EFFECTIVE BANDWIDTH MANAGEMENT OF ATM ABR CONNECTIONS BY USING MINIMUM INTER RM CELL TIME

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

INFORMATION TECHNOLOGY

By

SEKHAR BABU CH

IIT Roorkee - CDAC, NOIDA,
c-56/1, "Anusandhan Bhawan"
Sector 62, Noida-201 307

JUNE, 2004

CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation titled "**EFFECTIVE BANDWIDTH MANAGEMENT OF ATM ABR CONNECTIONS BY USING MINIMUM INTER RM CELL TIME**" in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Information Technology**, submitted in **IIT-Roorkee - CDAC campus, NOIDA,** is an authentic record of my own work carried out during the period from June 2003 to June 2004 under the guidance of **Dr.Moinuddin**, Professor, Jamia Millia Islamia (Central University), New Delhi.

I have not submitted the matter embodied in this dissertation for the award of any other degree or diploma.

Date: 26·6·2004
Place: NOIDA

(SEKHAR BABU CH)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date: 26·6·2004
Place: NOIDA

(Dr. Moinuddin)
Professor
Jamia Millia Islamia (Central University)
New Delhi.

ACKNOWLEDGEMENTS

I would like to thank my advisor **Prof. Moinuddin** for the excellent guidance and inspiration he has provided for me throughout this work.

I could have never achieved this goal without the steadfast support from my Parents.

Thanks are due to my good friends and roommates Murali Y, Viswanath V, Prem D, Suresh V and Sumanth V for putting up with my variable moods and for the fun time I had with them.

I take the privilege to express my deepest sense of gratitude to **Prof. PREM VRAT,** Director, Indian Institute of Technology, Roorkee, and **Mr. R.K.VERMA,** Executive Director, CDAC, Noida for providing me with this valuable opportunity to carry out this work. I am very grateful to **Prof. A.K.AWASTI**, Programme Director, **Prof. R.P. AGARWAL,** course coordinator, IIT Roorkee and **Mr. V.N.SHUKLA**, course coordinator, CDAC NOIDA, for providing the best of the facilities for the completion of this work and constant encouragement towards the goal.

(SEKHAR BABU CH)

ABSTRACT

The capability of Asynchronous Transfer Mode (ATM) networks to provide large bandwidth and to handle multiple Quality Of Service (QOS) support can only be realized by preparing effective traffic management mechanisms. ATM networks have multiple service classes for audio, video and data to share the same network. Of these the Available Bit Rate (ABR) service class is designed to efficiently support data traffic.

Traffic management involves the design of a set of mechanisms which ensure that the network bandwidth, buffer and computational resources are efficiently utilized while meeting the various Quality of Service (QoS) guarantees given to sources as part of a traffic contract. Several rules are specified for source, destination and switches present in the ATM network to use particular service class efficiently. In this dissertation, we address some modification to the current source rule number 3 for the ABR service class to achieve efficient utilization of link bandwidth for high-speed connections only.

We consider three aspects of this problem in this dissertation. First, the current source end system rule (SES) number 3 is evaluated to know how it works. SES rule number 3 says that for every 31 data cells one RM cell should be sent. Second, another technique for high-speed connections is provided by increasing the ABR service parameter Nrm. Since the inter RM cell time for high-speed connections is less compared to low-speed connections, one can increase Nrm value to avoid unnecessary control information. Third, a modified technique is introduced by modification to SES rule number 3 (with additional parameter MIRCT). This will form a coupling between switch averaging interval (AI) and inter RM cell time by which the parameter Minimum Inter RM Cell Time (MIRCT) reduces the control information and increases bandwidth for data cells.

In summary, this dissertation work addresses the current SES rule number 3 for ATM ABR connections and the techniques developed that are applicable to high speed ABR connections for greater efficiency than SES rule number 3.

CONTENTS

List of Figures

GLOSSARY OF ACRONYMS AND TERMS

ABR	Available Bit Rate
ACR	Allowed Cell Rate
ADTF	ACR Decrease Time Factor
AI	Averaging Interval
ATM	Asynchronous Transfer Mode
BECN	Backward Explicit Congestion Notification
B-ISDN	Broadband Integrated Services Digital Network
BN	BECN (bit in RM-cell)
BRM	Backward RM-cell
CCR	Current Cell Rate
CDF	Cutoff Decrease Factor
CI	Congestion Indication (bit in RM-cell)
CLP	Cell Loss Priority
CLR	Cell Loss Ratio
CRC	Cyclic Redundancy Check
CRM	Missing RM-cell Count
DES	Destination End-System
DIR	Direction (bit in RM-cell)
EFCI	Explicit Forward Congestion Indication
EPRCA	Enhanced Proportional Rate Control Algorithm
ER	Explicit Rate
ERICA	Explicit Rate Indication for Congestion Avoidance
FIFO	First In First Out queue service discipline
FRM	Forward RM-cell
FRTT	Fixed Round-trip Time
ICR	Initial Cell Rate
IRCT	Inter RM cell time
LAN	Local Area Network

MCR	Minimum Cell Rate
MIRCT	Minimum Inter RM cell time
Mrm	Minimum number of cells between RM-cell generation
NI	No Increase (bit in RM-cell)
Nrm	Maximum number of cells between RM-cell generation
PCR	Peak Cell Rate
QL	Queue Length (field in RM-cell)
QoS	Quality of Service
RA	Resource Allocation (bit in RM-cell)
RDF	Rate Decrease Factor
RIF	Rate Increase Factor
RM-cell	Resource Management Cell
SES	Source end system
SN	Sequence Number (field in RM cell)
TCP	Transmission Control Protocol
Trm	ABR service parameter related to RM cell generation
TTR	Threshold Transmission Rate
VC	Virtual Connection

CHAPTER 1

INTRODUCTION

1.1 Motivation

The main aim for Available Bit Rate (ABR) service development of ATM networks was the economical support of data traffic, where each packet of data is segmented into ATM cells. After studies showed that the indiscriminate dropping of ATM cells under congestion could lead to the collapse of throughput for packet data applications [4, 5, 14, 15], the goals of the ABR service were expanded to include the support of sharply defined objectives for cell loss. As a result, the class of control mechanisms considered for the ABR service was restricted to those, based on feedback from the network to the traffic source that could tightly control cell loss within the network. The ABR service would guarantee a particular cell-loss ratio for all traffic offered in proper response to network feedback. To maximize the odds that the vague requirements of an ABR connection were met by a network's available bandwidth, the class of control mechanism considered for the ABR service was further restricted to those that can use the available bandwidth efficiently and allocate it systematically among the connections active at a given time. In bandwidth limited communication systems, efficient techniques are to be introduced to achieve higher data rates of transmission.

1.2 Asynchronous Transfer Mode

Asynchronous transfer mode (ATM) is a cell based, circuit switching, and multiplexing technology that uses fixed length cells to carry a great variety of data types [2]. The main difference with other similar technologies like frame-relay and X.25 is the standard cell size of 53 bytes. The cells are time related and thus form a continuous data stream. The reason for using fixed length size cells to carry all the information is to ensure that switching and multiplexing can be carried out effectively by hardware. It is asynchronous in the sense that the recurrence of cells containing information from a particular user is not necessarily periodic.

ATM is a connection-oriented technology in the sense that before any transmission takes place a virtual circuit has to set-up by the intermediate switches and make sure that the requested QoS can be provided [16]. The allocation of bandwidth is occurring in a per channel basis thus allowing other connection to take place trough the same virtual path. The QoS is guaranteed by limiting the number of VCs that can be set-up for a particular channel. The user can assign service requirements at the time of the connections and may agree to control these parameters dynamically as demanded by the network.

1.3 Available Bit Rate Service

In August 1995, the Traffic Management Working Group of the ATM Forum released for stow ballot a specification for the Available Bit Rate (ABR) service [1]. This new service aimed at the economical support of applications with vague requirements for users by controlling the rate of offered traffic through feedback. ATM is a networking protocol with the potential to support applications with distinct tolerances for delay, jitter, and cell loss and distinct requirements for bandwidth or throughput [16].

To address this spectrum of needs, the ATM Forum defined a family of service categories [1]. The first two specified service categories, i.e. the Constant Bit Rate (CBR) and the Variable Bit Rate (VBR) services, were intended to address applications, like circuit emulation or entertainment-quality video, with precisely defined requirements for throughputs and delays. The third service category, the Unspecified Bit Rate (UBR), was intended for applications, like file transfers submitted in the background of a work station, with minimal service requirements.

The primary goal of the fourth service category, the ABR service, is the economical support of applications with vague requirements for throughputs and delays [9]. A user might know, for example, that a particular application runs well across a lightly loaded 100-Mbps Ethernet and poorly through a 56 Kbps modem. That same user, however, could have difficulty selecting a single number to serve both a guarantee and a bound on the bandwidth for the application, as would be required to set up a CBR connection. The ABR service is suited for such an application. An additional goal of the

ABR service was to allow a user to specify, at the time of connection setup, a lower and upper bound on the bandwidth allotted to the connection over its life.

A final goal of the ATM protocol was to support connections across Local Area Networks (LANs), Metropolitan Area Networks (MANs), or Wide Area Networks (WANs). The ability to work in a variety of environments is particularly important when traffic is controlled using feedback, as with the ABR service, for then the sizes of queue fluctuations depend not so much on the absolute size of network distances as on the amount of data that a connection can transmit during the time it takes feedback to reach the traffic source [8, 21].

The approach chosen by the ATM Forum's Traffic Management Working Group as the best match for the goals of the ABR service is to control the bandwidth of connections directly [9, 21]. Control of the cell rate for a connection would occur at least at the source terminal adapter, which would shape the connection's traffic as directed by feedback from the network. Under a rate-based framework, the share of the bandwidth allocated to a connection does not depend on the delays between points where data are shaped on a per-connection basis, so that a rate-based framework is ideal for architectural flexibility [23]. In addition, a rate-based framework can support fair allocations of the bandwidth, as well as bandwidth guarantees, even when the simple First-In-First-Out discipline is used at network queues.

1.4 Objective of the Dissertation

ATM networks are providing bandwidth in the order of hundreds of Mbps. ATM also has got sophisticated traffic management to meet the user needs, specifically for the ABR service. ABR feedback mechanisms perform the computation of available bandwidths (and hence the offered bandwidth) based on periodic averaging interval (AI) [10]. This averaging interval is generated by the system every few milliseconds. If the averaging interval is too long, the system may not use resources efficiently, since it may take a very long time to reach convergence towards fair share. Therefore, the performance of the ABR control loop depends on appropriate engineering of the averaging interval.

SES rule number 3 says that, a new RM cell has to be transmitted after every 31 other ATM cells. It can be readily seen that for high-speed ATM connections, the Inter-RM Cell Time gets negligibly small in comparison with the AI value. It is therefore obvious that in high-speed ABR connections, the unnecessary bandwidth gets lost for transmission of excess RM cells. In an ideal case, it would be enough to transmit a single RM cell in each averaging interval.

This dissertation proposes a coupling between the length of Averaging Interval and the Inter-RM cell time. Modification to SES rule number.3 is specified in order to increase the utilization of the available network resources, without influencing the feedback delay of ABR control loops. By introducing parameter minimum inter RM cell time (MIRCT), we actually limit the transmission speed of RM cells to 1/MIRCT cells per second, independently of individual ABR connection transmission speeds.

In view of the above points the objective of the present work is set as follow:

1. To make a comprehensive study of the SES rule number 3
2. To make a comprehensive study of the developed techniques for effective link bandwidth management in contrast to SES rule number 3
3. Comparison of the developed techniques with the current techniques

1.5 Organization of Report

This report was organized as follows.

Chapter 2 discusses about the nature of ABR service and ABR framework which gives the complete scenario of ABR service category.

Chapter 3 analyses two other techniques for efficient usage of link bandwidth compared to the present SES rule number 3

Chapter 4 introduces the design goals, also design of the source end system is given according to the rules it has to follow for both the techniques.

Chapter 5 deals with Implementation issues and simulation in NIST ATM simulator.

Chapter 6 analyses the results.

Chapter 7 concludes the report, also describes the future work.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

In the ABR service, the source adapts its rate to changing network conditions. Information about the state of the network like bandwidth availability, state of congestion, and impending congestion, are conveyed to the source through special control cells called Resource Management Cells (RM-cells). The following sections specify the format and contents of the RM-cell, the source, destination, and switch behavior, and the parameters used in the service.

2.2 The Nature of the ABR Service

The ABR service is intended for a narrower class of applications, specifically data applications that can adapt to time-varying bandwidth and tolerate unpredictable end-to-end cell delays. The nature of this service is different from VBR and CBR services in several ways. First, *ABR connections will share the available bandwidth [7]*. The concept of available bandwidth is intrinsic to the service; it is whatever bandwidth exists in "excess" of CBR/VBR traffic, as defined by the network provider. Figure 2.1 shows one approach to defining the excess bandwidth in a physical link.

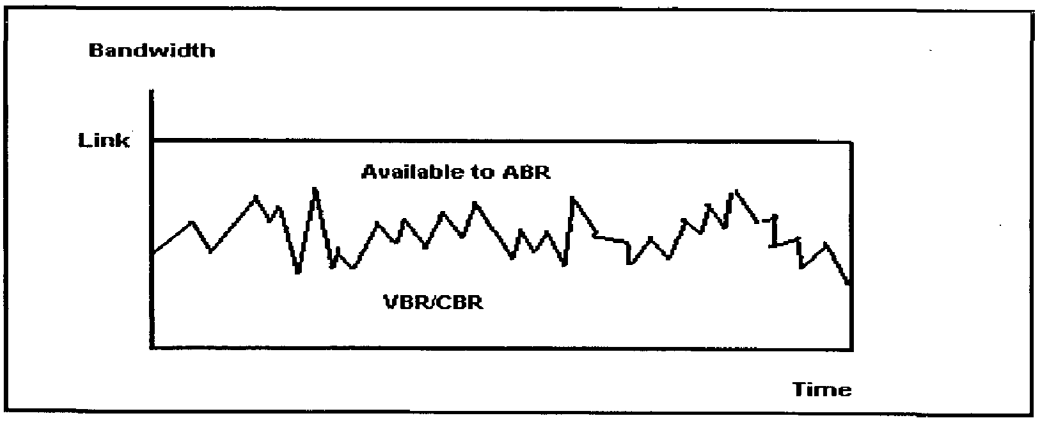


Figure 2.1: Example of excess bandwidth for ABR traffic.

The available bandwidth and the share of the bandwidth to each ABR connection will fluctuate dynamically due to randomness in the CBR/VBR traffic and changes in the number of ABR connections sharing the available bandwidth. Hence, in the ABR service, *the share of available bandwidth for each ABR connection is dynamic and may diminish down to a specified minimum cell rate (MCR) [7]*. The MCR is requested by the user (default = 0) and guaranteed in the sense that the network ensures that the bandwidth available to the connection will fluctuate between the peak rate and the MCR but not below the MCR.

The first two points capture the basic dynamic nature of the ABR service. The ABR sources are continually adapting their rates to their shares of the time-varying excess bandwidth. The performance of the network will depend on how well the sources can match their rates to the available bandwidth. Some amount of bandwidth mismatch is inevitable because delays are unavoidable in getting feedback information through the network. The potential mismatch between source rates and the available bandwidth implies that buffering will be necessary in the network. Buffers will be used to absorb ABR traffic during the momentary intervals when the source rates exceed the available bandwidth. The required amount of buffers is thus proportional to the bandwidth mismatch and feedback delay.

