS in Mechanical Engineering from North Carolina State University in 1991, followed by a MS in Computer Science in 1994. During this time he was employed by the Computer Science Department at North Carolina State University as a lecturer and course coordinator. He also authored a textbook and consulted for Prentice Hall Publishers. In 1994 he began work on a Ph.D. in Computer Engineering at North Carolina State University. At the end of his first year of study, he worked as a research assistant under the direction of Dr. Douglas S. Reeves. During his Ph.D. studies he also worked as a research assistant at the NEC C&C Research Laboratories in Princeton, NJ. This research has resulted in various publications and patents filed in the US and Japan. Errin W. Fulp is a member of the Phi Kappa Phi and Upsilon Phi Epsilon honor societies, and is a proud member of TUG.
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**Chapter 3 Dynamic Search Algorithm, (DSA+)**

- $t_n$ ........ Renegotiation instant $n$
- $A_n$ ........ Number of cell arrivals during interval $n$
- $I$ ........ DSA+ interrupt interval
- $K$ ........ DSA+ rate adjustment constant
- $L_n$ ........ Number of cell losses during interval $n$
- $R_{0...n}$ .... Cumulative cell loss probability of intervals 0 through $n$
- $Q_l$ ........ Desired cell loss probability
- $U_n$ ........ Update interval $n$
- $\mu_n$ ........ Server rate during interval $n$

**Chapter 5 Competitive Market Model**

- $b_j$ ........ Maximum desired resource amount for consumer $j$
- $h_{j,i}$ ....... Market indices
- $j,k$ .......... Consumer indices
- $p_i$ .......... Price of market $i$
- $p^*_i$ .......... Equilibrium price for market $i$
- $q^*_i$ .......... Utility for all consumers in market $i$
- $s_i$ .......... Resource supply of market $i$
- $u^j(\cdot)$ .... Utility function for consumer $j$
- $\bar{u}^j(\cdot)$ .... Aggregate inverse utility function for market $i$
- $w^j$ .......... Wealth of consumer $j$
- $A$ ........ Set of all consumers in the economic model
- $A^i$ .......... Set of consumers who participate in market $i$
- $C^i$ .......... Set of consumers who are completely satiated with market $i$
- $L$ ........ Set of all markets in the economic model
- $N^i$ .......... Set of consumers who are non-satiated with market $i$
- $R^j$ .......... Set of markets consumer $j$ participates in
Chapters 6 and 7 Spot Market and Multi-Market Approaches to Multi-User Allocation

\[ b_j \]  
Maximum desired bandwidth amount for user \( j \)

\[ d_{in} \]  
The total demand for link \( i \) spot bandwidth at the end of interval \( n \)

\[ e_j \]  
Maximum amount of reserved bandwidth used by user \( j \)

\[ g_{im} \]  
The \( m \)th reservation market auction price for segment \( l \) at link \( i \)

\[ h_{im} \]  
The sum of the reservation bids for segment \( l \) at the end of the \( m \)th auction update interval of link \( i \)

\( i \)  
Link index

\( j \)  
User index

\( p_{in} \)  
The spot market price for link \( i \) during interval \( n \)

\( p_s \)  
Equilibrium spot market price for link \( i \)

\( s_i \)  
Total bandwidth supply of link \( i \)

\( t_{in} \)  
The \( n \)th spot market time instant at link \( i \)

\( u^j(\cdot) \)  
Utility function for user \( j \)

\( w^j \)  
Wealth of user \( j \)

\( x^j \)  
The bid for reserved bandwidth of user \( j \)

\( y^j \)  
The amount of spot bandwidth to purchase for user \( j \)

\( G_i \)  
Auction update interval for link \( i \)

\( P_{in} \)  
The \( n \)th spot market price interval for link \( i \)

\( R^j \)  
Set of links in the route of user \( j \)

\( T_i \)  
The reservation segment length of link \( i \)

\( W^j \)  
Total wealth of user \( j \)

\( \alpha_i \)  
Constant for the modified tâtonnement process (spot market) of link \( i \)

\( \beta^j \)  
Percentage of link bandwidth sold in the reservation market of link \( i \)
Chapter 1

Introduction

Historically, different types of networks were developed to handle specific types of media. For example, telephony networks handled voice, cable networks supported only video, and computer networks transmitted discrete data. Today, advances in computer network technology have resulted in integrated networks that must accommodate a large number of users and a variety of media. Applications range from simple data transfer programs to sophisticated multimedia applications. Multimedia applications are of special interest since their presence is expected to increase in the future. For this reason, more functionality is needed from the network to support these applications.

1.1 Multimedia Applications

Multimedia applications incorporate various media such as, voice, video and data information. Example multimedia applications include, teleconferencing, video on demand, and broadcast video. These applications can be classified based on their interaction requirements [101]. Broadcast video is non-interactive, since the user typically has limited control over the audio, video and text presented. In contrast, teleconferencing is an example of an interactive application. Furthermore, video oriented applications can be classified based on whether the video is stored or live. Video on Demand (VoD) is the transmission of stored video to users, while teleconferencing is an example of live video transmission. Different combinations of these classifications are possible, for example VoD can be considered a
stored interactive multimedia application. Users can control the play of the stored video via rewind and fast-forward commands. Regardless of the classification, an increasing number of multimedia applications are video oriented. For this reason, video encoding techniques are needed to successfully transmit video over computer networks.

1.1.1 Video Encoding

The development of video encoding standards, such as H.263, MPEG-1 and MPEG-2, have made the transmission of video over computer networks possible [63, 87]. Compression techniques can reduce the bandwidth requirements of digital video from Mbps to a few hundred Kbps. This bandwidth reduction makes the transmission of video feasible over current computer networks. Video encoders can be classified as either Constant Bit Rate (CBR) or Variable Bit Rate (VBR). CBR encoders target a specific bit rate for the encoded video, which is achieved by varying the video quality. Such a method simplifies the network transmission requirements; however, the varying quality is unsuitable for certain multimedia applications (high definition video).

VBR encoding differs from CBR, since the objective is a certain video quality. Based on the frame contents of the video, the encoder will generate different bit rates in order to provide a constant picture quality. For this reason, rates produced by VBR encoders can have high, peak-to-mean ratios and autocorrelations [41, 89]. This signifies that, periods of time may exist when the bit rate of the encoded video is much higher than the average rate. For example, the encoded video given in figure 1.1 has a peak-to-mean ratio of 18.36 and a 2.35 coefficient of variation. As depicted in the figure, these burst periods are difficult to predict (both in amount and duration) and can occur at various times. Furthermore, these bit rates have been reported to have self-similar behavior [41, 89]. Self-similar behavior exhibits Long Range Dependence (LRD) or slowly decaying autocorrelation; however, implications of LRD on network transmission are still debated [25, 31]. In summary, the benefit of constant quality compressed video is at the expense of highly variable (bursty) and unpredictable bit rates. The efficient and reliable transmission of such sources is difficult, which is discussed next.
Figure 1.1: Bandwidth requirements for the transmission of an example MPEG video.

1.2 Quality of Service

To accommodate the variety of current and future applications, networks must now provide more functionality than previously offered. For example, many applications require Quality of Service (QoS) guarantees for their proper execution. QoS performance measures include bounds on the packet delay, delay variation and loss rate [3, 101].

1.2.1 Delay

The majority of real-time multimedia applications are delay sensitive because the information transmitted needs to re-played at the receiver in real-time. A small average delay is desirable; yet, a more important delay measurement is the delay bound. The delay bound is the maximum network delay experience by any packet. For a live video transmission, the delay bound is associated with the playback time of the receiver. If a packet arrives after this delay bound, it is useless to the receiver; therefore, the application requires a delay bound for each packet transmitted. If a packet in transit exceeds the delay bound, it is possibly better to immediately drop the packet and reduce congestion than to continue to transmit the packet to the receiver. Delay bounds will vary depending on
application type, due to playback environments. Non-interactive multimedia applications (VoD) may allow a higher delay bound than interactive applications (teleconferencing). Therefore, networks must expect a wide range of delay bounds from applications.

1.2.2 Delay Variation

The delay variation, also referred to as jitter, is the relative difference in delay that packets may experience in the network. A large delay variation can decrease the smoothness of the traffic, causing burstier traffic along the transmission path. Methods that smooth or reshape bursty traffic have been proposed; however, the implementation cost may be prohibitive [9, 42]. High delay variation also causes the receiver to maintain a large playback buffer in order to store packets until the information can be re-played.

1.2.3 Loss Rate

Loss rate is the result of congestion occurring in the network, where packets are dropped due to buffer overflow. The dropped packets directly impact the quality at the receiver; however, the degree of quality degradation depends on the application. For example, a teleconferencing application may tolerate a higher loss rate than the transmission of high definition video. Applications may also use error recovery to reduce the effects of packet loss [55]. In addition, research has also addressed the need for applications to “gracefully” adapt to packet losses [85, 96]. For example, a video application can alter the encoding of the video to offset any packet losses that may occur. This prevents any further quality degradation due to packet loss.

1.3 Quality of Service Management

Many different network components must work in concert to provide QoS in computer networks. These components include, packet scheduling, connection admission control, and source policing.
1.3.1 Scheduling

Packets arrive at a switch where they are switched to out-going links based on their destinations. Packets waiting to be transmitted are stored in a transmission queue for their output link. A switch typically has multiple logical queues associated with each out-going link. Each logical queue may represent packets from a single flow or a certain class of flows. Given a scheduling discipline, a packet scheduler at the switch determines the transmission order of the packets from these logical queues. Since the out-going link has a maximum speed, the scheduling algorithm directly affects the QoS.

The scheduler can provide the desired QoS by managing and allocating resources, such as link bandwidth and buffer space. In addition, the scheduler should maximize utilization and allocate resources in a fair manner. One approach is to allocate resources per flow or to a class of flows (aggregate flow) [55]. Such a scheme would then ensure packets are serviced with respect to their allocated resource share; thus, providing the desired QoS. However, determining the resource share that provides a desired QoS efficiently is a challenging problem. For VBR sources (especially live video), determining the appropriate allocation amounts is difficult due to their bursty behavior and limited a priori information.

1.3.2 Admission Control

Admission control determines if a new flow should be admitted into the network. The acceptance or denial of a new flow affects the amount of traffic in the network; therefore, proper admission control is essential for providing QoS [82]. It is important for an admission control mechanism to determine or predict the impact of a new flow in the network. Accurately determining whether the new flow can be accommodated and how it would impinge on existing flows is essential. Admission control requires traffic descriptors, that are used to describe the traffic characteristics of the flow. Typical descriptors may include the peak and mean bit rate of the source [35] or the parameters of a token bucket [78]. These traffic descriptors and the desired QoS are then used to determine if sufficient resources are available.

As mentioned in the previous section, determining the appropriate amount of
resources that provide a desired QoS may be difficult for certain applications. Traditional approaches to admission control use a priori source information to calculate the worst-case (peak rate) behavior of all flows, in addition to the new flow. While guaranteed QoS can be provided, such a method may lead to under utilization of resources (consider VBR sources). Measurement-based admission control attempts to address this problem by measuring the actual network traffic and performance [47, 48]. These methods provide predictive QoS, which allows occasional QoS degradation. A renegotiation process may be required to update the desired QoS and the traffic descriptors over time [85]. Renegotiations increase the network signaling load, so a balance between efficient allocations and few renegotiations is needed. When accepted, the user is expected to conform to the negotiated traffic descriptors. Source policing is performed to ensure user compliance.

1.3.3 Source Policing

Source policing is used to ensure flows comply with their negotiated traffic descriptors; otherwise, congestion and poor QoS could occur in the network. A disadvantage of using mean and peak bit rate traffic descriptors (as described in the previous section) is the period of time samples must be taken in order to reliably determine compliance. If too few samples are taken, then the policing mechanism may incorrectly detect non-compliance. An alternative method uses a leaky bucket mechanism to describe and police the traffic [55]. The traffic would have to agree to a set of leaky bucket parameters (a form of admission control) before transmission begins. Once the parameters are determined, the mechanism can detect violating packets and immediately drop or tag them. Tagged packets can be dropped at a switch if congestion occurs.

1.4 Resource Allocation

As described in the previous section, QoS guarantees can be provided if network resources are available. However, providing QoS guarantees efficiently is complicated by the diversity of applications and the network performance they require. Furthermore, network resources are expected to have costs associated with their usage (amount and renegotiation)
Users must consider the cost of transmitting traffic across the network, and will prefer to do this as cheaply as possible. As a result, an important issue for providing QoS guarantees is the proper allocation of network resources.

Resource allocation can be viewed as a single-user as well as a multi-user issue, and both contexts are addressed in this thesis\(^1\). Regardless, the objective throughout this thesis is to provide the requested level of QoS, while maintaining high utilization of resources and staying compatible as possible with current technology.

**1.4.1 Single-User Allocation**

As previously discussed, proper allocation of network resources is essential for QoS guarantees. Due to the large number of users in the network, the service provider is interested in providing QoS guarantees as efficiently as possible. Efficiency refers to the amount of resources required for transmission, as well as the number of renegotiations. Minimizing the amount of resources allocated can increase the utilization of the network by providing resources to more users. Reducing the number of renegotiations reduces the signaling strain on the network. In addition, the user is interested in reducing costs, which is also achieved by reducing the amount of resources and the number of renegotiations. For these reasons, it is important to determine the appropriate amount of resources required to provide a desired QoS. However, determining an efficient allocation is difficult for certain traffic sources (such as live or interactive video), due to their unpredictable nature [37]. Therefore, the diversity of applications and their QoS requirements makes efficient resource allocation a challenging problem.

**1.4.2 Multi-User Allocation**

Multi-user allocation differs from single-user allocation in that it concerns the allocation of resources for all users in the network. However, as described in [55] single-user and multi-user allocation decisions are related since, each connection should limit its resource allocation to the smallest single-user allocation along its path. Multi-user allocation typically has two goals: fairness, and the balance between throughput and QoS [6].

\(^1\)In [55], this is referred to as local and global allocation.
fairness is difficult because of the various types of applications and their desired QoS. In this thesis, standard network-oriented and microeconomic-based definitions of fairness are used. The balance between throughput and QoS is the concept that the network should seek high resource utilization, but not at the expense of poor QoS (and vice versa). Hence, due to heterogeneous networks, diverse resource requirements and the goals associated with multi-user allocation, proper multi-user allocation remains a challenging problem.

1.5 Network Service Models

In this section three important network service models, designed to provide end-to-end QoS, are discussed: Internet Integrated Services, Internet Differentiated Services and Asynchronous Transfer Mode. Each of these service models presents a different framework for providing QoS.

1.5.1 Internet

Currently, the existing Internet provides only best-effort datagram service, with no guarantees of delay, delay variation or loss rate. Since this best-effort service is inappropriate for multimedia applications, the IETF has proposed two enhancements to provide predictable and reliable services: Internet Integrated Services (IIS) and Internet Differentiated Services (IDS).

Internet Integrated Services

The Internet Integrated Services architecture (IIS), proposed by [10, 18], was the first attempt to provide QoS in the Internet. IIS defines three service classes: guaranteed, predicted and best-effort. The guaranteed and predicted service classes are connection oriented and rely on admission control mechanisms to ensure sufficient resources are available. The guaranteed service class provides a worst-case bounds on network delay for all packets. A connection requesting guaranteed service must declare its peak rate and the desired minimum delay. Admission control mechanisms use this information to determine if enough resources are available and whether the connection should be admitted. The predicted ser-
vice also uses admission control, but is more lenient than guaranteed service [47]. Admission control mechanisms for predicted services predict (estimate) traffic on existing connections based on actual measurements, instead of using the worst-case traffic descriptors. Predictive service can allow more connections than guaranteed service; however, this is at the risk of violating delay guarantees. For this reason, predicted services are better suited for applications that can adapt to congestion. The last category, best-effort, is the same as currently found in the Internet today.

Resource ReSerVation Protocol (RSVP) is a static resource reservation protocol for individual connections, proposed for supporting integrated services [11, 105]. RSVP sends information concerning the requesting connection, the desired service type and the token bucket parameters. First a PATH message is sent from the sender to receiver indicating the traffic characteristics. The receiver then returns a RESV message, which attempts to reserve the desired resources at each router in the path. If the resources were allocated, then transmission can proceed. The Real Time Protocol (RTP) can also be used to provide timing information that is helpful for transmitting multimedia traffic [93]. Unfortunately, IIS/RSVP models require that all routers, along the path, keep a record of all current service requests and check packets to determine if they need special handling. Therefore, IIS/RSVP does not scale well with the Internet, due to the high overhead given to the routers. Furthermore, RSVP may not be feasible for applications that send only a few packets (WWW browsing). Even RFC 2208 recommends that RSVP not be deployed at the network backbone [71].

Internet Differentiated Services

In 1998, the “Differentiated Services” working group at the IETF was created to develop simple methods for providing differentiated services for the Internet. The Internet Differentiated Services (IDS) architecture is based on a model where traffic entering a network is classified (and conditioned) at the boundaries, then assigned to different service classes [5, 8]. Inside the network, per-hop QoS is given to traffic aggregates which have been appropriately marked. To differentiate packets, IDS relies on the Differentiated Service field (DS field, which is the IPv4 ToS or IPv6 Traffic Class field). This field indicates the need
for low delay, high throughput or low loss rate; however, unlike IIS/RSVP, the type service choices are limited. For this reason, the amount of state information required at each router is proportional to the number of classes rather than the number of connections (IIS/RSVP). This yields a more scalable solution than IIS/RSVP.

Different service classes can be provided using the IDT classification, policing, shaping and scheduling mechanisms. For example, three service classes were defined in [75]: premium service, assured service and best-effort. Premium service is for applications requiring low delay and delay variation, while assured service provides better reliability than best-effort. In addition, pricing the service classes with respect to the service they provide (differentiated pricing, where a higher QoS has a higher price) is expected to encourage users to determine the most cost-effective service class for their connection.

1.5.2 ATM

Asynchronous Transfer Mode (ATM) is a packet-switched technology that supports different QoS requirements for different types of traffic. The ATM service model includes the following five service classes [3].

- Constant Bit Rate (CBR). The CBR service class allocates a static quantity of bandwidth for each connection. For this reason, CBR service provides bounds on delay and delay variation to traffic that can be characterized by its peak.

- Real-Time Variable Bit Rate (rt-VBR). rt-VBR relies on more complex traffic characterization to provide tight constraints on delay and delay variation. This service can provide higher network utilization than CBR due to multiplexing.

- Non-Real-Time Variable Bit Rate (nrt-VBR). The nrt-VBR service class provides guarantees on the average delay and maximum loss rate of a connection.

- Available Bit Rate (ABR). The ABR service class enforces a bound on the minimum throughput of a connection and divides the unused portion of bandwidth fairly among its connections.
• Unspecified Bit Rate (UBR). Similar to the Internet best-effort service class, UBR does not provide any QoS guarantees.

Of these service classes, CBR and rt-VBR are intended to transport real-time traffic (for example real-time multimedia). However, it is possible and advantageous to transmit video using the ABR service class [62, 88].

1.6 Thesis Contributions

This thesis concerns the allocation and pricing of network resources to provide QoS in computer networks. Contributions of this thesis address single-user and multi-user resource allocation.

1.6.1 Single-User Allocation

A single-user allocation technique called Dynamic Search Algorithm (DSA+) is presented, that allocates resources to provide a desired QoS. Specifically, DSA+ is used to allocate link bandwidth to provide a desired loss rate.

Simulation results demonstrate that DSA+ performs better than other comparable single-user allocation mechanisms. In addition, DSA+ is applied to multiple hop allocation and its robustness to initial parameter selection is addressed. This single-user resource allocation technique has the following unique features.

• An on-line design requiring minimal a priori source information, which has the ability to allocate resources for stored or live/interactive VBR sources. DSA+ performance is demonstrated to be better than other comparable on-line allocation methods.

• Provides efficient allocations with few renegotiations while providing a desired QoS. Reducing the allocation amount increases the utilization while reducing the number of renegotiations lowers the signaling strain on the network.

• DSA+ has a simple design that requires little processing time and storage (O(1)), which is beneficial for implementation in high speed networks.
1.6.2 Multi-User Allocation

Microeconomic-based methods are presented in this thesis for multi-user allocation. These methods are based on the competitive market model (and a variation). Network resources are priced based on supply and demand, and users purchase resources to maximize their own QoS. This results in distributed allocation methods that provide high resource utilization as well as fair allocations. In this thesis, microeconomic approaches are used to allocate link bandwidth for a variety of sources. Two unique microeconomic methods, the spot market and the multi-market, are described next.

Spot Market Approach

A method for multi-user resource allocation is presented based on a modified competitive market model (called the spot market). Switches own the network resources in the economic model and price these resources based on supply and demand. In the spot market resources are considered non-storable (similar to residential electricity). Users purchase these resources to maximize their own QoS.

The spot market method is proven to achieve high utilization and fair allocations (Pareto-optimal, weighted max-min and equitable) for constant demand sources. Simulation is used to measure the performance of the spot market approach under network dynamics (VBR sources and users randomly entering and exiting). Simulation results, presented in this thesis, will indicate the spot market performs better than max-min (optimal implementation) and demand-based weighted max-min [62]. The spot market method has the following unique properties.

- The dynamic competitive market model (spot market) allows network dynamics (VBR sources and users entering/exiting) to occur. This is due to the modified tâtonnement process, that is unique to this market. When demands change, the modified competitive market adapts (changes prices) on-line. Users have the advantage of immediate resource availability (no reservation overhead is required) unlike other price-based allocation schemes. This yields a more QoS aware environment than other strategies.
• Allocation computations are performed only at the edge of the network, which is unique. This greatly reduces the computation and storage requirements of switches. Therefore the implementation cost of the spot market is reasonable.

• The spot market approach has the flexibility to easily achieve various types of fairness (Pareto-optimal, weighted max-min and equitable). A wealth distribution algorithm is given in this thesis to achieve an equitable (QoS-fair) allocation. In addition, an approximation is defined that determines the wealth distribution that achieves an equitable allocation with reduced source information.

A Multi-Market Approach

Two types of markets are used in the multi-market approach, the spot market and the reservation market. The spot market has the unique advantage of immediate availability of resources, but the disadvantage of no guarantees. The reservation market provides guarantees of resource availability, for a period of time, but incurs reservation overhead (signaling and waiting for the reservation period to begin). The multi-market attempts to combine the advantages of both market types in a single economic model. In the multi-market approach, users have the flexibility to purchase various amounts from either market type, and can value reserved and spot bandwidth differently.

