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Effect of Bursty Source Traffic on Rate-Based ABR Congestion Control Schemes

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Abstract

Congestion control is an important function of traffic management in Asynchronous Transfer Mode (ATM) networks. Available Bit Rate (ABR) is a category of service for ATM networks wherein the source adapts its generation rate to network conditions based on feedback. In this paper we study closed-loop ABR congestion control using special cells called Resource Management (RM) cells to relay feedback to the source. In particular, we investigate both the effectiveness of rate-based ABR congestion control in the presence of bursty source traffic and the relationship between the burst time scale and the ABR control time scale. Two ABR congestion control schemes, the ABR Explicit Forward Congestion Indication (EFCI) and ABR Congestion Indication (CI) schemes, are compared with Unspecified Bit Rate (UBR) transport which makes no effort to control congestion. Traffic sources of various burst lengths of 100, 1000, 10000, and an equal mix of 100 and 10000 cells are used in simulations. It is found that ABR congestion control effectively controls low frequency, medium to long term traffic load transients, but does not control high frequency, short term load transients. In the latter case, ABR control is not necessary since short term transients do not require large amount of buffering. Of the two ABR schemes considered, the more sophisticated ABR CI scheme performs significantly better than the ABR EFCI scheme in terms of delay and buffer occupancy.

1. Introduction:

The effectiveness of congestion control is governed by the capacity of the network, traffic density, and the propagation delay in informing the traffic source to change its traffic generation rate. Since the link speeds are very high and propagation delays are long in ATM networks, traditional window flow control techniques may not be suitable.

There are five service categories for ATM networks: Constant Bit Rate (CBR), real-time and non-real-time Variable Bit Rate (VBR), Unspecified Bit Rate (UBR), and Available Bit Rate (ABR). UBR and ABR are the two categories that most closely match the needs of data traffic, which is both bursty and unpredictable (ATM Forum, 1995).

The UBR category does not involve any feedback from the network since it offers very minimal traffic-related service guarantees. All connection requests are accepted and sources generate cells at rates that are not dependent on network conditions i.e., there is no feedback from the network to inform the sources of congestion. The ABR category, however, expects a low cell loss rate. Sources of this category have to adapt their rates in response to changes in network conditions.

There are two kinds of congestion control - open-loop and closed-loop. Open-loop control involves assigning bandwidth to a connection based on its declared traffic parameters, such as the Peak Cell Rate (PCR), cell delay variation, etc. (Woodruff, 1990), (IEEECM, 1991). Open-loop control is not suitable for data transfer since it is difficult for a connection to take advantage of bandwidth assigned to another connection, even when it is not being utilized (Ohsaki, 1995).

Closed-loop or reactive congestion control limits the number of cells in the network by constant monitoring and sending feedback to sources. The sources, upon receiving feedback from the network, adapt their cell generation rates to the prevalent conditions of the network. There are two kinds of closed-loop control schemes, credit-based and rate-based. The credit-based scheme involves a large data buffer and a credit counter per connection.

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This scheme is based on a link-by-link window flow control (Kung, 1994). Each link has an independent flow control. A connection has to reserve resources for its cells at all the links in its route before it is allowed to transmit. This is the credit it accumulates at each node. A connection is not allowed to transmit if it fails to gain credit from the next node. The credit counter accumulates credits at a rate initiated from the network and is depleted every time a cell is sent. The number of credits cannot be reduced below a threshold level. Transient congestion is controlled very well by this scheme. There is almost no cell loss since cells are not transmitted if there are no credits. However, a very large buffer is needed and complex buffer management has to be performed at the switch.

The rate-based scheme involves controlling the source's rate according to feedback from the network, using special cells called Resource Management (RM) cells. The number of cells in the network is contained by having the sources themselves reduce their rate of transmission, thus simplifying control. There is no need for large buffers, which reduces cost. There are many such rate-based schemes which vary in complexity and performance. A detailed description of existing rate-based control schemes is presented in the next section.

Two important types of traffic sources that have been studied are: (1) Persistent - this type of source always has cells to transmit, and (2) Bursty - this type of source generates bursts of traffic. The burst length may assume a geometric or a uniform distribution, or a deterministic distribution. The period between two bursts usually follows an exponential distribution. Many ABR simulation and analysis studies have focussed on the simulation of persistent sources because these allow a good understanding of the behavior without interference of statistical fluctuations caused by random sources (Ohsaki, 1995).

