ABR Service in ATM Networks: Performance Comparison between BECN and Adaptive Stochastic Congestion Control Schemes with Guaranteed Minimum Cell Rate

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ABSTRACT*:* Two rate-based feedback schemes for congestion control in ATM networks: Backward Explicit Congestion Notification (BECN) and proposed Adaptive Stochastic (AS) are compared under heavy load conditions. Neither of the schemes dictates a particular switch architecture. The requirements tested include: utilization, queuing delay, queuing delay variance and queue size. The controllable sources' allowed cell rates (ACR) have been dynamically shaped by the feedback messages based on the instantaneous queue size in the ATM switch output buffer. The results of a simulation study are presented which suggest that AS scheme, while retaining practically the same link utilization, can provide for higher priority traffic considerably shorter average queuing delay, queuing delay variance, maximum and average queue size in the switch output buffer, particularly on longer network segments between terminals generating traffic and the switch.

1 Introduction

It is now widely assumed that the future ATM networks will be dominated by bursty traffic. Regarding the traffic control policies for ATM networks, the preventive congestion control implemented by a conjunction of connection admission control (CAC) and usage parameter control (UPC) is not sufficient. Unpredictable statistical fluctuations and burstiness of traffic sources make it difficult to guarantee quality of service and high utilization of the network resources using source traffic parameters declared by the users, such as average rate and burst duration. Traffic management and its most essential aspect - congestion control, in ATM networks should be, therefore, accomplished in a reactive manner in conjunction with a preventive manner. If a truly integrated transport network for all services is wanted, an unpredictable load pattern is inevitable. Therefore, no prediction algorithm is incorporated in the scheme and it is left to future considerations. A number of congestion control schemes for ATM networks have been developed [1] - [11].

The remainder of the paper is organized as follows: in Section 2 the assumed network structure and how it operates is described; in Section 3 the design of both control algorithms is outlined; in Section 4 the simulation models and obtained results are reported and in Section 5 conclusion remarks are made.

2 The Assumed Network Structure

It is assumed that two types of traffic share the ATM network resources. The first type consists of Variable Bit Rate (VBR) traffic which is delay sensitive i.e. which has stringent delay requirements and is not subjected to any control and hence is uncontrollable. The second type of traffic requires good loss performance, but agrees to have its bit rate controlled when necessary, thus accepting the possibility of longer mean delays during periods of high demand, i.e. cell loss is avoided at the expense of delay and hence is controllable. All delay insensitive Available Bit Rate (ABR) traffic can join this category which is designed for normal data traffic such as file transfer and email. In these experiments delay sensitive traffic was given a higher priority. A simple network topology involves an ATM switching node which is modeled as a single server queuing system fed by a number of highly bursty traffic sources (Fig. 1). The ACRs of the ABR traffic sources take the values being conveyed by the feedback messages which are carried from the switch to the sources' terminals through backward Resource Management (RM) cells. Each source could also be a switch acting as a virtual source and generating RM cells periodically as if it was a source. The switch acts as a virtual destination and returns all RM cells received from the source as if the switch was the destination. In this study RM cells are in-rate since they are counted toward the ACR, what means that the total rate of data and RM cells should not exceed the ACR of the source. During idle periods a source does not generate RM cells. A RM cell is always sent as the first cell after and idle period for the source. In the compared schemes each individual lower priority (controllable) traffic virtual channel (VC) is guaranteed by the network only a minimum bandwidth of a minimum cell rate (MCR), agreed during the connection setup. However, it is allowed to dynamically share the available resources left over from the higher priority (uncontrollable) traffic i.e. the lower priority traffic grabs whatever remains of the network resources (bandwidth and buffer space) after the higher priority traffic is served. Thus the ABR capacity is not fixed, but varies according to the VBR load. Switch complexity does not depend on the number of VCs since there is no per VC queuing. In the switch, output buffering is used, which means that the queuing happens at the output port. The cells of both traffic classes are treated in the switch output buffer, by equal priority and are served with FIFO discipline. The same service discipline applies also to all sources' queues. In order to support the feedback control scheme a simple CAC policy ensures that the peak cell rate of the total higher priority (VBR) traffic is within the ATM switch server capacity in every moment and that the long term mean rate of all the traffic (higher and lower priority together) is within the ATM switch server capacity. Both AS and BECN schemes operate at the ATM switch output queuing point. Large buffers are assumed and the effect of cell losses is not modeled. Neither packet discarding, nor packet retransmission mechanisms are included.

