Rate-Based End-to End Closed Loop Control for ABR Traffic Management

Elvina Djalal
Lecturer at Jabal Ghafur University, Sigli, Indonesia
Telecommunication Practicioner
elvina.djalal@yahoo.com

Abstract: ATM has one common feature which guarantees its success, namely the possibility to transport any ATM service, irrespective of its characteristics such as the bit rate, its quality requirements or its bursty nature. ATM also has high flexibility in allocate the bandwidth, and thus allows more calls to enter the network. Unfortunately, this advantage has a negative consequences. ATM presents congestion problems in the network as well as in the end terminals. This research describes about congestion control mechanism that will be applied for Available Bit Rate (ABR) Service in ATM networks, namely, the Rate-Based Congestion Control Scheme. This method supports end-to-end closed-loop control and has been indentified as the most appropriate for the support of this service by ATM Forum. ABR Service is a new ATM Service category. This kind of service automatically and dynamically allocates the available bandwidth to users by controlling the traffic flow based on feedback information. The source increases or decreases the source rate of cells transmission based on the information in the feedback Resource Management (RM) cell it receives. This method minimizes the duties of intermediate nodes and the destination node, so it is expected the source will receive the feedback information faster.

Keywords: ATM Networks, ABR, Traffic Management, Congestion Control, Rate-Based End-to End, Closed-Loop Control

1. Intoduction

In accordance with growths and advances in social business activities, demands in multimedia and broadband services increase rapidly. People have not yet been satisfied with the telecomunication services provided today; they still ask for the better ones. People need telecomunication services with higher bandwidth wich is required to support services such as LAN interconections, video, image, and so on so forth. On the other hand, development in computer and networking enable the realization of such services. All of these lead to the Broadband Integrated Services Digital Networks (B-ISDN) concept

B-ISDN uses a worldwide networking technology provided with a set of user interfaces and universal communications equipment. This kind of service will support not only current services, but also future services.

In order to support the B-ISDN services, the International Telecommunication Union on Telegraph and Telephone (ITU-T) has selected Asynchronous Transfer Mode (ATM) as the most appropriate transfer mode for B-ISDN. ATM is a packet-oriented switching and multiplexing technique which uses fixed-size cells to transfer information over a B-ISDN network. In ATM networks, one fixed-size cells consists of 48 bytes payload and 5 bytes header. The fixed-size cells makes the networks very suitable for integrated all types of traffic which consists of voice, video, and data. The short size of ATM cells is expected to give full bandwidth flexibility as well as high bandwidth utilization in a high transmission rate. It is also expected to provide Quality of Service (QoS) as required by the applications. Bandwidth is allocated according to demand in ATM networks.

ATM has one common feature which guarantees its success, namely the possibility to transport any ATM service irrespective of its characteristics such as the bit rate, the quality requirements or the bursty nature. ATM also has high flexibility in allocating the bandwidth, and thus, it allows more calls to enter the network. Unfortunately, this advantage has a negative consequences because it causes congestion problems in the network as well as in the end terminals. There are three locations that congestion problems can occur, and consequently, there are there levels to control that congestion as follows (Habib and Saadawi: 1991): in the end terminals, at the network access points, and in the internal elements of the network.

For convenience, the control at the network access point and the control in the internal element of the network can be grouped as network controls.

These two control scemes, that is the end-terminal controls and the network controls, have different objectives. The objective of the end-terminal control is to improve the utility and performance of the ATM connection in oder to get greater throughput. Whereas, the objective of network controls is to protect the network resource as well as to protect each ATM connection from other connections that compete for the same resources. Network controls occur at two levels, that is at connection level and at ATM cell level. Each level has a different method. Call Admission Control (CAC) is the method to control the congestion at the connection level. Wether a call will be accepted or not depends on the ability of the network to support the service parameters required by the call. CLP (Cell Loss Priority) and EFCI (Explicit Forward Congestion Indicator) are bits which may be used to control the congestion at the ATM cell level. When the CLP is set to 1, the cell may be discarded in any network element if there is local congestion. Like CLP, if EFCI is set to 1, it means that there was congestion along the virtual channel (VC) or virtual path (VP) passed through by the cell on the way to its destination.

Characteristics of ABR Service

ABR service is a new service available in ATM network, and until now it is still in a developmental stage. Its applications do not require a specific bandwidth, in other words those applications can be run in any bandwidth. The bandwidth range is between Minimamu Cell Rate (MCR) and Peak Cell Rate (PCR) which are specific for each application. This is because in ABR service user can determine minimum limit and maximum bandwidth allocated in a connection when the connection takes place. This process is performed by user (source) during the connection set up time.

The purpose of ABR service is to utilize unused bandwidth in a network. This bandwidth is remaining bandwidth which is not used by CBR and VBR applications at certain time. This available bandwidth will be allocated dynamically by the network to users (source) by controlling traffic flow using feedback.

ABR service is designed for normal data traffic, such as file transfer and email. Even though in principle services categorized in this class do not require guarantee or minimization for cell transfer delay and cell loss ratio, it will be better if the switches can minimized the delay and loss. The source should control its rate transmission which depends on the jamming condition in the network.

Several Congestion Control Methods which have been Suggested for ABR Service

Jain (1995: 5) states that "Congestion happens whenever the input rate is more than the available link capacity."

$$\sum Input\ Rate > Available\ Link\ Capacity$$

Congestion Duration		Congestion Mechanism
Long	↓	Capacity planning and network design
		Connection admission control
		Dynamic routing
		Dynamic compression
		End-to-End feedback
		Link-by-Link feedback
Short		Buffering

Figure 1. Congestion techniques for various congestion duration (figure is adopted from Jain 1996: 6)

Figure 1 shows how the duration of congestion affects the choice of the method. It can be seen from the figure that the duration of congestion for ABR traffic is estimated between short and medium. This is considering that ATM network has high speed technology so that the congestion has small probability to occur and takes place in relatively short time. Therefore, the required congestion control method is the one with end-to-end or link-by-link feedback characteristic.

Followings are several congestion schemes suggested to the ATMA Forum to overcome the occurrence congestion in ABR service (Jain, 1995: 11-23):

1. Fast Resource Management

To obtain desired bandwidth so that source can send its data, first it needs to send a resource management cell (RM cell). In the RM cell is included information about the amount of bandwidth required. If a switch that received the RM cell can not guarantee the request from source, then the RM cell will be discarded. In this case source has a time-out. If the time-out has passed and the source has not yet received its RM cell back, then it will resend the RM cell. If a switch can guarantee the requested bandwidth, then this switch will send the RM cell to the next switch. At the end the destination will send the RM cell back to the source so that it then can send its data.