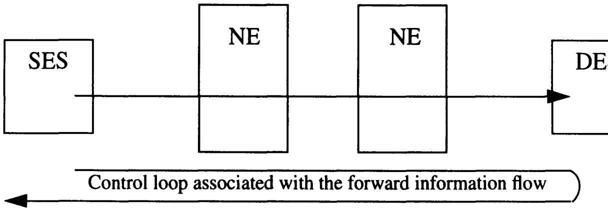
This paper investigates the effectiveness of ABR congestion control in the presence of *non-persistent* traffic sources. We present results of simulating three control schemes: UBR, ABR Explicit Forward Congestion Indication (EFCI), and ABR Congestion Indication (CI) with per-VC accounting in the presence of bursty sources. To see the effect of these schemes on sources of bursty traffic, we vary the burst length of the sources. Short, medium, long, and an equal mix of short and long burst lengths are used. We study the performance of the congestion control schemes in terms of Available Cell Rate (ACR) of the sources and the buffer queue length at the switch. We also measure mean queuing delay, cell loss, and link utilization under the different scenarios.

Section 2 of this paper describes ABR traffic control in detail and presents various algorithms that switches could implement to achieve it. Section 3 presents the network configuration and the parameters used for the simulation. Section 4 presents the results obtained and discussions of these simulation results. The conclusions drawn from these results appear in Section 5. The Appendix contains expansions of the acronyms used in this paper.

2. ABR Traffic Control

The ATM Forum has adopted rate-based control for ABR traffic and defined reference ABR source and destination behaviors (ATM Forum, 1995). ABR flow control occurs between two endsystems (refer to Figure 1). A connection between such a pair is bi-directional in that both endsystems are each a source and a destination. An ABR endsystem always has to implement both the source and the destination behaviors. For simplicity, we will consider information flow only in one direction, from the source endsystem to the destination endsystem. The forward direction is that from the source endsystem to the destination endsystem and the backward direction is that from the destination endsystem to the source endsystem.

ABR flow control involves closed-loop control implemented by RM cells which originate at the source endsystem, reach the destination endsystem, and are turned back to the source endsystem. RM cells are distinguished by the value six in the Payload Type Indicator (PTI) field of their ATM header. They also have a bit field DIR, to indicate their direction of travel - forward or backward with reference to their point of origin. The RM cells are generated by the source either every Nrm (number of cells between two RM cells) or every Trm (time between two RM cells). They carry information about the network conditions to the source endsystem after being turned around by the destination endsystem.



SES - Source End System
DES - Destination End System
NE - Network Element

Figure 1: An Example ABR control loop between a source and a destination

The Message Type field of RM cells contains the fields the Congestion Indication (CI), the No Increase (NI), and the Explicit Rate (ER) that are used by various rate-based congestion control schemes to alter source rates. The rate-based ABR congestion control schemes use the Explicit Forward Congestion Indication bit in the data cells too.

The network feedback information is written into RM cells by network elements. The network elements may do one of three things - (i) directly insert information into RM cells when they pass or, (ii) indirectly indicate congestion conditions to the source endsystem by setting EFCI bits in data cells, in which case the destination endsystem inserts information into RM cells before turning them around or, (iii) generate RM cells themselves.

The control loop may be segmented into multiple control loops by using a network element which implements virtual source/virtual destination behavior. This segmentation would isolate control segments and increase link utilization (Bonomi, 1995).

The sources have to declare the maximum required bandwidth and the minimum bandwidth necessary for the connection at the time of connection establishment. These connection parameters are called the Peak Cell Rate (PCR) and the Minimum Cell Rate (MCR). The actual rate at which the source can generate traffic is the Allowed Cell Rate (ACR).

The ABR traffic control maintains an ACR for each source, which will be equal to the guaranteed MCR or higher, but never higher than PCR, throughout the lifetime of the connection. It "provides rapid access to unused network bandwidth at up to PCR, whenever the network bandwidth is available" (ATMF, 1995). Low cell loss is expected to result from ABR traffic control if the source and destination endsystems follow reference behavior.