The dynamic nature of the ABR service can be seen from the feedback model shown in Figure 2.2

The buffer depicts the "bottleneck" link (the most constraining link along the connection), and the available bandwidth $A(t)$ on this link can fluctuate arbitrarily between zero and the full link rate L (for this discussion we have assumed MCR = 0). The source adjusts its rate $X(t)$ to a time-delayed version of $A(t)$, that is, $X(t) = A(t$ -p; $D)$ where D is a fixed parameter denoting the round-trip delay through the network. The buffer absorbs the traffic during the periods when $X(t) > A(t)$ and releases its contents (if any) when $X(t) < A(t)$. It can be seen that, in the worst case, the buffer can fill up to LD, which is commonly called the *bandwidth-delay product* of the network. The two factors represent the maximum possible bandwidth mismatch and the maximum duration of the mismatch. The large bandwidth-delay product in ATM networks, especially over wide areas, implies that large queues may accumulate and hence large ABR buffers will probably be necessary if cell losses must be low (e.g., L = 150 Mb/s and D = 100 ms correspond to buffers of 35,000 cells).

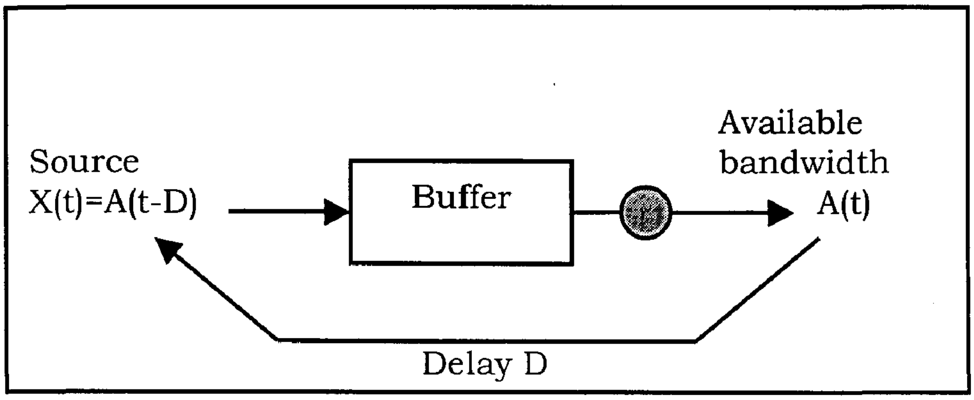


Figure 2.2: Example of a source matching its rate to the available bandwidth with feedback delay.

Since large queues may be possible, the network cannot guarantee strict bounds on end-to-end cell delays or cell delay variation even if ABR sources adapt their rates properly. Thus, *the ABR service is appropriate only for applications which can adapt their rates to the time-varying available bandwidth and tolerate unpredictable cell delays [7]*. The next question is whether cell loss should be limited, or if the ABR service is truly best effort like IP with no guarantees on cell delays or cell loss. The ABR service follows the former approach, while the best-effort ATM service with no QoS guarantees has been designated the *unspecified bit rate* (UBR) service.

In traditional packet networks, data applications can tolerate a certain amount of packet loss in the network layer by adding end-to-end acknowledgments and retransmissions in the transport layer protocol. However, retransmissions will decrease efficiency, and, in the case of TCP, packet losses will cause a connection to slow down following the normal congestion avoidance procedure. In ATM networks, data applications are even more sensitive to cell loss because of the effect of fragmentation (i.e., segmenting a packet into multiple smaller ATM cells). Fragmentation is a real issue because the 53-byte ATM cell is much shorter than typical data packets (e.g., TCP bulk data on the order of 500 bytes or larger). This problem motivates the fourth tenet of the ABR service: *a low or zero cell loss rate is guaranteed to users who adapt their rates properly [7]*. A target cell loss rate is determined by each network provider.

It can be seen that the ABR service is not exactly a best-effort service like IP with no assurance about QoS. There is an agreement between the network and user to achieve some guarantee of cell loss. However, this agreement is not in the form of an explicit traffic contract as used in VBR services, which specifies upper bounds on the source rate and minimal expectations on network performance. The ABR service is more dynamic; hence, the nature of the agreement is more procedural. The network and user have an implicit agreement to cooperate together to control the dynamics of the service. In a way this cooperative approach is an improvement over best-effort services like IP, which is not designed to give assistance to the flow control in the end-to-end transport layer protocol (e.g., TCP).

2.3 The Rate-Based Framework

In order to facilitate the development and deployment of ABR service class technology, the ATM Forum decided to avoid elaborate specification of feedback control loop mechanisms [8, 16, 24, 25]. The decision was made to specify only the rate-based framework, in order to assure interoperability.

Figure 2.3 presents the elements of a typical communication network implementing the ABR closed-loop rate-based framework. The three generic elements are traffic source, traffic destination and network switch. For the forward information flow from the source to the destination, there is a control loop consisting of two RM-cell flows, one in the forward direction and one in the backward direction.

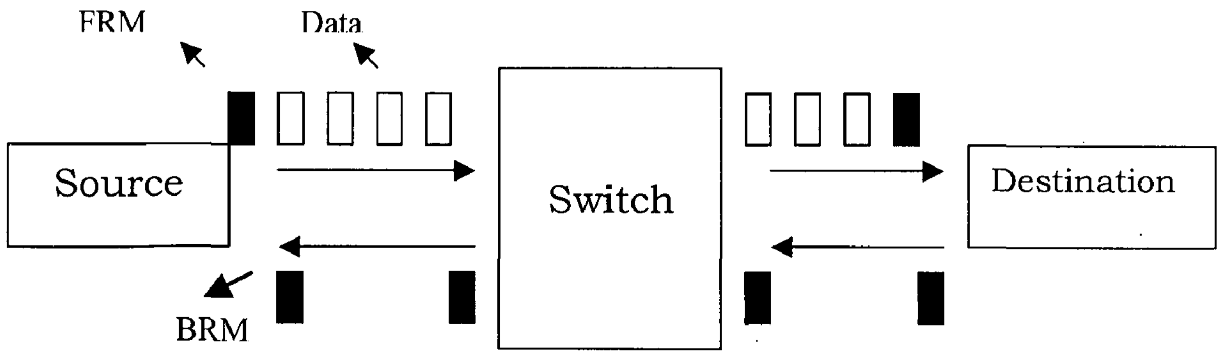


Figure 2.3: ABR traffic management model

2.3.1 ABR Service Parameters [1, 7, 27]

This section defines the parameters, which are used to implement ABR flow-control on a per-connection basis.

Label	Description	Units and range
PCR	The Peak Cell Rate, PCR, is the cell rate that the source may never exceed	Cells/Sec
MCR	The Minimum Cell Rate, MCR, is the rate at which the source is always allowed to send	Cells/Sec
ICR	The Initial Cell Rate, ICR, is the rate at which a source should send initially and after an idle period	Cells/Sec
Nrm	Nrm is the maximum number of cells a source may send for each forward RM-cell.	Default-32, Range: 2 to 256

Table 2.1: List of ABR service parameters (continued to next page)

Label	Description	Units and range
Mrm	Mrm controls allocation of bandwidth between forward RM-cells, backward RM-cells, and data cells	Constant fixed at 2
Rdf	The Rate Decrease Factor, RDF, controls the decrease in the cell transmission rate.	RDF is a power of 2 from 1/32,768 to 1
ACR	The Allowed Cell Rate, ACR, is the current rate at which a source is allowed to send	Cells/Sec
CRM	Missing RM-cell count. CRM limits the number of forward RM-cells that may be sent in the absence of received backward RM-cells.	CRM is an integer. Its size is implementation specific
ADTF	The ACR Decrease Time Factor is the time permitted between sending RM-cells before the rate is decreased to ICR	Units: seconds, range: .01 to 10.23 sec: with granularity of 10 ms
Trm	Trm provides an upper bound on the time between forward RM-cells for an active source.	Units: milliseconds Trm is 100 times a power of two Range: 100*2-7 to 100*20
FRTT	The Fixed Round-Trip Time, FRTT, is the sum of the fixed and propagation delays from the source to a destination and back	Units : 1 microseconds Range: 0 to 16.7 seconds
TBE	Transient Buffer Exposure, TBE, is the negotiated number of cells that the network would like to limit the source to sending during startup periods, before the first RM-cell returns	Units: Cells Range: 0 to 16,777,215
CDF	The Cutoff Decrease Factor, CDF, controls the decrease in ACR associated with CRM.	CDF is zero, or a power of two in the range 1/64 to 1
TCR	The Tagged Cell Rate, TCR, limits the rate at which a source may send out-of-rate forward RM-cells	TCR is a constant fixed at 10 cells/second

Table 2.1: List of ABR service parameters (Continued from previous page)

2.3.2 RM Cell Structure [1]

Table 2.2 shows the fields and their position within the Resource Management (RM) cell format.

FIELD	OCTET	Description	Initial value	
			if source-generated	if switch-generated or destination-generated
Header	1-5	ATM Header	RM-VPC: VCI=6 and PTI=110 RM-VCC: PTI=110	
ID	6	Protocol Identifier	1	
DIR	7	Direction	0	1
BN	7	BECN Cell	0	1
CI	7	Congestion Indication	0	either CI=1 or NI=1 or both
NI	7	No Increase	0 or 1	either CI=1 or NI=1 or both
RA	7	Request/ Acknowledge	0 or set in accordance with I.371	
Reserved	7 (3 bits)	Reserved	0	
ER	8-9	Explicit Cell Rate	a rate not greater than PCR parameter	Any rate value
CCR	10-11	Current Cell Rate	ACR Parameter	0
MCR	12-13	Minimum Cell Rate	MCR Parameter	0
QL	14-17	Queue Length	0 or set in accordance with I.371	
SN	18-21	Sequence Number	0 or set in accordance with I.371	
Reserved	22-51	Reserved	6A (hex) for each octet	
Reserved	52 (6 bits)	Reserved	0	
CRC-10	52 (2 bits) 53	Error Check		

Table 2.2: Fields in RM cell

2.3.3 Description of RM-Cell Fields

This section describes how each field of the RM-cell is used. See Table 5-1 for requirements and options for initializing these fields.

- **Header:** The first five bytes of an RM-cell are the standard ATM header with PTI=110 (binary) for a VCC, and additionally VCI=6 for a VPC. The CLP bit is 0 if the RM-cell is in-rate and 1 if it is out-of-rate.
- **ID:** The protocol ID identifies the service using the RM-cell. The ITU has assigned protocol ID = 1 to ABR service.
- **Message Type Field**
  - **DIR**: The DIR bit indicates direction of data flow associated with the RM-cell. A forward RM-cell, indicated by DIR=0, is associated with data cells flowing in the same direction. A backward RM-cell, indicated by DIR=1, is associated with data cells flowing in the opposite direction. DIR is changed from 0 to 1 when an RM-cell is turned around at a destination.
  - **BN**: The BN bit indicates whether the RM-cell is a Backward Explicit Congestion Notification (BECN) cell (i.e., non-source generated) or not. BN=0 indicates a source generated RM-cell while BN=1 indicates a BECN RM-cell generated by a destination or a switch.
  - **CI**: The CI (congestion indication) bit allows a network element to indicate that there is congestion in the network. When a source receives a backward RM-cell with CI=1 it decreases its ACR. When turning around a forward RM-cell, a destination will set CI=1 to indicate that the previous received data cell had the EFCI state set.
  - **NI**: The NI (no increase) bit is used to prevent a source from increasing its ACR. In contrast to CI=1, NI=1 does not require any decrease. A network element might set NI to 1 to indicate impending congestion. Normally, a source will initialize NI to 0 so that it might be allowed to increase its ACR, but it can indicate that it does not need a higher ACR by initializing NI to 1.

- **RA**: The RA bit is not used for ATM Forum ABR
- **ER:** The ER (Explicit Rate) field is used to limit the source ACR to a specific value. For each RM-cell ER is set by the source to a requested rate (such as PCR). It may be subsequently reduced by any network element in the path to a value that the element can sustain
- **CCR**: The CCR field is set by the source to its current ACR. It may be useful to network elements in computing a value to place in ER. For BECN cells, CCR=0.
- **MCR:** The MCR field carries the connection's Minimum Cell Rate. It may be useful to network elements in allocating bandwidth among connections. For BECN cells, MCR=0
- **QL:** The QL field is not used for ATM Forum ABR
- **SN:** The SN field is not used for ATM Forum ABR
- **CRC-10:** The RM CRC is the same CRC used for all OAM cells. It is computed as the remainder of the division (modulo 2) by the generator polynomial of the product of x10 and the content of the RM-cell payload excluding the CRC field (374 bits). Each bit of this payload is considered as a coefficient (modulo 2) of a polynomial of degree 373 using the first bit as the coefficient of the highest order term. The CRC-10 generating polynomial is: $1+x+x^4+x^5+x^9+x^{10}$. The result of the CRC calculation is placed with the least significant bit right justified in the CRC field

2.3.4 Source and Destination

The source and destination generate and receive the ATM cells transported through the network. They typically reside in the terminal adapters, at the extreme points of an ATM virtual connection. The virtual connection is routed through the network and includes a forward (from source to destination) and a backward (from destination to source) path. For both directions, the forward and backward components of a virtual connection use the same connection identifiers, and pass through identical transmission facilities. An ABR source and destination also form the two ends of the ABR control loop: the ABR source transmits cells for conveying feedback information towards the destination and the destination returns them towards the sourc0e. The behavior of the traffic source was defined in [1] by so called Source End System (SES) rules. Similarly, the behavior of traffic destination was defined in [1] by so called Destination End System (DES) rules.

2.3.5 Source Behavior [1]

The following items define the source behavior for CLP=0 and CLP=1 cell streams of a connection. By convention, the CLP=0 stream is referred to as in-rate, and the CLP=1 stream is referred to as out-of-rate. Data cells shall not be sent with CLP=1.

1. The value of ACR shall never exceed PCR, nor shall it ever be less than MCR. The source shall never send in-rate cells at a rate exceeding ACR. The source may always send in-rate cells at a rate less than or equal to ACR.

2. Before a source sends the first cell after connection setup, it shall set ACR to at most ICR. The first in-rate cell sent shall be a forward RM-cell.

3. After the first in-rate forward RM-cell, in-rate cells shall be sent in the following order:

   a) The next in-rate cell shall be a forward RM-cell if and only if, since the last in-rate forward RM-cell was sent, either:

      i) At least Mrm in-rate cells have been sent and at least Trm time has elapsed, or

      ii) Nrm-1 in-rate cells have been sent.

   b) The next in-rate cell shall be a backward RM-cell if condition (a) above is not met, if a backward RM-cell is waiting for transmission, and if either:

      i) No in-rate backward RM-cell has been sent since the last in-rate forward RM-cell, or

ii) No data cell is waiting for transmission.

c) The next in-rate cell sent shall be a data cell if neither condition (a) nor condition (b) above is met, and if a data cell is waiting for transmission.

4. Cells sent in accordance with source behaviors 1, 2 and 3 shall have CLP=0.

5. Before sending a forward in-rate RM-cell, if ACR > ICR and the time T that has elapsed since the last in-rate forward RM-cell was sent is greater than ADTF, then ACR shall be reduced to ICR.