The weakness of this method is a source has to wait until at least one trip delay before it can send its bursty data when the network is idle. Otherwise, the source has to wait until a time-out passes before it can resend its request. In order to avoid this delay, it is suggested an Immediate Transmission (IT) in which burst is transmitted immediately after the RM cell. It it then turns out that a switch can not accommodate the burst, then the switch will discarded the RM cell and the burst and send an indication to the source. Considering the amount of burst discarded, the amount of cell loss during congestion is very big. Therefore, this method is rejected by the ATM Forum.

2. Delay-Based Rate Control

Sources always monitor the round trip delay by sending RM cells periodically. The RM cells contain timestamp information, and later on, these cells will be returned by the destination. Sources use the timestamp to measure the round trip delay and to take a conclusion about level of congestion.

The advantage of this method is that it does not need any explicit feedback from a network. Thus, it can be applied in a path which is not an ATM network.

Unfortunately, there is no continuation of this suggestion, and also, there is no more detailed explanation about the use of delay.

3. Backward Explicit Congestion Notification

Switches monitor the length of its queue and then send RM cell when there is a jam. Source will reduce half of its rate after receiving the RM cells. If there is no BECN cell received during that time, then the rate for the corresponding VC will be doubled for the next period until it reaches the peak rate. To achieve fairness, a source recovery period is made proportional to the VC's rate such that the period gets shorter as the transmission rate gets slower. This method is rejected because the system is a bit unfair as the sources receiving BECNs is not always the ones that causes congestion.

4. Early Packet Discard

This method says that it is better to discard all cells from one packet than to discard cells randomly from different packets. Therefore, this method uses one bit in cell header which marks the end of message (EOM). A switch whose buffer is full will look for the EOM mark and discard all the next cells coming from the corresponding VC until the next EOM mark. This method is also rejected because there is probability that it is unfair as a cell coming to a full buffer does not necessarily come from a VC that causes the jam.

5. Fair queuing with Rate and Buffer Feedback

Sources periodically send RM cells in order to know the use of bandwidth and buffer during jam. Switches count the fair share of VC's. The share minimum value at this switch and other preceding switches is placed in RM cells. Switches also monitor the queue length of each VC. The maximum queue length at this switch and the preceding switches is also placed in the same RM cell. Every switch implements fair queuing by using seperate queue for each VC. The fair share of a VC is determined as the inverse of interval berween a cell arrival and its transmission. Interval reflects the total of active VC's. Sice the total and interval are random, it is suggested that the average of several observed interval is used.

This method is also rejected because it is very complex, that it is requires per VC (fair) queuing in switches.

6. Credit-based Approach

The approaches used are flow per-link control, flow per-VC and window flow control. Every link consists of a sender node which can be a source end system or a switch and a receiver node which can be a switch or a destination end system. Each node gives an individual queue for every VC. A receiver monitors queue length of every VC and determines the number of calls that can be sent by a sender to the VC. This number is called "credit".

If there is only one VC active then the number of credit must be quite big so that all links are full every time, or in other words:

$$Credit \geq Link\ Cell\ Rate \times Link\ Round\ Trip\ Delay$$

The link cell rate can be calculated by dividing link bandwidth (in Mbps) by the cell size (in bits). The above scheme is called "Flow Controlled Virtual Circuit (FCVC)". This scheme introduces two problem. First, if the credit is lost, the sender will not know. Second, every VC has to reserve the entire round trip worth or buffers even though the link is divided by a number of VC's. These problems are overcome by introducing credit resyncronization algorithm.

The credit resyncronization algorithm consists of senders and receivers that both maintain the number of cells sent and received for each VC and periodically interchange this number. The difference between the number of cells sent by a source and the number of cells received by the destination shows the total of cells that is lost in the link. The receiver reissues the amount of additional credits for the corresponding VC.

The adaptive FCVC algorithm only gives VC one fraction of round trip delay worth of buffer allocation. For a very active VC fraction is big, while for a less active one the fraction is smaller. An inactive VC gets a small fixed credit. If a VC does not use its credit, then it can be seen that the usage rate during this period is low, and thus, the VC will get smaller buffer allocation during the next period. Adaptive FCVC reduce buffer requirements, but it causes ramp-up time. If then the VC is active, then it will take some time before the VC can use its full capacity of the link even though there is no other user.

Credit-based is also not accepted, even though it is actually better than the previous methods. The most objectionable factor of the credit-based is that it requires per-VC queing which makes the switch complexity grows proportionally to te number of VCs. The greater is the number of VC to be supported by a switch; the more complex is the corresponding switch.

7. Rate-based Approach

There are three approaches suggested for this method, namely negative polarity feedback, positive polarity feedback, and bipolar.

Negative polarity feedback is when the RM cell is fed back in order to decrease the rate. On the contrary, positive polarity feedback is when the RM cell is sent (by the destination) back in order to increase the rate. Bipolar is when the RM cell is sent back to decrease or increase the rate. The negative polarity feedback gives a problem if the RM cells is lost due to jamming when it is sent back from the destination to the source. If this occurs, the source, which is on the forward direction of the transmission, will keep increasing the rate so that overload occurs. Positive polarity feedback is meant to handle this problem. It is better if the source keeps decreasing its rate when the RM cell is lost. Therefore, the positive feedback polarity is also called "proportional rate control algorithm (PRCA)".

The main objective of the rate-based proposal is to support ABR service and to define a flexible framework of rate-based loop schemes for congestion control various possibilities of implementation depending on the coast and level of complexity.

Due to the flexibility of the Rate-based approach, ATM Forum then decides to accept this approach as a congestion control for ABR service. One important advantage of the rate-based is this method does not require per-VC queuing.

8. Link Window with End-to-End Binary Array

This is a combination of credit-based and rate-based methods by using window flow control at each link and EFCI binary bit at end-to-end rate control. Unfortunately, this method is not accepted by either credit-based party or rate-based party because it contains elements from opposing parties.

Rate-Based Congestion Control Scheme for ABR Service

ABR service is specially designed to handle traffic efficiently. In order to achieve this purpose, the ATM Forum has released a specification called the Traffic Management Specification TM4.0 on April 1996. The traffic management is intended that the traffic in ATM network can mantain the QoS and simultaneously use networks resources (bandwidth and buffer) maximally.

a. ABR Rate-Based Traffic Management Model

The traffic management model for ABR is called the Rate-Based End-to End Closed Loop Model. This naming is based on how the traffic management itself works. It is called rate-based because sources send their data at determined rates. It is a closed loop model because there is a continous feedback sent by source-destination-source to monitor network situation. It is named end-to-end because the cell which monitors flow of information moves from a source to the destination and then returns to the source.

An information control is performed by a cell called the Resources Management (RM) cell. The operation of rate-based end-to-end closed loop model is as the followings:

1. When there is an ABR data call, the source requests for connection through a call setup request.
   The source negotiates values of PCR and MCR parameters at that time with the network. The values of other parameters, namely ACR, ICR, TCR, Nrm, Trm, RIF, RDF, ADTF, TBE, CRM, and FRTT, are determined by the network according to the network condition at that time. Tabel 1 shows a list of ABR parameters.