The switch algorithm is not defined by the ATM Forum and hence many algorithms are possible. Using a standardized format for the RM cell and control algorithms, different switch architectures will be able to coexist and interwork with each other. The switches can control the rate of the sources by one of several ways:

Relative Rate marking

The source sends RM cells with their CI bits reset either a certain number of cells (Nrm) apart or a certain amount of time (Trm) apart. The destination turns around the RM cells it receives from the source and sends it back to the source, using the same path. The switches on the path of the connection set the CI bit in these backward RM cells when there is congestion in the forward direction. When the source receives a backward RM cell with its CI bit set, it reduces its ACR by ACR * RDF. The resulting ACR, if lower than the MCR, is replaced by MCR. If the source receives backward RM cells with reset CI bits, it increases its ACR by (ACR * RIF) (ATMF, 1995).

Explicit Forward Congestion Indication (EFCI) marking

The source sends its data cells with the EFCI bit reset at a rate of one cell every 1/ACR time. It also sends RM cells. When a switch in the path of the connection detects congestion, it sets the EFCI bit in the data cells. The destination, on receiving data cells with their EFCI bits set, will set the CI bit in the very next forward RM cell that it receives. It then turns the RM cell around. The source will react to RM cells with their CI bits set by reducing its ACR. The source will increase its ACR if it receives RM cells with their CI bits reset (ATMF, 1995), (Hluchyj, 1994).

Explicit Rate (ER) marking

The source writes the rate it desires in the RM cells it sends between data cells at regular intervals. The switch computes the fair share of bandwidth that should be allocated to each VC, and traffic load by monitoring the queue length. It updates the ER field of backward RM cells with the calculated fair share. The source will change its ACR to the value in the ER field of returning RM cells (ATMF, 1995), (Barnhart, 1995).

There are many variations of these schemes. A separate queue can be used at the switch for RM cells, to speed up response. This queue could be given priority over the data queue in order that RM cells are not blocked for too long due to congestion. Deciding when to set the EFCI bit or CI bit or by how much to reduce ER is implementation specific. There are two common methods of congestion detection: queue length-based and link utilization-based (Bonomi, 1995). The queue length-based congestion detection is implemented by monitoring the queue length at the switch. If the length is greater than a certain threshold, congestion is declared. The link utilization-based congestion detection is based on the change in queue length, monitored at some fixed intervals.

Several works have appeared in literature on rate-based congestion control. Lee et al. formally represent ABR source and destination behavior using an extended finite state machine (Lee, 1996). Bonomi and Fendick compare the EFCI with the ER scheme in terms of fairness (Bonomi, 1995). Ohsaki et al. quantitatively evaluate the performance of all these three algorithms in terms of maximum queue length for persistent traffic. They vary propagation delay and the number of VCs to show the effectiveness of rate-based congestion control (Ohsaki, 1995). Chang et al. show that EFCI and ER switches can interoperate provided that the switch implementations conform to reference behavior in terms of congestion notification and usage of RM cells (Chang, 1995).

The source rate, in all of the above schemes, is controlled by an ABR rate scheduler. There are many parameters used to implement the congestion control which the ABR scheduler keeps track of, such as the ACR, PCR, etc. The scheduler uses the value of ACR to schedule a cell every 1/ACR time.

3. Simulation Configuration and Parameters:

We present results of simulating ABR EFCI, ABR CI and UBR congestion control. ABR EFCI congestion control scheme is simulated with FIFO queue length congestion triggering. This is the simplest of all those mentioned above. It is chosen to compare with ABR control against UBR control since switches implementing this scheme are currently available. We would expect more advanced methods to out-perform the EFCI based results presented here. It is also the least expensive scheme to implement.

The ABR EFCI scheme simulated involves a separate queue at the switches for RM cells, to avoid their being blocked during congestion conditions. The more sophisticated ABR CI scheme involves setting CI bits in backward RM cells by switches if congestion is detected in the forward direction. The switches perform per-VC accounting. i.e., they keep count of cells belonging to each VC and set the CI bits in the RM cells of those VCs that have exceeded the per-VC threshold.

To gain a better understanding of the issues being studied, this paper investigates the simple configuration which is described below.