3 Description of the Compared Schemes

3.1 Adaptive Stochastic (AS) Scheme

The traffic flowing from the sources to the ATM switch is assumed to be a process which takes place in random environment. The design of the control algorithm has been based upon input-output model of the process which allows analysis over the transfer function and realization of the control algorithm with minimal a priori knowledge about the dynamics and parameters of the process. The transfer function is defined as

$$y(k)u^{-1}(k) = B(z^{-1})A^{-1}(z^{-1}) . \quad (1)$$

where z^{-1} is delay operator meaning

$$z^{-1}y(k) = y(k - 1), \quad z^{-1}u(k) = u(k - 1) . \quad (2)$$

and integer k is the control interval's time index. Since the process is modeled here as the first order linear dynamical system where

$$A(z^{-1}) = 1 + a(k)z^{-1}, \quad B(z^{-1}) = b(k)z^{-1} . \quad (3)$$

it is described by the stochastic difference equation

$$y(k+1) = - a(k)y(k) + b(k)u(k) . \quad (4)$$

y(k) is the output equal to instantaneous queue length minus the reference level (threshold). The scalar u(k) is the control input generated by the algorithm. It is a function of the queue size measurement and is used for identification of parameters and for attaining the desired system response. u(k) determines the ACRs of the ABR traffic sources with the goal to maintain the ATM switch output buffer occupancy as close as possible to a certain reference level. u(k) is partitioned among active ABR traffic sources accordingly. ABR traffic sources seen by the switch as inactive are allocated MCR only. An active ABR traffic source's ACR is then formed as the sum of the source's long term mean cell rate and its share of u(k). In proportion to its absolute value, a negative u(k) reduces and a positive u(k) increases the ABR sources' ACRs. Hence, the ACRs fluctuations are dictated by u(k) but can not go below the MCR or above the link rate. The unknown parameters are a(k) and b(k). Their actual values are random and time varying. The uncertainty in b(k) corresponds to uncertainty in the system gain while the uncertainty in a(k) corresponds to uncertainty in the system time constant. Not knowing a(k) exactly is equivalent to not knowing the pole location of the system function. Since the system is operating in a stochastic environment, both y(k) and u(k) are random sequences. The objective of the problem is to find in each control interval the optimal control input that minimizes the scalar real-valued cost functional i.e. the performance criterion

$$J(u) = E\{qy^2(k+1) + ru^2(k) + qy^2(k)\} \quad k = 0, 1, \ldots . \tag{5}$$

where E denotes expected value. q and r are positive scalars (weighting factors). As the only information about the process comes from the observation of the queue size, since the queue size is the only directly measurable quantity at the switch, the optimal control policy can be interpreted as follows: at the end of the k-th control interval an optimal control input $u^o(k|k)$ (superscript o stands for 'optimal') is generated, based on the current queue length measurement. k on the left side of | denotes the control interval itself and k on the right side of | means that measurement/observation of the queue length was taken during the control interval k. The next control input $u^o(k+1|k+1)$ is again computed, but based on the information about the queue size available at the control interval k + 1. Thus, the optimal deterministic control shall be recomputed after new information becomes available at each control interval. The switch gives only one feedback value in a single control interval which is equal to the round-trip delay because there is little point in sending further control feedbacks to the sources until previous feedback has had time to take effect. The overall adaptive controller can be viewed as combined of an identifier and a zero-memory controller in the feedback loop. The former is the learning device where the estimates of the parameters are generated in real time and can be designed independently of the controller objectives. The later computes the on-line optimal control for a deterministic system and is parameter adaptive. Accordingly, as this adaptive control problem involves nonlinear parameter estimation, the extended Kalman filter is used to generate the approximate conditional means and the associated error covariances of the unknown parameters. This approach led to the design of a simple proportional controller that has the desired adaptive properties. The closed loop feedback optimal control is given by

$$u^o(k|k) = -g(k)y(k) \qquad k = 0, 1, \ldots . \tag{6}$$

The adaptive feedback gain g(k) depends not only on parameters a(k) and b(k) estimates ($a^{est}(k|k)$ and $b^{est}(k|k)$ resp.), but also on conditional error covariances