6. Before sending an in-rate forward RM-cell, and after following behavior 5 above, if at least CRM in-rate forward RM-cells have been sent since the last backward RM-cell with BN=0 was received, then ACR shall be reduced by at least ACR*CDF, unless that reduction would result in a rate below MCR, in which case ACR shall be set to MCR.

7. After following behaviors 5 and 6 above, the ACR value shall be placed in the CCR field of the outgoing forward RM-cell, but only in-rate cells sent after the outgoing forward RM-cell need to follow the new rate.

8. When a backward RM-cell (in-rate or out-of-rate) is received with CI=1, then ACR shall be reduced by at least ACR*RDF, unless that reduction would result in a rate below MCR, in which case ACR shall be set to MCR. If the backward RM-cell has both CI=0 and NI=0, then the ACR may be increased by no more than RIF*PCR, to a rate not greater than PCR. If the backward RM-cell has NI=1, the ACR shall not be increased.

9. When a backward RM-cell (in-rate or out-of-rate) is received, and after ACR is adjusted according to source behavior 8, ACR is set to at most the minimum of ACR as computed in source behavior 8, and the ER field, but no lower than MCR.

10. When generating a forward RM-cell, the source shall assign values to the various RM-cell fields.

11. Forward RM-cells may be sent out-of-rate (i.e., not conforming to the current ACR). Out-of-rate forward RM-cells shall not be sent at a rate greater than TCR.

12. A source shall reset EFCI on every data cell it sends.

13. The source may implement a use-it-or-lose it policy to reduce its ACR to a value that approximates the actual cell transmission rate.

2.3.6 Destination Behavior [1]

The following items define the destination behavior for CLP=0 and CLP=1 cell streams of a connection. By convention, the CLP=0 stream is referred to as in-rate, and the CLP=1 stream is referred to as out-of-rate.

1. When a data cell is received, its EFCI indicator is saved as the EFCI state of the connection.

2. On receiving a forward RM-cell, the destination shall turn around the cell to return to the source. The DIR bit in the RM-cell shall be changed from "forward" to "backward", BN shall be set to zero, and the CCR, MCR, ER, CI, and NI fields in the RM-cell shall be unchanged except:

   a) If the saved EFCI state is set, then the destination shall set CI=1 in the RM cell and the saved EFCI state shall be reset. It is preferred that this step is performed as close to the transmission time as possible;

   b) The destination (having internal congestion) may reduce ER to whatever rate it can support and/or set CI=1 or NI=1.

3. If a forward RM-cell is received by the destination while another turned-around RM-cell (on the same connection) is scheduled for in-rate transmission:

a) It is recommended that the contents of the old cell are overwritten by the contents of the new cell;

b) It is recommended that the old cell (after possibly having been over-written) shall be sent out-of-rate; alternatively the old cell may be discarded or remain scheduled for in-rate transmission;

c) It is required that the new cell be scheduled for in-rate transmission.

4. Regardless of the alternatives chosen in destination behavior 3 above, the contents of an older cell shall not be transmitted after the contents of a newer cell have been transmitted.

5. A destination may generate a backward RM-cell without having received a forward RM-cell.

6. When a forward RM-cell with CLP=1 is turned around it may be sent in-rate (with CLP=0) or out-of-rate (with CLP=1).

2.3.7 Network Switch

Switching elements provide the necessary resources for storing and forwarding ATM cells from sources to destinations, namely port bandwidth and buffers. These are limited resources, the contention for which may lead to congestion in the form of loss or excessive delays of cells. An ABR switching element must monitor the usage of its resources to provide a proper feedback to the source. The ATM Forum decided not to specify the feedback mechanisms, embedded in individual network switches. Still, in order to assure interoperability, switch rules were defined in [1]. It is the task of each switch developer to provide for a proper feedback mechanism, which naturally has to obey all ATM Forum specified switch rules.

2.3.8 Switch Behavior [1]

The following items define the switch behavior for CLP=0 and CLP=1 cell streams of a connection. By convention, the CLP=0 stream is referred to as in-rate, and the CLP=1 stream is referred to as out-of-rate. Data cells shall not be sent with CLP=1.

1. A switch shall implement at least one of the following methods to control congestion at queuing points:
   a) *EFCI marking*: The switch may set the EFCI state in the data cell headers;
   b) *Relative Rate Marking:* The switch may set CI=1 or NI=1 in forward and/or backward RM-cells;
   c) *Explicit Rate Marking:* The switch may reduce the ER field of forward and/or backward RM-cells;
   d) *VS/VD Control*: The switch may segment the ABR control loop using a virtual source and destination.
2. A switch may generate a backward RM-cell. The rate of these backward RM-cells (including both in-rate and out-of-rate) shall be limited to 10 cells/second per connection. When a switch generates an RM-cell it shall set either CI=1 or NI=1, shall set BN=1, and shall set the direction to backward.
3. RM-cells may be transmitted out of sequence with respect to data cells. Sequence integrity within the RM-cell stream must be maintained.
4. For RM-cells that transit a switch (i.e., are received and then forwarded), the values of the various fields before the CRC-10 shall be unchanged except:
   a) CI, NI, and ER may be modified as noted in 1 above
   b) MCR may be corrected to the connection's MCR if the incoming MCR value is incorrect.
5. The switch may implement a use-it-or-lose-it policy to reduce an ACR to a value that approximates the actual cell transmission rate from the source.

2.3.9 Feedback Mechanisms

Feedback from network switches to the end systems gives sources (users) the information necessary to respond, by appropriately modifying their transmission rates, so that congestion is controlled or avoided – only the available bandwidth is used. In this way traffic sources are always transmitting at maximum possible speed without causing congestion. Feedback (control) information is conveyed in Resource Management (RM) ATM cells [9, 11, 17]. The traffic source periodically generates and transmits new RM cells, as specified in SES rules. Network switches modify individual fields inside traversing RM cells, according to the specified switch rules and current network status. At traffic destination, all incoming RM cells are deflected back to the traffic source, as specified in DES rules.

2.4 ABR source's share

The ABR service provides better service for data traffic by periodically advising sources about the rates at which they should be transmitting. The switches monitor their load and divide the available bandwidth fairly among active flows. This allows competing sources to get a fair share of the bandwidth while also allowing the link to be fully utilized. The feedback from the switches to the sources is indicated in resource management (RM) cells, which are periodically generated by the sources and turned around by the destinations.

The RM cells contain the source's current cell rate (CCR) and several fields that can be used by the switches to provide feedback to the source. These fields are: explicit rate (ER), congestion indication (CI) flag, and no increase (NI) flag. The ER field indicates the rate that the network can support at the particular instant in time. When starting at the source, the ER field is usually set to the peak cell rate, and the CI and NI flags are clear. On the path, each switch reduces the ER field to the maximum rate it can support, and sets CI or NI if necessary [9, 11, 17].

The RM cells flowing from the source to the destination are called forward RM cells (FRM's) while those returning from the destination to the source are called backward RM cells (BRM's). When a source receives a BRM, it computes its allowed cell rate (ACR) using its current ACR, the CI and NI flags, and the ER field of the RM cell [8].

The ATM Traffic Management Specification Version 4.1 [1] supports two classes of rate-based flow control scheme: Binary feedback and Explicit Rate (ER) scheme. In the binary feedback scheme, any switch along a VC connection can set the EFCI bit value, the destination changes the CI bit in the RM cell before relaying it back to the source. And this algorithm is called as EFCI algorithm. If the source receives a RM cell and the CI bit is set (indicating network congestion), it reduces its ACR by the amount RDF * ACR, where RDF is called the Rate Decrease Factor. If the CI bit is not set (that is no congestion in network), ACR is increased by RIF * PCR, where RIF is the Rate Increase Factor. ACR never exceeds the PCR and never goes below MCR. The parameters PCR, MCR, RDF and RIF are negotiated during the establishment of the connection.

In the other rate-based class, the ER scheme, switches along the transfer path play a more active role than in the case of binary feedback. Basically, the switch computes a fair-share of the bandwidth for each connection passing through it. When a RM cell of a particular connection passes through this switch, the ER field value of the Resource Management (RM) cell is changed to the minimum of the ER field value and the connection fair-share as computed by the switch. Upon receiving of the backward RM cell, the source will change its ACR to the minimum of the ER field value and the new ACR calculated based on the CI bit value as in the case of the binary feedback scheme. There are a wide variety of ER schemes because the fair-share computation done in the switch can be performed by implementing different algorithms.

Generally these algorithms can be divided into two classes. The first class of schemes tries to compute the fair-share as accurately as possible. The computation is performed using state information for each VC stored locally in each switch. Due to inaccuracies in the local state information, the computed fair-share may not be equal to the exact fair-share. Congestion-indication mechanisms, such as the traffic load or the queue length, can be used to correct the computed fair-share, and improve performance. The examples of this class algorithm are ERICA [3] and NIST algorithms respectively. The second class of schemes uses an approximation per-VC, and also uses congestion-indication mechanisms to make the approximation converge to the fair-share. The schemes in this class are typically simpler than those in the former class, since they do not require state information per each VC and may be in certain circumstances more resilient to errors. EPRCA [8] is one of these kinds of algorithms.

2.5 Summary

The nature of the new service is different from VBR and CBR services in several ways. First, ABR connections will share the available bandwidth. Second, the share of available bandwidth for each ABR connection is dynamic and may diminish down to a specified minimum cell rate (MCR). Third, the ABR service is appropriate only for applications, which can adapt their rates to the time-varying available bandwidth and tolerate unpredictable cell delays.

The source and destination generate and receive the ATM cells transported through the network. The behavior of the traffic source was defined in [1] by so called Source End System (SES) rules. Similarly, the behavior of traffic destination was defined in [1] by so called Destination End System (DES) rules. Switching elements provide the necessary resources for storing and forwarding ATM cells from sources to destinations, namely port bandwidth and buffers. Switch rules were also defined in [1].

Feedback (control) information is conveyed in Resource Management (RM) ATM cells. The traffic source periodically generates and transmits new RM cells, as specified in SES rules. According to the switch algorithm, switch calculates the available bandwidth and put that information RM cell that will convey to the source. Source modifies its rate according to the information from RM cell.

CHAPTER 3

ANALYSIS OF SES RULE 3 AND ITS MODIFICATION

3.1 Introduction

Sources that use ABR service category should some way know the network information to adapt its rate properly. RM cells provide this information for the sources. But for high-speed connections, no need to send RM cells in excess by which the bandwidth will be lost in sending control information instead of data information. This chapter analyses SES rule 3 and modified SES rule 3 along with varying the parameter Nrm for high-speed connections.

3.2 SES Rule 3

At any instant, sources have three kinds of cells to send: data cells, FRM cells and BRM cells [12]. The relative priority of these three kinds of cells is different at different transmission opportunities.

First, the sources are required to send an FRM after every 31 cells (Nrm). However, if the source rate is low, the time between RM cells will be large and network feedback will be delayed. To overcome this problem, a source is supposed to send an FRM cell if more than 100*ms* (Trm) has elapsed since the last FRM. This introduces another problem for low-rate sources. In some cases, at every transmission opportunity the source may find that it has exceeded 100*ms* and needs to send an FRM cell. In this case, no data cells will be transmitted. To overcome this problem, an additional condition was added that there must be at least one other cell between FRMs.

An example of the operation of the above condition is shown in figure 3.1. The figure assumes a unidirectional VC that is there are no BRMs to be turned around and it has three parts. The first part shows that when the source rate is 500 *cells/sec*, every 32^{nd} cell is an FRM cell. The time to send 32 cells is always smaller than 100*ms*. In the second part, the source rate is 50 *cells/sec*; hence 32 cells take 640*ms* to be transmitted. Therefore, after 100*ms* an FRM is scheduled to in the next transmission opportunity. The third part shows the scenario when the source rate is 5 *cells/sec*. The inter cell time itself is 200*ms*. In this case, an FRM is scheduled every third slot.

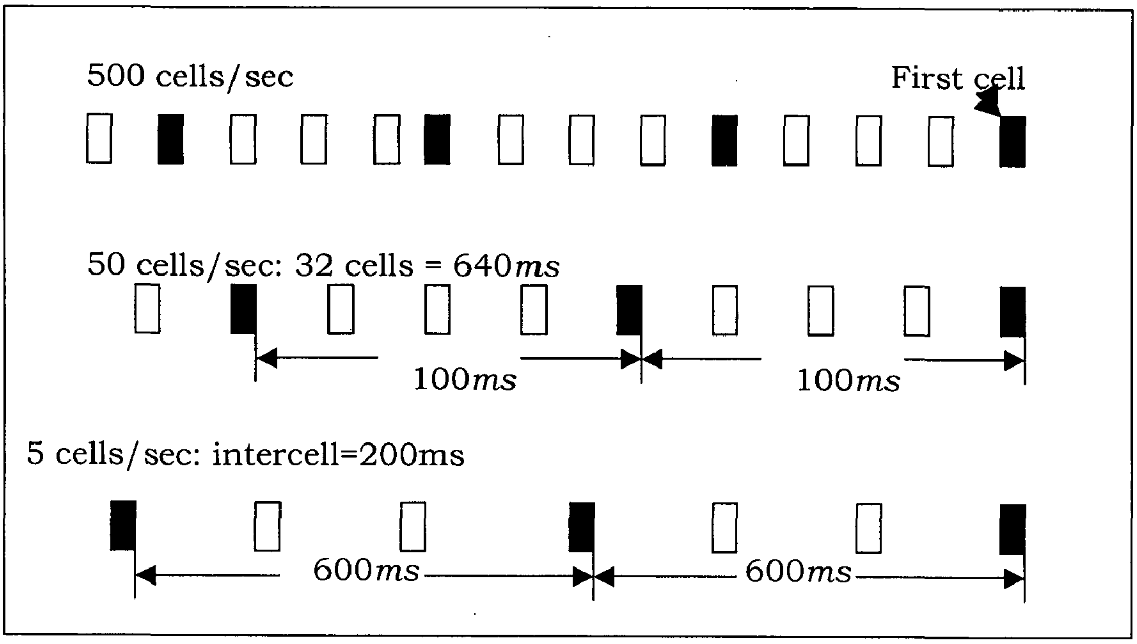


Figure 3.1: Frequency of forward RM cells

Second, a waiting BRM has priority over waiting data, given that there is no BRM has been sent since the last FRM. But, if there are no data cells to send, waiting BRMs may be sent.

Third, data cells have priority in the remaining slots. The second and third part of this rule ensures that BRMs are not unnecessarily delayed and that all available bandwidth is not used up by the RM cells.

Figure 3.2 illustrates the scheduling of FRMs, BRMs and data cells. In the first slot, an FRM is scheduled; in the next slot assuming that a turned-around BRM is awaiting transmission, a BRM is scheduled; and in the remaining slots data is scheduled.