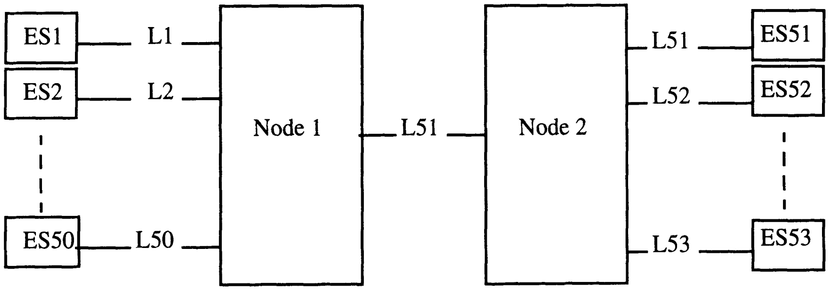


Figure 2: Two-Node topology (modified)

The backbone link between the two nodes and the expected point of congestion is an OC3 (150 Mbps) link. There are 50 endsystems connected to each of the nodes. The endsystems are connected to the node by DS3 (40 Mbps) links. The propagation delay between the two nodes is 10 ms (unless specifically noted). The propagation delay between the endsystem and the node is 0.01ms. There are 50 virtual connections between these endsystems, all passing through the backbone link.

The simulation is repeated for four source traffic scenarios.

1. All sources with a short mean burst length (100 cells)
2. All sources with a medium mean burst length (1000 cells)
3. All sources with a long mean burst length (10000 cells)
4. Half sources with a short mean burst length and half with a long burst length (100 cells and 10000 cells)

The burst length of the sources follows a geometric distribution around the mean value. The period between two bursts follows an exponential distribution.The activity fraction was 1/16 for each bursty source, resulting in a long-term traffic load of almost 85% (50 VCs * 96 cells/ms * (1/16) / 353 cells/ms, since there are 50 VCs initiated by sources with PCR 96 cells/ms and the capacity of the backbone link is 353 cells/ms). The observed load for each simulation is a statistical sample only and may be higher or lower than this value, as indicated by the results.

ABR Scheduler Parameters:

PCR (Peak Cell Rate) is 96 cells/ms or 40 Mbps.
ICR (Initial Cell Rate) is the PCR.
MCR (Minimum Cell Rate) is 0.
Nrm (Number of data cells between two RM cells) is 32.
Trm (Time between rate updates) is 20ms.
RIF (Rate Increase Factor) is 1/256.
RDF (Rate Decrease Factor) is 1/16.
The congestion threshold was set at 5000 cells for ABR EFCI and 1250 cells for ABR CI.

4. Performance:

Results of simulating UBR, ABR EFCI and ABR CI control schemes with 50 bursty sources for 10 seconds are collated here. The random sample does not accurately reflect long-term behavior and so the numerical values here may be better or worse than typical steady state performance of ABR control. For example, the observed load has a wide range of values, even though the calculated long term load is 85%. Hence, the simulation results cannot be used to make a quantitative assessment. However, the transient characteristics can illustrate important aspects of ABR behavior.

4.1. Short length bursty sources

Figures 3 and 4 show the buffer queue length in UBR, ABR EFCI and ABR CI control simulations with 50 bursty sources, all with a mean burst length of 100 cells. All these cases used identical random traffic. Table 1 summarizes the maximum buffer length, mean queuing delay, cell loss, and link utilization characteristics of these simulations.

The mean queuing delay values shown here resulting from ABR control are much higher than that from the UBR control. However, it does not incorporate the delay caused by retransmission by the upper layers.

From Figures 3 and 4 we can see that ABR control does not improve the maximum queue length resulting from UBR control for short length bursts. The transient congestion causes ACR of the sources to be adjusted down from their PCR. However, the ACR is not kept at that level for too long and is increased to restore its value to PCR almost immediately. ABR CI control neither reduces the ACR to levels as low nor as often as ABR EFCI does and the ACR recovers faster, resulting in a shorter delay. This is largely because the ABR CI control scheme is acting on RM cells travelling in the backward direction and so has a faster response time.

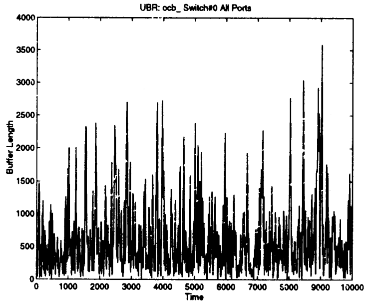
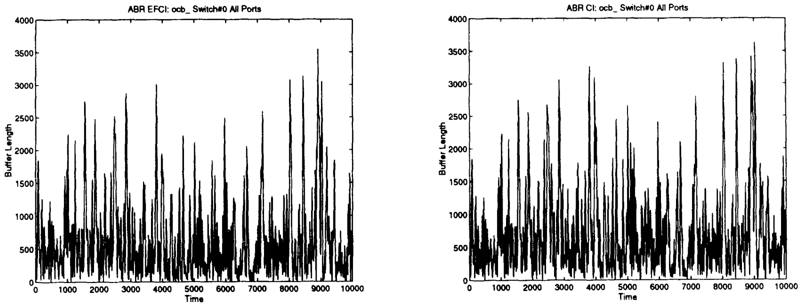