The multi-market is proven to achieve fair distributions (considering resources in the spot and reservation markets separately). In addition to the advantages described for the spot market approach, the multi-market approach has the following unique properties.

• The multi-market approach is a multi-user allocation method that effectively combines the advantages of traditional static and dynamic allocation techniques. For this reason, the multi-market approach provides immediate resource availability, resource guarantees as well as high utilization of resources.

• Users have the flexibility to purchase various resources and weigh the benefits and risks associated with the different market types. Cautious users can prefer the reservation market, while other users may prefer the immediate availability of the spot market. These are only two possibilities within a large range of choices.
• In the multi-market economy, users can dynamically change from one resource type to another during their session. This allows users to react quickly to market and source changes, reducing QoS degradation. No other microeconomic allocation method provides this capability.

1.7 Thesis Outline

This thesis discusses and presents allocation techniques for providing QoS in computer networks. As previously described, resource allocation can be addressed as a single-user allocation issue (chapters 2 - 3) and multi-user allocation issue (chapters 4 - 7). The following describes each chapter of this thesis in detail.

Chapter 2 reviews single-user allocation techniques and classifications. Methods will be differentiated based on when information is collected, as well as what type of information is used for making allocation decisions. Also, performance objectives for single-user allocation techniques are defined.

In chapter 3, a new on-line algorithm for resource allocation called DSA+ is presented. A detailed description of the algorithm is provided as well as performance goals. A comparison of DSA+ with peak rate, effective bandwidth, Hsu’s algorithm and RED-VBR is then presented. The robustness of initial parameter selection is discussed, as well as multiplexed source and multiple-hop allocation.

Chapter 4 reviews the goals and types of multi-user allocation. Multi-user allocation methods are categorized based on the how and where allocation decisions are made. Since this thesis concerns microeconomic-based allocation, a review of microeconomics is also provided. This is followed by a review of previous microeconomic-based allocation work. Finally, goals and objectives for microeconomic-based resource allocation methods are given.

The competitive market model will serve as the basis for the microeconomic-based allocation approaches presented in this thesis. Chapter 5, reviews the competitive market structure. Proofs that an economy consisting of competitive markets will achieve optimal and fair allocations are given. A wealth distribution algorithm that distributes wealth
for an equitable allocation is described. In addition, simple example allocations and their associated fairness are provided.

In chapter 6, a spot market approach to resource allocation is described. A detailed description of the spot market approach is provided as well as simulation results. The performance of the spot market approach is compared and contrasted with other rate control methods.

Chapter 7 introduces another microeconomic-based allocation method that uses two types of markets: spot market and the reservation market. Details of the multi-market design are provided as well as simulation results that demonstrate its performance. Finally, chapter 8 reviews the allocations methods presented in this thesis. Future work and some open questions are also discussed.
Chapter 2

Single-User Allocation

As discussed in chapter 1, the proper allocation of network resources is essential for providing the desired QoS. Both the network manager and the user are interested in obtaining the desired QoS as efficiently as possible. However, determining the amount of resources required for VBR sources is difficult, due to their bursty and unpredictable behavior, as seen in figure 1.1. Resource allocation becomes more difficult if reliable source information is not available before transmission begins.

While many different types of network resources exist, this thesis will focus on link bandwidth. Previous work in the area of single-user bandwidth allocation is presented and discussed in this chapter. Methods will be differentiated based on when information is collected, as well as what type of information is used for making allocation decisions.

2.1 Classifications and Previous Work

As seen in figure 2.1, there are many different categories of single-user bandwidth allocation. The categories are based on whether calculations are performed before or during transmission (off-line versus on-line). Off-line methods can be further divided into static (single allocation) and dynamic (varying allocation) methods. On-line methods are divided into groups depending on whether source measurements or QoS measurements are taken. Each of these categories have their own unique advantages and disadvantages. Their practicality is governed by the type and amount of a priori information required.
2.1.1 Off-Line Allocation

Conventional approaches of bandwidth allocation rely on predetermined traffic characteristics. In the case of MPEG-compressed video, an off-line approach would require the entire bandwidth trace. From this information statistical values, such as the peak-to-mean ratio, can be determined. These methods are called “off-line” because calculating the appropriate bandwidth allocation occurs before transmission begins. These methods can categorized as static or dynamic. Static methods allocate a single amount for the duration of the session, while dynamic methods adjust the allocated amount over time.

The earliest methods of resource allocation were based on the peak rate of the source [55]. Bandwidth statically allocated using this value provides strict deterministic guarantees. The drawback of this policy is the underutilization of resources. This is especially true for VBR sources which may have long periods of little traffic. For this reason, peak rate allocation is considered an upper bound for bandwidth allocation.

Effective bandwidth is another static resource allocation method. The effective bandwidth of a source can be defined as the minimum bandwidth required to satisfy a desired QoS. Formulas were originally developed to determine this value for a two-state
fluid flow model. Elwalid expanded the theory to include general Markovian models and defined the effective bandwidth to be the maximal real eigenvalue of a matrix derived from source characteristics and admission criterion [30]. Chou and Chang broadened the effective bandwidth theory to include video traces with limited success [17]. However, it has been demonstrated that a VBR source may not adhere to these models [41, 44]. Yet more complex models, e.g., Hidden Markov Models, may be computationally intractable [12].

Dynamic off-line allocation approaches change the allocation amount over time [13, 32]. These methods are targeted for the transmission of stored video. Using the complete source trace, a bandwidth delivery plan can be created for the stored video that takes advantage of the client-side buffer. Using this buffer, large bursts can be prefetched before they occur, which results in a smooth video stream. For example, the off-line method developed by Feng, et al., determines the minimum number of renegotiations (increases or decreases in resource allocation) required for the playback of a previously-stored MPEG video [32]. The video is transmitted at the calculated rates to prevent buffer overflow and underflow. Off-line methods can provide the desired QoS with few renegotiations; however, these methods require the bandwidth trace to determine the optimal interval or segment length. For this reason, they are not viable if the trace is not available. On-line approaches attempt to manage such a case.

2.1.2 On-Line Allocation

On-line schemes require minimal information about the source, since real-time observations are made to predict future bandwidth requirements. On-line methods also renegotiate allocation amounts over time based on these measurements. As seen in figure 2.1, off-line approaches can be categorized based on the information measured. Some techniques measure the source characteristics in order to predict future demands. It is important to note these methods do not attempt to provide any particular QoS. Alternatively, on-line methods that measure current QoS adjust allocation amounts to maintain a targeted QoS (no more or less).
Source Measurements

In [1], Adas used adaptive and non-adaptive least mean square error predictors to predict MPEG frame sizes. The MPEG source was divided into I B and P frames [63] then separate filters were used to predict future MPEG frames. Bandwidth was allocated based on this information. Similarly, Chong et al. examined on-line bandwidth allocation of MPEG-compressed video based on the previous frames observed [16]. Neural networks as well as filters were used to predict future frame sizes. A drawback of this method is the complexity associated with neural networks, and the significant amount of information required to make accurate predictions. Other similar renegotiation schemes which predict future allocation demands include [28, 91].

RED-VBR is a method for supporting VBR video, with an off-line or on-line allocation technique. RED-VBR is based upon the D-BIND model, that attempts to capture the property that a source may have different rates at different time intervals [57]. The allocation algorithm stores the currently reserved D-BIND parameters and calculates the D-BIND parameters for the last M frames. A renegotiation takes place when a difference exists between the reserved and measured D-BIND parameters. RED-VBR does not use nor measure the QoS for allocation. QoS is an issue when sources are multiplexed together and is provided on a “per-segment” basis as described in [104].

Another renegotiation algorithm specifically for MPEG-compressed video was introduced by Reininger et al. [86]. This method renegotiated the usage parameter control (UPC) values based on the targeted and observed quantization of MPEG frames. When a new set of UPC parameters are determined, the user adapts (scales) transmission of the video until the new parameters are granted. Adapting the transmission of the video reduces the cell loss during the renegotiation. Saito, et al. proposed a bandwidth renegotiation scheme for ATM virtual paths [92]. Bandwidth was altered in fixed increments depending on the availability and the state of other virtual paths.

As previously stated, these on-line techniques only predict future source demands. There is no attempt to determine the appropriate bandwidth allocation that results in a desired QoS. For this reason, these methods may over allocate bandwidth for a desired QoS.
In addition, none of these methods attempt to reduce the number of renegotiations required for transmission of a given source.

QoS Measurements

On-line methods that measure QoS attempt to allocate bandwidth to maintain a desired QoS (no more or less). Hsu and Walrand proposed an method that dynamically allocates the bandwidth of a connection in order to provide a desired cell loss probability [43]. Their technique consists of a dynamic (adaptive) algorithm that renegotiates bandwidth over fixed length intervals. The renegotiation amount is determined using a simple difference error function and previous loss measurements. The algorithm is proven theoretically to converge to a steady state rate using techniques developed in [4]. This proof is valid only for Markov-modulated fluid sources and no investigation into actual VBR traffic was performed. Other dynamic or feedback approaches include [29, 102]. Although these on-line renegotiation methods provide better resource utilization and can manage real-time traffic, they rely on multiple allocation changes. In most cases allocation changes are done at fixed intervals, which may be problematic over long spans of time or during bursty periods. It is desirable to reduce the number of allocation changes, since contention for more resources may occur.

REQS (Resource Efficient Quality of Service) is another on-line resource allocation method that measures actual QoS [83]. REQS attempts to converge to a steady state rate based on QoS observations over varying time intervals. As the algorithm converges, the time intervals are increased. As a result the number of allocation changes required is dramatically reduced. This method was shown to be robust with small convergence times under various conditions using a Markov Modulated Bernoulli Process (MMBP). However no proof of convergence was attempted and the effects of actual traffic, specially those having long range dependencies, were not investigated.
2.2 Chapter Summary

As mentioned in the introduction, the proper allocation of link bandwidth is essential for providing QoS in computer networks. Users and network managers are interested in providing QoS as efficiently as possible. Efficiency represents the amount of link bandwidth allocated as well as the number of renegotiations required.

There are many different methods of bandwidth allocation. These methods differ on the amount of a priori information and the number of renegotiations required. Offline methods compute the bandwidth allocation required for a certain QoS, but require accurate source information. These methods may determine a single bandwidth amount for the entire session (effective bandwidth [30]) or may renegotiate over time (PCBR [13] and Feng’s algorithm [32]). While these methods perform well for stored media, they are unable to efficiently allocate bandwidth for live or interactive media.

In contrast, on-line methods allocate bandwidth using little a priori information. Source or QoS measurements are used to allocate bandwidth, which may change over time. Using source measurements, on-line methods attempt to predict future demands. Yet, these methods do not determine the appropriate allocation for a desired QoS. Alternatively, on-line methods that measure actual QoS seek to allocate bandwidth to provide a desired QoS. These methods try to reduce the amount of resources required; however, few attempt to reduce the number of renegotiations. In the next chapter, a new on-line bandwidth allocation method based on measured QoS is introduced. This method will actively seek to reduce the bandwidth allocated as well as reduce the number of renegotiations required. This method will also successfully allocate link bandwidth for various VBR sources, which is difficult due to their unpredictable behavior.
Chapter 3

Dynamic Search Algorithm, DSA+

Network managers seek to provide QoS to users through the proper allocation of resources. The allocation should be as efficient as possible, which signifies reduced resource amounts as well as few renegotiations. Reducing the allocation amount provides higher utilization of resources, while reducing the number of renegotiations lessens the signaling strain on the network. Users are also interested in efficient allocations, since resources are expected to have costs associated with them (volume and renegotiation). In the previous chapter a review of different bandwidth allocation techniques was provided. Of the different approaches presented, on-line methods are the most versatile. On-line methods have the ability to determine the appropriate bandwidth amounts with limited a priori information; therefore, these methods are appropriate for stored or live media. Yet, few on-line methods attempt to reduce the allocation amount as well as the number of renegotiations.

In this chapter a single-user, on-line allocation method called the Dynamic Search Algorithm (DSA+) is presented [40]. DSA+ allocates resources to meet a desired QoS. In this thesis, DSA+ is used to allocate link bandwidth in order to provide a desired Cell Loss Probability (CLP). DSA+ has the advantages of other on-line allocation methods; however, it is unique because it attempts to reduce the number of renegotiations and can manage link bandwidth for VBR sources. In the experimental section, DSA+ is used to control the loss rate of simulated traffic and actual MPEG-compressed videos by the appropriate allocation of link bandwidth. Other on-line and off-line algorithms were also implemented
and their performance is compared and contrasted. The simulation results will show that DSA+ performs better than the other allocation methods, allocating less bandwidth with fewer renegotiations. Since ease of algorithm use is important, the robustness of DSA+ with respect to the initial parameter settings is demonstrated. Finally, the application of DSA+ for connection admission control and multiple hop allocation is investigated.

3.1 Dynamic Algorithms

Dynamic algorithms (also referred to as adaptive algorithms) have been applied in various applications such as system identification, filtering and pattern recognition [4]. The general idea is to dynamically adjust a vector towards some desired goal. The vector is changed as the behavior of the system is monitored using state information at certain instances of time. The state vector must adequately represent the information on which the adjustment is made. The conventional rule [4] used to update the vector is

$$\theta_n = \theta_{n-1} + \gamma \times H(\theta_{n-1}, X_n)$$  \hspace{1cm} (3.1)

where $\theta_n$ is the vector to control, $\gamma$ is a series of gains and $H(\cdot)$ is a function that determines how $\theta_n$ is updated based upon the state vector $X_n$. When applied to resource allocation it is possible to have $\theta_n$ represent a resource, $X_n$ the source state, $\gamma$ the gain and $H(\cdot)$ would be some function that defines how the resource amount is changed with respect to the source state. This general formula is used in Hsu’s algorithm, REQS and the DSA+ algorithm introduced in the next section. In [4] Benveniste, et al. a proof of convergence for dynamic algorithms is described. This can be used to prove convergence for other specific dynamic algorithm applications, as done in [43].

3.2 A New Dynamic Allocation Technique

This section introduces an on-line allocation technique called Dynamic Search Algorithm (DSA+). DSA+ encapsulates the general dynamic algorithm form with new features to better handle VBR sources. DSA+ dynamically renegociates the server rate
(bandwidth) of a queue in order to meet a desired QoS. The algorithm will seek to reduce the bandwidth required to provide the desired QoS, as well as the number of renegotiations.

### 3.2.1 System Model

Figure 3.1, depicts the system model under consideration. Cells, a fixed-length unit of traffic storage and transmission, arrive at a finite capacity queue and are serviced in a FIFO manner. All cells will receive the same amount of service, as described by the ATM standard. As seen in figure 3.1, any cell arriving at a full queue is immediately lost. In this thesis the QoS of interest is the cell loss probability (CLP) of a single source. Cell arrivals to and losses from this queue are monitored throughout the duration of the application and rate changes are renegotiated at discrete instances of time. Denote the nth renegotiation instant as \( t_n \), and the interval between renegotiation points \( t_n \) and \( t_{n+1} \) as the nth update interval, \( U_n \). The service rate during \( U_n \) is constant and is denoted as \( \mu_n \).

During the nth interval, let the number of arrivals be represented by \( A_n \) and the number of losses as \( L_n \). The CLP of the nth interval is then calculated as \( P_n = L_n / A_n \). The cumulative CLP of all the intervals up to and including the nth is

\[
P_{0..n} = \frac{\sum_{i=0}^{n} L_i}{\sum_{i=0}^{n} A_i}
\]
The CLP desired by the user is denoted \( Q_t \). The goal of DSA+ is to adjust the server rate, so to provide the desired CLP, \( Q_t \), as efficiently as possible with few renegotiations. Secondary goals are simplicity of implementation and robustness.

### 3.2.2 Dynamic Search Algorithm (DSA+)

At each renegotiation point DSA+ adjusts the server rate according to the following formula:

\[
\mu_{n+1} \leftarrow \mu_n + \frac{K}{\alpha} \times \ln \left( \frac{P_n}{Q_t} \right), \quad \alpha = \begin{cases} 
1 & \text{if } P_n > Q_t \\
2 & \text{if } P_n \leq Q_t 
\end{cases} \tag{3.2}
\]

This dynamic algorithm updates the server rate, \( \mu_n \), based on the observed CLP during the \( n \)th interval. This measurement along with the desired CLP value, \( Q_t \), are then used in the error function \( \ln(P_n/Q_t) \). This non-linear error function provides either a positive or negative feedback value based on the observation taken during the most recent interval. Note the feedback becomes smaller as the measured CLP approaches the desired value, keeping the rate at a more stable value. The error function is also appropriate due to the very small loss rates that are normally desired. The constant \( K \) amplifies the response of the error function and this product ultimately determines how much the server rate can be increased or decreased. Parameter \( \alpha \) allows the rate to be increased twice as fast as it can be decreased. This is done since, in an actual network, resources are more easily reduced than increased.

Algorithm 3.1 shows the complete DSA+ algorithm at one renegotiation instant \( t_n \). As seen in the algorithm, the renegotiation interval is lengthened (doubled) in two cases (lines 4 and 7). The interval is doubled on line 4 if the cumulative CLP \( P_{b...n} \) is worse than required and if the CLP during the most recent interval \( P_n \) is better than required. This will reduce the cumulative CLP towards the desired value, since the \( n \)th CLP is better than the desired CLP. The interval is doubled on line 7 when \( P_n \) and \( P_{n-1} \) are on different sides of (one greater than, the other less than) the desired CLP. Doubling the interval length also reduces the number of renegotiations required over time, a feature common to both DSA+ and REQS [84].
Algorithm 3.1 DSA+ algorithm for adjusting the server rate to achieve a desired CLP.

1: \( \text{curr.error} \leftarrow \ln(P_n/Q_l) \) /* current error */
2: \( \text{prev.error} \leftarrow \ln(P_{n-1}/Q_l) \) /* previous error */
3: if \( P_{0..n} > Q_l \) AND \( P_n \leq Q_l \) then
4: \( U_{n+1} \leftarrow 2 \times U_n \)
5: else
6: if \( \text{curr.error} \times \text{prev.error} \leq 0 \) then
7: \( U_{n+1} \leftarrow 2 \times U_n \)
8: end if
9: if \( P_n > Q_l \) then
10: \( \mu_{n+1} \leftarrow \mu_n + K \times \ln(P_n/Q_l) \)
11: else
12: \( \mu_{n+1} \leftarrow \mu_n + \frac{K}{2} \times \ln(P_n/Q_l) \)
13: end if
14: end if

As mentioned in the introduction, traffic sources such as MPEG-compressed video are complex due to their bursty and unpredictable behavior. A potential problem with the algorithm as shown is that the traffic characteristics may change drastically during a renegotiation interval, while the server rate cannot be renegotiated. This can lead to excessive QoS violations. Interrupts are used to reduce the severity of this problem. At fixed-length sub-intervals, called an interrupt interval \( I \), an interrupt is generated if both \( P_n \) and \( P_{0..n} \) are greater than the desired loss rate \( Q_l \). The relationship between update and interrupt intervals can be seen in figure 3.2. In this case, the server rate is increased immediately according to equation 3.2, rather than waiting until the end of the renegotiation interval. The renegotiation interval itself, however, is not changed by an interrupt. The use of interrupts allows DSA+ to be more responsive to sudden, severe traffic changes, which should occur infrequently. This is a unique and key element of DSA+.

Initially the user must assign the following values: initial renegotiation interval \( U_0 \), interrupt sub-interval \( I \), constant \( K \) and the initial server rate \( \mu_0 \). \( U_0, I, \) and \( K \) may depend on the source traffic, but their selection primarily impacts the number of renegotiations and the efficiency of the allocation. Initial variable selection is addressed in section 3.3.4.
3.3 Experimental Results

In this section the performance of DSA+ and other allocation techniques is investigated using simulated traffic and actual MPEG-compressed traffic. For each experiment the system described in section 3.2 was simulated. The desired QoS was a CLP of $1 \times 10^{-3}$ and the queue capacity was 80 ATM cells (48 byte payload) [84]. While the targeted QoS was cell loss probability, the queue size was selected to provide a minimum cell delay as well. The minimum allowed bandwidth was 1 Mbps, therefore the maximum delay for any cell is 34 msec. This value was selected to provide a wide range of available bandwidths, however almost any combination of minimum bandwidth and queue size could have been chosen. A more restrictive bandwidth selection will only improve the performance of the algorithm.

Efficiently managing bandwidth is of interest; therefore, two performance metrics are used. First, the number of renegotiations required for the entire simulation. This value is important since a large number of renegotiations will cause considerable strain on the signaling system of the network. Second, the number of bits reserved to transmit the video, or equivalently, the area under the allocation curve for the duration of the video. This measurement is important because the video should be transmitted with few bits as possible while maintaining the desired QoS. Minimizing the bits used can help increase the utilization of the network by providing more resources to other users.
3.3.1 MMBP Sources

A two state Markov Modulated Bernoulli Process (MMBP) was selected for simulated traffic. This model was chosen because it typifies burstiness and the correlation of interarrival times, two important characteristics of ATM traffic [79]. For these experiments, the performance of DSA+ is compared to effective bandwidth and peak rate allocation. The effective bandwidth was calculated using the method described in [30], which was presented for MMPP sources. The method was extended for MMBP sources using techniques described in [56]. The effective bandwidth is an off-line calculation that yields the smallest rate which ensures a certain CLP. While the effective bandwidth technique requires complete source information and no renegotiations, its is presented here only as a possible lower bound allocation amount. This is certainly true if there are no renegotiations. Since DSA+ attempts to minimize the number of renegotiations, its allocation is expected to approach the effective bandwidth. The peak rate allocation is also given to provide an upper bound on the allocation amount. A dynamic technique should allocate less bandwidth than peak rate since peak rate will result in a zero losses. Consequently, the allocation amount of an efficient on-line method should fall below the upper bound and close to the lower bound.

The two state MMBP model is given in figure 3.3. Using this model, if the current state is $S_0$ the probability of remaining there is $p$ and the probability of changing state is $1-p$. If the current state is $S_1$ the probability of remaining there is $q$ and the probability of changing state is $1-q$. The cell arrival rates of state $S_0$ and $S_1$ are $\lambda_0$ and $\lambda_1$ respectively. More details about the MMBP model are presented in [79].