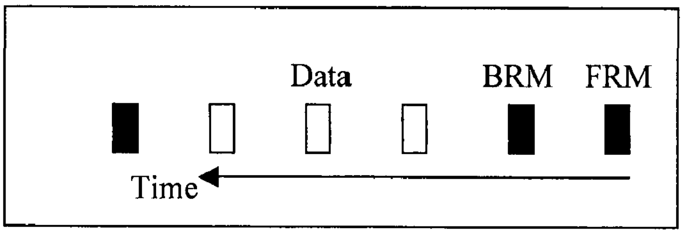


Figure 3.2: Scheduling of FRM, BRM and Data cells

3.3 Limitations of SES Rule 3 for High-Speed Connections

The specifications [1] select a default value of 32 for Nrm to ensure that the control overhead does not exceed approximately 6%. During normal operation, 1/32nd or 3% of all cells are FRM cells. Another 3% of cells are BRM cells resulting in a total overhead of 6% [6]. In practice, the choice of Nrm affects the responsiveness of the control and the computational overhead at the end systems and switches. For a connection running at 155 Mbps, the inter-RM cell time is 86.4 microseconds while it is 8.60 ms for the same connection running at 1.55 Mbps. Therefore, the inter-RM interval determines the responsiveness of the system [6].

At high data rates, a small RM cell interval can result in high frequency rate variations caused by the ABR feedback [20, 22]. If traffic such as video is being transported over ABR, the rate variations must be minimized to reduce variations in the quality of service. Users require a constant quality of service in a real-time application such as real-time video. One way of reducing the ABR rate changes is to send RM cells less frequently, i.e., set Nrm to a large value, instead of 32.

In the experiment shown in next chapter, we vary Nrm and examine the allowed cell rates at the sources, as well as the queue lengths at the switches. Nrm takes the values 8, 32 and 256. The reason why we have selected these values is that values smaller than 8 incur a very high control cell overhead and are not very realistic. 32 is the default value, and 256 is the maximum allowed value.

3.4 Control Loop Response Time

This section briefly describes the three main factors that are influencing the ABR control loop response time.

3.4.1 Inter-RM Cell Time (IRCT)

ABR enabled ATM switches can send feedback information only when RM cells traverse through them. Inter-RM cell time is therefore limiting the fastest possible response time. IRCT is not a constant value since it depends upon ABR connection transmission speed. Lower transmission speeds result in higher IRCT values. Procedure for calculation of IRCT time is specified in SES rule no. 3 [1]. It says that traffic sources must transmit a new RM cell at least after transmitting 31 other ATM cells (parameter Nrm [1]).

3.4.2 Round Trip Time (RTT)

Round trip time is time needed for a RM cell to travel from traffic source to traffic destination and then back to traffic source. Two most important parts of RTT are delays on transmission paths and time spent in queues.

3.4.3 Averaging Interval (AI)

ABR feedback mechanisms in ATM switches have to be constantly aware of what is going on in the network in order to make reasonable transmission speed adjustments and thus maximize network utilization. The best way to gather the required network status information is by measuring of real data [3, 16]. Unfortunately, due to short-lived fluctuations in traffic flows, the use of instantaneous values of measured parameters is not advisable and can even destabilize the entire ATM network – the control loop may not be able to reach stability, resulting in low network utilization. It is therefore necessary for average measured parameter values to be calculated over a pre-specified measurement interval. The length of measurement interval is known as Averaging Interval (AI).

3.5 Modified Version of SES Rule 3

As mentioned in the previous section, ABR feedback mechanisms perform the computation of available bandwidths (and hence the offered bandwidth) based on periodic averaging interval (AI). This averaging interval is generated by the system every few milliseconds [3, 4, 5, 10, 11]. If the averaging interval is too short, the system will be very dynamic (reacts to even small changes) and can show oscillatory behavior. On the other hand, if the averaging interval is too long, the system may not use resources efficiently, since it may take a very long time to reach convergence towards fair share. Therefore, the performance of the ABR control loop depends on appropriate engineering of the averaging interval.

Defining the AI value is not an easy task. The following factors can influence the required length of an averaging interval:

- Characteristics of cell rate fluctuations in VBR and UBR service class virtual connections,
- Characteristics of cell rate fluctuations of individual ABR virtual connections,
- Minimum and maximum cell rates of individual ABR virtual connections,

- Selected ABR feedback mechanism,
- RTT value,
- ATM switch hardware capabilities.

The only AI values obtained so far were derived through simulations and field trials [3, 4, 5, 10]. Typically, AI takes values from 1 ms to 10 ms. As mentioned in the previous section, a new RM cell has to be transmitted after every 31 other ATM cells. It can be readily seen that for high-speed ATM connections, the Inter-RM Cell Time gets negligibly small in comparison with the AI value. It is therefore obvious that in high-speed ABR connections, the unnecessary bandwidth gets lost for transmission of excess RM cells. Unfortunately, this kind of situation was not envisioned when SES rule no. 3 was composed. In an ideal case, it would be enough to transmit a single RM cells in each averaging interval. In reality, two possible obstacles are imminent:

- various ATM switches do not necessary use the same AI value,
- due to asynchronous network, there is no synchronization between the end of an averaging interval and arrival of a new RM cell.

Therefore more than one RM cell should be transmitted within one averaging interval.

According to the motives presented above, we propose a coupling between the length of Averaging Interval and the Inter-RM Cell Time. That modification of SES rule number 3 increases the utilization of the available network resources, without influencing the feedback delay of ABR control loops. As a direct consequence of the aforementioned averaging interval limitations, introduction of a new parameter Minimum Inter-RM Cell Time (MIRCT) is suggested. By doing this we actually limit the transmission speed of RM cells to 1/MIRCT cells per second, independently of individual ABR connection transmission speeds. In order to minimize the influence of a reduced number of RM cells on ABR control loop response times, the MIRCT value should be calculated according to Eq. (3.1). The factor ten in the denominator nullifies the aforementioned synchronization problems.

$$\mathbf{MIRCT = AI/10} \qquad \text{--------------------} (3.1)$$

In the following calculations, we presume an averaging interval (AI) length of 5 ms. Increment of network utilization depends upon individual ABR connection transmission rate. Threshold Transmission Rate (TTR), where IRCT = MIRCT, can be calculated as depicted in Eq. (3.2). In our case, it amounts to approximately 27 Mbps. In this case, RM cells use 848 kbps of the ABR connection bandwidth.

TTR = 424 * 32 / MIRCT -------------------- (3.2)

Following is an example of 2.4 Gbps ABR connection. When using original SES rule no. 3, we need 75 Mbps of ABR connection capacity just to transfer RM cells. On the other hand, when implementing proposed SES rule no. 3 modification and assuming AI = 5 ms, only 848 kbps of ABR connection capacity is required for transfer of RM cells. By using the proposed modification, a gain of additional 74 Mbps of the bandwidth is achieved. This amounts to a good 3 % of the total available bandwidth.

IRCT = 32 * 1/ ABR Connection cell rate ----------- (3.3)

Gain = **(1/32) * (MIRCT-IRCT)/ MIRCT, if IRCT < MIRCT**

= **0,** **Otherwise** ----------- (3.4)

Increment of network utilization can be directly calculated by using Equations (3.3) and (3.4). It can be readily seen that maximum gain of 1/32 = 3.125 % of total ABR connection capacity can be achieved by using the MIRCT value. In order to implement this proposal, merely some logic in ABR traffic sources (SES) has to be modified. Other elements included in ABR connections (network switches, traffic destinations, feedback mechanisms) remain unmodified.

3.6 Summary

SES rule number 3 indicates that after sending 31 data cells one RM cell should be sent (Nrm). This indicates that Nrm determines the responsiveness of the system. For high-speed connections inter RM cell time is less and for that of low-speed, it is high. So in the former case, there will be excess of RM cells in the network and we can increase Nrm value. But experiments prove some limitations to this approach. So SES rule 3 was modified by introducing additional parameter MIRCT which is $1/10^{th}$ of averaging interval. With this technique there is gain up to 3% of total bandwidth.

CHAPTER 4

DESIGN

4.1 Introduction

The design goals represent the overall objectives that need to be achieved after imposing the modifications. The main goals of the system that to be built are efficient utilization of link bandwidth, stable and robust operation after induction of the modifications. This chapter introduces the goals that have to be met as well as the design of the source behavior for the both techniques. These are shown in the form of flow-charts.

4.2 Design Goals

In designing the system with modified approach our main goal is to maximize link utilization and achieve stable and robust operation. Each of these goals is explained below.

1) *Utilization:* Our goal was to maximize the link utilization. This is done by allocating as much of the available capacity to active ABR flows as possible. The entire link capacity that is not used by the higher priority VBR and CBR service categories is potentially available to ABR. To reduce amount of bandwidth for control information RM cells are sent according to the modified SES rule 3.
2) *Stability and Transient Performance:* A *stable* system one that can reestablish its steady state after perturbations. The *transient performance* of the scheme determines how quickly the steady state is reestablished.
3) *Robustness:* In cases where the system has *no steady state* (e.g., due to persistent variation in capacity and demand), the scheme should be robust. This means that its essential performance metrics should not degrade to unacceptable levels. Among the switch algorithms ERICA has got more importance and proved to be stable and robust. So ERICA is used as the standard switch algorithm in this thesis.

4.3 Design of Source Behavior for SES Rule 3

The figure 4.1 provides conforming behavior for the source end system (SES). It represents a minimal but complete implementation of the specified end system behavior. It assumes, but does not detail, a cell scheduler mechanism that controls the cell emissions from the SES. For simplicity of example, it also assumes that only out-of-rate forward RM-cells will be sent when ACR < TCR.

The behavior of the SES is controlled by the values assigned to a set of parameters. PCR, MCR, and ICR, are in units of cells per unit time, and RIF is dimensionless. RDF, CDF and Nrm are dimensionless. PCR and MCR are agreed upon at connection setup time. ICR, RIF, RDF, CDF and Nrm are established by the network(s) at connection setup time, with values that are determined to best optimize performance over various network trade-offs. Values for these parameters observe the following constraints:

MCR <= ICR <= PCR

MCR <= ACR <= PCR

0 <= CCR <= min (ACR, PCR)

where CCR is the current cell rate, reflecting the user's offered traffic.

4.4 Design of Source Behavior for Modified SES Rule 3

In order to design this proposal, merely some logic in ABR traffic sources (SES) has to be modified. Other elements included in ABR connections (network switches, traffic destinations, feedback mechanisms) remain unmodified. Only SES rule 3 was changed to introduce additional parameter *mirct*. The design of source behavior for this portion was represented in figure 4.2.

SES Variables (Per connection)

count - Number of cells sent (all kinds) since the last forward RM-cell

unack- Number of forward RM-cells sent without an RM received

time-to-send- The time scheduled to send the next cell (in-rate)

last-RM- The time that the most recent RM was sent

turn-around- A flag indicating there is an RM-cell to turn-around

first-turn- A flag indicating the (first) turn-around RM has priority over data cells