2. After the connection established, the source starts sending the data. The source sends its data according to the value of ACR value, that is:

$$source\_rate \le ACR \quad (2.1)$$

At the beginning of transmission, ACR is set to ICR whose value is according to

$$MCR \le ICR \le PCR \quad (2.2)$$

The choice of ICR value is as the followings:

i. According to values of TBE and FRTT parameters:

$$ICR \times FRTT \le TBE$$

Or: (2.3)

$$ICR \le [\frac{TBE}{FRTT}]$$

Are the maximum number of cells that can be sent by a source which can arrive for the first time at the switch during the first round trip time (before closed-loop starts). Considering this, CRM parameter also depends on values of TBE and Nrm parameter:

$$CRM = \left\lceil \frac{TBE}{Nrm} \right\rceil \quad (2.4)$$

which shows the maximum limit of number of RM cells that can be sent in forward direction as long as any backward RM cells have not been received yet.

ii. ICR from the result of negotiating with the network

Then, ICR used by source is the minimum ICR of (i) and (ii), or:

$$ICR = Min\left(\left\lfloor \frac{TBE}{FRTT} \right\rfloor, ICR\ negotiated\ with\ the\ network\right) \quad (2.5)$$

This means that ICR value will be updated after the connection setup process. This is done to guarantee that the value of TBE parameter given by the network is achieved.

Transmission is started by sending an RM cell which will be followed by data cells. RM cell will be sent by the source every (Nrm – 1) data cells.

3. An RM cell is sent from a source to the destination. On its way to the destination, the RM cell will be process by intermediate switches. There are three ways for switches to give feedback via an RM cell (Jain et al 1995: 51).
   i. Binary or EFCI switch, that is the switch gives EFCI mark bit on every data cell header at the switch experiencing jamming.
   ii. Relative rate marking switch, that is the switch sets CI and NI bits of a payload RM cell if congestion occur at the corresponding switch.
   iii. Explicit rate switch, that is the switch reduce the value of explicit rate in ER field of the RM cell at the switch experiencing jamming.

Table 1. List of ABR parameters

Label	Full Name	Units	Default Value	Comments
PCR	Peak Cell Rate	cells/s	-	Will be policed by network
MCR	Minimum Cell Rate	cells/s	0	Will be guaranteed
ACR	Allowed Cell Rate	cells/s	–	Current rate which source is allowed to send
ICR	Initial Cell Rate	cells/s	PCR	Start up rate after source being idle
TCR	Tagged Cell Rate	cells/s	10 cells/s	Rate which source may send out-of rate forward RM cells
Nrm	Number of cells between FRM cells	None	32	Nrm = 2^N(Nrm-1) data cells between RM cells
Mrm	Controls bandwidth allocation between FRM, BRM, and data cells	None	2	-
Trm	Upper bound on inter-FRM cells time	sec	100 ms	-
RIF	Rate increase factor	None	1/16	Rate increase permitted
RDF	Rate decrease factor	None	1/16	Rate increase permitted when EFCI bit set or RMs delayed
ADTF	ACR decrease time factor	sec	500 ms	The time permitted between sending RM cells before the rate is decreased to ICR

TBE	Transient buffer exposure	None	16,777,215	Number that limits number of cells that is sent by source during start up periods, before the first RM cell returns
CRM	Missing RM-cell count	None	[TBE/Nrm]	Limit the number of RM cells sent in the absence of receiving backward RM cells
CDF	Cutoff decrease factor	None	1/16	Controls the decrease of ACR related to CRM
FRTT	Fixed round trip time	sec.	-	Total delays that may be taken from source to a destination and back to source

4. The destination will change direction bit of an RM cell before the cell is returned to the source. For switches using EFCI method, the destination will check whether the last data cell it receives have EFCI bit that has been set, if it is so then the destination will set the CI bit of RM cell to indicate jamming. Alternatively, for switches using other methods, the destination will only return the RM cell to the source without doing any process. This will speed up the feedback receiving process by the source. In the end it will accelerate the achievement of maximal bandwidth usage.
5. The source will reset its ACR rate according to the information that it receives from RM cell coming from the destination, that is, based on the CI and NI values in the RM cell which is showed by Table 2 below.

Table 2. Actions corresponding to NI and CI bit values

NI	CI	ACTION
0	0	ACR ← Min(ER, ACR + RIF x PCR, PCR)
0	1	ACR ← Min(ER, ACR – ACR x RDF)
1	0	ACR ← Min(ER, ACR)
1	1	ACR ←Min(ER, ACR – ACR x RDF)

b. RM Cell Structure

Table 3. Field and their positions in RM cells

FIELD	OCTET	BIT(s)	DESCRIPTION	Initial Value: If source-generated	Initial Value: If switch-generated or destination generated
Header	1 to 5	all	ATM Header	RM-VPC: VCI=6 dan PTI=110 RM-VCC: PTI=110	
ID	6	all	Protocol Indentifier	1	
DIR	7	8	Direction	0	1
BN	7	7	BECN Cell	0	1
CI	7	6	Congestion Indication	0	Either CI=1 or NI=1 or both
NI	7	5	No Increase	0 or 1	
RA	7	4	Request/ Acknowledge	0 or set in accordance with I.371-draft	
Reserved	7	3 to 1	Reserved	0	
ER	8 to 9	all	Explicit Cell Rate	A rate not greater than PCR Parameter	Any rate value
CCR	10 to 11	all	Current Cell Rate	ACR Parameter	0
MCR	12 to 13	all	Minimum Cell Rate	MCR Parameter	0
QL	14 to 17	all	Queue Length	0 or set in accordance with I.371-draft	
SN	18 to 21	all	Sequence Number	0 or set in accordance with I.371-draft	
Reserved	22 to 51	all	Reserved	6A (hex) for each octet	
Reserved	52	8 to 3	Reserved	0	
CRC-10	52	2 to 1	CRC-10	See section 5.10.3.1	

As it can be seen in Table 3, RM cells consist of field headers, ID, message type field, ER, ER, CCR, MCR, QL, SN, and CRC-10. Special for QL and SN, they are not used for the ATM Forum's ABR. CRC-10 is calculated as the remainder of a division (modulo 2) by the polynomial generator of product x^{10} and payload RM cell contain outside CRC field (374 bits).

The contains of ER, CCR, and MCR are the same as the result of negotiation at connection setup.