The parameters of the MMBP model were adjusted to vary two burstiness measurements. First, the rate of state $S_0$ was increased to magnify the squared coefficient of variation, $C^2$. The parameter settings and resulting $C^2$ values for these MMBP sources are
<table>
<thead>
<tr>
<th>Source</th>
<th>S0 State</th>
<th>S1 State</th>
<th>C²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Rate (cells/second)</td>
<td>Duration (second)</td>
<td>Mean Rate (cells/second)</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>0.2</td>
<td>$1 \times 10^4$</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>0.2</td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.2</td>
<td>$4 \times 10^3$</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.2</td>
<td>$7 \times 10^3$</td>
</tr>
</tbody>
</table>

Table 3.1: MMBP parameter values for the $C^2$ experiments.

given in table 3.1. Second, the duration of state $S_0$ was lengthened to magnify the peak to mean ratio. The parameter setting for these MMBP sources are presented in table 3.3. For each experiment, separate and independent simulations were executed to provide averages and 95% confidence intervals. Experiments ran for 6000 simulated seconds and each data point represents 100 simulations. The initial DSA+ parameters for all the MMBP experiments were: 40 cells/second for $K$, and 0.5 seconds for both $U_0$ and $I$ and the peak rate of the source for $\mu_0$.

$C^2$ Experiments

The following experiments used the MMBP sources described in table 3.1 and were performed to show the effect of an increasing $C^2$ values (30 - 207). Table 3.2 shows the results of the $C^2$ experiments and figure 3.4 shows the average bandwidth allocation and cumulative CLP graphs for source 1. As seen in the table and graphs, DSA+ allocated slightly fewer bits than effective bandwidth (2.5% less) and achieved a lower CLP. The DSA+ allocation for each experiment had slightly larger confidence intervals at the beginning, since the algorithm is searching for the appropriate value. As the algorithm approached an allocation level which provided the desired QoS, the allocated amount stabilized and the confidence intervals reduced in size. This was evident for all the MMBP experiments. Since the peak rate allocation was no greater than 15% for any experiment, peak rate allocation can be considered an efficient allocation for these sources, only if its value is known in advance. DSA+ was able to provide a lower allocation amount and better QoS (lower CLP), than the effective bandwidth method, with no a priori information about the source.
Figure 3.4: Average allocation and cumulative CLP values for MMBP source 1.

Figure 3.5: Average bandwidth and cumulative CLP values for MMBP source 5.
<table>
<thead>
<tr>
<th>Source</th>
<th>DSA+</th>
<th>Effective Bandwidth</th>
<th>Peak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. Bits Used (x 10^9 bits)</td>
<td>Bits Used (x 10^9 bits)</td>
<td>Bits Used (x 10^9 bits)</td>
</tr>
<tr>
<td>0</td>
<td>2.20</td>
<td>2.27</td>
<td>2.54</td>
</tr>
<tr>
<td>1</td>
<td>4.67</td>
<td>4.80</td>
<td>5.09</td>
</tr>
<tr>
<td>2</td>
<td>9.70</td>
<td>9.89</td>
<td>10.2</td>
</tr>
<tr>
<td>3</td>
<td>17.2</td>
<td>17.5</td>
<td>17.8</td>
</tr>
</tbody>
</table>

Table 3.2: Allocation comparison for varying C² MMBP traffic.

<table>
<thead>
<tr>
<th>Source</th>
<th>S0 State</th>
<th>S1 State</th>
<th>Peak/ Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Rate (cells/second)</td>
<td>Duration (second)</td>
<td>Mean Rate (cells/second)</td>
<td>Duration (second)</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>0.04</td>
<td>2.5 x 10^3</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.06</td>
<td>2.5 x 10^3</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0.08</td>
<td>2.5 x 10^3</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0.1</td>
<td>2.5 x 10^3</td>
</tr>
</tbody>
</table>

Table 3.3: MMBP parameter values for peak-to-mean experiments.

**Peak-to-Mean Experiments**

The following experiments used the MMBP sources described in table 3.3 and were performed to show the effect of an increasing peak to mean value (16 - 20). Table 3.4 shows the results of peak to mean experiments and figure 3.5 shows the average bandwidth allocation and cumulative CLP graphs for source 5. Similar to the C² experimental results, DSA+ was able to provide a slightly better QoS for each experiment. The number of bits reserved for transmission by DSA+ is consistently lower than the effective bandwidth allocated amount (an average of 6.75% less than effective bandwidth). In addition, there was a significant savings over peak rate allocation (an average of 94.5% less than peak rate allocation). Both sets of experiments indicate that DSA+ is able to efficiently manage the stationary traffic of various MMBP sources. The performance of DSA+ with non-stationary traffic is presented in the next section.
Table 3.4: Allocation comparison for varying peak-to-mean MMBP traffic.

### 3.3.2 MPEG Traffic

In this section the performance of DSA+ is investigated using fifteen MPEG-compressed videos. All traces were obtained from Oliver Rose at the University of Würzburg, Germany [89]. Each trace is a thirty minute segment of the original video and was encoded with constant quality using the same MPEG-1 encoder card. Relevant statistics of each video are presented in [40, 89]. As reported in [89], the Hurst parameters indicate all videos exhibit long-range dependency, and significant peak-to-mean ratios ranging from 18.4 to 4.63 based on average frames. Therefore it is evident that these are very difficult sources to regulate, and to date there has been no successful attempt to efficiently manage them on-line.

For each I, B or P MPEG frame, the equivalent number of ATM cells was determined. The cell arrival times were then uniformly distributed over the duration of the frame. This process was repeated for each frame until the end of the trace was reached. No smoothing, multiplexing, filtering or quantization changes of any kind were made to the videos. For this reason, these experiments can be considered to be a “hard-case” test of any on-line allocation technique.

As an example of the performance of DSA+, figure 3.6 shows the bandwidth allocation and cumulative CLP for the Simpsons video. In this experiment, the initial parameter settings are given in table 3.5. As seen in the figure, DSA+ quickly reduces the bandwidth allocated, until the cumulative CLP is approximately the desired value. Afterwards, when the measured CLP was worse than the desired value, the algorithm

---

1Traces can be obtained from the ftp site ftp-info3.informatik.uni-wuerzburg.de in the directory /pub/MPEG
Table 3.5: Initial settings of DSA+ parameters for MPEG-compressed videos.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_0$ (Mbps)</td>
<td>4.25</td>
</tr>
<tr>
<td>$K$ (Kbps)</td>
<td>100</td>
</tr>
<tr>
<td>$U_0$ (second)</td>
<td>4</td>
</tr>
<tr>
<td>$I$ (second)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 3.6: DSA+ bandwidth allocation and cumulative CLP for the Simpsons video.

increased the rate with interrupts. The cumulative CLP graph shows that the algorithm is able to tightly control the bandwidth for the desired CLP. A total of 36 renegotiations were required, with approximately half occurring in the first 60 seconds. This is due to the high initial server rate; improvements can be obtained if the initial rate is less than the peak. Only sixteen of the renegotiations were for more bandwidth. This low number of renegotiations is due to doubling the update interval, as described in section 3.2.

3.3.3 Comparison with Other Allocation Techniques

In this section DSA+ is compared to other allocation techniques: peak rate, Hsu’s algorithm, and RED-VBR. The system described in section 3.2 was implemented and all fifteen MPEG videos were used as traffic sources. Again individual frames were split into
ATM cells as described in the previous section. No smoothing, multiplexing, filtering or quantization changes of any kind were made to the videos. DSA+ initial parameters, the same for each video, are given in table 3.5.

**Peak Rate**

Peak rate allocation was chosen since it is an accepted allocation method [55]. To determine the exact peak rate requires the trace in advance. For that reason, this is an off-line method. In a sense this comparison is unfair to the remaining on-line methods. An on-line peak rate algorithm would require an overestimation of the traffic by a significant percentage to be cautious. Another difference is that peak rate allocation would result in zero losses, while other methods were targeted for a loss rate of $1 \times 10^{-3}$. Small but non-zero losses are considered to be acceptable for typical multimedia applications. Instead of a weakness, the ability to manage QoS targets based upon the needs of the user should be considered a strength of any on-line algorithm. Other off-line methods, such as PCBR [13] or Feng’s algorithm [32], are not comparable, as they directly control the transmission of the source.

**Hsu’s Algorithm**

Hsu’s method is a dynamic algorithm which has been proven to find the minimum bandwidth required for a stationary MMBP source [43]. This method was chosen since it is a simple on-line method that requires minimal source information. The algorithm renegotiates bandwidth over fixed length intervals, using previous loss measurements and a simple difference error function. Initial parameters for this algorithm were 4.5 Mbps for the initial server rate, 1 second for the interval and 1 Mbps for $c$ the constant. No method of parameter selection was presented in the original paper. The values used were found to be the best experimentally. It was also observed that the algorithm was very sensitive to parameter values. Small variations in the initial parameter values did result in over-allocation.
RED-VBR

RED-VBR is a method for supporting VBR video, with an off-line or on-line allocation technique. For this comparison, the on-line version was implemented using a similar segmentation algorithm as presented in [104]. RED-VBR is based upon the D-BIND model [57]. This model consists of a set of rate-interval pairs, which characterize the source over various interval lengths. The allocation algorithm stores the currently reserved D-BIND parameters and calculates the D-BIND parameters for the last $M$ frames. A renegotiation takes place when a difference exists between the reserved and measured D-BIND parameters; more details are presented in [104]. RED-VBR does not use nor measure the QoS for allocation. QoS is an issue when sources are multiplexed together and is provided on a “per-segment” basis as described in [104]. As a comparison, only the renegotiation and allocation performance of this method will be considered. The initial parameters are given in table 3.6. The $\alpha$ and $\beta$ values were taken from the original paper, while MIN\_RENEG\_INTERVAL, $P$ and $M$ were selected to reduce the number of renegotiations.

### Comparison Results

Table 3.7 shows the performance of all the algorithms for each individual MPEG video as a source. Example allocation and cumulative CLP graphs for the Asterix MPEG video, seen in figure 3.7, are also given. The performance of each method is described next.

DSA+ was able to provide the desired QoS for each video, with significantly fewer bits than the peak rate. Saving of 21 - 61% were observed over peak rate. The average number of renegotiations required was 36.2 and only 44% of the renegotiations were requests for more bandwidth. Bandwidth increases averaged 189 Kbps.
Hsu’s algorithm was not able to provide the desired QoS for the Goldfinger, News and Lambs videos. This method also over-allocated bandwidth (more than the actual peak) for the Formula 1 Race, Mr. Bean, News, Simpsons, Super Bowl and Talk videos. This was a result of an over-allocation early in the trace, from which the algorithm was unable to reduce the bandwidth quickly enough. Placing bounds on the highest bandwidth allocated (peak) reduces this effect, but it requires the knowledge of the value a priori. Another difficulty with this method was the number of renegotiations. The algorithm uses constant intervals to renegotiate the bandwidth. Consequently, renegotiating every second would place a significant burden on the network’s signaling system.

RED-VBR was able to provide the desired QoS for each video with CLP values ranging from zero to $2 \times 10^{-4}$. Fewer bits than peak allocation (11 - 52% less) were used, but the algorithm required a large number of renegotiations. On average 284 renegotiations were performed, with 56% being for more bandwidth. As seen in figure 3.7, these increases were large, averaging 575 Kbps. The calculation of D-BIND parameters may also be problematic since it is done for each frame.

Overall DSA+ performed better than the other algorithms. It always required fewer bits for transmission than the peak, and on average less than the other on-line methods, while still providing the desired CLP. The significant savings was in the number of renegotiations. The algorithm required no more than 52 renegotiations and on average only 44% were for more resources. The number can be further reduced with a lower initial bandwidth value, as discussed in the next section. On average Hsu’s algorithm required 47 times more renegotiations, while RED-VBR required 8 times as many. The magnitude of increases were relatively small, 189 Kbps, while RED-VBR increased three times as much. DSA+ also has the advantage of a simple algorithm that does not require large amounts of processing time.

### 3.3.4 Robustness and Appropriate Parameter Selection

As described in section 3.2, four initial parameters must be specified in order to use DSA+: the initial server rate $\mu_0$, the first renegotiation interval $U_0$, the rate adjustment coefficient $K$, and the interrupt sub-interval $I$. A capable dynamic allocation method
<table>
<thead>
<tr>
<th>Video</th>
<th>DSA+ Bits Used (×10⁹ bits)</th>
<th>Hsu’s Bits Used (×10⁹ bits)</th>
<th>RED-VBR Bits Used (×10⁹ bits)</th>
<th>Peak Bits Used (×10⁹ bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asterix</td>
<td>30</td>
<td>1666</td>
<td>305</td>
<td>6.51</td>
</tr>
<tr>
<td>ATP Tennis</td>
<td>30</td>
<td>1666</td>
<td>308</td>
<td>8.43</td>
</tr>
<tr>
<td>Formula 1 Race</td>
<td>25</td>
<td>1666</td>
<td>293</td>
<td>8.95</td>
</tr>
<tr>
<td>Goldfinger</td>
<td>47</td>
<td>1666</td>
<td>269</td>
<td>10.8</td>
</tr>
<tr>
<td>Jurassic Park</td>
<td>39</td>
<td>1666</td>
<td>296</td>
<td>5.28</td>
</tr>
<tr>
<td>Movie Review</td>
<td>35</td>
<td>1666</td>
<td>315</td>
<td>7.63</td>
</tr>
<tr>
<td>Mr. Bean</td>
<td>52</td>
<td>1666</td>
<td>269</td>
<td>10.1</td>
</tr>
<tr>
<td>MTV</td>
<td>44</td>
<td>1666</td>
<td>283</td>
<td>10.1</td>
</tr>
<tr>
<td>News</td>
<td>28</td>
<td>1313</td>
<td>220</td>
<td>8.60</td>
</tr>
<tr>
<td>Lambs</td>
<td>46</td>
<td>1666</td>
<td>279</td>
<td>5.93</td>
</tr>
<tr>
<td>Simpsons</td>
<td>36</td>
<td>1666</td>
<td>296</td>
<td>10.2</td>
</tr>
<tr>
<td>Soccer</td>
<td>25</td>
<td>1666</td>
<td>307</td>
<td>8.28</td>
</tr>
<tr>
<td>Super Bowl</td>
<td>34</td>
<td>1666</td>
<td>268</td>
<td>6.21</td>
</tr>
<tr>
<td>Talk</td>
<td>37</td>
<td>1666</td>
<td>261</td>
<td>4.73</td>
</tr>
<tr>
<td>Terminator</td>
<td>38</td>
<td>1666</td>
<td>293</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Average: 36.5, 4.38, 1666, 7.17, 284, 4.95, 7.72

Legend: N.R. = number of renegotiations

Table 3.7: Single-user allocation comparison.
should be relatively insensitive to the initial parameter values, so user insight into these parameters is not a requirement. Four experiments were performed to investigate whether this was the case. For each experiment, the parameters were set to a particular value and the behavior of DSA + was simulated for all 15 videos. Then, the average number of bits and number of renegotiations per video were calculated. The system described in section 3.2 was simulated and the desired CLP for each experiment was $1 \times 10^{-3}$. Minimizing the number of renegotiations as well as the amount of bandwidth allocated is of interest. Yet, improving one value may result in a negative effect on the other. For example, a higher number of renegotiations can result in a more efficient allocation, since the algorithm can closely follow the arrival pattern of the source.

Figure 3.8 shows the effect of varying the initial parameters individually. It was observed that the coefficient $K$, did not significantly impact the number of renegotiations, but values over 350 Kbps did increase the number of bits used. In general, for MPEG videos smaller $K$ values (100 - 350 Kbps) are better, since the additional number of renegotiations is not significant compared to the savings in bandwidth. The initial server rate does impact both the number of renegotiations and the bits used. Small initial server rates (less than half peak rate) have fewer renegotiations, but allocate more bits. This is a result of interrupts
occurring early in the trace. Large initial server rates (more than 75% peak rate) cause more renegotiations but fewer bits used. The higher number of renegotiations is the effect of reducing the rate more slowly than it can be increased (see equation 3.2). Generally, larger initial bandwidths are better due to the savings in bits used. However, like any renegotiation method, the better the initial rate guess, the better the performance. The intervals, \( U_0 \) and \( T \), have some impact on performance; however their values should be set in accordance to the desired CLP. For example, a more stringent CLP would need a smaller interrupt interval to prevent excessive losses during an interval. Overall DSA+ is robust to initial parameter settings. It can accept a variety of values and still provide the desired QoS. Like any method of resource allocation, a priori information can help guide the initial parameter selection; however it is not a necessity.

### 3.3.5 Multiplexing

In this section, the ability of DSA+ to allocate bandwidth for multiplexed MPEG videos is examined. The motivation for this experiment is the use of DSA+ for connection admission control. An admission control technique could simply use DSA+ to predict bandwidth usage of the current sessions. Subtracting this value from the total amount would provide a quick and accurate measure of the remaining resources available. For this experiment, DSA+ was used to manage a multiplex stream of fifteen different MPEG videos. The QoS provided to the multiplexed stream is an aggregate value, thus individual guarantees are not provided. The performance was then compared to the summation of bandwidth from controlling each video independently, as in section 3.2. Each multiplexed video was randomly started at frame \( x \), where \( x \) was uniformly distributed between the start and end frame. The frames of each video were then added together to create one multiplexed video stream. This multiplexed stream had a peak rate of 17.2 Mbps and mean rate of 7.61 Mbps, yielding a peak to mean ratio of 2.26. The stream was then broken into ATM cells in the same manner as described in section 3.3.2. The cells then arrived at a FIFO queue (80 cell capacity), where any cell encountering a full queue was immediately lost. The desired CLP was \( 1 \times 10^{-3} \). Multiplexing is expected to reduce burstiness and LRD behavior [81]; thus a multiplexed source should be easier to manage.
Figure 3.8: Measuring the impact of the initial DSA+ parameters.
Figure 3.9: DSA+ bandwidth allocation and cumulative CLP for the multiplexed stream.

Figure 3.9 shows the allocation and cumulative CLP of the DSA+ managed multiplexed stream and the summed individual DSA+ managed streams. As noted in the figure, significant savings occurs from managing the multiplexed stream. Savings of 15\% over peak and 66\% over the summed individual streams were observed. The primary source of savings (over controlling each video individually) is from multiplexing. Multiplexing smooths the stream, reducing burstiness and LRD. The result is a source that is “well-behaved” as compared to the individual videos. The number of renegotiations for the multiplexed stream is 67 as compared to 546 total renegotiations for the individual videos. Over half of the renegotiations for the multiplexed stream occurred in the first two minutes.

3.3.6 Multiple Hop Allocation

In the previous sections, DSA+ has only been used for controlling the QoS of a single hop. In this section the application of DSA+ for a multiple hop connection is investigated. For these experiments four nodes are connected in series. The nodes are interconnected with 155 Mbps links, each measuring 50 meters in length. Each node consists of an adjustable rate server and finite capacity FIFO queue (80 ATM cells) as described in section 3.2. Each MPEG-video was segmented as described in section 3.3.2. The stream
entered the network at node zero and proceeded forward until node three was reached. For these experiments the desired QoS is an end-to-end cell loss probability of $1 \times 10^{-3}$. Two implementations of DSA+ were investigated: each-node and first-node.

The each-node implementation requires each node to run DSA+ separately and independently, as seen in figure 3.10. The end-to-end CLP was divided evenly among the nodes resulting in a target CLP of $2.5 \times 10^{-4}$ per node. If each node provides this CLP, the end-to-end CLP would be the desired $1 \times 10^{-3}$. The end-to-end QoS could have been divided differently, perhaps based on the current condition of the individual nodes. The remaining DSA+ initial parameters were identical for each node and are given in table 3.5. One primary advantage to the strategy is that no inter-node algorithm communication is necessary, thus eliminating any need for algorithm control packets.

First-node implementation only requires the first node of the connection to run DSA+, as seen in figure 3.11. The initial DSA+ parameters are given in table 3.5. The first node controls the bandwidth for all the remaining downstream nodes. The first node has a CLP of $1 \times 10^{-3}$, therefore the remaining nodes can have zero losses. When a renegotiation occurs at the first node a control packet, containing the new bandwidth value, is sent downstream. Once a downstream nodes receives the bandwidth control packet it must immediately renegotiate to this value then forward it downstream. The control packets are sent on another reliable connection, as done in many communication protocols [99]. Only transmission and propagation delays were factored for the control packets.
Figure 3.11: Multiple hop connection with first-node DSA+ implementation.

Table 3.8 shows the total number of bits (summation of the bits reserved for the four nodes) reserved by each method. Figures 3.12 and 3.13 show the allocation and observed CLP for the Talk video of each-node and first-node respectively. For the each-node method, downstream nodes required less bandwidth. This was evident for all the each-node experiments performed. This is primarily due to a reshaping effect each node has on the traffic. As the traffic passes through a node some fluctuations in the arrival stream are removed due to the storage and transmission, resulting in a less bursty departure stream. Downstream nodes benefit from this effect, resulting in a lower bandwidth allocation (1 - 47% less than the first node). However, the first node implementation consistently reserved fewer total bits, as seen in table 3.8; yet this implementation requires the overhead of inter-node algorithm communication.

Either implementation of DSA+ for end-to-end QoS showed promising results. The each-node arrangement provided the end-to-end QoS with no inter-node algorithm communication overhead, yet there are a few disadvantages. One disadvantage is that this method requires more bits as seen in the table. This is primarily due to the more stringent QoS required at each node, especially the first node. Another disadvantage is dividing the QoS among the individual nodes. This may be problematic if either there is a large number of nodes and/or if the end-to-end QoS is very stringent. For example, if the end-to-end CLP was $1 \times 10^{-6}$ in for a 10 node connection, each node would have an individual CLP of $1 \times 10^{-7}$. This individual CLP value may be too small for any type of on-line method. One possible solution could include the use of importance sampling or restart [61]. First-node implementation does not have the disadvantage of individual QoS requirements, but
<table>
<thead>
<tr>
<th>Video</th>
<th>Each-node Total Bits Used ($\times 10^{10}$ bits)</th>
<th>First-node Total Bits Used ($\times 10^{10}$ bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asterix</td>
<td>1.54</td>
<td>1.35</td>
</tr>
<tr>
<td>ATP Tennis</td>
<td>2.03</td>
<td>1.58</td>
</tr>
<tr>
<td>Formula 1 Race</td>
<td>2.31</td>
<td>2.06</td>
</tr>
<tr>
<td>Goldfinger</td>
<td>1.73</td>
<td>1.28</td>
</tr>
<tr>
<td>Jurassic Park</td>
<td>1.12</td>
<td>0.86</td>
</tr>
<tr>
<td>Movie Review</td>
<td>1.56</td>
<td>1.15</td>
</tr>
<tr>
<td>Mr. Bean</td>
<td>1.31</td>
<td>1.07</td>
</tr>
<tr>
<td>MTV</td>
<td>2.21</td>
<td>1.78</td>
</tr>
<tr>
<td>News</td>
<td>1.51</td>
<td>1.17</td>
</tr>
<tr>
<td>Lambs</td>
<td>1.14</td>
<td>0.78</td>
</tr>
<tr>
<td>Simpsons</td>
<td>1.56</td>
<td>1.27</td>
</tr>
<tr>
<td>Soccer</td>
<td>2.11</td>
<td>1.64</td>
</tr>
<tr>
<td>Super Bowl</td>
<td>1.39</td>
<td>1.06</td>
</tr>
<tr>
<td>Talk</td>
<td>0.85</td>
<td>0.71</td>
</tr>
<tr>
<td>Terminator</td>
<td>0.76</td>
<td>0.66</td>
</tr>
<tr>
<td>Average</td>
<td>1.54</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 3.8: Multiple-hop each-node and first-node DSA+ allocation comparison.

it does require more support for inter-node algorithm communication. It is possible that both methods could be combined to lessen the effects of both disadvantages.