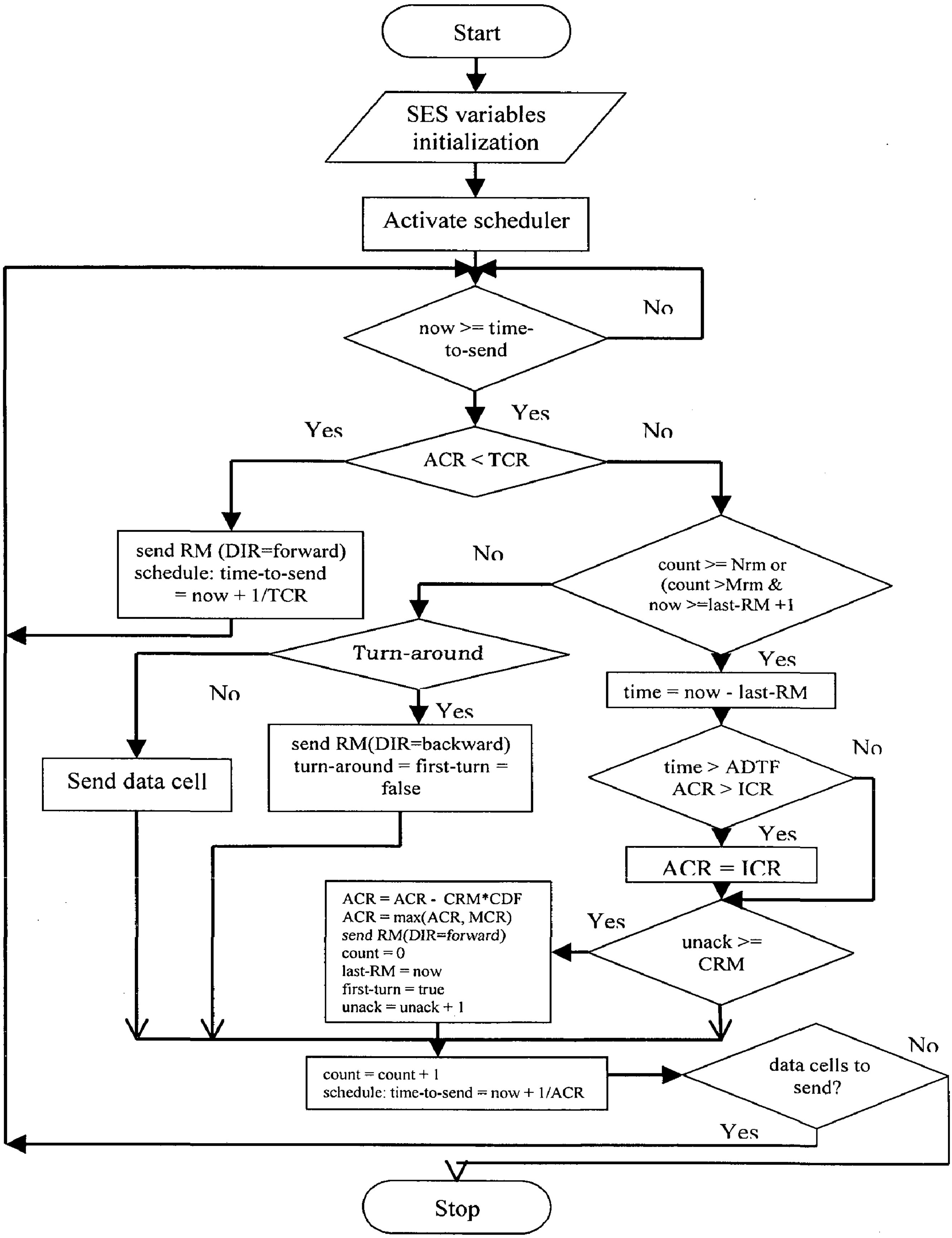


Figure 4.1: Design of source end system as per current rules

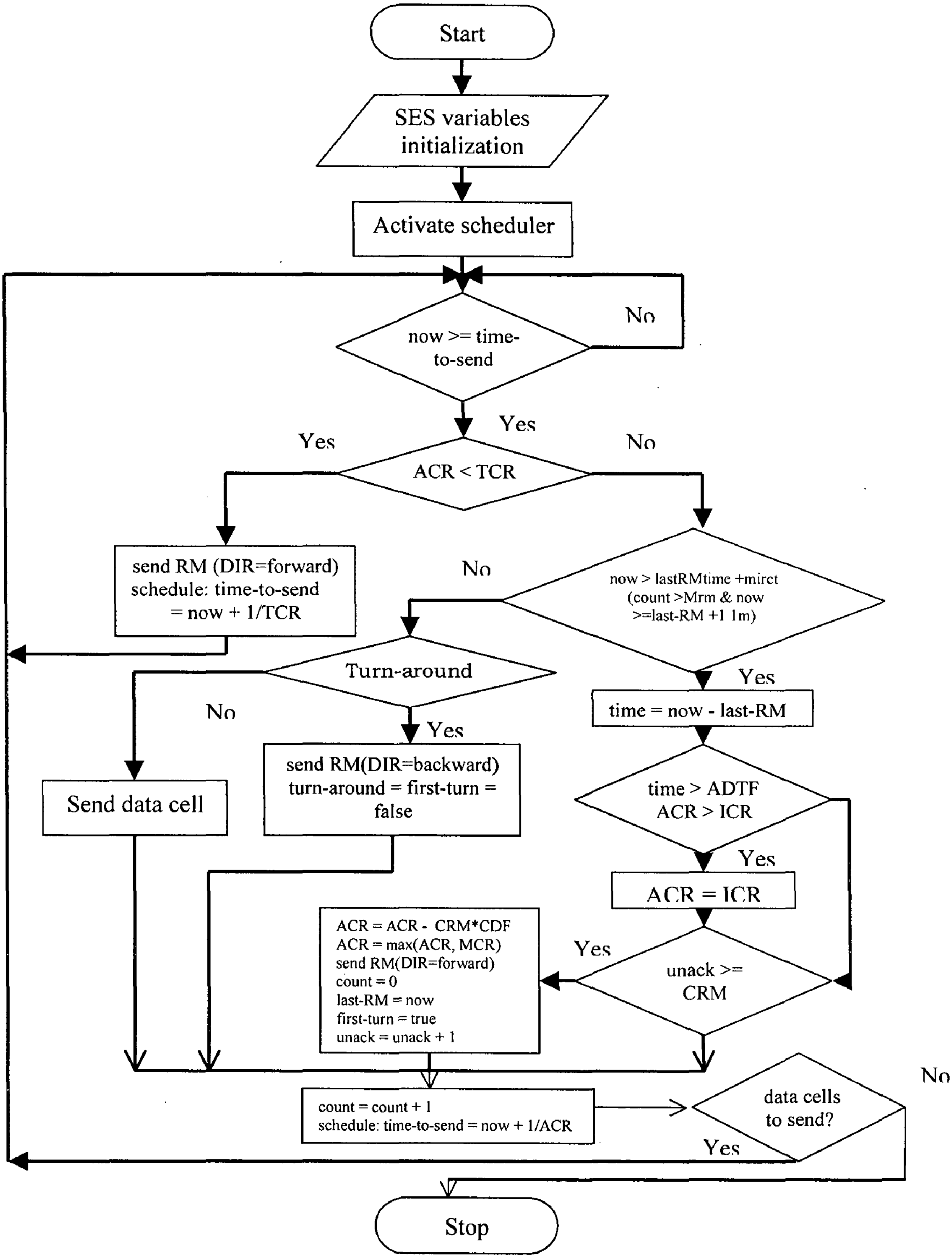


Figure 4.2: Design of source end system as per modified rules

4.5 Summary

The design part has someway introduced the goals that need to be met. More bandwidth utilization for data cells, stable and robust operations are described as goals. Following design of the source end system is specified for current technique as well as the proposed technique.

CHAPTER 5

IMPLEMENTATION

5.1 Introduction

Several parameter values have to be chosen before proceeding with the system implementation. Similarly there are other implementation issues also. This chapter prepares to deal with such issues. Main issues considered are parameter choices, queue control function and fairness parameter choices. Values chosen for parameters are measurement parameters like averaging interval (AI) and averaging parameters like α. Queue control function is used by ERICA to drain the queues. The fairness parameter attempts put the system towards a stable operating region. Rest of the chapter deals with the implementation in simulator. All the settings and the files that has to be modified are listed.

5.2 Implementation Issues

5.2.1 Measurement and Averaging Related Parameters

The essential metrics used in ERICA that is load factor (z) and number of active connections N for FairShare calculation are measured during consecutive switch averaging intervals [3, 4, 16]. Variation in demand, available capacity, and number of currently active connections could lead to errors in the estimation of these metrics, which, in turn, would lead to errors in feedback. Therefore, the choice of the switch averaging interval is critical to the performance of ERICA.

To determine a reliable averaging interval, observe that the activity of any source is determined within a round-trip time (RTT). Moreover, the maximum time for feedback from any switch to reach a source, and the resultant activity to be experienced at the switch (called the "feedback delay") is the maximum RTT (max RTT) plus the maximum inter-RM-cell-time (max inter-RM-cell-time). Allowing time for transient loads between averaging intervals to subside, a reliable value for the switch averaging interval is at least 2 (max RTT + max inter-RM-cell-time). Choosing averaging intervals smaller than max RTT poses the risk of errors in z and N (due to temporary inactivity of sources), and choosing intervals smaller than max inter-RM cell time poses the risk of not giving feedback to some sources in every measurement interval [4].

One solution for above problem is to use a single *base averaging interval* [3] and optionally use exponential averaging techniques to improve reliability and reduce variance in the measurements. Several simulations have showed that the base averaging interval is to be chosen statically in the range [1 ms, 10 ms]. In this simulation we use a static averaging interval of 5 *ms*.

Exponential averaging can be applied for the load factor *z* using the formula:

z = **[exponential average of input rate / (f (Q) * exponential average of available capacity)]** -------------------- (5.1)

Where the exponential average of input rate or available capacity (denoted as x) is calculated as $x = \alpha x + (1-\alpha)\, x$. Simulations indicate that a value of 0.8 is sufficient given a base averaging interval choice in the range [5 ms, 10 ms] [3]. This value gives significant weight to the latest sample of input rate or available capacity.

Averaging the number of active VC's, *N* is performed in a different manner. The problem is that when not even one cell of an "active" VC is seen in the base averaging interval, it would be counted as inactive [4, 14]. This error would result in an increase in FairShare, which the minimum allocation is given to VC's, and could lead to instability. This problem can be simply addressed by using a separate interval for measuring *N* and set this interval to *max {RTT, 1/ (minimum rate allocation)}* of any VC. Since this is not possible, approximate it though this procedure. First define the "activity level" of a VC as a real number between 0 and 1. The activity level is initialized to 1 whenever any cell from the VC is seen and decayed by a multiplicative parameter *DecayFactor* in each successive interval in which a VC is inactive. At the end of each interval, the sum of all activity levels would give the value of which is now a real number). Setting *DecayFactor* to a value sufficiently close to unity would ensure that the error in estimation due to the exponential decay would be small. It is observed that a value of *DecayFactor* in the range [0.9, 0.95] is sufficient given our base averaging interval choice in the range 5 ms, 10 ms] [4, 14].

5.2.2 Queue Control Function for ERICA

The queue control function *f (Q)* used in ERICA is one of several possible functions [24, 25], and has four parameters: T_0, *QDLF, a and b*. The parameter T_0 which specifies the target queuing delay is affected by several other system parameters such as the available buffer size, the bottleneck link speed, and the maximum round trip time (or the base averaging interval length). T_0 also affects the decrease function component of *f (Q)* in conjunction with the parameters *a* and *b*. The decrease function affects how quickly excess queues are drained.

A heuristic used in ERICA ensures that the maximum oscillation of queues in the steady state will be no larger than Q_0. In steady state, the maximum deviation of the load factor is determined by the parameter δ [16, 17]. Specifically, assuming that queueing deviations are corrected in one averaging interval, we have the relationship:

$$T_0 \geq \delta \geq \textbf{Base Averaging Interval} \qquad \text{----------- (5.2)}$$

Given that our choice of is 0.1 and the base averaging interval lies between [5 ms, 20 ms], then lies between [0.5 ms, 2 ms].

The parameter QDLF (queue drain limit factor) limits the amount of available capacity that can be allocated as *drain capacity* to clear excess queues, and determines the effectiveness of the queue control policy in reacting to transient queues. When the aggregate input rate is equal to the available capacity QDLF also determines the minimum value of the load factor *z*. The range of *z* determines the range of possible feedback values or the maximum possible oscillations in feedback (a stability concern). QDLF choice of 0.5 balances these conflicting concerns for a wide range of configurations and loads.

5.2.3 The Max–Min Fairness Parameter δ

The max–min fairness parameter δ defines the steady-state operating region toward which ERICA attempts to drive the system. Specifically, in ERICA, we consider the system be max–min fair when the load factor *z* is in the range $[1, 1 + \delta]$ and all allocations are equal.

In the steady state, the minimum drain capacity is determined by the relation

$$0 \leq \delta * \textbf{Target Capacity} \leq \textbf{Available Capacity - Target Capacity} \qquad \text{-- (5.3)}$$

Rearranging the terms and applying the relationship that

Target capacity is at least QDLF × Available Capacity,

$$\boldsymbol{\delta \in (0, (1/QDLF) - 1]} \qquad \text{----------- (5.4)}$$

For QDLF of 0.5, this gives us a range of (0, 0.5] for **δ**. The upper bound is a weak one since a value of 0.5 would result in minimal drain capacity and possibly large transient queues (due to the equalization of rates to the maximum allocation). The value of **δ** chosen in ERICA is 0.1, which allows sufficient drain capacity and leaves a nontrivial zone for rate equalization to improve convergence toward max–min fairness.

5.2.4 Selection of ABR Parameters

All the ABR service parameters are set to their default values specified in the ATM Forum specification [1]. Only Nrm was varied to have a better utilization of the network bandwidth. These are listed in the following table.

ABR parameters	PCR (Mbps)	155
	ICR (Mbps)	7.49
	MCR (Mbps)	1.49
	Nrm	8,32and 256
	RIF	0.0625
	RDF	0.0625
	Crm	32
	Mrm	2
	TRM (ms)	1
	ATDF (ms)	50
	CDF	0.0625
	Distance (KM)	20

Table 5.1 Default ABR parameters used

ERICA parameters	ALPHA	0.8
	DELTA	0.1
	Factor a/b	1.15/1
	QDLF	0.5
	AI (ms)	5
	DF	0.9
Source parameter	MIRCT (ms)	5

Table 5.2: ERICA switch algorithm parameters and source parameter

5.2.5 Selection of Testing Suit

We use the popular configuration-specified by ATM Forum to test the utilization, queue lengths and fairness of the scheme. The configuration has multiple bottlenecks and connections with different round-trip times. This configuration was selected by the ATM Forum traffic management working group as the test configuration to compare various schemes.

The system model is as shown in figure 5.1 There are three ABR connections, S1-D1 goes through three switches sw1, sw2 and sw3, and S2-D2 and S3-D3 goes through only two switches of sw2 and sw3 respectively. Using this simple network rather than a large one could get better understanding of the unfair problems. ABR source S1 is bottlenecked in [0,100] milliseconds; the highest rate is 10 Mbps. After 100 milliseconds S1 can send cells as usual, and the PCR is 155 Mbps. The other two sources S2 and S3 are normal ABR sources, and the PCR of S2 and S3 is 155 Mbps. All links are 155 Mbps and 20 KM long. The same configuration was used for all 20Mbps connections.

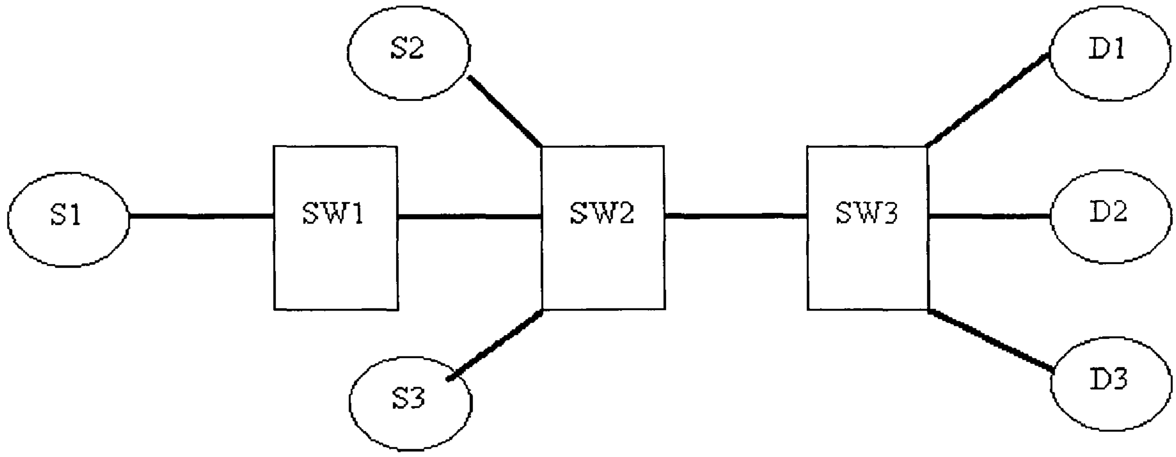


Figure 5.1: Multiple source configuration

5.3 Simulation in NIST ATM simulator

5.3.1 Simulator Framework

The ATM/HFC Network Simulator was developed at the National Institute of Standards and Technology (NIST) to provide a flexible test bed for studying and evaluating the performance of ATM and HFC networks. The simulator is a tool that gives the user an interactive modeling environment with a graphical user interface. NIST has developed this tool using both C language and the X Window System running on a UNIX platform. The ATM/HFC Network Simulator allows the user to create different network topologies, set the parameters of component operation, and save/load the different simulated configurations.

The simulator is *event* driven [13]. Components send each other events in order to communicate and send cells through the network. The software contains an event manager which provides a general facility to schedule and send or "fire" an event. An event queue is maintained in which events are kept sorted by time. To fire an event, the first event in the queue is removed, the global time is set to the time of that event and any action scheduled to take place is undertaken. Events can be scheduled at the current time or at any time in the future. Scheduling events for the past is considered illogical. Events scheduled at the same time are not guaranteed to fire in any particular order.