Figure 3: UBR for 50 bursty sources with mean burst length 100 cells - Buffer queue length vs. time

Table 1: Maximum buffer length, mean queuing delay and link utilization for 50 bursty sources with mean burst length of 100 cells

Congestion control scheme	Maximum buffer length in cells	Mean queuing delay in ms	Number of cells dropped	Link Utilization (%)
UBR	3600	1.1722	0	85.24
ABR EFCI	3600	2.7295	0	85.23
ABR CI	3700	1.8392	0	85.24



(a) (b)

Figure 4: ABR EFCI and CI for 50 bursty sources with mean burst length 100 cells - Buffer queue length vs. time

4.2. Medium length bursty sources

Figures 5 and 6 show the buffer queue length in the UBR, ABR EFCI, and ABR CI control simulations with 50 bursty sources, all with a mean burst length of 1000 cells. All these cases used identical random traffic.

It can be seen from comparing Figures 5 and 6 and table 2 that for the medium length bursts, the maximum buffer length with ABR EFCI is significantly less than that with UBR control. The ACR of the sources is reduced sometimes to very low values to contain the number of cells in the network. ABR CI results in using the same maximum buffer length as ABR EFCI, though the average buffer occupancy is much lower than that of ABR EFCI, as can be seen from Figures 5 (a) and 5 (b). It results in a significantly shorter delay for comparable link utilization, since it does not lower the ACR to very low levels as often as ABR EFCI does.

Table 2: Maximum buffer length, mean queuing delay and link utilization for 50 bursty sources with mean burst length of 1000 cells

Congestion control scheme	Maximum buffer length in cells	Mean queuing delay in ms	Number of cells dropped	Link Utilization (%)
UBR	17000	7.1380	0	83.61
ABR EFCI	11000	53.7136	0	82.74
ABR CI	10700	19.9260	0	83.37

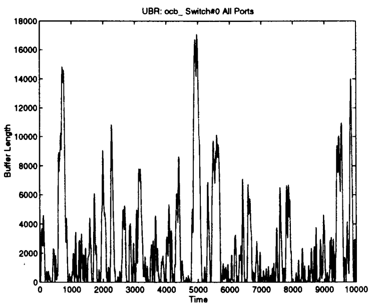
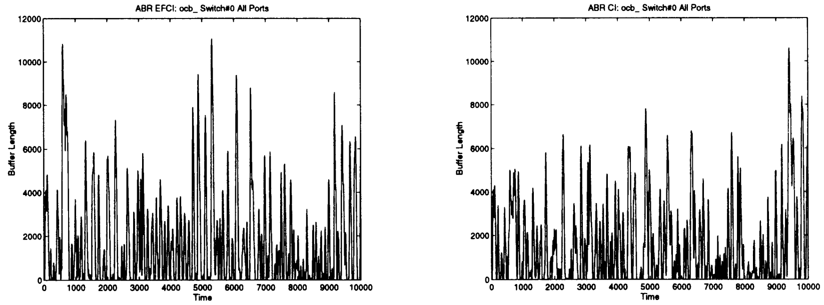


Figure 5: UBR with 50 bursty sources with mean burst length 1000 cells - Buffer queue length vs. time



(a) (b)

Figure 6: ABR EFCI and CI with 50 bursty sources with mean burst length 1000 cells - Buffer queue length vs. time

4.3. Long length bursty sources

Figures 7 and 8 show the buffer queue length in the UBR, ABR EFCI and ABR CI control simulations with 50 bursty sources, all with a mean burst length of 10000 cells.

Figure 7 shows that for long length bursts, even a maximum buffer length of 50000, which is a reasonable number for OC3 links, is not adequate for UBR control, resulting in significant cell loss. On the other hand, ABR EFCI and ABR CI perform extremely well in inhibiting buffer occupancy and result in zero cell loss, the most important QoS (Quality of Service) criterion for ABR traffic. Again, ABR CI performs better than ABR EFCI in terms of delay and buffer occupancy, as can be seen from table 3.