3.4 Chapter Summary

This chapter introduced an on-line algorithm, called Dynamic Search Algorithm (DSA+), that determines the resource allocation amount for a desired QoS. This chapter focused on providing a desired cell loss probability by allocating link bandwidth. DSA+ attempts to reduce the bandwidth amount as well as the number of renegotiations required with limited a priori source information. To date no other on-line method is able to reduce the number of renegotiations required for MPEG sources. Furthermore, DSA+ has a simple implementation requiring $O(1)$ processing time and storage.

Experimental results demonstrated the capability of DSA+ to allocate link bandwidth to provide a desire cell loss probability for simulated and actual MPEG compressed video. MPEG compressed video is an especially difficult source to manage since its behavior
Figure 3.12: Four node connection, each running DSA+ independently (each-node implementation).

Figure 3.13: Four node connection, only first node running DSA+ and controlling all allocation (first-node implementation).
can be described as bursty and unpredictable. For the MPEG experiments fifteen actual MPEG traces were collected and used. As compared to an off-line peak-rate allocation, DSA+ sawd 13–58% in bandwidth. On average 36 renegotiations were required, but only 44% were for more bandwidth, which seems acceptably low. Other methods which were compared, either over-allocated bandwidth or required up to 47 times more renegotiations. Multiple hop connection allocation was also addressed. In this case a connection of four nodes was simulated to evaluate the performance of DSA+ for end-to-end CLP. Two implementations were investigated; each-node and first-node. Both methods were able to provide the end-to-end QoS, however each method may suffer from some possible disadvantages.

This chapter presented a method for allocating resources for a single user. However, the network manager must also consider the allocation requirements of all users in the network. In this multi-user environment, contention can occur for the limited network resources. For this reason, the network should allocate resources to all users in an efficient and fair manner. Multi-user allocation techniques are presented in the next chapter.
Chapter 4

Multi-User Allocation and Pricing Techniques

As described in chapter 1, computer networks must contend with a diverse variety of network applications. Given a finite supply of network resources and ever changing demands, networks need to allocate resources in a fair and efficient manner to provide the QoS these applications require. Different from single-user allocation (chapters 2 and 3), this chapter concerns the allocation of resources to all users in the network. Objectives in the multi-user environment include efficient and fair allocation of network resources.

This chapter reviews and categorizes various multi-user allocation methods. Since this thesis concerns microeconomic approaches to multi-user resource allocation, a brief discussion of basic microeconomic principles is also provided. This is followed by a review of previous microeconomic-based allocation work. Finally, multi-user allocation performance objectives are presented and discussed.

4.1 Multi-User Allocation Objectives and Classifications

There are two objectives associated with multi-user resource allocation, fairness among applications and the balance between throughput and QoS. Fairness can be defined in various manners. For example, fairness can refer to the amount of resource allocated
to each application (for example, the max-min fairness criterion). The max-min fairness criterion provides all users a "fair" share of the resource [6]. Alternatively, fairness can be defined with respect to the QoS observed by each application (social welfare criterion) [38, 76]. Now the objective is to provide applications equivalent QoS, which is better suited for multimedia applications [39]. The second objective of resource allocation, the balance between throughput and QoS, is the concept that the network should seek high utilization but not at the expense of QoS (and vice versa).

Resource allocation methods can be classified as either static or dynamic in nature. Static resource allocation techniques reserve a single amount for the duration of the session. In general, static methods can be too conservative for bursty traffic such as MPEG-compressed video, or rely heavily on statistical models to predict resource requirements. In either case, static methods require a priori source information (for example, peak transmission rate or bounds on the maximum burst size), which is not available for live or interactive applications. Alternatively, dynamic allocation methods adjust resource amounts based on network conditions and application requirements. This responsiveness attempts to provide the desired QoS while maintaining high utilization; however, providing strict QoS guarantees is difficult, since contention for resources may occur.

Methods that perform dynamic resource allocation can be generally classified on whether they maintain per-connection state information [51]. Methods that maintain per-connection state information that is directly used in the calculation of the allocations will be referred to as state-maintaining. Alternatively, if per-connection state information is not required for the calculation of the allocations, it will be referred to as state-less. Of these two categories, a state-less method is preferred. Such a method does not require the overhead (storage and computational) of connection tables when computing allocations. Also, state-less implementations are scalable to larger networks since additional data structures are not required.

Recently, economic theory has been applied to multi-user resource allocation. Modeling the network as an economy, economic theory can be used to allocate network resources. A simple network economy consists of two types of agents, consumers (applications) and producers (switches). Consumers require resources to satisfy their QoS. Produc-
ers own the resources sought by consumers, and maximize their satisfaction by renting or selling. Economic-based allocation methods have several advantages. Many of economic-based techniques offer a distributed allocation method, eliminating the need for a central controlling entity. Economic-based methods can also achieve optimal allocations (Pareto-optimal, proportionally fair per unit charge [53] and weighted max-min fair). These methods are typically able to scale to large networks and provide a framework for economic goals (such as, cost recovery and profit maximization).

4.2 Economics and Resource Allocation

Economics is often defined as the study of ‘the allocation of scarce resources among competing ends’ [76]. This definition contains two fundamental concepts of economics: scarcity of resources and allocation choices. Scarcity of resources signifies that there is never enough of a resource to satisfy all wants all the time. Choices must be made concerning possible allocations and their impact. Therefore, economic theory examines the interaction of agents to understand how resources are allocated.

Economic theory can be divided into two categories, microeconomics and macroeconomics. Macroeconomics concerns large aggregate behavior (group of agents), instead of individual actions (a single agent). In contrast, microeconomics, also known as price theory, concerns the behavior of individual agents and their interaction in the market. Microeconomic paradigms will be the focus of this thesis, because the attention to individual behavior is appropriate considering the need for individual QoS in a computer network.

4.2.1 Economic Models

An economic model is composed of a finite amount of resources, a set of agents, and rules specifying their interaction. Given this framework, agents in the economy acquire resources in an attempt to optimize some metric. For example, an agent may seek to maximize their utility, which is a measurement of satisfaction. The utility obtained from an amount of a resource is determined from a utility function. The utility function maps a resource amount to a real number, that corresponds to a satisfaction level. Assuming $u(\cdot)$
is a utility function, if the agent prefers an allocation amount $a$ over $\hat{a}$ (this is represented using the notation $a \succ \hat{a}$) then $u(a) > u(\hat{a})$. Using a utility function, an agent can rank possible allocations and acquire resources that maximize their utility. Once the structure is defined, the performance of the economy can be analyzed.

Various criteria can be used to measure the distribution of resources in the economy. Two "economic-oriented" optimal criteria are used in this thesis: *Pareto-optimal allocation* and an *equitable allocation*. A Pareto-optimal allocation is one in which no agent can increase their utility with out decreasing the utility of another. Many different Pareto-optimal allocations exist; however only a few can be considered equitable [76]. Social welfare economics defines an equitable allocation as one where all agents achieve the same level of utility. In addition, this thesis will use the "network-oriented" criterion weighted max-min fair to define optimal allocations. All of these criteria are important for determining the success of an economic-based network allocation method.

### 4.3 Microeconomic-Based Multi-User Allocation

Microeconomic-based allocation methods use microeconomic theory to allocate network resources and have several advantages. Many of economic-based techniques offer a distributed allocation method, eliminating the need for a central controlling entity. Economic-based methods can also achieve optimal allocations (Pareto-optimal, proportionally fair per unit charge and weighted max-min fair). These methods are typically able to scale to large networks and provide a framework for economic goals (such as, cost recovery and profit maximization). Pricing network resources also provides a disincentive to over-allocate network resources.

Microeconomic-based methods can be categorized based on how the allocations are determined (centralized or distributed). In addition, some techniques are designed for certain networks, such as ATM or the Internet. A review of these categories is provided next.
4.3.1 Constrained Maximization

One approach of applying microeconomics to computer networks uses optimization techniques to maximize utility [49, 50, 53, 67, 70]. The maximization process determines the optimal resource allocation such that the utility of users is maximized subject to budget and resource availability constraints [15, 76]. Since the computation required for the maximization process increases as the number of users increases, these methods are not scalable to networks with a large number of users. To provide scalability, some approaches group users and use a single utility curve to represent the group. The maximization process is then performed for the smaller number of groups instead of individual users. Groups can be created based on desired QoS [49, 50] or on traffic types (or service classes) [67]. Accurately grouping users together may be problematic due to the wide variety of applications and their diverse resource requirements. Another problem is that these approaches generally require a centralized entity to determine the optimal allocation amount. This is undesirable because the economy relies on one entity, which is not reliable or fault tolerant. Furthermore, a centralized entity can also become a source of congestion in the network when demands or prices change.

4.3.2 Congestion Pricing

Congestion pricing [70] is another approach that charges users for their consumption of resources [2, 19, 33, 34, 53, 70, 73, 90]. Users act independently, attempting to maximize their own utility and prices are set in a distributed fashion based on local resource conditions (supply and demand). It has been shown that pricing based on supply and demand results in higher utilization than traditional flat (single) pricing [19, 70]. These methods are able to achieve Pareto-optimal allocations [34], proportional fairness per unit charge [53], max-min fair, and equitable (QoS-fair) allocations [38]. For these reasons, many of the following allocation methods use congestion pricing as a means to efficiently allocate resources. However, one important disadvantage of congestion pricing, in its original form, is the inability to handle changing demands on various time scales. For this reason, many of these methods can not easily handle VBR sources.
4.3.3 ATM Virtual Circuit and Virtual Path Allocation

One application of microeconomic theory to network resource distribution is for allocating ATM Virtual Circuits (VC) [2, 33, 34, 73]. Prices are iteratively determined at each link based on user demand and capacity. In [33, 34], users purchase bandwidth at each link along their path, attempting to achieve a certain minimum throughput and to minimize the average delay (assuming a M/M/1 queueing model). In this model users are considered “selfish” since purchasing decisions are based only on the interests of the user. When a price is determined that causes demand to equal supply (equilibrium price), Ferguson et al. proved the Nash equilibrium is achieved. A Nash equilibrium, normally associated with game theory, is a point where the strategy chosen by each player is the best considering the choices of all other players. This model was extended to include Virtual Paths (VP) by Anerson et al. [2]. In this paper, pricing is done to control VP demand and VC blocking probability experienced by users. At equilibrium, VC prices are higher per unit capacity than VP prices, which is expected due to the increase signaling costs. An alternative method for VC pricing was presented by Murphy et al. [73]. Again, prices for link bandwidth are iteratively determined based on supply and demand; however, users determine the amount of bandwidth that will maximize their marginal benefit (benefit minus cost). The benefit function of the user is assumed to be concave increasing. Normally assumed in economics, the user has a higher value of the initial amount of a resource, and has a diminishing value as the amount increases [73]. Once the equilibrium prices are determined, they and the demand are fixed for a period of time. This procedure repeats for the next segment of time. Therefore, demands change over a long time-scale, which is unsuitable for bursty traffic. This marginal benefit model is also used by Kelly, et al. for generic bandwidth pricing (not necessarily ATM) [53].

4.3.4 Microeconomic ABR Rate Control

Microeconomic-based techniques designed specifically for ABR rate control include [20, 21]. In [20], switches allocate ABR bandwidth in a proportionally fair manner based on the “willingness-to-pay” (wealth declaration) submitted by each user. When conditions
change, users determine a new willingness-to-pay via a curve fitting process which relies on a history of previously optimal decisions. In the ABR rate control method of [21], users bid for some amount of effective bandwidth. While effective bandwidth allocates over a longer time scale, these techniques are difficult to apply to sources with little or no a priori information (for example, live and interactive video) and can be considered too conservative [21].

4.3.5 Effective Bandwidth Pricing

Another method of resource pricing uses effective bandwidth [52] to measure resource usage [22, 24, 54, 95, 97]. Charging considers the “static traffic contract” (a priori traffic contract and information) and dynamic traffic measurements. Users are then charged for their session length as well as their traffic volume [54]. This method guarantees that users will provide truthful estimates of their traffic parameters, which avoids the need for traffic policing. Effective bandwidth pricing has been proposed to control ABR bandwidth (as described in the previous section) [22, 24]. Users bid for an effective bandwidth and the network controls the flow by adjusting the allowed transmission rate of the user. These approaches to rely on heavy multiplexing to provide accurate effective bandwidth calculations [22]. Otherwise the effective bandwidth values can be considered too conservative.

4.3.6 Smart Market

A method for pricing services in the Internet called the “smart market” was proposed by MacKie-Mason and Varian [69]. In this congestion control strategy, the user attaches a bid to the header of each packet sent. Routers in the network calculate a price based on the equilibrium price or the marginal cost of sending one more packet. The marginal cost consists of a non-congestion cost associated with transmission, and a congestion cost. Packets with bid amounts that exceed the current price for the link are transmitted. As a result, users have an incentive to quickly reveal their true value of each packet.
4.3.7 Game Theory

Game theory can be applied to network flow control and resource allocation. In this approach, each application is considered a player in a cooperative or non-cooperative game. A cooperative game requires players communicate information about their strategies. Alternatively, a non-cooperative game requires players to work individually without information from others. In either type of game, the goal of each player is to optimize their performance. Non-cooperative games have the advantage of less player-to-player communication overhead [94]. Nonetheless, the use of this information in cooperative games can result in a Pareto-optimal allocation [60, 72].

Park et al. describe a non-cooperative provisioning game to provide multiple levels of QoS [14, 80]. In [14, 80], QoS agents are installed at each switch in the network. The QoS agent intercepts the packets entering the switch and determine the appropriate QoS class for the packet in order to satisfy the end-to-end QoS (specified by the user). For this reason, the end-to-end QoS must be mapped to a local QoS at each switch along the route. Once the local QoS responsibility has been determined, the agent determines the QoS class that satisfies this value at the lowest cost [14]. It is assumed that classes with a proportionally higher QoS (for example, lower loss rate) also have a proportionally higher price (linear price differential); however, exactly how these prices are determined is not discussed.

Another non-cooperative game approach to bandwidth allocation was proposed by Korilis et al. [59]. Users split their traffic across multiple paths in the network so to minimize its individual costs. Prices associated with a link are proportional to the congestion at the link. This acts as an incentive for users to route traffic away from expensive (congested) paths.

4.3.8 Allocating Multiple Resource Types

Methods for pricing bandwidth and buffer space are described by [67, 68, 90]. In these methods, buffer space and link bandwidth are priced independently to reflect supply and demand. In [90], users compete for buffer space and link capacity to achieve a certain loss rate by employing certain queueing models (M/M/1/B). When the markets are in
equilibrium (price where supply equals demand), the resulting allocations (both buffer and bandwidth) are proven to be Pareto-optimal. However, the application of this method to actual VBR sources is not addressed.

4.4 Chapter Summary

This chapter discussed the various goals and categories of multi-user allocation. Goals normally associated with multi-user allocation include, fairness among applications and the balance between throughput and QoS. Fairness can be defined in various manners and is difficult due the various applications types and demands. The balance between throughput and QoS, is the concept that the network should seek high utilization but not at the expense of QoS (and vice versa). Methods can be categorized as either static or dynamic. Static methods allocate a single amount for the duration of the session, while dynamic methods can reallocate resources depending on network conditions. Static methods have the advantage of simple connection admission and control, but tend to be too conservative resulting in low utilization. Dynamic allocation methods achieve higher resource utilization, but can not guarantee resource availability. In addition methods can be classified based on the information required to determine allocation amounts. A state-maintaining approach requires per-connection state information to calculate allocation amounts, while a state-less approach uses only aggregate information. State-less approaches are preferred since less overhead (storage and computational) is required.

This chapter also reviewed microeconomic-based allocation methods. These techniques use microeconomic theory to allocate network resources and have several advantages. Many of economic-based techniques offer a distributed allocation method, eliminating the need for a central controlling entity. Economic-based methods can also achieve optimal allocations (Pareto-optimal, proportionally fair per unit charge and weighted max-min fair). These methods are typically able to scale to large networks and provide a framework for economic goals (such as, cost recovery and profit maximization). In addition, pricing network resources provides a disincentive to over-allocate network resources.

None of the microeconomic methods discussed in this chapter are able to han-
dle network dynamics over multiple time scales (changing user demands and users entering/exiting the network). When demands change new prices must be calculated, typically, off-line. Such methods are not suitable for allocating resources for VBR traffic. Furthermore, no method of wealth distribution is provided in order to achieve any desired measure of fairness in the economy. Therefore, a microeconomic-based allocation method should: achieve the advantages associated with microeconomic approaches (distributed technique and fair allocations), handle network dynamics, and have a reasonable implementation cost.

In the next chapter, a review of the competitive market is given. This market model will serve as the basis of the microeconomic-based allocation methods presented in chapters 6 and 7. The competitive market model has the ability to achieve efficient and fair resource allocations. How to distribute wealth in order to achieve certain measures of fairness is also provided. A modified version of this market model is then used in chapters 6 and 7 to allocate network resources.
Chapter 5

Competitive Market Model

The competitive market model serves as the basis for the two different multi-user allocation methods presented in this thesis. This market model prices resources based on supply and demand. Consumers (users) purchase these resources at the market price in order to maximize their happiness (QoS for a network application). Producers (switches) own the resources and maximize their utility by selling or renting. This model was chosen because of its ability to achieve certain desirable goals, such as Pareto-optimal distribution and price stability. The competitive market also has a structure that is simple to implement, and a well founded mathematical basis for analysis.

In this chapter, a description of the competitive market is provided as well as definitions of optimality (Pareto) and fairness (weighted max-min and equitable). Proofs that an economic model, consisting of multiple competitive markets, can achieve these measures of fairness are then given. An algorithm that determines the wealth distribution required for an equitable allocation is provided. Finally, some examples of optimal allocations are given for a simple network economy.

5.1 Market Definition

The competitive market model consists of scarce resources and two types of agents, consumers and producers. A resource is an item (or service) which is valued by agents in the economy. Since it is scarce, there is never enough of the resource to satisfy all the agents all
the time. For this reason, allocation decisions must be made. The agents come together at a market, where they buy or sell resources. Usually these exchanges are intermediated with money and the exchange rate of a resource is called its price. In the competitive market, prices are adjusted until supply equals demand. At this price the market is in equilibrium and the resulting allocation is Pareto-optimal [100]. The economies presented in this thesis will consist of multiple independent competitive markets, where each resource type will be sold in its own market.

Consumer $j$ has wealth $w^j$ and acts independently (selfishly) purchasing resources to increase utility. For each resource, it is assumed that the utility function, of each user, is monotonically increasing [100]. In addition, a user normally becomes satiated with some amount, above which the utility may decrease. Assume consumer $j$ desires a maximum resource amount $b^j$; therefore $u^j(b^j)$ is the highest utility consumer $j$ can achieve. When maximizing utility, consumers must adhere to their budget constraints. Assuming consumer $j$ wishes to purchase an amount $a^j$, where $a^j \leq b^j$, at price $p$ the budget constraint $p \cdot a^j \leq w^j$ must be true. The wealth signifies purchasing power of each consumer, since consumers with more wealth can afford more resources. Therefore, the wealth can also be viewed as a weight when resources are allocated.

The competitive market always seeks the equilibrium price that causes supply to equal demand. The equilibrium price can be determined directly; however, in a decentralized economy some terms (the utility and wealth of each agent) may not be known. For this reason, the equilibrium price is determined via a tâtonnement process [103]. First proposed by Léon Walras, the tâtonnement process iteratively adjusts the price with respect to excess demand. The excess demand is a function of the total (aggregate) demand and supply of the resource. The price increases if the demand is greater than the supply and decreases when the demand is less than the supply. It is important to note that the demand and supply at the current price must be known before an adjustment can occur. The iterative process repeats until a price is reached such that supply equals demand; at this point the market and price are in equilibrium. This is referred to as “clearing the market,” where

---

1 Not to be confused with the indifference curve which is normally convex.

2 Alternatively, an auction or bidding procedure can be used [76].
consumers maximize utility given their budget constraints and producers maximize profits. Refer to the prices calculated before the equilibrium price is reached as intermediate prices. Buying and selling normally do not occur with the intermediate prices [100]; however, this constraint will not apply to the bandwidth “spot market” (described in the next chapter), since bandwidth in this market is considered a non-storable resource. This allows demands to change dynamically and is achieved using a modified tâtonnement process. Once the market is in equilibrium the resulting allocation is Pareto-optimal and weighted max-min fair, which is proven in the next sections.

5.2 Fairness and Optimality

The allocation provided by an economy consisting of multiple independent competitive markets in equilibrium can be described as efficient (Pareto-optimal) and weighted max-min fair. Furthermore, with appropriate wealth distribution the allocation is also equitable. This section formally defines the terms efficient (Pareto-optimal), weighted max-min fair and equitable allocations. Then three theorems are introduced, that indicate conditions under which an economy consisting of multiple competitive markets can achieve these important goals.