5.3.2 Simulator Settings

1) List of components in the network

ATM applications	-traffic generator
Link	-simulates a link which carries data
Broadband terminal equipment	-simulates a Broadband ISDN node, e.g., a host computer, workstation, etc.
ATM switches	-component that switches or routes cells over several virtual channel links

2) Types of cells

Data cells, RM cells

3) List of files modified in the source code of the simulator

i) For present SES rule 3:

Rbbte.c - Nrm value is varied

Rbswitch.c - Exponential averaging method was added for ERICA

ii) For modified SES rule 3

Rbbte.h - new parameter *mirct* was added

Rbbte.c - modified SES rule 3 was added to the code

Rbswitch.c - Exponential averaging method was added for ERICA

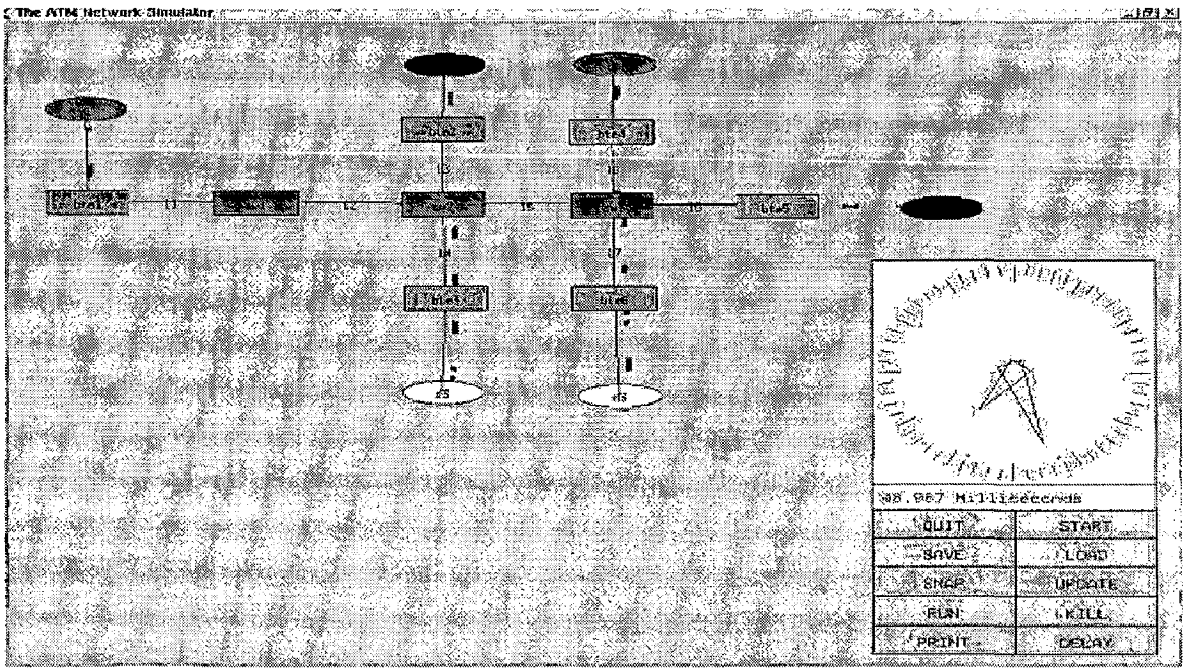


Figure 5.2: Multiple source configuration in NIST ATM simulator

5.3.3 Logging Data [13]

Data logging is a method of recording the values of a parameter while the simulation is running (in the NIST's ATM simulator). Logging for a parameter is toggled on and off by clicking the middle mouse button on the right hand box on the information window line for that parameter. When logging for a particular parameter is turned on, its box in the information window becomes white, and every new value of that parameter with a corresponding time stamp is saved in a file. The file is created in the current directory with the name *sim_log.xxxx* where *xxxx* is the process ID of the simulator. The file created by this process will contain an entry for every value change of every parameter that was tagged for data logging. Every entry will consist of parameter number, time tick, and parameter value at that tick. The parameter number will be identified by name in the file header. For Switch and B-TE components, clicking on the right-hand box next to the component name in an information window results in the arrival of each cell (on n cells) into that component being logged into the sim_log file. For these components there is an input parameter, "Logging every (n) ticks," that lets the user decide on the frequency of the data logging.

The following brief example shows the format of a sim_log file:

```
# 1 'switch3' 'Name'
# 2 'switch2' 'Cells in ABR Q to link22'
# 3 'switch2' 'Cells dropped in ABR Q to link22'
2 3003 1
2 3003 2
2 3043 3
1 3277 switch3 link22 4
2 4095 3
3 4175 1
...
```

The lines at the head of the file starting with pound sign (#) are a listing of all of the parameters that were marked for data logging when the simulator was running. The number immediately following the # is the ID number that will be used in the remainder of the file to identify the parameter. The rest of the line gives the component name and parameter name respectively.

All lines following the ones marked with # are the actual data recorded during the simulation. The first column is the parameter ID, the second column is the time (in ticks), and the third column is the value of the parameter at that time. A slightly different format is used for the case where the data logged represents cell arrival at a switch or B-TE component. (This is the logging enabled with the box on the component's name line.) In this case the third column is the name of the component on which the data is collected (switch3 in the example). The fourth column is the name of the link from where the cell arrived (link 22), and the fifth column is the route number.

5.3.4 Post Simulation Analysis Using the Log File

In many cases it desirable to have data on one or more network components plotted or otherwise presented for further analysis.

The Filter script

One way of doing this is to parse the sim_log file in order to get a data file with two columns (X, Y) that can be fed into any datasheet program such as Lotus 1-2-3, GnuPlot, etc. A "filter" program is provided with the simulator package for this purpose. The usage for the filter is as follows:

filter.sh sim_log.*xxxx* ***component_name parameter_name > output file***

The above line will send the filter output to the output file, if nothing is mentioned output is displayed on standard output device.

5.4 Summary

The reasons for selecting values for measurement and averaging related parameters, queue control function and fairness parameter δ are explained. The implementation part deals with simulation in the NIST ATM simulator. NIST ATM simulator was event driven and specially designed for ATM networks analysis.

Regarding implementation in the simulator, some part of code has to be changed to introduce the modifications. List of all those files are given along with simulator settings. Finally method of capturing the data while simulation is running, and how to do the simulation analysis after the data obtained from the simulator was given.

CHAPTER 6

SIMULATION AND RESULTS

6.1 Introduction

Chapter 4 specifies that the goals to be achieved are utilization, stability and robustness. This chapter discusses about each goal through results. At first the default value of 32 for Nrm is varied and results are compared. Then the modified version of SES rule 3 is evaluated to find out whether the technique has satisfied the goals. In this case links of bandwidth 155Mbps and 20Mbps are considered to prove that if the transmission rate is less than 27Mbps, this technique works worse.

6.2 Results for Varying Nrm

1) *Utilization*: It is clear that there will be much better utilization of the link if Nrm = 256. Because number of RM cells received in this case are less compared to the case of 32 and 8. So the extra bandwidth available was given to data cells and we have reduced the control information in this case.

2) *Stability and Transient performance*: From the figures 6.1 and 6.2 there is a difference in the rate of increase of ACR for the three Nrm values. Since RIF is set to 1/16, the ACR comes up in steps on the receipt of every BRM cell. With Nrm = 8, the source receives BRMs more frequently than with Nrm = 256. As a result, the ACR for sources first reaches optimum value faster for Nrm = 8. But the overhead with small Nrm values is quite high, however. Another interesting observation is that for smaller Nrm values, sources does not start rising as fast as with larger Nrm values because the high RM cell overhead causes the data of the sources to take a longer time to be transmitted, and hence the three sources must share the bottleneck link for a longer time. Source 3 ACR values are exact replica of source 2 and are not shown here. At *100ms* source 1 becomes active and for Nrm = 256 it has taken so may steps to achieve stable value. Before that the variation is huge for Nrm = 256. So this approach should not be used for high-speed connections as it may not give us a stable and transient system.

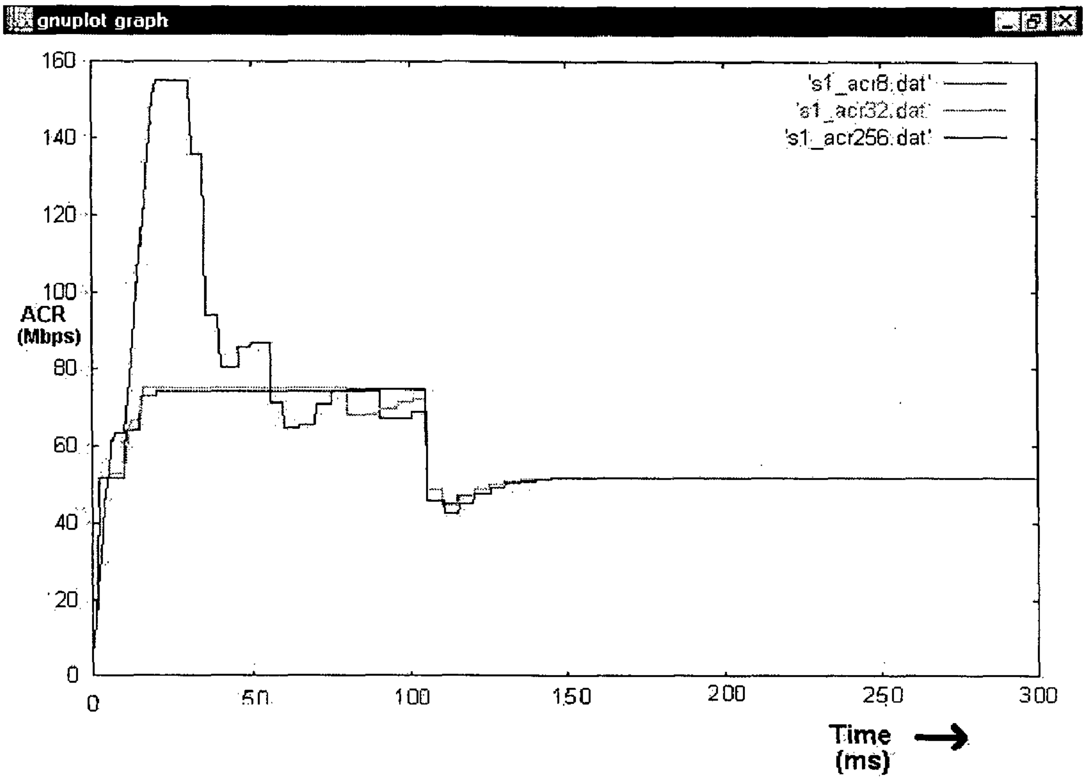


Figure 6.1: Source 1 ACR values for Nrm=8, 32 and 256

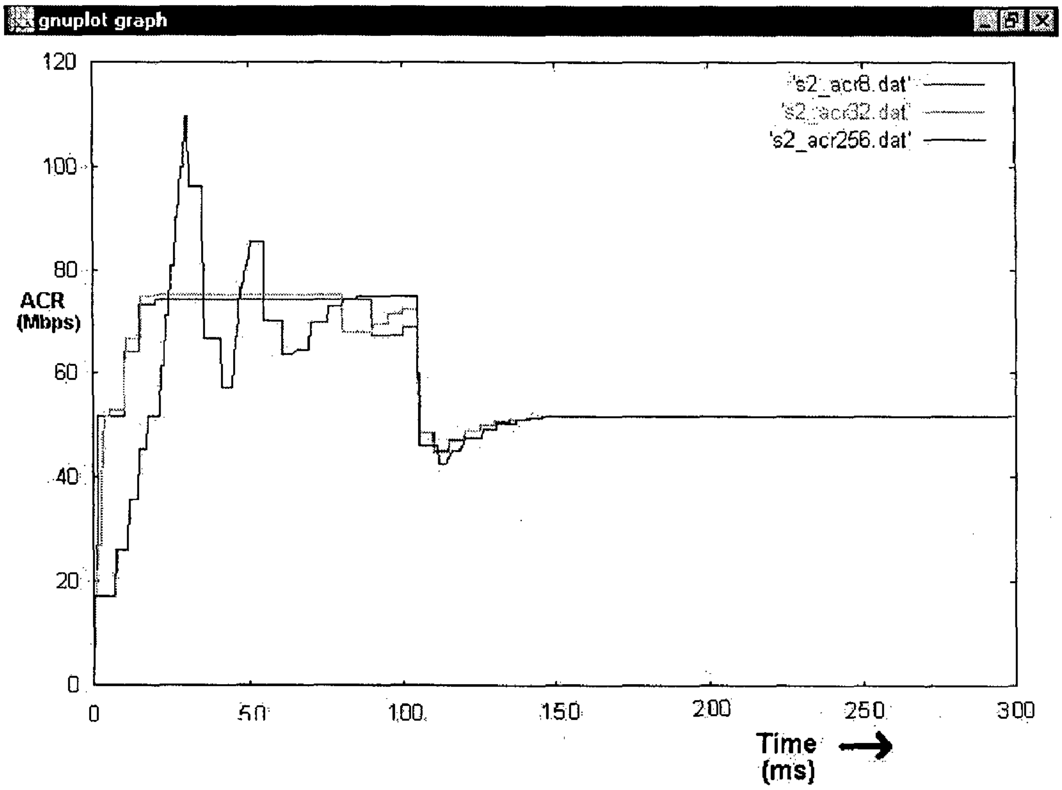


Figure 6.2: Source 2 ACR values for Nrm=8, 32 and 256

3) *Robustness:* This can be considered as robust because even after the source 1 becomes active at 100*ms* system continues to be in stable state even for Nrm = 256. This can be checked from figures 6.1, 6.2 and 6.3. ACR values of S1 and S2 continues at 45-50Mbps, also queue lengths are similar to when Nrm =8 or 32.

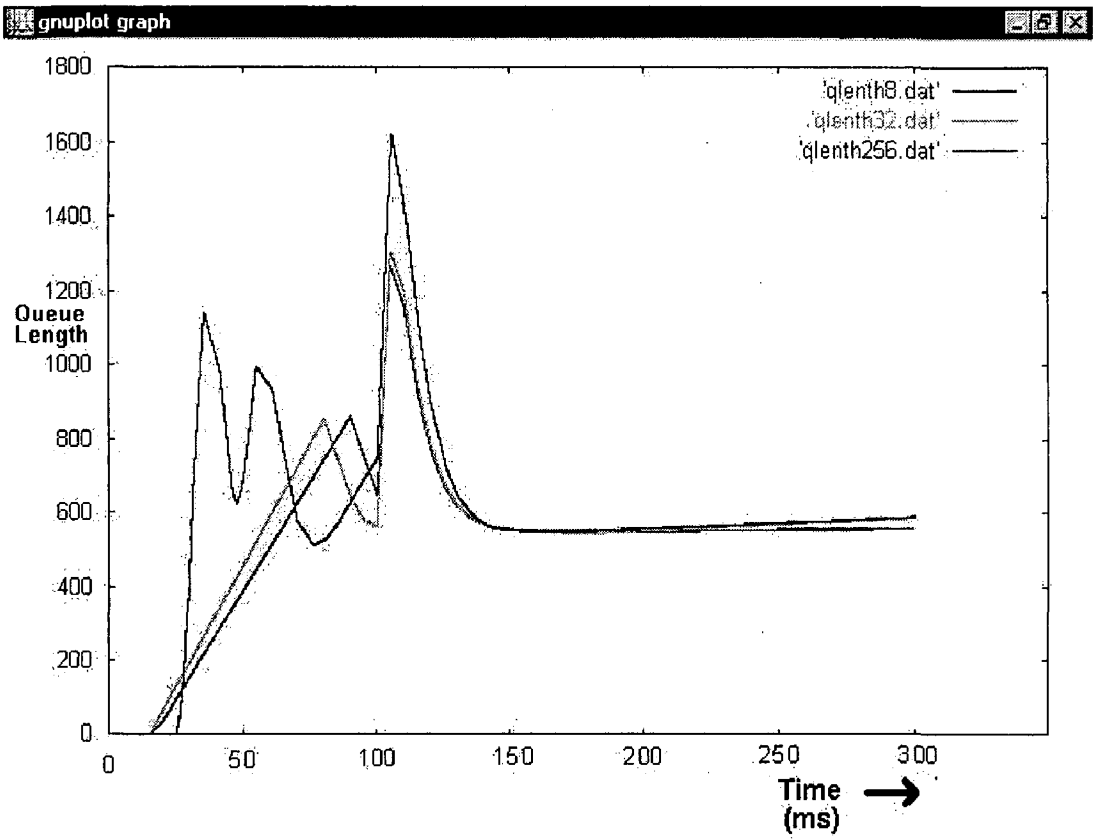


Figure 6.3: Queue lengths at bottlenecked switch for Nrm = 8, 32 and 256

6.3 Results for SES Rule 3 Modification

The modified SES rule 3 is implemented on the same configuration and the results are as follows.