We have determined that the additional queuing delay for ABR control is a consequence of using binary rate control with a moderately large propagation delay. With a 10 ms propagation delay between the switches, it is not possible to choose AIR and RDF to result in full utilization, even in steady state. A mathematical derivation for this is given in (Ikeda, 1995). When the burst lengths are big and the steady state throughput is less than 100%, the traffic will bank up in the endsystem creating a pseudo-persistent source, as reflected by the regular patterns in Figure 8. To demonstrate that this is the issue, we have presented the results of ABR control simulations with a 0.01 ms propagation delay between the switches in the last two rows of table 3. The queuing delay in these cases are much less than for the cases with a 10 ms propagation delay between the switches. Although not verified here, we would expect much better delay performance from an explicit rate scheme.

Table 3: Maximum buffer length, mean queuing delay and link utilization for 50 bursty sources with mean burst length of 10000 cells

Congestion control scheme	Maximum buffer length in cells	Mean queuing delay in ms	Number of cells dropped	Link Utilization (%)
UBR	50000	49.6040	61694	85.49
ABR EFCI (10 ms)	6900	765.8332	0	70.14
ABR CI (10 ms)	1450	525.1764	0	75.46
ABR EFCI (0.01 ms)	6000	105.3194	0	85.1
ABR CI (0.01 ms)	950	99.2834	0	85.25

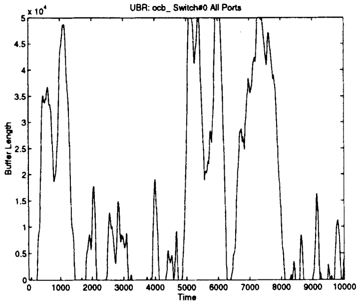
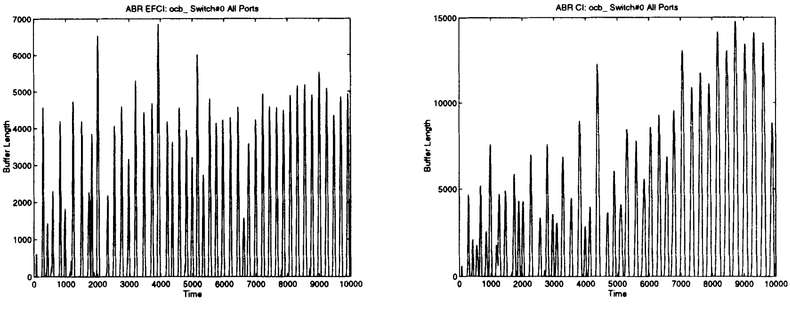


Figure 7: UBR with 50 bursty sources with mean burst length 10000 cells - Buffer queue length vs. time



(a) (b)

Figure 8: ABR EFCI and CI with 50 bursty sources with mean burst length 10000 cells - Buffer queue length vs. time

4.4. Mixture of short and long length bursty sources

Figures 9 and 10 show the buffer queue length in UBR, ABR EFCI and ABR CI control simulations with 25 bursty sources with a mean burst length of 100 cells and 25 bursty sources with a mean burst length of 10000 cells. All these cases used identical random traffic. Table 4 summarizes the maximum buffer length, queuing delay, cell loss and link utilization characteristics of these simulations.

It can be seen from Figure 9 and table 4 that UBR control results in significant cell loss since the maximum buffer length of 50000 cells is not sufficient. Again, both ABR EFCI and ABR CI work extremely well in curbing switch buffer occupancy, as observed from Figures 10 (a) and 10 (b).

However, it is most important to note from table 4 that the ACR of the sources with short burst length are not much altered, as can be deduced from the reasonable delay they face. The sources with long bursts, on the other hand, face long delays, indicating that ABR control has been instituted.

As before, we present the results of simulating ABR control with a 0.01 ms propagation delay between the switches in the last two rows of table 4. It can be seen that the queuing delay in these cases are much lower than in the cases with a propagation delay of 10 ms between the switches, thus showing the limitation of binary rate control schemes.