5.2.1 Pareto-Optimal Allocations and Weighted Max-Min Fairness

Assume an economy consists of a set of independent competitive markets $L$. Each market $i$ sells only a unique type of resource with supply $s^i$. This implies that an array of prices exists $\{p\}$ in the economy, where the price for the resource sold at market $i$ is $p^i$. All consumers in the economy belong to set $A$, where consumer $j$ desires resources belonging to the set $R^j \subseteq L$. Consumer $j$ has an amount of wealth for each market $i \in R^j$. Denote $w^{ji}$ as the amount alloted for market $i$ by consumer $j$; in addition, assume this amount is equal for all markets the consumer participates in ($w^{jh} = w^{ji}, \forall h, i \in R^j$). Therefore, the second superscript of $w^{ji}$ ($i$, indicating the market) will be dropped for brevity. Each consumer has a maximum amount $b^j$ which is desired for any resource. Let $a^{ji}$ be the allocation for consumer $j$ in market $i$. Furthermore, assume the consumer must
purchase the same amount in each market\(^3\) \((a^{j,h} = a^{j,i}, \ \forall h, i \in R^j)\). As done for \(w^j\),
the second superscript of \(a^{j,i}\) (indicating the market) will be dropped\(^4\). Denote \(A^i\) as the set of consumers participating in market \(i\). Consumer \(j\) is either “completely satiated” or “non-satiated” with their allocation \(a^j\) at market \(i\). Let \(C^i\) be the set of completely satiated consumers and \(N^i\) be the set of non-satiated consumers at market \(i\); therefore, \(C^i \cup N^i = A^i\) and \(\sum_{j \in A^i} a^j \leq s^i\) must always be true for all markets in the economy.

**Definition 5.2.1.** Completely satiated: At market \(i\) with price \(p^i\), consumer \(j\) is completely satiated with \(a^j\) if the amount of resources affordable is greater than what is desired, \(b^j\).

\[
\text{if } \frac{w^j}{p^i} \geq b^j \text{ then } a^j = b^j \tag{5.1}
\]

**Definition 5.2.2.** Non-satiated: At market \(i\) with price \(p^i\), consumer \(j\) is non-satiated with \(a^j\) if the amount of resources affordable is less than or equal to what is desired, \(b^j\).

\[
\text{if } \frac{w^j}{p^i} < b^j \text{ then } a^j = \frac{w^j}{p^i} \tag{5.2}
\]

Consumer \(j\) will purchase resources from each market \(i \in R^j\). Depending on the price associated with each market, the consumer can afford different amounts. As previously mentioned, assume the consumer will always purchase the same amount at each market \(i \in R^j\). This amount \(a^j\) is equal to the minimum amount that is affordable at any market \(i \in R^j\) (but no more than the maximum desired \(b^j\)),

\[
a^j = \min \left\{ \min_{i \in R^j} \left\{ \frac{w^j}{p^i}, b^j \right\} \right\} \tag{5.3}
\]

The market in \(R^j\) with the highest price is considered saturated for consumer \(j\), since only the minimum amount of resources can be purchased (which ultimately determines the amount to purchase at the remaining markets in \(R^j\)). At the saturated market the consumer is non-satiated; however, for the remaining markets in \(R^j\) the consumer is considered

\(^3\)This assumption becomes clear when the economy is a computer network and the resource is link bandwidth.

\(^4\)The requirements \((w^{j,h} = w^{j,i}, \ \forall h, i \in R^j)\) and \((a^{j,h} = a^{j,i}, \ \forall h, i \in R^j)\) can be removed and weighted max-min fair and equitable allocations can proved for individual markets (instead of an entire economy).
satiated. For example, assume \( R^j \) consists of three markets and the consumer can afford 10 units at market 1, 5 units at market 2 and 20 units at market 3. Market 2 is saturated and the consumer will only purchase 5 units at each market. In the case where the consumer can afford \( b^j \) at each market in \( R^j \), then the consumer is considered completely satiated at each market in \( R^j \).

**Definition 5.2.3.** Feasibility: For competitive market \( i \), the price and an allocation array, \([p^i, \{a\}]\), are said to be feasible if and only if,

(i) \( s^i = \sum_{j \in A^i} a^j \)

N.B. The case where \( s^i > \sum_{j \in A^i} a^j \) is not considered since resources are not scarce.

(ii) \( p^i \cdot a^j \leq w^j \quad \forall j \in A^i \)

**Definition 5.2.4.** Competitive equilibrium: At price \( p^i \) and allocation array \( \{a\} \), competitive market \( i \) is in equilibrium if and only if,

(i) \([p^i, \{a\}]\) is feasible

(ii) \( u^j(a^j) \geq u^j(\hat{a}^j) \) for all \( \hat{a}^j \leq b^j \) and \( p^i \cdot \hat{a}^j \leq w^j \), such that \( p^i \cdot a^j \geq p^i \cdot \hat{a}^j \) for all \( j \in A^i \)

**Lemma 5.2.1.** If \([p^i, \{a\}]\) is the allocation of competitive market \( i \) in equilibrium, then the following is true

\[
\frac{a^j}{w^j} = \frac{a^k}{w^k}, \quad \forall j, k \in N^i
\]  

(5.4)

**Proof.** Assume \([p^i, \{a\}]\) is the allocation of competitive market \( i \) in equilibrium, and \( j, k \in N^i \). From definition 5.2.2, the allocation of non-satiated consumers is,

\[
a^j = \frac{w^j}{p^i}, \quad a^k = \frac{w^k}{p^i}
\]  

(5.5)

From lemma 5.2.1,

\[
\frac{w^j}{p^i} = \frac{w^k}{p^i} \quad \Rightarrow \quad \frac{1}{p^i} = \frac{1}{p^i}
\]  

(5.6)

\(\square\)
Lemma 5.2.2. If \([p^i, \{a\}]\) is the allocation of competitive market \(i\) in equilibrium, then the following is true

\[
\max_{\forall j \in C^i} \left\{ \frac{a^j}{w^j} \right\} \leq \frac{a^k}{w^k}, \quad \forall k \in N^i
\]

(5.7)

Proof. Assume \([p^i, \{a\}]\) is the allocation of competitive market \(i\) in equilibrium. Denote \(a^j = \max_{\forall j \in C^i} \{a^j/w^j\}\) and \(k \in N^i\). Suppose contrary to lemma 5.2.2 that, \(\frac{a^j}{w^j} > 1/ p_i^i\).

Substituting for \(a^j\) and \(a^k\),

\[
\frac{b^j}{w^j} > \frac{u^j}{p_i^i} \quad \rightarrow \quad \frac{b^j}{w^j} > \frac{1}{p_i^i}
\]

(5.8)

From the definition 5.2.1,

\[
b^j \leq \frac{u^j}{p_i^i}
\]

(5.9)

Dividing both sides by \(w^j\)

\[
\frac{b^j}{w^j} \leq \frac{u^j}{w^j} \quad \rightarrow \quad \frac{b^j}{w^j} \leq \frac{1}{p_i^i}
\]

(5.10)

Combining equations 5.8 and 5.10,

\[
\frac{1}{p_i^i} < \frac{b^j}{w^j} \leq \frac{1}{p_i^i}
\]

(5.11)

which is not feasible.

\[\square\]

Definition 5.2.5. Pareto Optimality: The feasible allocation array \(\{a\}\) is said to be Pareto-optimal if there does not exist another feasible allocation array \(\{\tilde{a}\}\), such that \(u^j(\tilde{a}) \geq u^j(a)\) \(\forall j \in A\) with a strict inequality for at least one \(j\).

Theorem 5.2.3. The allocation of an economy consisting of independent competitive markets in equilibrium, \([\{p_i\}, \{a\}]\), is Pareto-optimal.

Proof. A proof that the allocation of an economy consisting of independent competitive markets in equilibrium is Pareto-optimal is given in [100]. This proof can be used for the
Suppose \( \{a\} \) is not Pareto-optimal. Then there exists \( \{\hat{a}\} \) where

(i) \( \{p_s\}, \{\hat{a}\}\) is feasible

(ii) \( u^j(\hat{a}^i) \geq u^j(a^i) \) for all \( j \in A \)

(iii) \( u^j(\hat{a}^i) > u^j(a^i) \) for at least one \( j \)

From definition 5.2.4 (ii) we have

\[
p_i^j \cdot \sum_{j \in A^i} \hat{a}^j > p_i^j \cdot \sum_{j \in A^i} a^j
\]

However, definition 5.2.3, condition (i) requires

\[
p_i^j \cdot \sum_{j \in A^i} a^j = p_i^j \cdot s^i
\]

Therefore we have

\[
p_i^j \cdot \sum_{j \in A^i} \hat{a}^j > p_i^j \cdot s^i
\]

which contradicts the feasibility of \( \{\hat{a}\} \).

**Definition 5.2.6.** Weighted max-min fair: An allocation of resources \( \{a\} \) with weights \( \{w\} \) is weighted max-min fair if it is feasible, and if, for any other feasible allocation \( \{\hat{a}\} \),

\[
\exists j : \hat{a}^j > a^j \implies \exists k : \frac{\hat{a}^k}{w^k} < \frac{a^k}{w^k} \leq \frac{a^j}{w^j}
\]

**Theorem 5.2.4.** The allocation of an economy consisting of independent competitive markets in equilibrium is weighted max-min fair, where the weight of each consumer is their wealth.
Proof. Assume \([\{p_i\}, \{a\}]\) is the allocation of an economy consisting of independent competitive markets in equilibrium. Let \(\{\hat{a}\}\) be any other feasible allocation, where \(\hat{a}^i = a^i + \delta^i \geq 0\) and \(\sum \delta^i = 0\). Only non-satiated consumers may increase their allocation, requiring other consumers(s) to decrease their allocation. Let two consumers \(j\) and \(k\) participate in market \(i\) \((i \in R^j, R^k)\). Assume consumer \(j\) is a non-satiated and gains resources under \(\{\hat{a}\}\) implying \(\delta^j > 0\). Denote consumer \(k\) as a consumer that loses resources under \(\{\hat{a}\}\) implying \(\delta^k < 0\). Consider two cases, (i) consumer \(k\) is satiated and, (ii) consumer \(k\) is non-satiated.

Case (i), consumer \(k \in C^i\).
Combining the assumptions above with lemma 5.2.2
\[
\hat{a}^i > a^i \quad \text{and} \quad \frac{\hat{a}^k}{w^k} < \frac{a^k}{w^k} \leq \frac{a^j}{w^j}
\] (5.16)
which satisfies the requirement for weighted max-min fairness.

Case (ii), consumer \(k \in N^i\).
Combining the assumptions above lemma 5.2.1
\[
\hat{a}^i > a^i \quad \text{and} \quad \frac{\hat{a}^k}{w^k} < \frac{a^k}{w^k} = \frac{a^j}{w^j}
\] (5.17)
which satisfies the requirement for weighted max-min fairness.

To provide perspective to the different types of fairness and optimality, consider all the possible weighted max-min fair allocations as a set. Each member of this set represents the allocation achieved with a certain wealth distribution. Given the conditions required for a weighted max-min allocation and the shape of the utility curve, each member of the set is Pareto-optimal (the conditions required for theorem 5.2.4 include those for theorem 5.2.3). A max-min fair allocation is a member of this set, where the wealth of each consumer is equal. In addition, an equitable allocation (defined in section 5.2.2) is also a member of this set, where the wealth distribution results in equal utility for each consumer.
An Alternative Weighted Max-Min Fair Proof

The fairness proofs introduced in this chapter are based on the competitive market model and are defined in a microeconomic context. However, since the economic model will be used for network resource allocation in chapters 6 and 7, the “network-oriented” fairness proofs described by [6, 45] can be used (with some modifications) to prove weighted max-min fairness. When using these proofs, users are consumers and links are markets.

In [6, 45] the following proposition is made; an allocation \{a\} is max-min fair if every user has a bottleneck link. This proposition depends on the definition of a bottleneck link, which has two parts [6]. First, if any user considers link \(i\) a bottleneck then the entire capacity of the link must be allocated \(\sum_{j \in A^i} a^j = s^i\). Second, if user \(j\) considers link \(i\) a bottleneck then \(a^j \geq a^k, \forall k \in A^i\). However, this proposition and definition does not apply to weighted max-min fairness, and does not permit users to have a maximum desired allocation \(\hat{b}^i\) (as done in the economic model). Therefore, changes must be made to apply the proposition to the economic model.

A modification to the bottleneck definition is required to apply the proposition to weighted max-min fairness [45]. Accounting for the weights (wealths) of each user, the second part of the bottleneck definition becomes; if user \(j\) considers link \(i\) a bottleneck then \(\frac{a^j}{w^j} \geq \frac{a^k}{w^k}, \forall k \in A^i\). The first part of the bottleneck definition remains the same. To account for the maximum desired allocation of each user \(\hat{b}^i\), it is suggested in [6] that a fictitious link be added to the end of the route of each user. Each fictitious link will have capacity equal to \(\hat{b}^i\), which forces each user to have a bottleneck link (a requirement for the proposition, but not for the microeconomic-based theorem 5.2.4).

Using the modified proposition and the addition of fictitious links, the economic model can be proven to achieve weighted max-min fair allocations. First, lemmas 5.2.1 and 5.2.2 are required to prove the allocation of a competitive market in equilibrium adheres to the bottleneck definition. Due to the fictitious links, every user will have a bottleneck link. For that reason, the proposition can be used to prove the allocation of an economy consisting of multiple competitive markets in equilibrium is weighted max-min fair.
5.2.2 Equitable Allocation

A Pareto-optimal resource allocation in microeconomics is called efficient, and many different efficient allocation exist for a competitive market in equilibrium (consider the different possible allocations of wealth) [76]. For this reason, a social welfare criterion, the equitable criterion, is used to compare and rank efficient allocations. In economics, the equitable criterion states that each user in the economy should enjoy approximately the same level of utility [76]. This definition must be extended to apply to an economy consisting of multiple independent competitive markets. For such an economy the equitable criterion states that users, who share a common saturated market, must enjoy approximately the same level of utility.

**Definition 5.2.7.** Equitable allocation: An allocation of resources \{a\} is equitable if it is feasible, and if, for any other feasible allocation \{\tilde{a}\},

\[ \exists j : u^j(\tilde{a}^j) > u^j(a^j) \implies \exists k : u^k(\tilde{a}^k) < u^k(a^k) \leq u^j(a^j) \]  \hspace{1cm} (5.18)

It is important to note this does not necessarily correspond to equal amounts of a resource (the goal of max-min). In a network economy, this can also been referred to as a “QoS-fair” or “utility-fair” allocation. An equitable allocation can be achieved by a competitive market in equilibrium when the wealth of each consumer is correctly assigned. This is described next.\footnote{A method for determining weights in a “Fair Queuing” wireless scheduler presented in [7] can be viewed as wealth distribution technique; however, the method would only apply to a single market not an economy consisting of multiple markets.}

Consumer \( j \) has utility function \( u^j(a^j) \) that indicates a utility value \( q^j \) for an allocation amount \( a^j \). The inverse of the utility function, denoted as \( \tilde{u}^j(q^j) \), indicates an allocation amount \( a^j \) that achieves a utility value of \( q^j \). Define the aggregate inverse utility function for all consumers who participate in and consider market \( i \) saturated as,

\[ \tilde{u}^i(\cdot) = \sum_{j \in A^i} \tilde{u}^j(\cdot) \]  \hspace{1cm} (5.19)

Since \( \tilde{u}^j(\cdot) \) is monotonic, \( \tilde{u}^i(\cdot) \) is monotonic and has a unique solution for any feasible utility value. At equilibrium the supply equals the demand; let \( q^i_0 \) be the utility value for
all consumers at which this occurs, i.e.,

$$s^i = \bar{u}^i(q^i_j) = \sum_{j \in A^i} \bar{u}^j(q^i_j)$$  \hspace{1cm} (5.20)

$q^i_j$ can be found quite easily, since $\bar{u}(\cdot)$ is monotonic. To provide each consumer the same utility level $q^i_j$ when the market is in equilibrium, the wealth of consumer $j$ is set as follows:

$$w^j = \bar{u}^j(q^i_j)$$  \hspace{1cm} (5.21)

The previous description determined the wealth distribution that achieves an equitable allocation for a single competitive market. Using this as a basis, algorithm 5.1 determines the wealth distribution that achieves an equitable allocation for an entire economy consisting of multiple independent markets.

Algorithm 5.1 requires the utility curve and route of each consumer in the economy. Acquiring such information reliably may not be possible; therefore, the algorithm may not be applicable to an actual network. The algorithm is presented for completeness of this section. Approximations of algorithm 5.1, that require far less information, are presented and used in section 6.4.1.

**Lemma 5.2.5.** If $\{w\}$ is the wealth allocation provided by algorithm 5.1 and $\{a\}$ is the allocation of competitive market $i$ in equilibrium, then the following is true,

$$\max_{v \in C^i} \{u^j(a^i)\} \leq u^k(a^k), \quad \forall k \in N^i$$  \hspace{1cm} (5.22)

**Proof.** Assume an economy consists of two independent competitive markets $L = \{h, i\}$ and two consumers $A = \{j, k\}$. Let consumer $j$ participate in markets $R^h = \{h, i\}$ and consumer $k$ participate in market $R^k = \{i\}$. Furthermore, assume on the first iteration of algorithm 5.1, market $h$ has the lowest utility $(q^h_j < q^h_i)$. User $j$ is assigned a wealth that will yield a utility of $q^h_j$ and is a member of sets $N^h$ and $C^i$. On the second iteration, market $i$ has the lowest utility. User $k$ is assigned a wealth that will yield utility of $q^h_j$ and remains a member of set $N^i$. Therefore, once the markets have reached equilibrium

$$q^h_j < q^h_i \rightarrow u^j(a^i) < u^k(a^k) \quad \text{where} \quad j \in C^i, \quad k \in N^i$$  \hspace{1cm} (5.23)
Algorithm 5.1 Wealth calculation algorithm for an equitable allocation.

1: //=**** variable initialization ****/
2: D ← L // set of markets */
3: for all i ∈ L do
4: C^i ← ∅
5: for all j : i ∈ R^j do
6: N^i = N^i ∪ j // assume all consumers of market i are non-satiated */
7: end for
8: end for
9: //=**** start wealth calculation algorithm ****/
10: while D ≠ ∅ do
11: q_{min} ← ∞
12: for all i : i ∈ D do
13: calculate q^i_{h} using consumers in N^i
14: // determine market with smallest q^i_{h} */
15: if q^i_{h} ≤ q_{min} then
16: q_{min} = q^i_{h}
17: h = i
18: end if
19: end for
20: // assign wealth to all consumers participating in */
21: // and who are non-satiated with market h */
22: for all j : h ∈ R^j and j ∈ N^h do
23: w^j = \tilde{\alpha}^j(q^i_{h})
24: // consumer is satiated w.r.t. remaining markets in R^j */
25: for all i : i ∈ R^j and i ≠ h do
26: C^i ← C^i ∪ j
27: N^i ← N^i \setminus j
28: end for
29: end for
30: D ← D \setminus h // market h has been processed, remove from set */
31: end while
Theorem 5.2.6. Allocating wealth using algorithm 5.1 yields an equitable allocation for an economy consisting of independent competitive markets in equilibrium.

Proof. Assume \([\{p_i\}, \{a\}]\) is the allocation of an economy consisting of independent competitive markets in equilibrium, where the wealth of consumers \([w]\) was determined from algorithm 5.1. Let \(\{\hat{a}\}\) be any other feasible allocation, where \(\hat{a}^j = a^j + \delta^j \geq 0\) and \(\sum \delta^j = 0\). Only non-satiated consumers may increase their allocation, requiring other consumers(s) to decrease their allocation. Let two consumers \(j\) and \(k\) participate in market \(i\) (\(i \in R^j, R^k\)). Assume consumer \(j\) is a non-satiated (considers market \(i\) saturated) and gains resources under \(\{\hat{a}\}\) implying, \(\delta^j > 0\) and \(u^i(\hat{a}^j) > u^i(a^j)\). Denote consumer \(k\) as a consumer that loses resources under \(\{\hat{a}\}\) implying, \(\delta^k < 0\) and \(u^k(\hat{a}^k) < u^k(a^k)\). Consider two cases, (i) consumer \(k\) is satiated and, (ii) consumer \(k\) is non-satiated.

Case (i), consumer \(k \in C^i\).

Combining the assumptions above with lemma 5.2.5

\[
  u^i(\hat{a}^j) > u^i(a^j) \quad \text{and} \quad u^k(\hat{a}^k) < u^k(a^k) \leq u^i(a^j) \tag{5.24}
\]

which satisfies the requirement for an equitable allocation.

Case (ii), consumer \(k \in N^i\).

As specified in algorithm 5.1, all non-satiated consumers of market \(i\) receive the same utility. Combining this with the assumptions above

\[
  u^i(\hat{a}^j) > u^i(a^j) \quad \text{and} \quad u^k(\hat{a}^k) < u^k(a^k) = u^i(a^j) \tag{5.25}
\]

which satisfies the requirement for an equitable allocation. \(\square\)
5.3 Example Competitive Market Allocations

In this section, examples of weighted max-min and equitable allocations are given for a simple economy consisting of two markets. For each example assume the economy is the network given in figure 5.1. This network consists of three users, two switches and two links, where each link has a total capacity of ten units. Users 0 and 1 use links 0 and 1 (in that order), while user 2 uses only link 1. Users are considered consumers in the economy and the switches are the producers. Switches sell link bandwidth to the users; therefore, switch 0 sells link 0 bandwidth and switch 1 sells link 1 bandwidth. Each link is considered an independent competitive market, which is the economic model described in section 5.2.

5.3.1 Weighted Max-Min Fair

Assume the users have the wealths and maximum demands given in table 5.1. Assuming the markets have reached equilibrium, the equilibrium price\(^6\) for link 0 bandwidth is \(\frac{3}{5}\) and the equilibrium price for link 1 bandwidth is \(\frac{2}{5}\). As defined in section 5.2.1, all users find that link 1 is their “saturated” market. At this link, user 2 can afford 3 units of bandwidth; however the maximum demand is 1 unit. For this reason, user 2 is considered “completely satisfied” according to definition 5.2.1. Users 0 and 1 can only afford 6 and 3 units respectively at link 1; therefore, these users are considered “non-satisfied” as defined by definition 5.2.2. The final allocations are given in table 5.1 and are weighted max-min fair as defined by 5.2.6.

\(^6\)How the equilibrium price is determined is given in chapter 6
<table>
<thead>
<tr>
<th>User</th>
<th>Wealth $w^j$</th>
<th>Demand $p^j$</th>
<th>Allocated $a^j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: Example weighted max-min fair allocation.

(a) Utility curves for users 0, 1 and 2.  
(b) Cumulative utility curve for link 1.

Figure 5.2: Utility curves for the equitable allocation example.