6.3.1 Results for all 155Mbps connections

1) *Utilization*: From figure 6.4 it is clear that there will be better utilization of the link if *mirct* was introduced. Because number of RM cells received in this case are less compared to that when using normal SES rule 3. From the figure a gain of 1700 RM cells that is 1700 * 53 * 8 = 721Kbits per 300*ms* is obtained. This extra bandwidth was given to data cells.

2) *Stability and Transient performance*: Figure 6.5, 6.6 depicts the ACR values for source 1 and 2 respectively. Source 3 ACR values are similar to source 2. From the figures it is observed that by implementing modification to SES rule number 3 the results are almost similar to that when using the default Nrm value. The queue lengths are also similar. This was shown in figure 5.6. There is a negligible difference between them. ACR for sources reaches optimum value faster similar to Nrm = 32.

3) *Robustness:* This can be considered as robust because even after the source 1 becomes active at 100*ms* system continues to be in stable state. This can be checked from figures 6.5, 6.6 and 6.7. ACR values of S1 and S2 continues at 45-50Mbps, also queue lengths are similar to when Nrm =32.

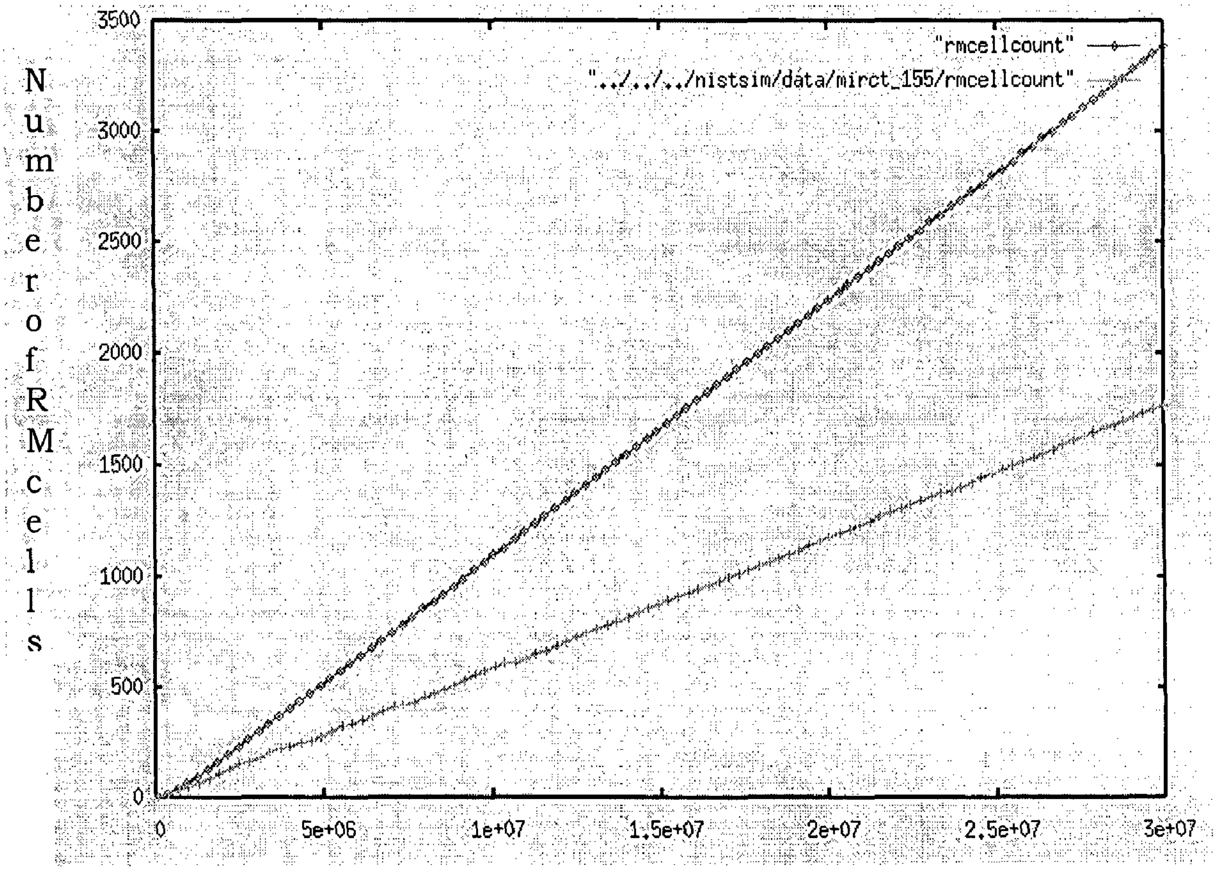


Figure 6.4: Comparison of Number of RM cells

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

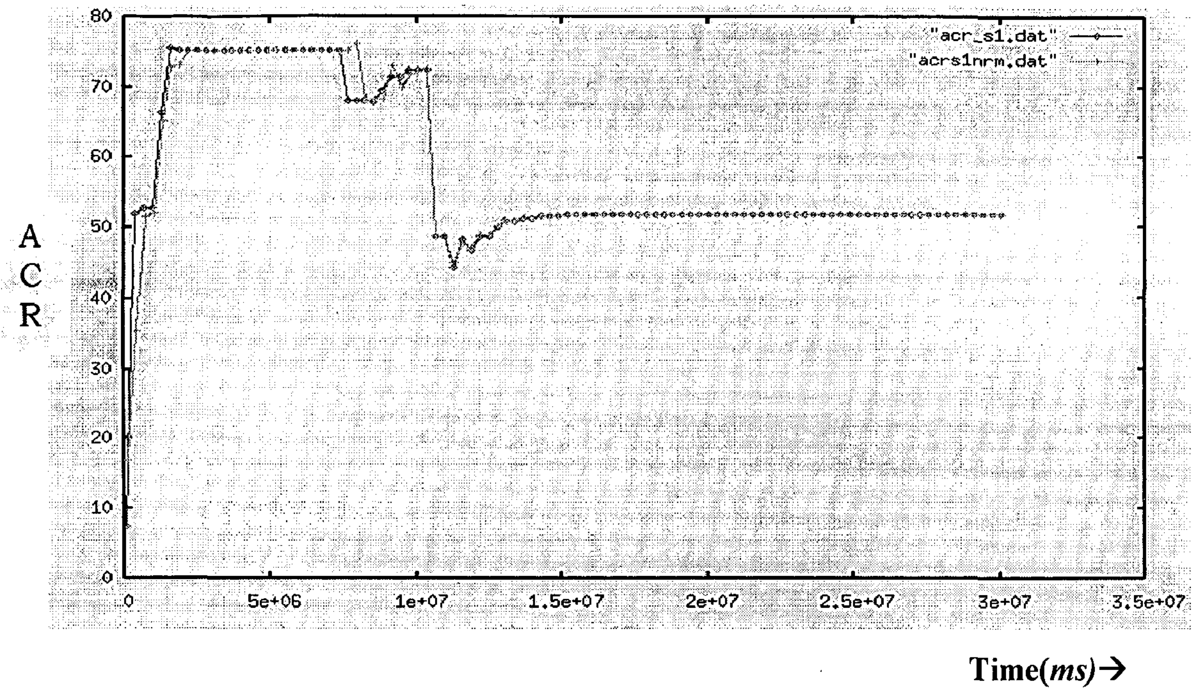


Figure 6.5: Comparison of Source 1 ACR values for all 155Mbps link connections

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

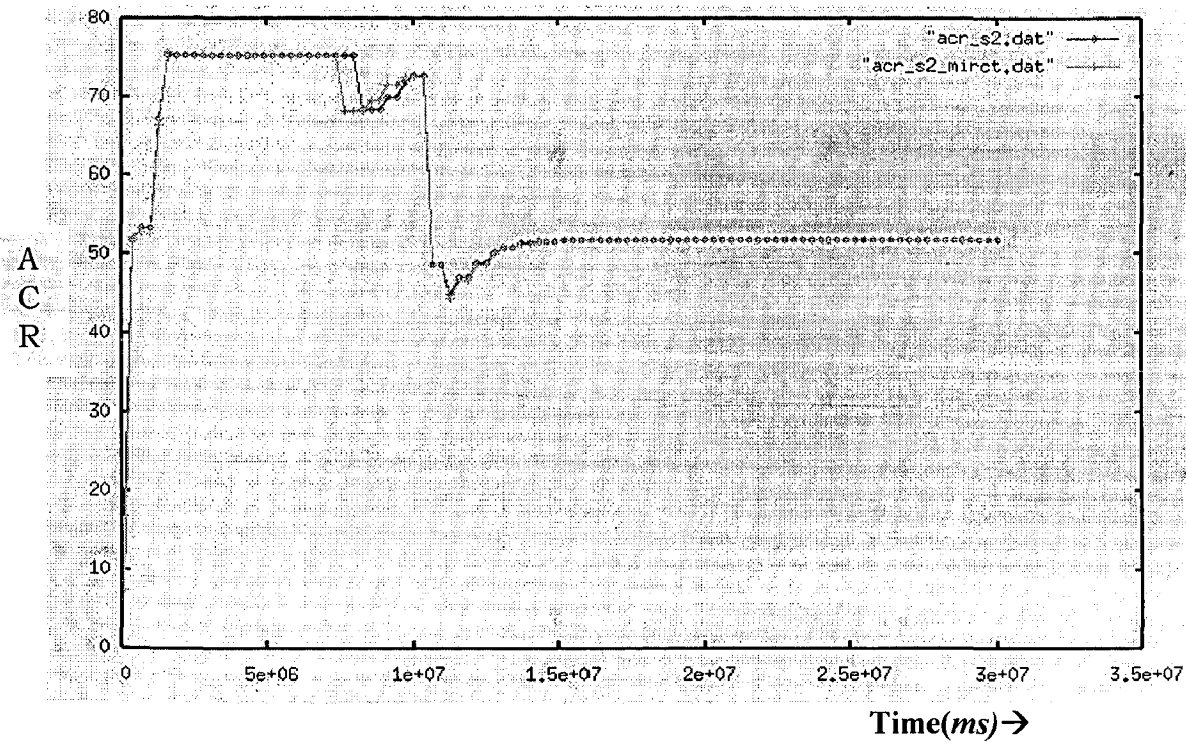


Figure 6.6: Comparison of Source 2 ACR values for all 155Mbps link connections

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

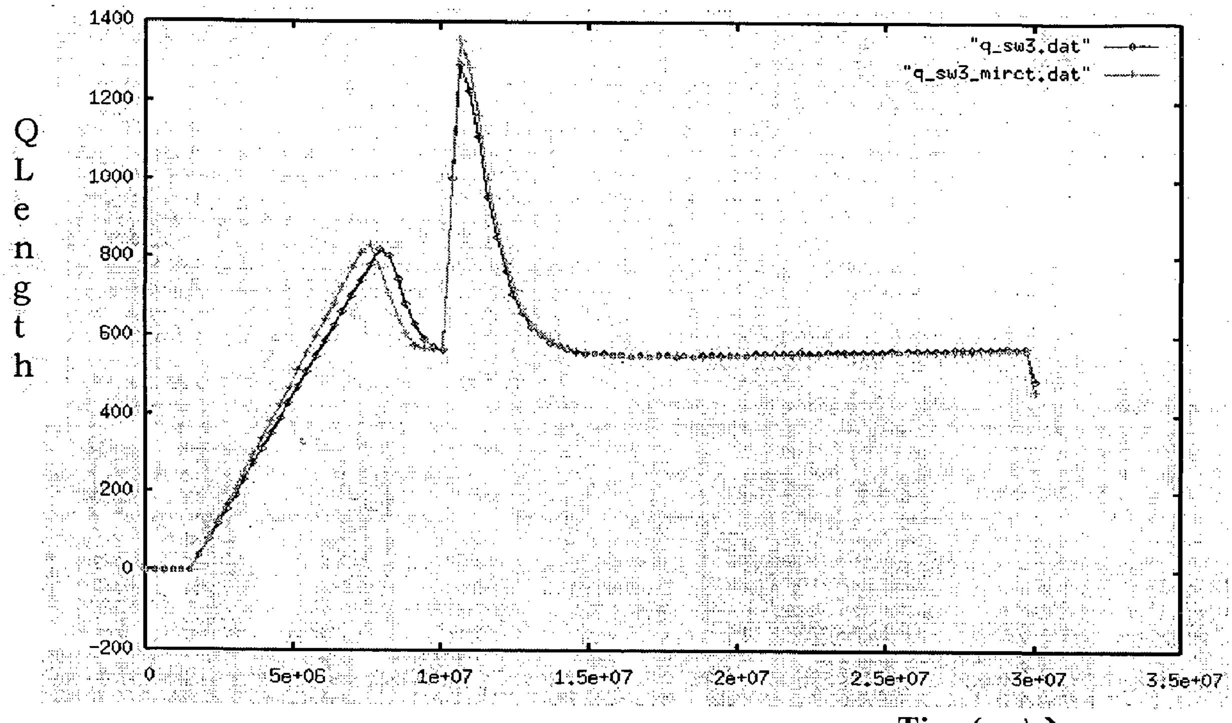


Figure 6.7: Comparison of queue length at switch2 for all 155Mbps link connections

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

6.3.2 Results for all 20Mbps connections

Links of all 20Mbps are chosen to prove that if the transmission rate falls below 27Mbps this modification works worse.

Figure 6.8 and 6.9 depicts the ACR values for source 1 and 2 respectively. In this case also the ACR values for both the bottlenecked source and normal sources are nearly similar except the number of RM cells. Figure 6.10 shows the number of RM cells received. In this case nearly 1250 RM cells are received for the modified approach, but normal rule works much better with 380 RM cells. So control information is more in this case and this approach should be avoided for rates less than 27Mbps.