DIR, BN, CI, NI, and RA are included in message type field. DIR marks the direction of data flow carried by RM cell. DIR = 0 means forward RM, while DIR = 1 is for a backward RM cell. BN marks whether or not the corresponding RM cell is a BECN. If it is a BECN cell (generated by non-source) then BN =1, and on the other hand, if the RM cell is generated by source then BN = 0. The values of CI and NI bits will be given by intermediate switches or destination. CI and NI are bits which are used as a reference for the source to decrease or increase its current ACR. RA is not used for ATM Forum's ABR.

c. In-rate and Out-of-Rate RM cells

There are two types of ABR RM cells, that is in-rate RM cell out-of-rate RM cell. In-rate RM cells means that the total rate of data and RM cells should not exceed the ACR of the source. And in-rate RM cells will be sent with CLP=0. On the other hand, out-of-rate RM cells can be generated by switches, destinations or even sources and will be sent with CLP=1. Therefore, out-of-rate RM cells will be carried by the network only if there is plenty of bandwidth and can be discarded if congested. Out-of-rate RM cells also can be generated by sources if the ACR given by the network is smaller than the TCR. They are limited to 10 out-of-rate RM cells per second per VC.

Work Done

The Flowchart for Traffic Management Rate-Based End-to-End Closed-Loop Control per-VC

The following flowchart for traffic management rate-based end-to-end closed-loop control provides an example of conforming behavior for the source end system (SES) and destination end system (DES) which is enclosed in the appendices of this stufy. It represents a minimal but complete implementation of the specified end system behavior. This flowchart is for a single source connection. It also assumes a cell scheduler mechanisms that controls the cell emissions from the SES, which is represented as the equation below:

$$time\_to\_send = now + (1000/ACR) \qquad (4.1)$$

Where ACR is in unit of cells per millisecond.

For simplicity, it also assumes that only out-of-rate FRM-cells will be sent when ACR < TCR.

The behavior of the SES is controlled by the values given to a set of parameters, that is PCR, MCR, ICR, RIF, RDF, CDF, Nrm, Mrm and ADTF. PCR and MCR is agreed at connection setup time, whereas others are determined by the network at the same time with values given to get the best optimize performance over various network trade-off. PCR, ICR, ACR and ICR are in unit cells per unit time based on the following constraints:

$$MCR \leftarrow ICR \leftarrow PCR \qquad (4.2)$$

$$MCR \leftarrow ACR \leftarrow PCR \qquad (4.3)$$

$$0 \leftarrow CCR \leftarrow min(ACR, LCR) \qquad (4.4)$$

Where CCR is current cell rate, reflecting the user's offered traffic. Generally, CCR is equal to ACR or zero depends on whether the source has traffic flow to be sent. LCR is cell rate due to physical line limitation.

The following is some definitions that is used in the flowcharts:

End Systems Variables (Per connection)

ACR = Allowed Cell Rate

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

Last-RM = The time that the most recent RM was sent

Per-connection Initialization

ACR = ICR

Count = Nrm

Unack = 0

Last-RM = now – Nrm/ICR

The first flowchart is for the initialization process. It represents the process of incoming ABR data call, connection setup and cell emission.

The second flowchart is for receiving feedback process by the source. It represents the process of checking BRM cell by source whether it experienced congestion, which is represented by the CI and NI bits. Then, source adjusts its ACR based on that information for the next cell transmission.

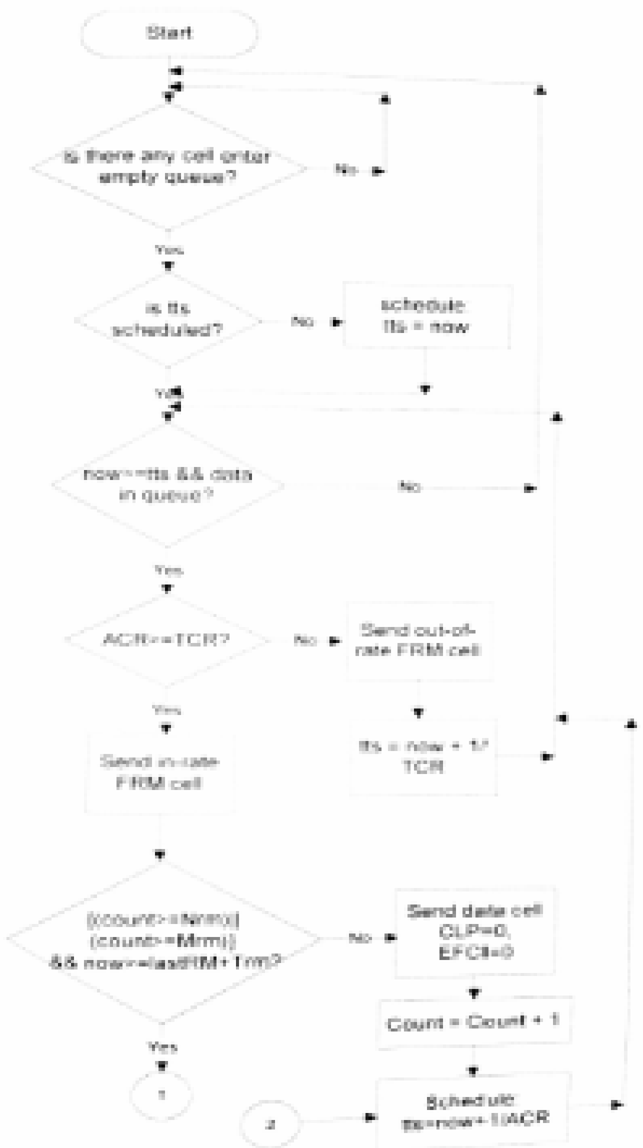

Figure 3. Flowchart of initialization per connection

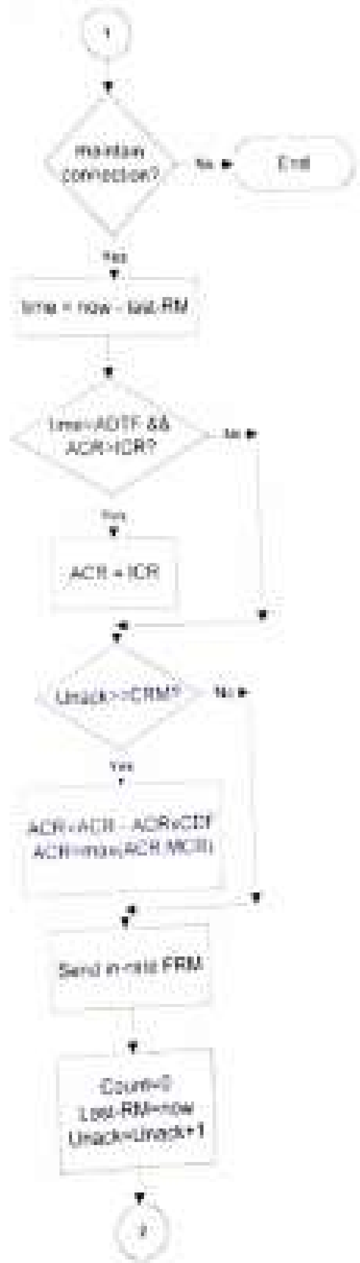

Figure 3. Flowchart of initialization per connection [illegible]