5.3.2 Equitable Allocations

As discussed in section 5.2.2, an equitable allocation measures fairness in terms of the utility obtained from the resources. To obtain an equitable allocation, the wealth of each user must be distributed according to algorithm 5.1. This algorithm requires the route and utility curve of each consumer (user) in the economy. As described in section 5.2.2, utility curves are assumed to be continuous and monotonic, as seen in figure 5.2. The horizontal axis of the utility curve measures utility (satisfaction) as a real number, while the horizontal axis measures the corresponding allocation amount. For example, users 0 and 1 require 6 units of bandwidth to receive the highest possible utility (5).

To determine the equitable allocation, the utility $q^j_i$ (equation 5.20) must be calculated for the two links (step 12 of algorithm 5.1). For link 0 $q^0_i$ is 4.2, and for link 1 $q^1_i$
<table>
<thead>
<tr>
<th>User</th>
<th>Demand $b_j$</th>
<th>Wealth $w_j$</th>
<th>Allocated $a_j$</th>
<th>Utility $u_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6</td>
<td>3.9167</td>
<td>3.9167</td>
<td>3.3333</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>3.9167</td>
<td>3.9167</td>
<td>3.3333</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2.1667</td>
<td>2.1667</td>
<td>3.3333</td>
</tr>
</tbody>
</table>

Table 5.2: Example equitable allocation.

is 3.3333. Therefore, link 1 is the saturated market and all users of this link will have a utility of 3.3333. The wealth of each user must result in a utility of 3.3333. As seen in figure 5.2(a), the wealth for users 0 and 1 should be 3.9167 (resulting in a QoS score of 3.3333). Similarly, the wealth for user 2 should be 2.1667. Note that the wealth distribution equals the final allocation for each user. This is expected since one unit of currency is exchanged for one unit of bandwidth.

5.4 Chapter Summary

In this chapter, the competitive market model was discussed. This model consists of two types of agents, consumers and producers. Consumers purchase resources to maximize utility (happiness), while producers sell or rent resource at the market price to maximize profits. When a price is determined that causes supply to equal demand; the market and price are in equilibrium. At equilibrium, consumers maximize utility given their budget constraints and producers maximize profits.

This chapter also discussed a model that consists of multiple independent competitive markets. When the markets are in equilibrium, it was proven that optimal and fair allocations are obtained. Possible fairness measures include, weighted max-min fair and equitable allocations. In addition, a method of wealth distribution is described that achieves an equitable allocation.

The competitive market model is used as the basis for the multi-user allocation methods described in chapters 6 and 7. This model provides a simple method for allocating network resources, that achieves efficient and fair allocations.
Chapter 6

A Spot Market Approach to Multi-User Allocation

As described in chapter 4, there are several advantages associated with microeconomic based, multi-user allocation. Many economic-based techniques offer a distributed allocation method, eliminating the need for a central controlling entity. Economic-based methods can also achieve optimal allocations (defined in section 5.2). These methods can scale to large networks and provide a framework for economic goals (such as, cost recovery and profit maximization). Furthermore, pricing network resources provides a disincentive to over-allocate resources. However, none of the microeconomic methods described in chapter 4 are able to handle network dynamics (changing user demands and users entering/exiting the network). When demands change, typically new prices must be calculated off-line. For this reason, these microeconomic-based methods are not suitable for VBR traffic sources.

In this chapter a multi-user allocation method based on the competitive market model is described. Referred to as a “spot market approach,” the economic model consists of multiple dynamic competitive markets [38] (spot markets) working asynchronously and independently. Users are considered consumers and purchase link bandwidth to maximize their QoS. Switches are producers and sell link bandwidth at the current market price. This allocation approach has all the advantages associated with other microeconomic-based methods; however, the spot market approach allows and encourages network dynamics to
Figure 6.1: Example network consisting of users, network brokers and switches.

occur. In addition, the spot market moves the allocation calculations to the edge of the network. This reduces the computation and storage overhead required at the switches.

A detailed description of the spot market approach is provided in this chapter, followed by discussions concerning network dynamics and optimality. Simulation results will indicate that the spot market approach is able to achieve optimal and equitable allocations under network dynamics, performing better than other bandwidth allocation methods.

6.1 Spot Market Economy

This proposed network allocation method is based on a modified competitive market model (dynamic competitive market [38] or spot market), where pricing is done to promote high utilization of resources and Pareto-optimal allocations. The spot market has the unique ability to adjust to changing resource demands and provides users with immediate availability of resources.

As seen in figure 6.1, the network economy consists of three entities: users (those who execute network applications), Network Brokers (NB) and switches. Using the competitive market nomenclature, users are consumers, switches are producers and network brokers are used to assist the exchange of resources in the market. As mentioned in the introduction, there are many different types of network resources desired by users. This chapter will only consider link bandwidth; however, the techniques presented can be applied to other network resources.
6.1.1 Switch

In the economy, the switch owns the link bandwidth that is sought by consumers. The network consists of several switches interconnected with links. For a unidirectional link between two switches, consider the sending switch as owner of the bandwidth of that link. Each switch prices its link bandwidth based on local supply and demand for that link. Therefore a single switch, having multiple output links, will have one price associated with each output port. Bandwidth available in the spot markets is considered a non-storable resource (similar to residential electricity) and is available for immediate use (no reservation overhead required). The entire network can be viewed as multiple spot (dynamic competitive) markets, one market per link (similar to the New York Stock Exchange). These spot markets operate independently and asynchronously since there is no need for market communication (for example, price comparisons) or synchronization from switch to switch. Consequently, this results in a decentralized economy, where the physical failure of one switch/link does not necessarily cause failure of the entire economy.

The price computation for link $i$ is performed at the switch, at discrete intervals of time. Denote the $n$th calculation instant as $t_n^i$ and the interval of time between the calculation points $t_n^i$ and $t_{n+1}^i$ as the $n$th price interval, $P_n^i$. The price during $P_n^i$ is constant and is denoted as $p_n^i$. The demand for bandwidth at link $i$ is measured as the total (aggregate) traffic received at its associated output port. During the $n$th price interval, $P_n^i$, the total demand is expected to change; even so, the calculation of $p_{n+1}^i$ will only use the demand measured at the end of the interval. For this reason, let the demand for bandwidth at link $i$, at the end of the $n$th price interval, be denoted as $d_n^i$. The supply of bandwidth at link $i$ is constant and denoted as $s^i$.

At the end of the price interval, $P_n^i$, the switch updates the price of link $i$ using a modified tâtonnement process. A tâtonnement process sets the price of a resource with respect to the excess demand [103]. A limitation of the tâtonnement process, in its original form, is the inability to dynamically adapt to changing network demands. Yet these dynamics, such as changing number of users and non-stationary multimedia traffic, are prevalent in current integrated service networks. To handle such dynamics, a modified tâtonnement
process [36] is used to price network resources,

\[
p_{n+1}^i = p_n^i - \frac{d_n^i}{\alpha \cdot s^i}
\]

where \( p_{n+1}^i \) is the new bandwidth price, \( p_n^i \) is the current price and \( d_n^i \) is the aggregate demand for bandwidth. The modified tâtonnement process adjusts the price at regular intervals, based on the demand (received traffic) and the supply. The bandwidth supply is the total bandwidth times a constant \( \alpha \), where \( 0 < \alpha \leq 1 \). This modification causes the price to increase after some percentage (\( \alpha \)) of the total bandwidth has been sold. This is evident from the equation, since the price will only increase if the numerator is greater than the denominator (\( d_n^i > \alpha \cdot s^i \)). When demand changes, the modified tâtonnement process can dynamically adjust the price towards the new equilibrium. An equilibrium price \( p_n^i \) is reached at link \( i \) when the supply equals the demand. The resulting allocation at equilibrium is Pareto-optimal and fair (chapter 5 defines fairness). This dynamic bandwidth market is also state-less since the price is calculated using only the aggregate demand, supply and current price.

After the new price, \( p_{n+1}^i \), is calculated it is delivered to each NB using this link. A simple technique for distributing new prices is discussed in section 6.4.2, other price distribution methods are described in [38, 39]. As previously stated, the unique advantages of the dynamic competitive market include: ability to adjust to network dynamics, state-less implementation, distributed control of individual QoS, no restrictions on the statistical behavior of the users and profit maximization during “congested periods.”

6.1.2 User

User \( j \), executing a network application, requires bandwidth for transmission. The amount of bandwidth desired is determined from the application and is denoted as \( b^j \). Assume \( b^j \) is constant for the duration of the application. In section 6.3, \( b^j \) is allowed to vary over time, which is desirable for multimedia transmission.

Based on prices and wealth, the user can afford a range of bandwidth (less than or equal to \( b^j \)), and some amounts will be preferred over others. In economics these preferences are represented with a utility function (curve), which provides an important link between
resource amounts and user satisfaction. For this economy QoS profiles [85] are used as the utility curves. Based on psycho-visual experiments, the QoS profile is a two dimensional graph, as seen in figure 6.2. The profile can be approximated by a piece-wise linear curve with three different slopes. The slope of each linear segment represents the rate at which the performance of the application degrades when the network allocates a percentage of the desired bandwidth, $b^j$. A steeper slope indicates the inability of the application to easily scale bandwidth (for example, high quality video), while a flatter slope signifies the application can more readily scale bandwidth requirements (for example, teleconferencing or data transmission). The horizontal axis measures the bandwidth ratio of allocated bandwidth to desired bandwidth, $b^j$. The vertical axis measures the satisfaction and is referred to as a QoS score. For this these, QoS scores range from one to five, with five representing an excellent perceived quality and one representing very poor quality. Any value greater than or equal to 3 will be referred to as an acceptable QoS score. As seen in the figure, if the allocated bandwidth is equal to the desired bandwidth, the ratio is one and the corresponding QoS score is 5 (excellent quality). As this ratio becomes smaller the QoS score reduces as well. Profiles can be created for a variety of applications and redefined as users gain more experience. New and updated profiles can be easily incorporated within the economy as they become available. More information about QoS profiles and the relationship between bit-rate and quality can be found in [66, 74, 85].

Finally, user $j$ is charged continuously for the duration of the session (analogous to a meter). Assume user $j$ will provide an equal amount of money over regular periods of time to pay for expenses. The budget rate of user $j$ will be denoted as $W^j$ ($$/sec$). A single initial endowment could have been used, but would necessitate defining how it is spent during the session. To simplify simulation and analysis, budget rates are used.

### 6.1.3 Network Broker

A user can only enter the network economy through a network broker (NB). The NB serves as an agent for the user and is located between the user and the edge of the network. The functions of the NB can be part of the protocol stack that executes on a host system, just as current protocol stacks provide flow control to individual users. Representing
the user in the economy the NB performs the following tasks: connection admission control, policing, and purchase decisions. Although the NB works as an agent for the user (making purchasing decisions), assume the NB operates honestly in regards to the switches and the user.

The NB controls network admission by initially requiring the user to have enough wealth to afford at least an acceptable QoS; otherwise, the user is denied access. The purpose of this requirement is to be certain all users are viable consumers in the market, which also prevents overloading the economy. In this thesis, it is assumed the social welfare of the economy is better when it consists of fewer users each receiving a good QoS, instead of many users each receiving a poor QoS. Hence, the goal is to maximize the number of users in the economy, where each user can afford an acceptable QoS. If the desired bandwidth is constant, then the test is relatively simple. However, for sources where the desired bandwidth will change over time, a more complex admission test is required.

The NB monitors the user and the prices by gathering and storing information about each. From the user, the NB collects and stores; the QoS profile, $b^j$ and $W^j$. The NB also stores the route, $R^j$, that connects source to the destination. For each link in $R^j$, the current price $p^j$ is collected. Prices will change over time, since they represent link supply

$^1$The requirement that the NB must know the entire route, and store a distinct price per link, can be relaxed. Methods for price distribution and collection are discussed in section 6.4.2.
and demand. For this reason, the NB will only store the most recent price from each link in the route. The NB will divide $W^j$ into separate budget rates, one for each link in the route. Denote $w^{j,i}$ as the budget rate of user $j$ for link $i \in R^j$. As discussed in section 5.2.1, assume for user $j$ all $w^{j,i}$ are equal ($w^{j,h} = w^{j,i} \forall h, i \in R^j$). For this reason, the second superscript of $w^{j,i}$ ($i$, indicating the link) will be dropped for brevity. Separate budgets are used to localize the effect of prices to each link. This prevents spending the entire budget on one expensive link. Of course depositing and withdrawing to and from these individual budgets is possible and perhaps advantageous. Using this information the NB levies the user for their consumption. Users will be charged based on usage (similar to electricity), since bandwidth is a non-storable resource. Using this information the NB polices the user, ensuring only the bandwidth purchased is used.

Finally, the NB determines the amount of dynamic bandwidth to use. This value is based on the budget, current prices and QoS profile of the user. Denote the amount of dynamic bandwidth to purchase (use) as, $y^j$. Once the NB determines $y^j$, the user will start sending at this rate immediately. There is no need for direct confirmation/feedback from the switches. A new amount of bandwidth to purchase will be determined in response to a new price (or change in demand, as will be described in section 6.3) using the following equation,

$$y^j = \min \left\{ \min_{i \in R^j} \left\{ \frac{w^j}{p^i} \right\}, b^j \right\}$$  \hspace{1cm} (6.2)

As defined by the equation, the NB uses no more bandwidth than the minimum which is affordable on any link in $R^j$. It is possible that $y^j$ will be less than what is acceptable (determined from the QoS profile), due to the QoS constraint, prices and budgets. If this case arises, the user must either; increase the budget rate, accept a lower QoS, or drop the connection. This is a motivation for the second bandwidth market described in chapter 7.

As described earlier, once the NB has determined $y^j$ it will start sending immediately at this rate. No signaling is performed. This technique provides a significant reduction in overhead; however an over allocation of resources may occur. Consider the following scenario. Assume many users are using one link and the price has reached an equilibrium value. Now assume one user exits the network and this reduction of bandwidth results in
a lower price. If the remaining users react to this lower price, over-allocation of bandwidth may occur. An over-allocation may still occur if many users using a link start sending at a higher rate simultaneously due to their application (not price); however this would require a correlation of these events. In general, adjusting the price based on $\alpha \cdot s^t$ and the high capacity of most links diminish the significance of this problem.

6.2 Price Stability

In section 5.2 it was proven that an economy consisting of multiple competitive markets can yield a Pareto-optimal, weighted max-min fair and equitable allocations; however, this occurs only when the market is in equilibrium (supply equals demand). For this reason, the tâtonnement process, equation 6.1, must be proven to reach the equilibrium price $p_\ast$. In this section assume the aggregate demand, $d_n^k$, is constant (as done in [33]). This assumption is removed in section 6.3, where the effects of network dynamics (users entering/exiting and variable user demand) are properly addressed.

The equilibrium price $(p_\ast)$ occurs when a price is reached such that the demand equals the supply. At this point, the resources are fully utilized. If the demand changes, the pricing mechanism should alter the price to return to equilibrium. For that reason, adjustments in the price are driven by knowledge from the market concerning the excess demand at a specific price. Denote the demand for bandwidth at price $p$ as $d(p)$. For a link in the network, the change in price over time is,

$$
\frac{dp}{dt} = p \cdot \left( \frac{d(p)}{\alpha \cdot s^t} - 1 \right) = p \cdot x(p)
$$

(6.3)

where $x(p)$ is the excess demand at price $p$. Example supply, demand and excess demand curves for the system are given in figure 6.3. As seen in figure 6.3(a), the demand curve has a negative slope which represents that an increase in price will reduce demand. The supply curve is a vertical line, because the supply of bandwidth is constant (the link does not produce bandwidth). From the supply and demand curves the excess demand curve can be derived. Using these graphs the behavior of the price rule 6.1 can be predicted.
Define stability as,

\[
\lim_{t \to \infty} p_t \to p_s
\]

The price rule will increase the price \( p \) when it is lower than equilibrium price \( p_s \). This is done because the excess demand is greater than one. When \( p \) is greater than \( p_s \), it is lowered towards \( p_s \) because the excess demand is less than one. Therefore the price rule always moves the price towards \( p_s \), resulting in price stability. It should be noted that the slope of the supply curve must be positive for this to be true.

The stability of the price rule can be proven mathematically as well [15]. Using the excess demand equation, the price adjustment of equation 6.1 over time can be written as,

\[
\frac{dp}{dt} = p \cdot x(p) = y(p)
\]

Viewing the price adjustment as a differential equation, the local response can be analyzed in the region of an equilibrium price using the Taylor approximation,

\[
\frac{dp}{dt} = y(p_s) + y'(p_s) \cdot (p - p_s) \\
\frac{dp}{dt} = y'(p_s) \cdot (p - p_s)
\]

The general solution to this equation is,

\[
p = (p_0 - p_s) e^{y'(p_s) \cdot t} + p_s
\]
where \( p_0 \) is the initial price. As seen from the solution, \( p \) approaches \( p_+ \) as time increases. However, it must be the case that \( y'(p_+) \) is negative, which is illustrated in figure 6.3(c). To provide some insight into the speed of convergence (number of iterations required by the equation), 30000 independent simulations were performed. Each consisted of a competitive market (output link) with 10, 30 or 50 users. For each simulation user \( j \) was assigned a random demand \( b^j \) and a random wealth \( w^j \). The initial bandwidth price was 1 for each simulation. At every price iteration, the relative difference from the equilibrium price was recorded. As seen in figure 6.4, the relative difference was 0.26 after one iteration, 0.02 after two iterations and 0.002 after three iterations.

### 6.3 Network Dynamics and Optimality

Thus far, the analysis of the network economy has not considered the dynamic nature of an actual computer network. The dynamics we are interested in include; users entering/leaving the network, and allowing Variable Bit Rate (VBR) sources. Although prevalent in actual networks, these dynamics have been either or both excluded in other microeconomic flow control methods. If the number of users and/or the demands for bandwidth change over time, then the aggregate demand, \( d_n \), for a link will vary as well. As
a result, there is not a single equilibrium price, \( p_s \), for all time. However, the market can be viewed as having multiple equilibrium prices, each for some segment of time. During a segment the pricing technique will seek the equilibrium price as described in section 6.2. Once this price is found, the resulting distribution is Pareto-optimal and fair. When the aggregate demand changes, the stability of the price equation ensures that the price always moves towards \( p_s \).

Due to the complexity of the changing source demands, simulations are used to demonstrate the performance of the spot market approach under network dynamics. Experimental results have shown the spot market approach achieves optimal allocations over 90% of the time under realistic network conditions [36]. Additional experimental data is presented in the next section, including a comparison with other bandwidth allocation methods.

### 6.4 Spot Market Experimental Results

In this section the performance of the spot market approach is investigated under network dynamics (changing user demands and users entering/exiting the network). Two sets of experiments were performed. The first set of experiments defines and tests an approximation to the wealth distribution method given in algorithm 5.1. The second set of experiments compares the performance of the spot market approach with other bandwidth allocation methods.

As described in the introduction, multimedia applications are expected to play a more prevalent role in computer networks, but are difficult to manage due to their unpredictable nature. To provide a realistic environment, each experiment simulated two different types of multimedia applications: Multimedia on Demand (MoD) and teleconferencing. MoD applications require the transmission of high quality voice and video. These applications can scale bandwidth requirements only within a limited range, since bandwidth control is achieved through quantizer control [85]. The QoS profile associated with MoD applications is given in figure 6.5(a). As seen in the profile, the acceptable bandwidth ratio range (resulting in a QoS score greater than or equal to 3) is relatively small, 0.85 to 1.0.
Teleconferencing applications, in contrast, transmit a lower quality voice and video and can scale bandwidth requirements within a larger range. This is primarily due to quantizer control as well as the ability to transmit below the standard 24 or 30 frames-per-second. The QoS profile associated with teleconferencing applications is given in figure 6.5(b); the acceptable bandwidth ratio range is 0.4 to 1.0. Regardless of the application type, each user transmitted one of 15 MPEG-compressed video traces (described in section 3.3.2). The goal for each experiment is to achieve and equitable allocation for these two different applications.

6.4.1 Wealth Distribution Approximation

The wealth distribution algorithm for an equitable allocation (algorithm 5.1) requires complete knowledge of the users and network configuration. The availability and reliability of such information is limited in an actual network environment; therefore, a simpler approximation is needed. In this section, an approximation of the wealth distribution algorithm is presented. The performance of the approximation is compared against other wealth distributions to measure its effectiveness.

The approximation of the wealth distribution algorithm assigns wealth based on
the bandwidth-ratio required to achieve a QoS score of 3 for each type of application in the network [36, 38]. The ratio of these bandwidth-ratios are then used to distribute wealth for an equitable allocation. For example using the QoS profiles given in figure 6.5, a MoD user requires a bandwidth ratio of 0.85 to receive a QoS score of 3, while a teleconferencing user requires a ratio of 0.4. This yields a ratio of

\[
\frac{0.85}{0.4} \approx 2
\]

Assuming MoD applications have a budget rate\(^2\) (wealth) of \(3 \times 10^8/\text{sec}\), then teleconferencing users would have a budget rate of \(1.5 \times 10^8/\text{sec}\).

To measure the effectiveness of this approximation, a simulation of a single 55 Mbps link with 38 users was performed. Half of the users were considered MoD applications. The remaining users were considered teleconferencing. As previously described, each user transmitted one of 15 MPEG-compressed video traces (described in section 3.3.2). As defined in section 5.2.2, an equitable allocation is one in which all users achieve the same utility. In this experiment, the difference in the QoS observed by each type of application was recorded as the budget-ratio ranged from 0.5 to 2.5 (MoD/teleconferencing). The QoS differences are given in figure 6.6. As seen in this figure, the approximation method (budget-ratio of 2) yields a QoS difference of 0.4, which is slightly higher than the lowest

\(^2\)The denomination is based on bps; if based on Mbps, the budget would be 300/sec.
QoS difference possible (0.18). Note that a zero QoS difference is not possible, since the budget rate is constant and the source demands are variable. The approximation method is less complex than the original wealth distribution algorithm; however, it does result in an allocation slightly less equitable than possible. Considering the reduction in information required, the approximation method provides acceptable results. This is also demonstrated in the next experiment.

6.4.2 Spot Market Comparison

In this section the performance of the spot market approach is evaluated and compared with two other allocation methods: Lakshman, et al. demand-based weighted max-min [62] and a centralized max-min method. Results will show that the spot market approach achieves high network utilization and equitable (QoS-fair) allocations, as well as better QoS control than the other methods.