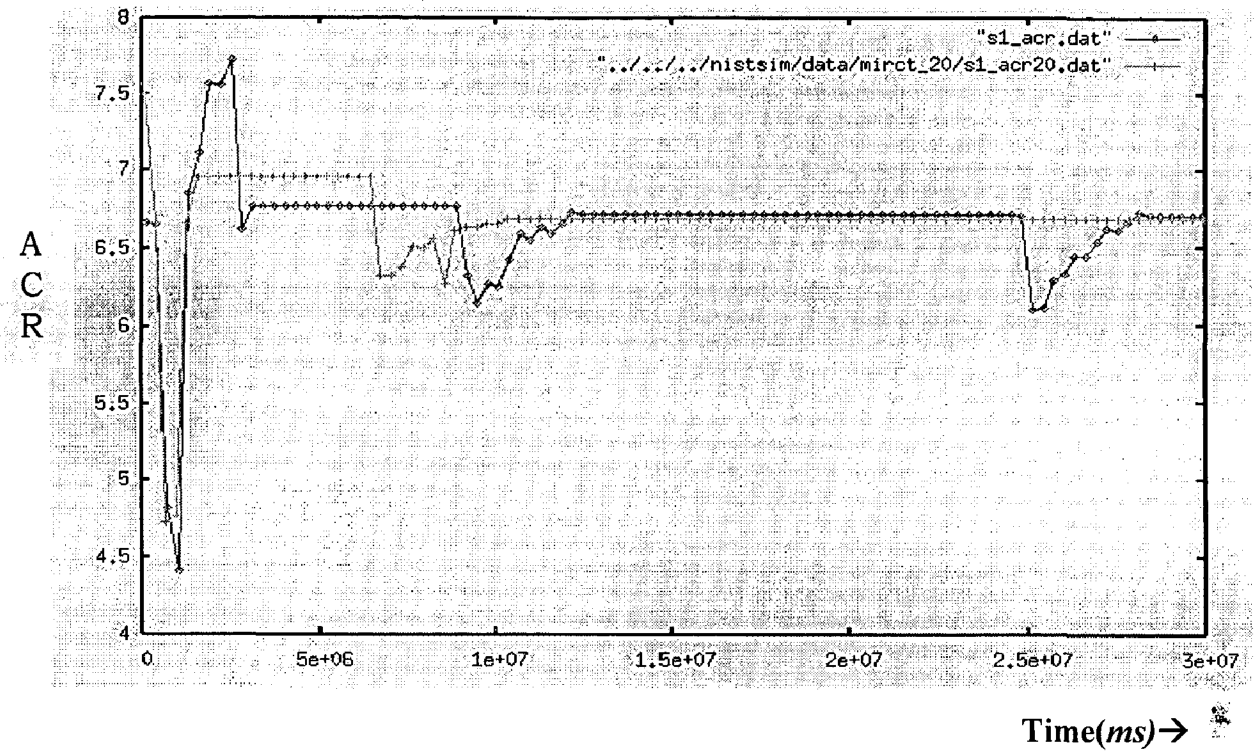


Figure 6.8: Comparison of Source 1 ACR values

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

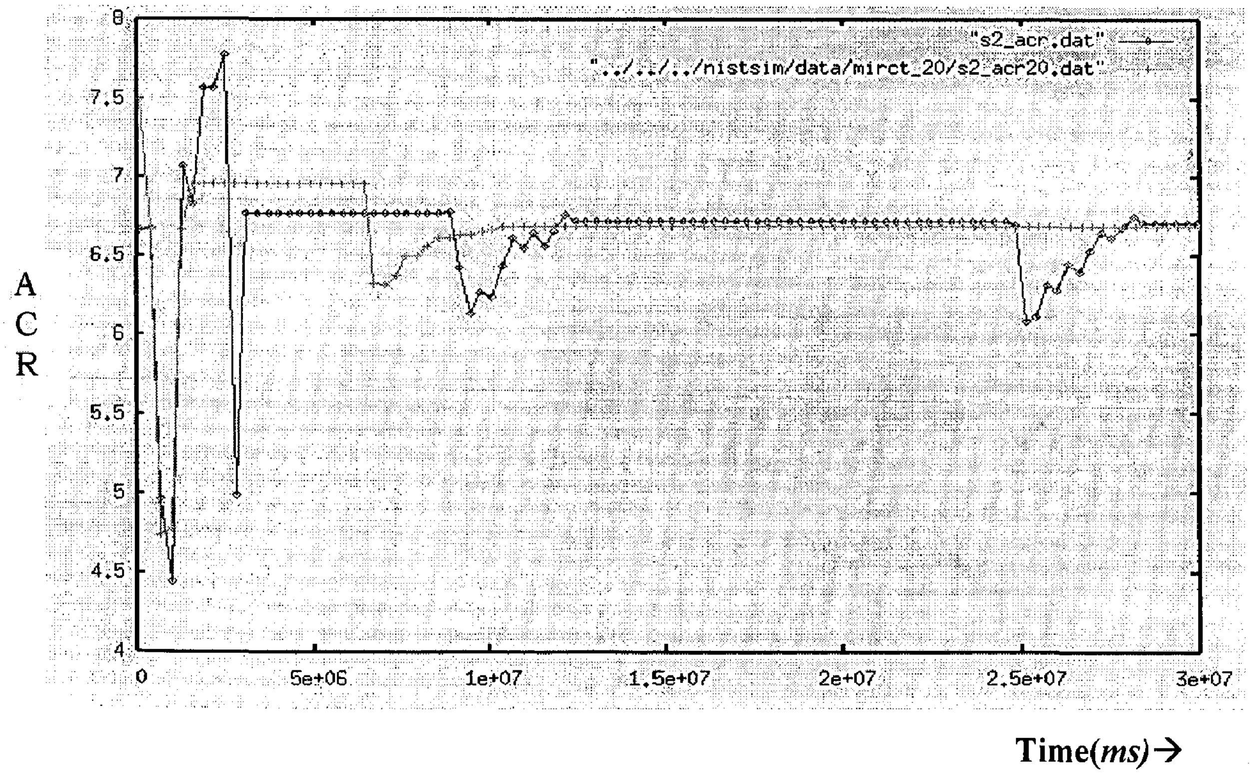
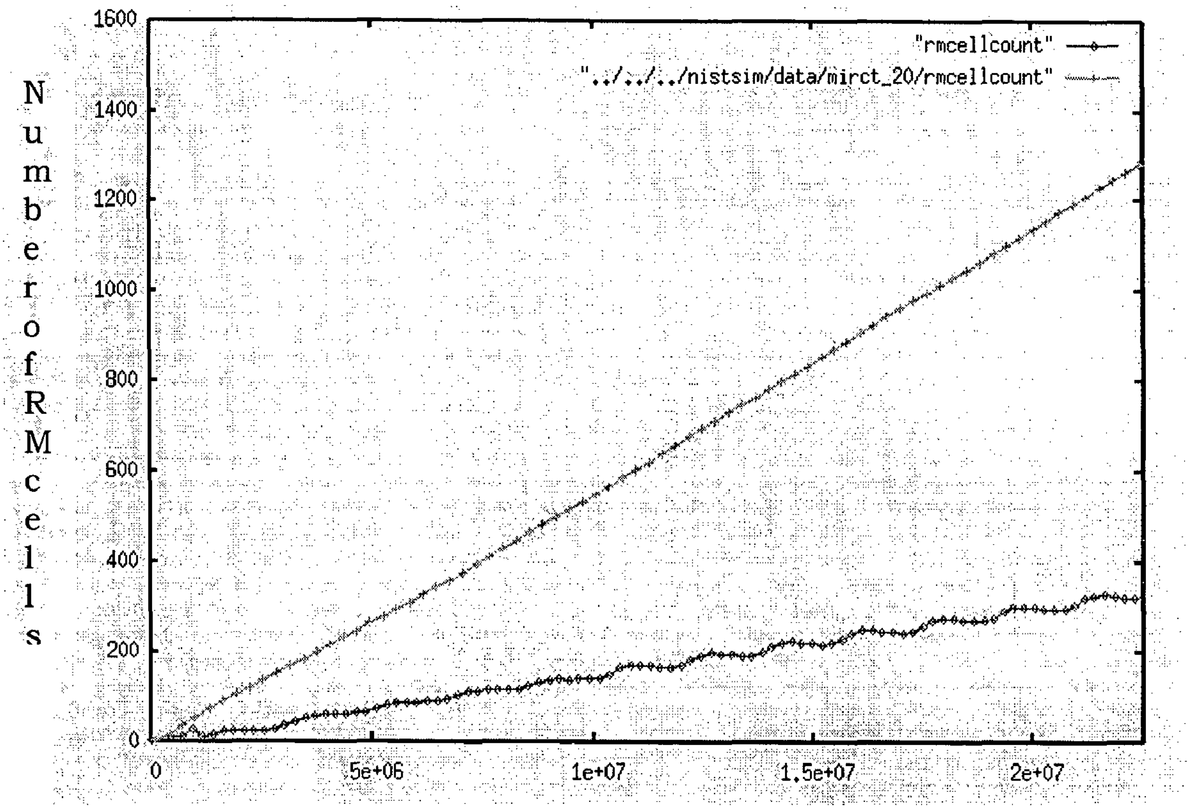


Figure 6.9: Comparison of Source 2 ACR values

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*



Time(*ms*)→

Figure 6.10: Comparison of Number of RM cells

Note: 1. Black line is that of normal case and grey line indicates modified rule 3

2. TIME axis is scaled to 1 unit = 10^{-5} *ms*

6.4 Summary

SES rule number 3 was implemented in the case of high-speed connections that is for Nrm =32. Also Nrm was varied to get better utilization of network. Limitations of this approach were presented. Then a better technique of modified SES rule 3 results are analysed for high-speed and proved that there is efficient utilization of link bandwidth with this technique. Also it is pointed that there should be some threshold rate to apply this technique.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

This dissertation successfully pointed out the advantages by increasing Nrm value in the case of high-speed networks with the help of results. To overcome the disadvantages we have proposed modification to rule no.3. As a consequence of this modification, the amount of overhead information in ABR connections is reduced and network utilization is increased, respectively. The response time of the ABR control loop remains unaffected. The higher the transmission speeds the higher the gain. The maximum gain of 3.125 % of the total connection bandwidth can be achieved. It should be noticed, however, that utilization remains unchanged until the ABR connection rate exceeds the Threshold Transmission Rate (app. 27 Mbps if AI = 5 ms). The results are plotted in chapter 6.

Future work:

The AI value and consequently the MIRCT value (5ms) were chosen according to the values depending on the other parameters in the network. For example different switches may use different averaging interval (AI) values which will cause some problems during the operation. Some fool-proof mechanism has to be developed to avoid these kinds of problems. Even though, it is possible that these values will change in future, this will not reduce the importance of our proposal. The threshold transmission rate will increase, but the ABR connection speeds will increase, too. The bandwidth gain will remain.

REFERENCES

[1] The ATM Forum Technical Committee, "*Traffic Management Specification Version 4.1*", California, USA, 1999. ftp://ftp.atmforum.com/pub/approved-specs/af-tm-0121.000.pdf, March 1999.

[2] W. Stallings, *High-Speed Networks: "TCP/IP and ATM Design Principles"*, New Jersey, USA, Prentice Hall Inc., 1998.

[3] S. Kalyanaraman, R. Jain, S. Fahmy, R. Goyal, and B. Vandalore, "*The ERICA Switch Algorithm for ABR Traffic Management in ATM Networks*", *IEEE/ACM Transactions on Networking*, Vol. 8, No. 1, February 2000, pp. 87-98.

[4] H. M. Choi, K. E. Nygard, and W. Perrizo, "*Measured Average Cell Rate-Based Congestion Avoidance for ABR Traffic in ATM Networks*", North Dakota State University, Dept. of Computer Science, USA, September 2001.

[5] S. Li, S. Chong, and C. Hwang, "*Link Capacity Allocation and Network Control by Filtered Input Rate in High-Speed Networks*", *IEEE/ACM Transactions on Networking,* Vol. 3, No. 1, February 1995, pp. 10- 25.

[6] S. Fahmy, R. Jain, R. Goyal, and B. Vandalore, "*ABR Engineering: Roles and Guidelines for Setting ABR Parameters*", Department of computer and Information science, Ohio state university, Nov. 1999. http://www.cis.ohio-state.edu/~jain/abr_eng.pdf

[7] T. M. Chen, S. S. Liu, and V. K. Samalam, "*The available bit rate service for data in ATM networks, IEEE Communications magazine*", Vol. 34, Nov. 1996, pp 117-123.

[8] Ohsaki H, Murata M, et al. "*Rate based congestion control for ATM networks*", *ACM SIGCOMM Computer communications review,* 1995. vol. 25, No.3, 17-23.

[9] Flavio Bonomi and Kerry W. Fendick, *"The rate-based flow control framework for the available bit rate ATM service", IEEE Network Magazine*, March/April 1995, pp 25-39.

[10] Peter Homan and Janez Bešter, "*Increasing Network Utilization of ATM ABR Connections by Using Minimum Inter-RM Cell Time", Elektrotech.* Vestn., 2002, vol.68, no.4, pp 207-212.

[11] Ambalavanar Arulamabalam and Xiaoqiang Chen, "*Allocating fair rates for available bit rate service in ATM networks", IEEE Networks magazine*, Nov. 1996, pp 92-100.

[12] Raj Jain, S. Kalyanaraman et al., "*Source behavior for ATM ABR traffic management: An explanation", IEEE communications magazine*, Nov. 1996, pp 50-55.

[13] Nada golmie, Frederic Mouveaux, et al, "*The NIST ATM/HFC network simulator: Operation and programming guide version 4.0*", Dec. 1998.

[14] M. Aida, and K. Horikawa, "*Stability Analysis for Global Performance of Flow Control in High- Speed Networks Based on Statistical Physics", IEICE Transactions on Communications*, Vol. E82-B, No. 12, pp. 2095-2106, December 1999.

[15] Y. Kim, and S. Li, "*Performance Analysis of Data Packet Discarding in ATM Networks", IEEE/ACM Transactions on Networking*, Vol. 7, No. 2, pp. 216-227, April 1999.

[16] S. Kalyanaraman, "*Traffic Management for the Available Bit Rate (ABR) Service in Asynchronous Transfer Mode (ATM) Networks*", The Ohio State University, PhD. Dissertation, Ohio,pp. 23-68,117-182, USA, 1997.

[17] E. Altman, T. Basar , and R. Srikant, "*Multi-user rate-based flow control with action delays: A team-theoretic approach,*" in *Proc. 36th Conf. Decision and Control*, pp. 2387–2392, Dec. 1997.

[18] R. Jain and K. K. Ramakrishnan, "*Congestion avoidance in computer networks with a connectionless network layer: Concepts, goals, and methodology,*" in *Proceedings IEEE Computer Networking Symposium*, pp. 134–143. Apr. 1988.

[19] R. Jain "*Congestion control and traffic management in ATM networks: Recent advances and a survey*", Computer Networks and ISDN Systems, 28(13):pp.1723-1738, November 1996.

[20] A. Koike, H. Kitazume, H. Saito, and M. Ishizuka. "*On end system behavior for explicit forward congestion indication of ABR service and its performance*", IEICE transactions on communications, E79-B(4), pp. :605-610, April 1996.

[21] D. Lee, K. K. Ramakrishnan, W. M. Moh, and A. U. Shankar. "*Protocol specification parameterized communicating extended finite state machines- a case study of the ATM rate control scheme*", In Proceedings of ICNP, pp 208-217, October 1996.

[22] Sonia Fahmy, Raj Jain, Shivkumar Kalyanaraman, Rohit Goyal, and Fang Lu, "*On source rules for ABR service on ATM networks with satellite links*", in Proceedings of the First International Workshop on Satellite-based Information Systems, vol.4, pp. 108-115, Rye, New York, November 1996.

[23] Lotfi Benmohamed and Semyon M Meerkov, "*Feedback control of congestion in packet switching networks: The case of multiple congested nodes*", Proceedings of the American control conference, Baltimore, Maryland, pp. 1104-1108, June 1994.

[24] K Horikawa, M Aida and T Sugawara, "*Traffic control scheme under the communication delay of high-speed networks*", proceedings ICMAS, pp.111 – 117, September 1996.

[25] D. Chiu and R. Jain, "*Analysis of the Increase/Decrease Algorithms for Congestion Avoidance in Computer Networks,*" Journal of Computer Networks and ISDN, Vol. 17, pp. 1-14, June 1989.

[26] C. Fang and A. Lin, "*A Simulation Study of ABR Robustness with Binary-Mode Switches: Part II,*" ATM Forum/1328R0, Oct. 1995.

[27] R Jain "*Out-of-rate RM cell issues and effect of Trm, TOF and TCR*", ATM Forum/95-973R1, Aug. 1995.