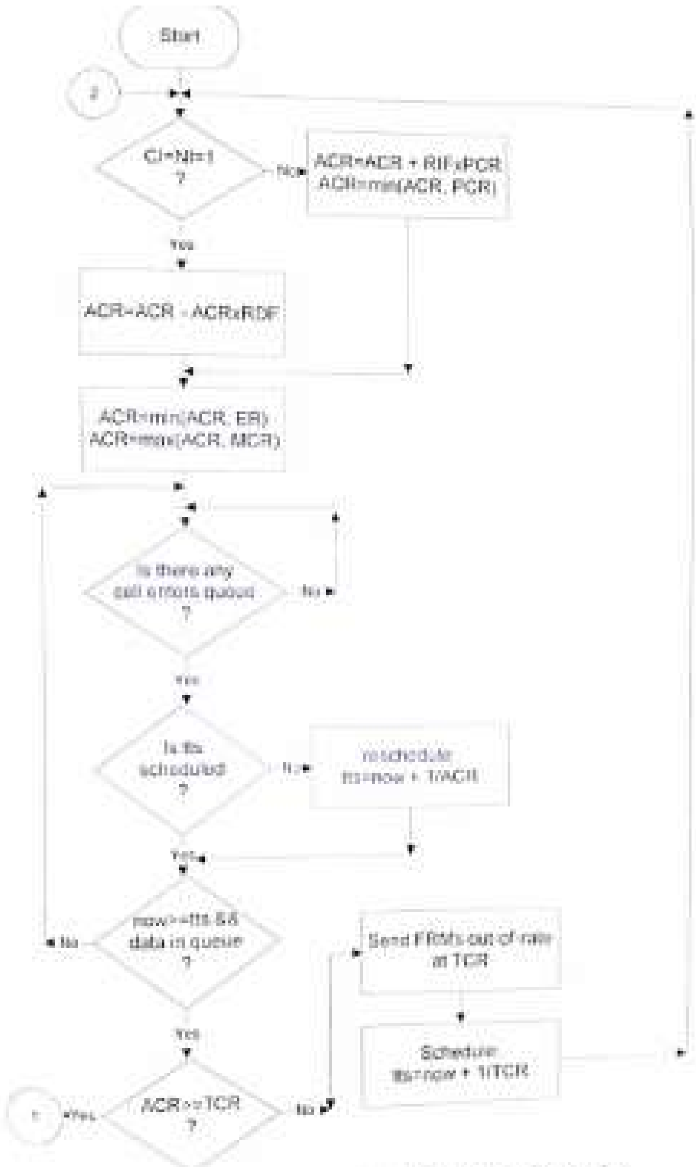

Figure 4. Flowchart after receiving feedback per connection

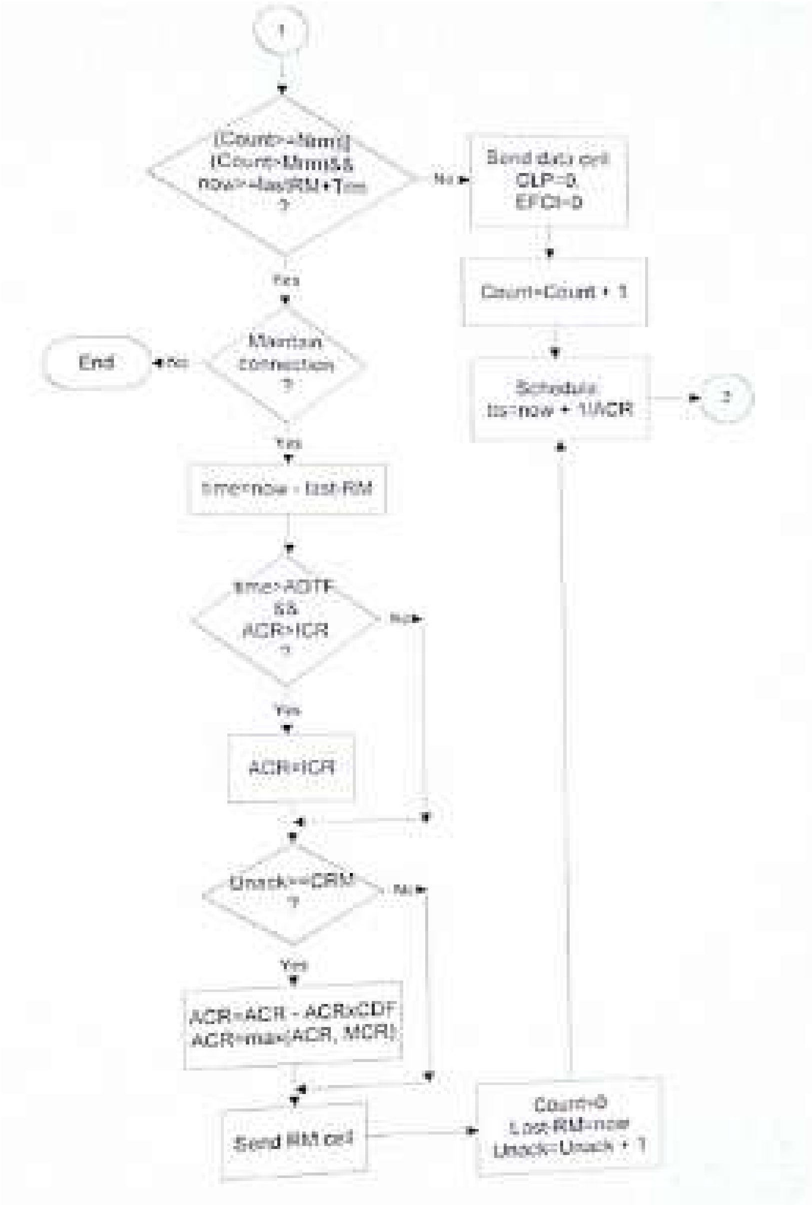

Figure 4. Flowchart after receiving feedback per connection (cont)

Computer Program

The program is developed in Borland C++ language to simulate how the rate-based end-to-end closed-loop works. Parameters such as PCR, MCR, ICR, RIF, Nrm, Mrm, RDF, ACR, CRM, ADTF, Trm, TBE, CDF and TCR are stored in struct type named *Struck con_set*.

PCR, MCR, ACR, CRM, ADTF and TBE contain data type of unsigned long because the maximum value of PCR is 4,290,772,992 and unsigned long is suitable for it. On the other hand, other parameters contain data type of integer or float.