Comparison Configuration

Similar to [23, 62], a rate based simulator was used that propagated rate changes through the network. This resulted reduced simulation times, considering the number of users, traffic type and network modeled. The network simulated consisted of 152 users, four switches and seven 55 Mbps links, as seen in figure 6.7. The network can be described as
a “parking lot” configuration, where multiple sources use a primary path. This configuration was agreed upon by members of the ATM Forum [58] as a suitable benchmark for allocation methods; it models substantial competition between users with differing routes and widely-varying propagation delays.

Half of the users (even numbered) were considered MoD, while the remaining users were teleconferencing. The application types, QoS profiles and MPEG source traces are discussed in section 6.4. Users entered the network at random times uniformly distributed between 0 and 120 seconds.

Centralized Max-Min Allocation

A comparison with max-min is provided since it is a fairness goal sought by many bandwidth allocation methods [3]. When contention occurs for link bandwidth, max-min provides each user (of the congested link) with an equal share. However, allocating equal amounts of bandwidth may not be best when considering the individual QoS expected by each user [38, 62]. The max-min implementation was centralized and no communication overhead was included for distribution allocation information. For this reason, the max-min results presented should be considered better than what is possible in practice.

Demand-Based Weighted Max-Min

In [62], Lakshman, et al. proposed an ABR explicit rate control method for transmitting compressed video. ABR explicit rate control relies on network feedback provided by Resource Management (RM) cells that are circulated for each connection [3]. The RM-cell consists of several fields, one of which is the Expected Rate (ER). This field indicates the maximum rate the network can support for this user. As the RM-cell travels along the path, a switch and/or destination may alter its contents. When a switch determines the ER of a user, it attempts to allocate the ABR bandwidth in a fair manner. The rate control method proposed by Lakshman, et al. provides a form of weighted max-min fairness. Weights are equal to the desired bandwidth of each application; therefore this method will be referred to as “demand-based weighted max-min.” This method requires frame prediction to allocate bandwidth before it is required; however a look-ahead buffer was used instead. For this rea-
son, the performance of this method should be considered best possible\textsuperscript{3}. In addition, this method is state-maintaining since it requires per connection information to determine the allocation amount (ER). Once the cell reaches the destination it is returned to the source, which must alter transmission based on the RM-cell information.

**Spot Market Approach**

The spot market approach was implemented as described in section 6.1. As mentioned in section 6.1.1, there are many different methods for distributing prices. For example, the switch could send prices to users of the link, as done in [38]. Alternatively, a user could periodically generate packets (Route Price packets or RP-packets) to collect prices along the route. The purpose and function of the RP-packet is very similar to the ABR RM-cell. The RP-packet would circulate between the source and destination storing prices along the route. Switches along the route insert the current link price (on the return path). When the RP-packet returns to the source it contains an array of prices \( \{p_j^i\}, \forall j \in \mathbb{R}^i \); therefore, the size of the RP-packet will depend on the number of links in the route. An alternative approach would use the RP-packet to store the highest link price in the route. A switch would insert the link price only if it is higher than what is currently stored. The returned RP-cell contains “route price” for the user [39]. The single “route price” approach is used for this simulation comparison.

The following initial values were used for the spot market approach. MoD users had a budget rate, \( w \), of \( 3 \times 10^8 / \text{sec} \), while teleconferencing users had a budget rate of \( 1.5 \times 10^8 / \text{sec} \). The budget rates were determined using the approximation method presented in section 6.4.1. Switches initialized their prices to 50 and \( \alpha \) (the target utilization) to 95\%. Switches updated their link prices at 10 msec intervals, a compromise between the desire for responsiveness, and the need for stability.

**Comparison Results**

For comparisons, the link bandwidth utilization and the QoS provided to each user were recorded. Allocation graphs are provided to measure the utilization of link bandwidth.

\textsuperscript{3}A correction was made to the algorithm presented in [62] and was confirmed by the author.
To measure the QoS observed, average QoS graphs, percent Good or Better (GoB) measurements and average QoS scores are provided. Average QoS graphs measure the average QoS score observed over time and are based on all users or on individual type. The percent Good or Better (GoB) measurement is the average percentage of time a user had a quality score of at least 3.

Results from the simulation are given in figure 6.8 and in table 6.1. As seen in figure 6.8(a), the allocation provided by the spot market approach for link 0 indicates the total allocation stayed in the vicinity of 95% (α, the target utilization), yet never crossed 100%. Therefore, pricing was able to properly manage bandwidth demand (allocation results for the other links are very similar). For all users, the max-min and demand-based weighted max-min methods yielded lower average QoS and percent GoB values. This indicates, on average, users experienced lower QoS scores and enjoyed an acceptable QoS for shorter durations than the pricing method. More importantly, the pricing method provided both application types similar QoS scores and percent GoB values. This represents a more equitable (QoS-fair) allocation by the price method than max-min or demand-based weighted max-min. This is due to the inability of max-min or demand-based weighted max-min to differentiate between different classes of users. When equitable allocations are desired, allocation decisions must consider the fact that a reduction in bandwidth reduces the QoS for MoD users more quickly than teleconferencing users (as defined by their profiles). This was accomplished by the spot market approach via wealth distribution. The spot market approach is also state-less and requires less overhead than the other methods.

6.5 Chapter Summary

This chapter introduced a distributed, multi-user allocation method based on microeconomics. A computer network was viewed as multiple dynamic competitive (spot) markets consisting of three entities; users (those who execute network applications), Network Brokers (NB) and switches. Using competitive market nomenclature, users were consumers, switches were producers and network brokers were used to assist in the exchange of network resources. Link bandwidth was the resource exchanged in these markets, and is
Figure 6.8: Allocation and average QoS graphs for the spot market comparison.

<table>
<thead>
<tr>
<th></th>
<th>%GoB</th>
<th>Average QoS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>MoD</td>
</tr>
<tr>
<td>Spot market</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Demand-based WMM</td>
<td>72</td>
<td>54</td>
</tr>
<tr>
<td>Max-min</td>
<td>80</td>
<td>66</td>
</tr>
</tbody>
</table>

Table 6.1: Percent GoB and average QoS scores for the spot market comparison.
considered a non-storable resource (similar to residential electricity). Each switch owns the bandwidth of any output link connected to it and prices bandwidth based on local supply and demand. Pricing is done locally and asynchronously using a modified tâtonnement process. The modified tâtonnement process allows user demands to change over time, which is unique to the spot market approach. The user, executing a network application, requires link bandwidth for transmission and is represented in the economy with a NB. The NB, located at the edge of the network, collects prices and determines usage levels that maximize the user's utilization. Since these calculations occur at the NB, this greatly reduces the computation and storage overhead of the switches. Once a new amount is determined, it is immediately used (no signaling or reservations are required). These are unique features of the spot market approach. This spot market economy also encourages high utilization, with Pareto-optimal and equitable (QoS-fair) allocations.

An approximation of the wealth distribution algorithm (for equitable allocations, defined in section 5.2) was also defined in this chapter. The approximation greatly reduces the amount of information required to distribute wealth, that will result in an equitable allocation. Simulations demonstrate that the approximation yields comparable allocations to the original algorithm, with less source information. Simulation results also demonstrate the ability of the spot market to successfully allocate bandwidth of a network to a large number of diverse users, each transmitting an actual MPEG-compressed video trace. The economy also provided substantially better control of QoS than max-min or demand-based weighted max-min [62]. The allocation calculations are performed at the edge of the network. This reduces the computation and storage overhead of switches. The implementation cost of the spot market method will be very reasonable, since it is a state-less technique.

One disadvantage of the spot market approach is the absence of resource guarantees. It is possible that a user may enter the network during a period of time when prices are low, then at a later time find prices have increased dramatically. These unpredictable price changes can cause the QoS of the user to suffer or even force the user to exit the network prematurely. For this reason, a method is needed to provide guarantees of resource availability (price stability). The multi-market approach addresses this issue and is described in the next chapter.
Chapter 7

A Multi-Market Approach to Multi-User Allocation

A primary limitation of the spot market approach (described in chapter 6) for multi-user allocation is the inability to provide resource guarantees. It is possible that a user may enter the network during a period when the prices are low, only to find at a later time prices have increased significantly. These unpredictable price changes can cause the QoS of the user to suffer or even force the user to exit the network prematurely. In either case, the economy should provide some protection from these possible market changes, which is the primary goal of the multi-market approach.

In this chapter, a multi-market approach to multi-user resource allocation is presented. Two types of markets exist in the economy, the spot market and the reservation market. The spot market has the advantage of immediate availability of link bandwidth; however, this market has the disadvantage of possible price fluctuations. In contrast, the reservation market has the advantage of resource guarantees (price stability), but incurs the overhead associated with traditional reservation methods. The multi-market approach provides users the unique ability to invest in either market type. In addition, users can dynamically switch from one market to another based on network (economic) conditions, which is a unique feature of this multi-market approach. Simulation results will demonstrate the benefits and risks associated with purchasing bandwidth from the various markets.
7.1 A Multi-Market Economy

This proposed distributed resource allocation method uses two types of independent markets to buy and sell link bandwidth: the reservation market and the spot market. Each market type is based on the competitive market model (described in chapter 5), where pricing is done to promote high utilization as well as Pareto-optimal and fair distributions [15]. As with the spot market approach, there are three entities in this multi-market network economy: users, Network Brokers and switches.

7.1.1 Switch

The network consists of several switches interconnected with links. For a unidirectional link between two switches, consider the sending switch as owner of the bandwidth of that link. For link \( i \) denote the total capacity of link bandwidth as \( s^i \). The capacity is then divided into two types, reserved and spot bandwidth. Reserved bandwidth is sold as an amount for a duration of time, while spot bandwidth is sold as a non-storable resource. With this distinction, reserved and spot bandwidth are considered separate resources. Reserved bandwidth has the unique advantage of ownership over a period of time, while the advantage of spot bandwidth is its immediate availability. Each resource is sold in its own local (link) market, therefore the switch will associate two markets per output port (thus the “multi-market” designation). As with the spot market approach, these markets operate independently and asynchronously since there is no need for market communication (for example, price comparisons) or synchronization from switch to switch. Since the link capacity is divided into reserved and spot bandwidth, the switch must differentiate the traffic using either type. Assume that a bit will be set in the header of the packet, indicating the packet is using reserved bandwidth.

Reserved Bandwidth Market

Link \( i \) will sell a maximum percentage \( \beta^i \) of \( s^i \) as reserved bandwidth. The reserved bandwidth is divided into equal non-overlapping intervals of time called segments, where the length of each segment is denoted as \( T^i \). Portions of the segment are then sold to users
with an auction procedure. Users are only able to bid for an amount of the next segment; therefore, the reserved bandwidth of segment \( l \) is auctioned during segment \((l - 1)\). At the beginning of the auction for segment \( l \) of link \( i \), users forward bids to the switch for an amount of reserved bandwidth. The sum of these bids, denoted as \( h_{m}^{i,l} \), is recorded by the switch and is used to update the price. During the auction, the price of reserved bandwidth for segment \( l \) is adjusted at regular intervals \( G^{i} \), as seen in figure 7.1. The price for reserved bandwidth of link \( i \), segment \( l \) is denoted as \( g_{m}^{i,l} \) and is adjusted using the following tâtonnement process,

\[
g_{m+1}^{i,l} = g_{m}^{i,l} \cdot \frac{h_{m}^{i,l}}{\beta^{i} \cdot s^{i}}
\]  

Figure 7.1: Example segments and price calculation points for link \( i \) reserved bandwidth.

After a new auction price is calculated, it is distributed to NB’s, who may submit updated bids. It is important to note the switch does not need to store individual bids. Users can initially submit a bid amount, then send only changes (differences) to the switch. New bidders (users who have not yet participated in bidding for the segment) are not allowed to participate after \( T^{i} \cdot \gamma \) has passed. This provides time for the auction to converge to the equilibrium price before the segment begins (convergence time is addressed in section 6.2). This process repeats until the end of segment \((l - 1)\), after which the switch notifies the users that a new segment has begun. Users are then able to use the amount of reserved bandwidth they defined in their last bid (explicit notification is not necessary). Since only aggregate information (not individual) is used and it is not necessary for the switch to store individual bids, the auction process for the reservation market can be considered a state-less implementation.
There are two important parameters associated with the reservation market; the supply of reserved bandwidth ($\beta^i \cdot s^i$) and the segment length ($T^i$). The percentage of capacity for the reservation market can be based upon various goals, such as maximizing utilization, QoS, or profits. Furthermore, $\beta^i$ can be statically or dynamically set. For example, the switch could adjust $\beta^i$ to maximize total revenue of that link by measuring the demand and the prices for each market. Similarly, segment length can be set to achieve several goals. Longer segment lengths provide more price stability, however this lengthens the time between auctions (and consequently the wait time to use reserved bandwidth for the next segment). Shorter segment lengths reduce the wait time, but reduce the stability of the reservation market as well. An alternative approach would partition the reserved bandwidth of a switch into smaller divisions, where each division would represent a reservation sub-market. These sub-markets could have various segment lengths and different auction start-times. This would offer users more choices of reserved bandwidth (different reservation times) and reduce the waiting time for the next segment. The effect of segment length on QoS is discussed further in section 7.3.2.

**Bandwidth Spot Market**

The bandwidth spot market operates as described in chapter 6. Denote the amount of reserved bandwidth currently used as $u^i$. The supply of spot bandwidth for link $i$ is $s^i - u^i$; therefore any reserved bandwidth that is not used can be sold in the spot market. As done in section 6.1, the spot market price is determined at regular intervals using the modified tâtonnement process,

$$p_{n+1}^i = p_n^i \cdot \frac{d_n^i}{\alpha^i \cdot s^i - u_n^i}$$  \hspace{1cm} (7.2)

Once a new bandwidth spot price is determined, it is forwarded to users of this link. Users are also required to maintain a smooth transmission at their allowed rates (also required by [73]). Upon receiving a new price, users determine their allowable transmission rate.
Similarities of the Multi-Market and SENET

The goal of the multi-market economy is to provide guarantees and immediate availability of bandwidth in one resource allocation method. An earlier, non-economic based, bandwidth allocation method that sought a similar goal was the Slotted Envelope Network (SENET) [6, 26]. SENET is an integration of circuit and packet switching that transmits data in frames. Each frame consists of two compartments. The first compartment contains circuit switched traffic while the second compartment contains packet switched traffic. The boundary between the two compartments can be fixed or movable, depending on the implementation.

A circuit switched connection is assigned a slot in the first compartment large enough to handle the desired bit rate. Each circuit switched connection can hold its assigned slot for the duration of the session, which provides guaranteed service. The size of the first compartment is bounded by a value less than the frame size; therefore, some space is available for packet switched traffic. An arriving circuit switched session is blocked if the residual capacity of the first compartment cannot accommodate the requested bit rate. The second compartment is used for transmission of packets waiting in a queue. In the movable boundary version, packet switched traffic can occupy the second compartment bandwidth plus any unused circuit switched capacity. This provides high bandwidth utilization [64].

From this description, there are some similarities between the multi-market approach and SENET. The reserved bandwidth market is similar to the first compartment of SENET. Both provide a guarantee of bandwidth; however, the reserved market provides the guarantee only for the duration of the segment. This ensures users will eventually conform to market changes, preventing them from holding bandwidth indefinitely. The second compartment of SENET is similar to the spot market. No guarantees are provided for packet switched traffic in SENET or in the spot market, but high utilization of bandwidth is achieved in both methods. An advantage of the multi-market approach is the flexibility users have to move from one market type to the other based on QoS and/or prices. In addition, pricing in the multi-market approach (as well as other microeconomic-based methods) creates a disincentive for overallocating bandwidth.
7.1.2 User

User $j$, executing a network application, requires link bandwidth for transmission. The amount of bandwidth desired is determined from the application and is denoted as $b^j$. Based on prices and wealth, $W^j$, user $j$ can afford a range of bandwidth (less than or equal to $b^j$), where some amounts will be preferred over others. These preferences are represented with a QoS profile (described in section 6.1.2). Since there are two different types of resources in the economy (reserved and spot bandwidth), the user must identify how the reserved and spot bandwidth may be substituted for one another. In microeconomics, this is represented with an indifference curve.

An indifference curve indicates the combinations of resources that result in the same utility [15, 76]. For example in figure 7.2(a), the allocation $(x_1, y_1)$ results in the same utility as the allocation $(x_2, y_2)$. The curve between these points is the indifference curve. The slope of the indifference curve is called the marginal rate of substitution and indicates the rate at which a user trades one resource for another. In figure 7.2(a), only one indifference curve was depicted; however, the graph actually contains an infinite number of these curves, where each curve indicates a level of utility. In figure 7.2(b), multiple indifference curves are drawn in the same graph. Typically the level of utility increases as you move towards the north-east (more is better). Given this assumption, the indifference curves given in figure 7.2(b) can be ranked based on utility as $I_3 > I_2 > I_1$.

For the multi-market economy, indifference curves indicate the combination of reserved and spot bandwidth that result in the same utility. These curves are normalized to the current desired amount of bandwidth $b^j$, as seen in figure 7.3. In this figure the indifference curve labeled “prefer-reserved” was generated from the equation $y^j = k \cdot (1 - x^j)^2$, where $y^j$ is the amount of spot bandwidth and $x^j$ is the amount of reserved bandwidth for user $j$. The preference for reserved bandwidth increases as $k$ increases, which is reflected in the marginal rate of substitution. The other indifference curve given in figure 7.3 represents a user who has no preference for reserved or spot bandwidth. In this case the user will always prefer the cheaper (lower cost) bandwidth. In the case where the two types of bandwidth have the same price, assume the user will prefer equal amounts of both types
of bandwidth. The only assumptions required for the indifference curve is that it must be continuously differentiable and convex to the origin (required for determining the amount of bandwidth to purchase).

Finally, the user is charged continuously for the duration of the session (analogous to a meter). To pay for the expenses, assume the user provides an equal amount of money over regular periods of time (as done in 6.1.2).

7.1.3 Network Broker

Users can only participate in the network economy through a network broker (NB). This entity is an agent for the user and is located between the user and the edge of the network. Representing the user in the economy the NB performs the following tasks: connection admission control, policing, packet marking, and purchasing/bidding decisions. Although the NB works as an agent for the user (making purchasing decisions), assume the NB operates honestly in regards to the switches and the user.

The NB monitors the user and the prices by gathering and storing information about each. From the user, the NB collects and stores the QoS profile, indifference curve, $b^i$
and $W^j$. The NB also stores the route of user $j$, $R^j$, that connects source to the destination. For each link on $R^j$, the NB collects current reserved and spot bandwidth prices. The NB will divide $W^j$ into separate budget rates, one for each link in the route (as described in section 6.1.3). Using this information the NB controls network admission by initially requiring the user to have enough wealth to afford at least an acceptable QoS; otherwise, the user is denied access. For example, the NB/user could require a minimum amount of reserved bandwidth be purchased before transmission begins. The NB also levies the user for their consumption. In addition, the NB polices the user, ensuring only the bandwidth purchased is used, and marks the packets (assigning which are to use reserved bandwidth). Finally, the NB determines the reserved bandwidth bid and the amount of spot bandwidth to purchase.

**Bidding and Purchasing Bandwidth**

Since reserved bandwidth is sold in an auction format, the NB must bid for reserved bandwidth at each link on the route. The bid (the amount the user will purchase) for link $i$ is based on the budget $w^j$, a statistic of the spot market price, and the reserved bandwidth auction price for this link $g^{i,j}$. A statistic is required for the spot market bandwidth price due to its volatility. For this discussion (and simulation) the maximum spot price $\tilde{p}$,
Figure 7.4: Example equilibrium point, where slopes of the the indifference curve and budget line are equal.

measured during the current segment, is used as the spot market price statistic. Using this information the NB maximizes the utility of the user $u^j(x^j, y^j)$,

$$\max \{u^j(x^j, y^j)\}, \quad g^j \cdot x^j + p^j \cdot y^j \leq w^j$$  \hspace{1cm} (7.3)$$

where $x^j$ is the amount of reserved bandwidth and $y^j$ is the amount of spot bandwidth of user $j$. As defined in [15], the first order condition of this constrained maximization problem is,

$$\frac{u^j(x^j)}{u^j(y^j)} = \frac{g^{j,i}}{p^i}$$  \hspace{1cm} (7.4)$$

The NB must spend the budget to equalize the ratio of marginal utility to the price of each resource. Assuming the indifference curve is convex to the origin, the derivative of the curve is,

$$\frac{dy}{dx} = -\frac{u^j(x^j)}{u^j(y^j)}$$  \hspace{1cm} (7.5)$$

Plotting the budget line with the indifference curve, as seen in figure 7.4, the slope of the budget line is $\frac{g^{j,i}}{p^i}$. Therefore, the point where the slope of the indifference curve and the budget line are equal is where the utility of the user is maximized. The second order condition is not required due to the convexity assumption of the indifference curve [15]. The reserved bandwidth bid is the $x^j$ component of this point and is forwarded to link $i$.  


The NB keeps a table storing the amount and price of reserved bandwidth purchased at each link in the route. When the segment for link $i$ is sold, the amount user $j$ purchased $e_{ji}$ and the price $f_i$ is updated in the table. The maximum amount of reserved bandwidth that can be used by user $j$ is,

$$e_j = \min_{\forall i \in \mathcal{L}} \{e_{ji}\} \quad (7.6)$$

which is the minimum amount of reserved bandwidth purchased at any link. If the desired bandwidth is greater than the purchased reserved bandwidth, then spot bandwidth is used for transmitting the remaining portion $(b^j - e^j)$. The amount of spot bandwidth to use $y^j$ by user $j$ is,

$$y^j = \min \left\{ \min_{\forall i \in \mathcal{L}} \left\{ \frac{w^j - e^j \cdot f_i}{p_i} \right\}, b^j - e^j \right\} \quad (7.7)$$

which is the maximum amount of spot bandwidth that is affordable, but no more that what is required $(b^j - e^j)$.

### 7.1.4 Equilibrium Surfaces

The bidding procedure described in section 7.1.3 uses the indifference curve and the budget line to determine the reservation bid amount. The bid is the x-component of the equilibrium point, where the slope of the budget line equals the slope of the indifference curve. At this point the user achieves the highest utility based on their budget constraint and indifference curve. However, it is difficult to visualize how the shape of the indifference curve impacts the bidding procedure.

To provide another perspective on the bidding procedure, the equilibrium points for all reservation and spot prices (normalized) can be graphed. This yields two equilibrium surfaces, one representing the amount of reserved bandwidth, the other surface representing the amount of spot bandwidth (both normalized). On these graphs, the x-axis measures the reservation price, the y-axis measures the spot price, and the z-axis indicates the amount (reserved or spot, depending on the surface).