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Table 4: Maximum buffer length, mean queuing delay and link utilization for 25 bursty sources with mean burst length of 100 cells and 25 bursty sources with mean burst length of 10000 cells

Congestion control scheme	Maximum buffer length in cells	Mean queuing delay (100 cells) in ms	Mean queuing delay (10000 cells) in ms	Number of cells dropped	Link Utilization (%)
UBR	50000	33.1059	41.1097	30588	86.83
ABR EFCI (10 ms)	6500	4.3085	823.6975	0	79.34
ABR CI (10 ms)	11900	5.2705	439.3031	0	83.37
ABR EFCI (0.01 ms)	8600	6.3523	129.9396	0	86.54
ABR CI (0.01 ms)	17000	11.7227	105.9821	0	86.68

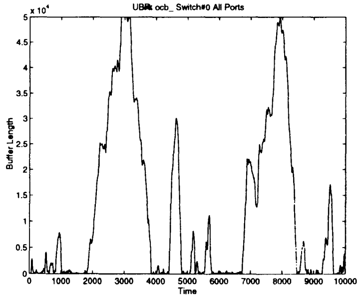
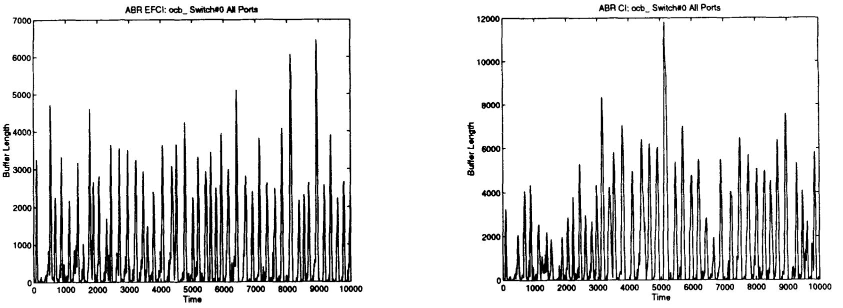


Figure 9: UBR with 25 bursty sources with mean burst length 100 cells and 25 bursty sources with mean burst length 10000 cells - Buffer queue length vs. time



(a) (b)

Figure 10: ABR EFCI and CI with 25 bursty sources with mean burst length 100 cells and 25 bursty sources with mean burst length 10000 cells - Buffer queue length vs. time

5. Conclusion:

Rate-based congestion control is an architecturally flexible approach for handling ABR traffic in ATM networks. Since all the different schemes proposed for the control use standardized RM cells, switches implementing them can interoperate. Closed-loop control is necessary for ABR traffic since its bursty feature can be utilized to service more connections by allocating unused bandwidth of one connection to other connections that can use it.

We study the performance of various ABR congestion control algorithms in the presence of bursty traffic sources since they are very likely to occur in reality. Results of simulating ABR EFCI and ABR CI control schemes show that ABR control is extremely effective in controlling low frequency, medium to long length bursts. This is very desirable since it is the low frequency behavior which results in extended periods of overload and corresponding cell loss. By controlling the low frequency behavior, ABR control reduces trunk queue lengths and minimizes overflow and cell loss. ABR control does not control high frequency, short length traffic bursts. However, since short bursts do not require a large amount of buffering, ABR control is not required in these cases. Another limitation of these two binary rate control schemes is that they result in large queuing delay when the propagation delay is large. We believe that explicit rate (ER) ABR control schemes will perform much better in such cases.

ABR EFCI control is the simplest and most cost-effective ABR control to implement. Our results show that it is effective in minimizing buffer occupancy. ABR CI performs significantly better than ABR EFCI in terms of delay and maximum buffer length, since network feedback information reach the traffic sources faster.

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Appendix:

Acronyms used in the paper:

ABR - Available Bit Rate
ACR - Allowed Cell Rate
AIR - Additive Increase Rate
AIRF - Additive Increase Rate Factor

ATM - Asynchronous Transfer Mode
CCR - Current Cell Rate
CI - Congestion Indication (bit in RM cell)
DES - Destination End System
DIR - Direction (bit in RM cell)
EFCI - Explicit Forward Congestion Indication
ER - Explicit Rate
FIFO - First In First Out
MCR - Minimum Cell Rate
NI - No Increase
Nrm - Maximum number of data cells between RM cell generation
PCR - Peak Cell Rate
PTI - Payload Type Indicator
QL - Queue Length (not used by ABR Forum)
RDF - Rate Decrease Factor
RIF - Rate Increase Factor
RM - Resource Management cell
SES - Source End System
SN - Sequence Number (not used by ABR Forum)
Trm - Time for RM generation
UBR - Unspecified Bit Rate
VC - Virtual Connection
VCI - Virtual Connection Identifier
VP - Virtual Path
VPI - Virtual Path Identifier

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