RM cell parameters are also stored in a struct because it consists of some variables and thus it will be easier to assign a value for each parameter. The data type for every variable is also different. DIR, CI, NI and CLP are in integer type because they need only one bit, whereas CCR and ER are in unsigned long type.

Flag_cell_enter is a variable needed for checking process whether there are some data cell entering the source buffer. Initially, *flag_cell_enter* is set to 0, and if there is a cell entering the buffer it is set to 1. *Flag_com_set* is used for checking whether the connection has been established. Initially, it is set to 0, and after the connection is established it will be set to 1. Next, another variable is required to check whether the cell scheduler has been activated. The variable is called *flag_time_to_send*. Initially, it is set to 0, and if the cell has been scheduled it will be set to 1.

Function *picture()* is used for invoking parameters such as *ABR_Par*, *RM_Par*, *time-to-send*, *in-rate* and *out-rate* so that they can be seen on the computer monitor. The command *print_ABR_Par(conset)* is used to get the values of ABR parameters, *print_FRMOR_Par(RMPar)* is used to get the values of RM Parameters, especially for out-of-rate FRM cells, *print_BRMOR_Par(RMPar)* is used to invoked the values of out-of-rate BRM cells parameters, *print_FRMIR_Par(RMPar1)* is used to invoke the values of in-rate FRM cells parameters, and *print_BRMIR_Par(RMPar1)* is used to invoke the values of in-rate BRM cells parameters.

Data cells tables, in-rate RM cells tables and out-of-rate RM cells tables are the result of the simulation. Function *vprint_data(da_ta_pointer)* is used to invoke data cells table, where *da_ta_pointer* is of struct *data* type. Function *vprint_irFRM(inrate_pointer)* is used to invoke in-rate RM cells table *inrate_pointer* is of struct *in-rate* type. Function *vprint_orFRM(outrate_pointer)* is used to invoke out-of-rate RM cells tables, where *outrate_poiinter* is of struct *in-rate* type.

Discussion

The first data:

ACR is greater than TCR and network did not experience congestion

Table 4. RM cells during the connection without congestion

	DIR	CCR (c/s)	ER (c/s)	CI	NI	CLP	STS (ms)	STD (ms)	ACR (c/s)
In-rate RM cell [1]	0	100	700	0	0	0	10	0	100
In-rate RM cell [1]	0	100	700	0	0	0	0	10	100
In-rate RM cell [1]	1	100	700	0	0	0	0	10	100
In-rate RM cell [2]	0	700	700	0	0	0	75.756	0	700
In-rate RM cell [2]	0	700	700	0	0	0	0	75.758	700
In-rate RM cell [2]	1	700	700	0	0	0	0	75.758	700
In-rate RM cell [3]	0	700	700	0	0	0	120.1	0	700
In-rate RM cell [3]	0	700	700	0	0	0	0	120.1	700
In-rate RM cell [3]	1	700	700	0	0	0	0	120.1	700
In-rate RM cell [4]	0	700	700	0	0	0	164.41	0	700
In-rate RM cell [4]	0	700	700	0	0	0	0	164.41	700
In-rate RM cell [4]	1	700	700	0	0	0	0	164.41	700

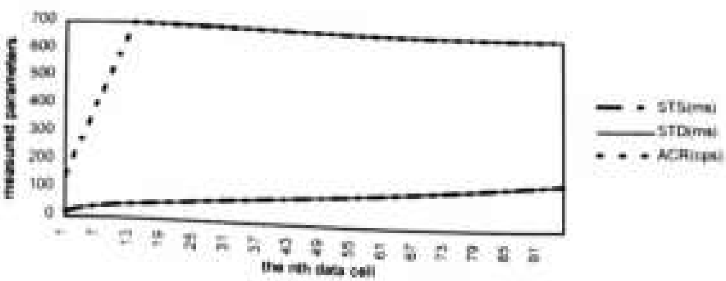

Figure 5. Result of the simulation without congestion

Every cell is sent based on the time schedule which is set after the connection setup. The time schedule for every cell depends on the last value of ACR parameter. The time to send in the simulation is given in unit of millisecond which is calculated relative to a reference time.

It can be seen from Table 4 that the first in-rate RM cell is sent at 10 ms. Since source receives backward RM cell with CI=NI=0, it means that the forward RM cell doesn't not experience congestion in the network. Thus, the source is allowed to increase its ACR from its previous value of 100 cps.

From Table 2:

$ACR = ACR + (RIF \times PCR)$

$ACR = 100 + (0{,}0625 \times 700)$

$ACR = 143{,}75\ cps$

This ACR value is less than ER so that this value is used for next calculation. Since ER is set to PCR, thus the minimum value of ACR is 143.75 cps.

From equation **(4.1)**, by using *now* equal to 10 ms:

$time\text{-}to\text{-}send = 10 + \left[\frac{1000}{143{,}75}\right]$

$time\text{-}to\text{-}send = 16{,}956\ ms$

Thus, the first data cell is sent at 16.956 ms.

For the second data cell:

$ACR = 143{,}75 + (0{,}0625 \times 700)$

$ACR = 187{,}5\ cps$

still this ACR is the minimum between ER and ACR.

And,

$time\text{-}to\text{-}send = 16{,}956 + \left[\frac{1000}{187{,}5}\right]$

$time\text{-}to\text{-}send = 22{,}289\ ms$

By using the same way the chart in Figure 5 is formed. The chart represents the rate at which data cell is sent, and the time when it is sent. Since there is no congestion in the network, the next RM cells will be sent after every 31 data cells because the Nrm is set to 32. At the 14^{th} data cell, the rate becomes stable, that is ACR equal to PCR. In this case, constraint **(4.3)**, which is $MCR <= ACR <= PCR$, is used. The value of ACR never exceeds the value of PCR, and also it is never below the MCR. Therefore, when ACR is greater than PCR, ACR is set to PCR.

Since ACR of the source is 100 cps while the TCR is 10 cps, ACR is greater than TCR. In this case source sends in-rate FRM cell. DIR=0 represents the RM cell is sent in forward direction. CCR=ACR represents the rate at which the cell is sent, which is 100 cps, whereas ER indicates that the application will get its best performance if it is sent at rate of 700 cps. CI=NI=0 indicates that the congestion does not happen when the RM cell travels from source to switch. STS represents the time that has been scheduled by source to send the RM cell from the source to switch. Value of 10 ms means that the RM cell will be sent after 10 ms from reference time. STD represents the time that has been scheduled for sending the RM cell from switch to destination. The data in ATM network wil travel fast because ATM network is a high speed network. Thus, the cell will be in a switch for a very short time. Therefore, it is set that the sending time from the source to the switch is the same with that from the switch to destination in case there is no congestion. The sending time from switch to destination is delayed for 1 ms compared with that from source to switch in case the congestion happened.