Given a constant amount of wealth, the graphs given in figure 7.5 display the equilibrium surfaces of three different indifference curves: prefer-reserved bandwidth, prefer-
cheaper and prefer-equal (equal amounts of reserved and spot bandwidth). The prefer-cheaper surface, figure 7.5(a), indicates that the user purchases only the cheaper resource. When the price for spot and reserved are equal, the user purchases equal amounts of both. In contrast, the surface for prefer-reserved, figure 7.5(b), indicates that the user continues to purchase only reserved bandwidth when the price for spot bandwidth is cheaper. The total amount of bandwidth (spot and reserved) for prefer-cheaper and prefer-reserved is given in figure 7.5(d). In this graph the prefer-reserved user purchases less (total bandwidth) than the prefer-cheaper user when the spot price is less. This is the “penalty” the prefer-reserved user faces. Therefore, the prefer-cheaper indifference curve always maximizes the amount of bandwidth purchased.

7.2 Network Dynamics and Optimality

As described in section 6.1, once the tâtonnement process reaches equilibrium the resulting allocation is Pareto-optimal and fair. Proofs that the resulting allocation of competitive markets (for the entire network) in equilibrium is Pareto-optimal and fair are given in chapter 5. Users are allocated bandwidth based on their budget as well as the competition they face in their markets. This results in a weighted max-min fair allocation.

The multi-market model consists of two different types of competitive markets (spot and reservation) and can be view as two separate sub-economies. Collectively, the spot markets can be considered one sub-economy, while the reservation markets create the other. For either sub-economy the proofs of Pareto-optimal and fair allocations, given in chapter 5, are applicable. Therefore, when the spot markets are in equilibrium, their allocation is is Pareto-optimal and fair. Similarly, when the reservation markets are in equilibrium the allocation of reserved bandwidth is Pareto-optimal and fair. A user will receive a fair allocation of spot bandwidth based on the competition in the spot markets as well as the portion of their budget spent in this sub-economy. A user will also receive a fair allocation of reserved bandwidth based on the competition in the reservation markets as well as the portion of their budget spent in this sub-economy. The budget is divided between in the two market types based on the indifference curve of the user as well as the
Equilibrium Amounts for Prefer Cheaper Indifference

Equilibrium Amounts for Prefer Reserved Indifference

Equilibrium Amounts for Prefer Equal Indifference

Total Equilibrium Amounts

(a) Prefer cheaper bandwidth.
(b) Prefer reserved bandwidth.
(c) Prefer equal amounts.
(d) Total bandwidth requested for prefer-reserved and prefer-cheaper.

Figure 7.5: Equilibrium allocation amounts for various types of indifference curves.
current spot and reservation prices, as described in section 7.1.3.

A single equilibrium price will not exist due to the changing source demands (VBR source and users entering/exiting the network), as described in section 6.3. However, the market can be viewed as having multiple equilibrium prices, each for some segment of time. During a segment the pricing technique will seek the equilibrium price as described in section 6.2. Once this price is found, the resulting distribution is Pareto-optimal and fair. When the aggregate demand changes, the stability of the price equation ensures that the price always moves towards $p_t$. Simulation results are provided in the next section to demonstrate the performance of the multi-market approach in this environment.

7.3 Multi-Market Experimental Results

Simulations are used in this section to demonstrate the performance of the multi-market economy under network dynamics (changing user demands and users entering/exiting the network). Experiments will consist of a realistic network configuration, allowing users to randomly enter the network and use actual MPEG-compressed traffic. The first experiment will provide an example of the benefits of purchasing different amounts in the reservation and spot markets. The second experiment will investigate the effect of the reservation market segment length on QoS.

7.3.1 A Demonstration of the Multi-Market Approach

This experiment will provide an example of the QoS obtained by users with different bandwidth preferences. The network simulated consisted of 160 users and their associated NB’s, three switches and seven primary links, as seen in figure 7.6. Each output port carried traffic from 40 users and connected to a 45 Mbps link. Links interconnecting switches were 1000 km in length, while links connecting sources to their first switch were 25 km in length. Users had routes consisting of one, two or three hops. The network can be described as a “parking lot” configuration, where multiple sources use one primary path. This configuration was agreed upon by members of the ATM Forum [46] for allocation comparisons since it provides competition among users with different routes and various
propagation delays. The multi-market economy had the following initial values. The spot market parameter $\alpha$ (targeted utilization) was 90%. Switches sold equal amounts of reserved and spot bandwidth; therefore $\beta$ was 45%. Reserved bandwidth prices were initialized to 55 and segments were 15 minutes in duration. Longer segments could have been selected; however, transition effect from one segment to another is of interest. Spot market prices were initialized to 50. There was no propagation delay between the user and their NB.

Users had a budget rate, $W$, of $3 \times 10^8$/sec and used the QoS profile given in figure 7.7(a). Since all users have the same budget rate, they are considered equal (purchasing power) in the economy. The source for each user was one of 15 MPEG-compressed traces, as described in section 3.3.2. Although users have the same wealth and QoS profile, for this demonstration users are considered either long-term or short-term. Long-term users measure, over the duration of the simulation, the different QoS obtained from preferring different amounts of reserved and spot bandwidth. Short-term users are introduced in the economy to cause sudden demand shifts, which may occur in actual networks (peak load times). Together, how the various users impact the QoS achieved in the multi-market economy is of interest.

A total of 120 users were considered long-term and had sessions that lasted the duration of the simulation. Half of the long-term users preferred reserved bandwidth, the
remaining preferred cheaper bandwidth (indifference curves given in 7.3). The long-term users entered the network at random times uniformly distributed between 0 and 600 seconds. The remaining 40 users were considered short-term. These users transmitted a short segment of an MPEG video (under 3 minutes, randomly determined). Due to the relative shortness of their session, these users only purchased bandwidth from the spot market. Starting at 3000 seconds the short-term users entered the network with a Poisson distribution of mean 120 seconds. The link bandwidth utilization and the QoS provided to each type of long-term user is of interest. Allocation graphs are provided to measure the utilization of link bandwidth, while QoS graphs measure the average QoS observed by long-term users.

For this simulation, the example bandwidth allocations, prices and average QoS are given in figures 7.7(b) - 7.7(d). Only the results from 1800 to 6500 seconds are displayed, since the effect the short-term users have on the economy is of interest. As seen in figure 7.7(b), all of the available reserved bandwidth for link 3 was sold, while the total bandwidth allocated stayed within the vicinity of \( \alpha \) (targeted utilization). Similar results were noted for the remaining links. As seen in figure 7.7(d), before the short-term users entered the network (time less than 3000 seconds) prefer-cheaper users enjoyed a higher QoS. During this time, prefer-cheaper users only purchased bandwidth from the spot markets, since prices were lower (as seen in figure 7.7(c)). In contrast, prefer-reserved users spent their entire budget in the reservation markets. Purchasing from the spot markets yielded higher QoS for the prefer-cheaper users, because these users only purchased what they needed at any time. This allows users to efficiently share the spot market bandwidth. In the case where the total demand of the prefer-cheaper users exceeded the spot market supply, each prefer-cheaper user received an equal-share (weighted max-min fair) of the spot market bandwidth. The prefer-reserved users were allocated an equal-share of the reserved bandwidth supply for the duration of the simulation (no more). For this reason, prefer-reserved users observed a lower QoS, until the short-term users arrived. When the short-term users arrived (during segment 3 of figure 7.7(b)), the spot market price increased in response to the increase in demand. During this time prefer-cheaper users received a lower QoS, since they had to compete with the new arrivals. In contrast, prefer-reserved users continued to receive approximately the
(a) QoS profile.

(b) Link 3 allocation.

(c) Link 3 bandwidth prices.

(d) Average QoS scores for all long-term users.

Figure 7.7: Multi-market simulation QoS profile and results.
same level of QoS since they purchased reserved bandwidth for segment 3. The spot market price increase, during segment 3, did cause a higher reservation market price for segment 4, as seen in figure 7.7(b). The prefer-reserved users could afford less reserved bandwidth during this segment, resulting in a slightly lower QoS. Afterwards, prices and QoS observed by the users returns to the previous values.

This simulation provides some insight to the rewards and risks of purchasing various amounts of bandwidth in the spot and reservation markets. In the example, prefer-cheaper users enjoyed the reward of a higher QoS, but were susceptible to the risk of spot market price fluctuations, that can cause large changes in their QoS. In contrast, prefer-reserved users opted for the lower risk reservation market, but generally received a lower QoS.

7.3.2 The Effect of Varying the Segment Length on QoS

In this experiment the effect of varying the segment length (of the reservation market) on QoS is considered. Similar to the experimental setup of section 7.3.1, the QoS of long-term users was measured for different segment lengths. The simulation consisted of a single 12 Mbps link and 12 users. Each user transmitted a MPEG-compressed video and had a wealth of 3 x 10^8/sec. A total of 10 users were considered long-term. Half of the long-term users were prefer-cheaper, while the remaining long-term users were prefer-reserved (section 7.3.1 describes users and their preferences). Long-term users started their sessions at random times, uniformly distributed between 0 and 10 seconds. The remaining 2 users were short-term and started their sessions at 2020 seconds. The multi-market economy had the following initial values. The spot market parameter α (targeted utilization) was 90%. Switches sold equal amounts of reserved and spot bandwidth; therefore β was 45%. Reserved bandwidth prices were initialized to 55. For the first experiment, segments were 50 seconds in duration. This was increased by 50 seconds for each subsequent experiment, until segments were 400 seconds in duration. For each experiment, the link bandwidth utilization and the QoS provided to each type of long-term user is of interest. Allocation graphs are provided to measure the utilization of link bandwidth, while QoS graphs measure the average QoS observed by long-term users.
Figures 7.8 - 7.11 show the allocation, bandwidth prices and QoS scores for segment lengths of 50, 100, 300 and 400 seconds. The presence of short-term users (starting at 2020 seconds and ending at 2180 seconds) increases the demand as well as the spot market price, which is evident in each of the experiments. The spot market price increase also impacts the reservation market price; however, this change occurs in the next segment. At this time prefer-reserved users have a slightly lower QoS score due to the higher reservation market prices. In contrast, prefer-cheaper users have a slightly higher QoS due to the lower spot market prices. This typically lasted for one segment; however, the worst case (for these experiments) is given in figure 7.10. In this experiment, short-term users enter the network at the end of one segment and leave at the start of the next segment. This causes the reservation market price to remain “high” for two segments, as seen in figure 7.10(b). This indicates the need for a better spot market price statistic (other than the maximum spot market price) for determining the reservation market bid. For example, a better spot market price statistic would account for the duration of the segment as well as the duration of any spot market price change.

7.4 Chapter Summary

This chapter introduced a distributed, multi-user bandwidth allocation method based on a multi-market economy. A computer network can be viewed as an economy consisting of three entities (users, Network Brokers and switches) and two different markets/resources (reserved and spot bandwidth). Switches own the bandwidth, which is sold in the reservation and spot markets. Reserved bandwidth has the advantage of ownership over a period of time, providing the user with some predictability of their expected QoS. In contrast, spot bandwidth has the advantage of immediate availability without the reservation overhead. Both market types are modeled as competitive markets; therefore efficient as well as Pareto-optimal and fair allocations are possible. Users require link bandwidth for their applications and are represented in the economy by a Network Broker (NB). The NB buys bandwidth to maximize the utility (QoS) of the user and considers the risks and benefits associated with the two bandwidth types (demonstrated in the simulation
Figure 7.8: Allocation, prices and QoS scores for segment length of 50 seconds.

Figure 7.9: Allocation, prices and QoS scores for segment length of 100 seconds.
(a) Bandwidth allocation.  (b) Bandwidth prices.  (c) Average QoS score.

Figure 7.10: Allocation, prices and QoS scores for segment length of 300 seconds.

(a) Bandwidth allocation.  (b) Bandwidth prices.  (c) Average QoS scores.

Figure 7.11: Allocation, prices and QoS scores for segment length of 400 seconds.
results). This multi-market approach uniquely integrates the benefits of the spot market (such as Pareto-optimal and equitable allocations) with the price stability offered with the reservation market. This is done in a distributed and state-less manner. Unique to the multi-market approach is the ability of users to dynamically change bandwidth amounts in response to market and source requirements. This provides the user greater flexibility when maximizing their QoS.
Chapter 8

Conclusions and Future Work

Current and future networks must support a variety of applications that differ widely in terms of their traffic characteristics and Quality of Service (QoS) requirements. Network resources (such as buffer space and link bandwidth) must be allocated efficiently and fairly to these applications in order to provide QoS. Two important resource allocation issues were addressed in this thesis: single-user resource allocation and multi-user resource allocation.

8.1 Single-User Allocation

The service provider and the user are interested in allocating network resources as efficiently as possible, while providing a desired QoS. Efficiency refers to the amount of resources required, as well as the number of renegotiations. Minimizing the amount of resources allocated can increase the utilization, while reducing the number of renegotiations reduces the signaling strain on the network. Similarly, the user is interested in reducing costs, which can be achieved by reducing the amount of resources and the number of renegotiations required. Determining an efficient allocation is difficult due to unpredictable nature of certain traffic sources (such as live or interactive video). While there are many different types of network resources and QoS measures, this part of the thesis (single-user allocation) focuses on the allocation of link bandwidth to provide a desired cell loss probability.

Many different methods of single-user bandwidth allocation have been proposed.
These can be categorized as either off-line or on-line. Off-line techniques require complete source information before transmission begins in order to determine the appropriate allocation amounts. While these methods are able to achieve efficient allocations, they are not applicable to live or interactive sources. In contrast, on-line methods allocate link bandwidth using real-time measurements. Due to the limited a priori information required, on-line methods are suitable for allocating bandwidth for stored or live media. However, none of the on-line methods have the ability to reduce the bandwidth and number of renegotiations required for various VBR sources.

This thesis presented an on-line algorithm, DSA+, which efficiently allocates resources to provide a required QoS. DSA+ was used to manage link bandwidth to achieve a desired cell loss probability for MMBP generated traffic and MPEG-compressed video traces. Reducing the bandwidth allocated and the number of renegotiations are the goals of this allocation mechanism. For MMBP traffic, DSA+ allocated the same (slightly less) bandwidth than the effective bandwidth value. However unlike the effective bandwidth calculation, DSA+ does not require prior knowledge of statistics of the underlying traffic generation process. For the MPEG experiments, fifteen actual MPEG traces were collected and used. As compared to an off-line peak-rate allocation, DSA+ saved 13–58% in bandwidth. On average 36 renegotiations were required, but only 44% were for more bandwidth, which seems acceptably low. Other methods which were compared, either over-allocated bandwidth or required up to 47 times more renegotiations. The effect of multiplexing was investigated and showed DSA+ has no problem guaranteeing QoS to such a traffic source.

Experiments also indicate the algorithm is fairly insensitive to the choice of initial parameter values. For all the experiments performed the same initial parameters were used and showed excellent results. DSA+ requires limited information about the source, however any a priori information can, of course, benefit the performance of any on-line algorithm.

Multiple hop connection allocation was also addressed. In this case, a connection of four nodes was simulated to evaluate the performance of DSA+ for end-to-end CLP. Two implementations were investigated: each-node and first-node. Both methods were able to provide the end-to-end QoS, however each method may suffers from some possible disadvantages.
8.1.1 Future Work

While the focus of this thesis was the allocation of bandwidth for network applications, DSA+ may be useful for other real-time applications. Examples include CPU scheduling and disk bandwidth management. In both cases the central idea is to provide guaranteed service to variable traffic, with the minimum amount of resources and user input.

For the single-user allocation experiments, no limit on the availability of resources was made. When any allocation method renegotiated for more resources, they were instantly granted. However in an actual implementation this assumption can not be made. In the case of network overload, where contention for more resources is high, resources may not be available. This was the primary purpose for reducing the number of renegotiations for more resources. Nevertheless, if more resources are required yet not available the users QoS will suffer. If the QoS manager has access to the MPEG compression rate, the shortage of resources can be compensated by altering the Q factor of the compression [86]. The result is a loss of picture quality, until resources are available.

Finally, how DSA+ manages resources for other QoS measures should be investigated. For example, it may be possible to allocate bandwidth to provide some desired delay bound. Such a method could be integrated into a Weighted Fair Queue scheduler [27], where the weights of each class/user is dynamically adjusted based on measured delay.

8.2 Multi-User Allocation

Multi-user allocation differs from single-user allocation since it concerns the allocation of resources for all users in the network. Multi-user allocation typically has two goals: fairness, and the balance between throughput and QoS. Defining fairness is difficult because of the various types of applications and their desired QoS. In this thesis, standard network-oriented and microeconomic-based definitions of fairness were used. The balance between throughput and QoS is the concept that the network should seek high resource utilization, but not at the expense of poor QoS (and vice versa). Hence, due to heterogeneous networks, diverse resource requirements and the goals associated with multi-user allocation, proper allocation remains a challenging problem.
Microeconomics can be used to allocate network resources in an efficient and fair manner. A simple network economy consists of finite resource (link bandwidth) and two types of agents: consumers (applications) and producers (switches). Consumers purchase resources to satisfy their QoS. Producers maximize their satisfaction by renting or selling resources to consumers. Economic-based allocation methods have several advantages. Many economic-based techniques offer a distributed allocation method, eliminating the need for a central controlling entity. Economic-based methods can also achieve Pareto-optimal and fair allocations (weighted max-min fair, proportionally fair per unit charge and equitable). These methods are typically able to scale to large networks and provide a framework for economic goals (such as, cost recovery and profit maximization). However, to date none of the microeconomic methods are able to allocate resources under network dynamics (changing user demands and users entering/exiting) or provide guarantees of price stability. This thesis introduced two microeconomic-based methods for allocating link bandwidth to multiple users: the spot market approach and the multi-market approach.

8.2.1 Spot Market Approach

In the spot market approach, a computer network was viewed as an economy consisting of three entities; users, Network Brokers (NB) and switches. Switches own the resources sought by users, and price their resources based on local supply and demand using a modified tâtonnement process. The modified tâtonnement process allows demands for bandwidth to change dynamically and is a unique feature of the spot market approach. In addition, price updates are performed using only aggregate information. For this reason, the spot market approach is state-less and should have a reasonable implementation cost. Bandwidth is sold as a non-storable resource, so users are charged based on their consumption (similar to residential electricity). A user requires link bandwidth to maximize their individual QoS. Representing the user in the economy, the NB makes the resource purchasing decisions based on current needs of the user and prices. Once a new allocation amount has been determined, the user can send using this amount immediately. There is no reservation overhead required. Therefore, users are able to dynamically change their demands based on their application requirements and link prices. Users and switches act indepen-
ently, which yields a distributed allocation method. This competitive market structure is also proven to achieve Pareto-optimal and fair (weighted max-min and equitable) allocations when demands are constant. The spot market approach is flexible, easily achieving a variety of fair allocations. In addition, pricing bandwidth in the spot markets provides a disincentive to over-allocate bandwidth.

The spot market approach was simulated to measure the performance under network dynamics. Simulation results demonstrate the ability of the spot market approach to successfully allocate bandwidth of a network to a large number of diverse users, each transmitting an actual MPEG-compressed video trace. The economy also provided substantially better control of QoS than max-min or demand-based weighted max-min [62]. To date, no other microeconomic-base allocation method has been tested under such conditions.

A limitation of the spot market approach is the inability to provide resource guarantees (price stability). It is possible that a user, who enters the network when prices are low, may be forced out of the economy if prices become too high. In addition, price “spikes” may cause a degradation in QoS. For this reason, a method that provides resource guarantees is needed. This is the motivation for the multi-market economy.

### 8.2.2 Multi-Market Approach

To address the need for resource guarantees, a multi-market economy was introduced in this thesis. Similar to the spot market approach, a computer network is viewed as an economy consisting of three entities (users, Network Brokers and switches) and two different markets/resources (reserved and spot bandwidth). Switches own the bandwidth, which is sold in the reservation and spot markets. Reserved bandwidth has the advantage of ownership over a period of time, providing the user with some predictability of their expected QoS. In contrast, spot bandwidth has the advantage of immediate availability without reservation overhead. Both market types are modeled as competitive markets; therefore efficient as well as Pareto-optimal and fair allocations are possible. Users require link bandwidth for their applications and are represented in the economy by a Network Broker (NB). The NB buys bandwidth to maximize the utility (QoS) of the user and considers the risks and benefits associated with the two bandwidth types (demonstrated in
the simulation results). This multi-market approach uniquely integrates the benefits of the spot market (such as Pareto-optimal and equitable allocations) with the price stability offered with the reservation market. This is done in a distributed and state-less manner. To date, no other microeconomic approach has integrated these two types of markets into one allocation method. Users are able to dynamically change bandwidth amounts in response to market and source requirements. This is another unique feature of the multi-market approach.

8.2.3 Future Work

The market-based approaches to multi-user allocation presented in this thesis assumed the user only had one path available from source to destination. However, in reality multiple paths may exist. One area of research is price based routing. Given a set of possible paths the user could reroute traffic based on current prices or availability of reserved bandwidth. Such a method gives the user more choices when sending traffic. In addition, the wealth rate was assumed to be equally divided among all the switches in the route. An alternative approach would allow the user to dynamically adjust the amount of wealth spent on these switches. This would allow the user to save money over time.

Another issue not directly addressed is price-based admission control. The spot market and the multi-market approaches provide a unique method of admission control. Given the prices associated with a route (or set of routes), the NB can determine quickly whether the user should be allowed to enter the network. Alternatively, the NB/user could require a minimum amount of reserved bandwidth be purchased before transmission begins.

A generic implementation of the spot market approach was provided in this thesis. However, a more urgent application is to the Internet. Future work should address the compatibility of the spot market with the current Internet. For example, price distribution methods should be addressed. Such a method should have low overhead and work with legacy networks. In addition, future work should address the integration of the spot and reservation markets with differentiated services. Differentiated services relies on a pricing mechanism to help users select the appropriate service class. The pricing mechanisms presented in this thesis may be suitable for differentiated services.
Finally, the reservation market sells bandwidth for fixed periods of time. If the session of the user finishes before the end of the current segment, the user returns the bandwidth to the switch. Since the user does not pay for the returned bandwidth, there is an incentive to return unused bandwidth. However, an alternative approach would allow the user to re-sell this bandwidth to others users. In this environment users could increase their wealth by purchasing reserved bandwidth at low prices, then re-selling at higher prices.
Bibliography