The second data:

ACR is greater than TCR and with congestion

Source sends the first RM cell and congestion happens. Thus, CI and NI bits are set to 1 by the switch. As the consequence, there will be delay of 1 ms for sending the cell from switc to destination. Once the source gets the backward RM cell, it adjusts its ACR:

From Table 2:

$ACR = ACR - (RDF \times ACR)$

$ACR = 100 - (0{,}00625 \times 100)$

$ACR = 93{,}75$

And this value is less than the value of ER, so that it is carried out to next calculation. Forum equation **(4.3)**:

MCR <= ACR <= PCR

The value of ACR=93.75 satisfies that constraint, and thus the first data cell will be sent at 93.75. From equation **(4.1)**:

$time\text{-}to\text{-}send = now + \left\lceil \frac{1000}{ACR} \right\rceil$

$time\_to\_send = 10 + \left\lceil \frac{1000}{93{,}75} \right\rceil$

time_to_send = 20,667 *ms*

From Table 5 it can be seen that the second RM cell is sent at STS=122.16 ms. From Figure 6, the value of 122.16 is the time for sending the 8th cell. It means that the next RM cell has already been sent before 31 data cells are sent. It happens because at every oppurtunity to send a cell, the source has two kind of cells, that is data cells and FRM cells. The source will send data cell or RM cell depending on the priority at that time. In normal condition, source will send an FRM cell after every 31 data cells. In the circumstances when the ACR is low, the distance between two FRM cells will be wider and as the consequences, the time required by the source to receive feedback from the network will be delayed. This contradicts to the objective of rate-based its self, which is to optimize the bandwidth usage in the network referenced to feedback, namely backward RM cells.

In this case, when network experienced congestion, the value of ACR is decreased every time the next cell is scheduled to be sent. Therefore, the next FRM cell is sent after the 8th data cell because the condition above is satisfied at that time. This can be represented as below:

$$now \geq last\_RM + Trm$$

$$now \geq 10\ ms + 100\ ms$$

$$now \geq 110\ ms$$

while the *time_to_send* is 122.16 and it is greater than *now*. Tus, the ninth cell will be FRM cell.

From Figure 6 it can be seen that the first eight data cells are sent with the ACR decreasing at every sending time. Although after sending the second FRM cell, the ACR is increased gradually until it reaches the stable rate at ACR=PCR. Again, this chart satisfies the constraints stated previously. After the 40th data cell, the source decrease its ACR. This can also be seen from Table 5 where there is no information about the sending of this FRM cell from the switch to destination. This happens because this third FRM cell experiences congestion on its way from the source to switch and lost in the network.

Since there is only one BRM cell that is not received by source, whereas CRM is set to 524287, source can still continue the connection provided that its ACR is decreased. Thus, by knowing the information about RM cells as it is given in Table 5, the network condition can be predicted. If congestion happens then the ACR will be decreased gradually, and vice versa. Also by knowing the time scheduled for sending RM cells, it can be seen from the chart that the RM cell is sent after a number of data cells.

Table 5. RM cells during the connection with congestion and no congestion

	DIR	CCR (c/s)	ER (c/s)	CI	NI	CLF	STS (ms)	STD (ms)	ACR (c/s)
In-rate RM cell [1]	0	100	700	0	0	1	10	0	100
In-rate RM cell [1]	0	100	700	1	1	1	0	11	100
In-rate RM cell [1]	1	100	700	1	1	1	0	11	100
In-rate RM cell [2]	0	52	700	0	0	0	122.16	0	52
In-rate RM cell [2]	0	52	700	0	0	0	0	122.17	52
In-rate RM cell [2]	1	52	700	0	0	0	0	122.17	52
In-rate RM cell [3]	0	700	700	0	0	0	197.8	0	700
In-rate RM cell [3]	0	0	700	0	0	0	0	0	0
In-rate RM cell [4]	0	118	700	0	0	0	299.34	0	118
In-rate RM cell [4]	0	118	700	0	0	0	0	299.34	118
In-rate RM cell [4]	1	118	700	0	0	0	0	299.34	118
In-rate RM cell [5]	0	700	700	0	0	0	362.55	0	700
In-rate RM cell [5]	0	700	700	0	0	0	0	362.55	700
In-rate RM cell [5]	1	700	700	0	0	0	0	362.55	700

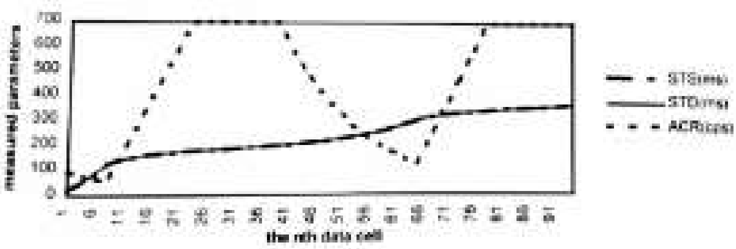

Figure 6. Result of the simulation with congestion and no congestion

The third data:

ACR is greater than TCR and with no congestion and congestion

Table 6 and Figure 7 below can be analysed as in the second case above.

Table 6. RM cells during the connection with no congestion and congestion

	DIR	CCR (c/s)	ER (c/s)	CI	NI	CLP	STS (ms)	STD (ms)	ACR (c/s)
In-rate RM cell [1]	0	100	700	0	0	0	10	0	100
In-rate RM cell [1]	0	100	700	0	0	0	0	10	100
In-rate RM cell [1]	1	100	700	0	0	0	0	10	100
In-rate RM cell [2]	0	700	700	0	0	0	75.756	0	700
In-rate RM cell [2]	0	700	700	1	1	0	0	76.758	700
In-rate RM cell [2]	1	700	700	1	1	0	0	76.758	700
In-rate RM cell [3]	0	118	700	0	0	0	177.3	0	118
In-rate RM cell [3]	0	118	700	1	1	0	0	178.31	118
In-rate RM cell [3]	1	118	700	1	1	0	0	178.31	118
In-rate RM cell [4]	0	59	700	0	0	0	286.69	0	59
In-rate RM cell [4]	0	59	700	0	0	0	0	286.69	59
In-rate RM cell [4]	1	59	700	0	0	0	0	286.69	59

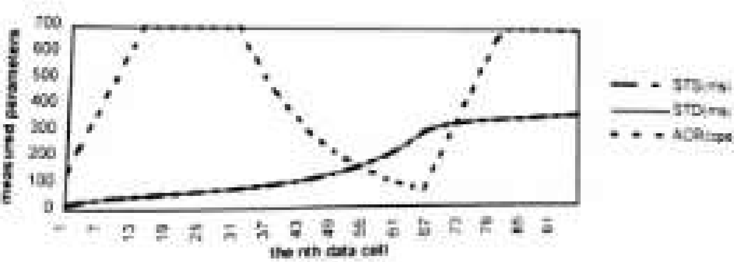

Figure 7. result of the simulation with no congestion and congestion

The fourth data:

ACR is less than TCR at the initialization of connection and no congestion

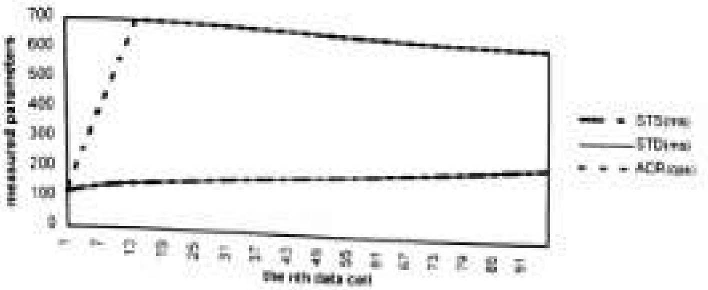

Figure 8. Result of the simulation for ACR < TCR and no congestion

Out-of-rate RM cell is sent by source as the first RM cell. This is due to the value of ACR from negotiation is less than the value of TCR, where ACR=5 cps and TCR=10 cps. From Table 7 it can be seen that CLP bit is set to 1 indicating the out-of-rate RM cell and the rest of the information is for in-rate RM cells as discussed above.

Then it is found that the out-of-rate RM cell does not experience congestion because source receives it with CI=NI=0. Thus, source increases its ACR. From the chart in Figure 8, the ACR increases gradually indicating that congestion never happens in the network during the connection. Eventually, ACR equals to PCR which happens when the source sends the 15^{th} data cell, and then source keeps sending data cells with constant rate.

Table 7. RM cells during the connection for ACR < TCR and no congestion

	DIR	CCR (c/s)	ER (c/s)	CI	NI	CLP	STS (ms)	STD (ms)	ACR (c/s)
Out-of-rate RM cell [1]	0	5	700	0	0	1	10	0	5
Out-of-rate RM cell [1]	0	5	700	0	0	1	0	10	5
Out-of-rate RM cell [1]	1	5	700	0	0	1	0	10	5
In-rate RM cell [1]	0	91	700	0	0	0	110	0	91
In-rate RM cell [1]	0	91	700	0	0	0	0	110.01	91
In-rate RM cell [1]	1	91	700	0	0	0	0	110.01	91
In-rate RM cell [2]	0	700	700	0	0	0	177.23	0	700
In-rate RM cell [2]	0	700	700	0	0	0	0	177.23	700
In-rate RM cell [2]	1	700	700	0	0	0	0	177.23	700
In-rate RM cell [3]	0	700	700	0	0	0	221.54	0	700
In-rate RM cell [3]	0	700	700	0	0	0	0	221.54	700
In-rate RM cell [3]	1	700	700	0	0	0	0	221.54	700
In-rate RM cell [4]	0	700	700	0	0	0	265.86	0	700
In-rate RM cell [4]	0	700	700	0	0	0	0	265.86	700
In-rate RM cell [4]	1	700	700	0	0	0	0	265.86	700

The fifth data:

ACR is less than TCR at the initialization of connection and with congestion happened

The explanation for this case is the same as that for the fourth data, except the first three in-rate FRM cells experienced congestion after the source sends out-of-rate FRM cell. Thus, from the chart it can be seen the ACR decreases gradually. Since the decrease of ACR does not cause the value of ACR becomes smaller than TCR, the source sends in-rate RM cells for the rest of connection.

Table 8. RM cells during the connection for ACR < TCR with congestion

	DIR	CCR (c/s)	ER (c/s)	CI	NI	CLP	STS (ms)	STD (ms)	ACR (c/s)
Out-of-rate RM cell [1]	0	5	700	0	0	1	10	0	5
Out-of-rate RM cell [1]	0	5	700	0	0	1	0	10	5
Out-of-rate RM cell [1]	1	5	700	0	0	1	0	10	5
In-rate RM cell [1]	0	91	700	0	0	0	110	0	91
In-rate RM cell [1]	0	91	700	1	1	0	0	110.01	91
In-rate RM cell [1]	1	91	700	1	1	0	0	110.01	91
In-rate RM cell [2]	0	52	700	0	0	0	212.63	0	52
In-rate RM cell [2]	0	52	700	1	1	0	0	213.63	52
In-rate RM cell [2]	1	52	700	1	1	0	0	213.63	52
In-rate RM cell [3]	0	33	700	0	0	0	332.93	0	33
In-rate RM cell [3]	0	33	700	1	1	0	0	333.94	33
In-rate RM cell [3]	1	33	700	1	1	0	0	333.94	33
In-rate RM cell [4]	0	24	700	0	0	0	440.46	0	24
In-rate RM cell [4]	0	24	700	0	0	0	0	440.47	24
In-rate RM cell [4]	1	24	700	0	0	0	0	440.47	24
In-rate RM cell [5]	0	700	700	0	0	0	525.96	0	700
In-rate RM cell [5]	0	700	700	0	0	0	0	525.96	700
In-rate RM cell [5]	1	700	700	0	0	0	0	525.96	700
In-rate RM cell [6]	0	700	700	0	0	0	570.33	0	700
In-rate RM cell [6]	0	700	700	0	0	0	0	570.34	700
In-rate RM cell [6]	1	700	700			0	0	570.34	700

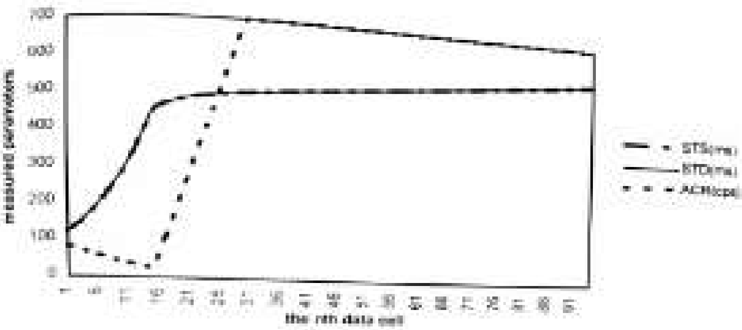

Figure 9. Result the simulation for ACR < TCR with congestion

Conclusion

Mechanism of ABR allows a network to divide available bandwidth fairly and efficiently to traffic generator sources. Traffic Management Specification TM4.0 has been released by the ATM Forum in order to avhieve this purpose. This traffic management is called the Rate-Based End-to End Closed-Loop.

By using rate-based control, the cell delay or loss due to jamming in a network can be detected by a source immediately, once the backward RM-cell arrive at the source. Thus, the problem can be anticipated by the source, that is by decreasing its ACR. On the other hand, if the arriving backward RM-cell is setwith no indicator of congestion, the the source can take advantage by increasing its ACR to use more bandwidth in the network. Therefore, the bandwidth can be used optimally.

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