$$e_a(k|k) = a^{est}(k|k) - a(k) . \tag{7}$$

$$e_b(k|k) = b^{est}(k|k) - b(k) . \tag{8}$$

i.e. it is modulated by the current parameters uncertainty (vectors and matrices are denoted in bold letters, superscript T stands for 'transposed')

$$g(k)=-\{[R(k|k) + \mathbf{b}^T(k|k)\mathbf{Q}\mathbf{b}(k|k)]^{-1}\mathbf{b}^T(k|k)\mathbf{Q}\mathbf{\Phi}(k|k) + R^{-1}(k|k)\mathbf{d}^T(k+1|k)\}[1,0,0]^T. \tag{9}$$

$$\mathbf{b}^T(k|k) = [b^{est}(k|k), S_{bb}(k|k), S_{ab}(k|k)] . \tag{10}$$

$$\mathbf{d}^T(k+1|k) = [qS_{ab}(k|k), qa^{est}(k|k), 0] . \tag{11}$$

$$\mathbf{\Phi}(k|k) = \mathbf{F}(k|k) - \mathbf{b}(k|k)R^{-1}(k|k)\mathbf{d}^T(k+1|k) . \tag{12}$$

$$\mathbf{F}(k|k) = \begin{bmatrix} a^{est}(k|k) & 0 & 0 \\ S_{ab}(k|k) & a^{est}(k|k) & 0 \\ S_{aa}(k|k) & 0 & a^{est}(k|k) \end{bmatrix} . \quad (13)$$

$$R(k|k) = r + qS_{bb}(k|k) . \quad (14)$$

$$\mathbf{Q} = \begin{bmatrix} q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} . \quad (15)$$

$$S_{aa}(k|k) = e_a^{\,2}(k|k) . \quad (16)$$

$$S_{bb}(k|k) = e_b^{\,2}(k|k) . \quad (17)$$

$$S_{ab}(k|k) = S_{ba}(k|k) = e_a(k|k)e_b(k|k) . \quad (18)$$

The parameters estimates are generated via the equations

$$\mathbf{p}^{est}(i+1|i+1) = \mathbf{p}^{est}(i|i) + \mathbf{G}(i+1)[y(i+1) - \mathbf{c}^T(i)\mathbf{p}^{est}(i|i)] . \quad (19)$$

where
$$\mathbf{p}^{est,T}(i|i) = [a^{est}(i|i), b^{est}(i|i)] . \quad (20)$$

$$\mathbf{c}^T(i) = [-y(i), u(i)] . \quad (21)$$

The filter gain matrix $\mathbf{G}(i+1)$ satisfies the relation

$$\mathbf{G}(i+1) = \mathbf{S}(i|i)\mathbf{c}(i)[\mathbf{c}^T(i)\mathbf{S}(i|i)\mathbf{c}(i)]^{-1} \quad i = 0, 1, \ldots , k-1 . \quad (22)$$

$$\mathbf{S}(i+1|i+1) = [\mathbf{S}(i|i) - \mathbf{G}(i+1)\mathbf{c}^T(i)\mathbf{S}(i|i)] / ff . \quad (23)$$

$$S(i|i) = \begin{bmatrix} S_{aa}(i|i) & S_{ab}(i|i) \\ S_{ba}(i|i) & S_{bb}(i|i) \end{bmatrix} . \quad (24)$$

with the initial estimates given by

$$\mathbf{p}^{est,T}(0|0) = [a_0, b_0] . \quad (25)$$

$$\mathbf{S}(0|0) = \begin{bmatrix} S_{a0} & 0 \\ 0 & S_{b0} \end{bmatrix} . \quad (26)$$

The AS control algorithm expresses its dual nature by simultaneously performing two functions: perpetual parameters estimation i.e. “learning” and process control. The forgetting factor ‘ff’ allows the controller’s capacity for adaptation on changes in the system parameters to be preserved, by preventing error covariance matrices to become approximately equal to zero. Estimating of parameters could continue only if the matrices are different from zero, i.e. if some level of parameters uncertainty remained. Owing to the forgetting factor, the identification of parameters even if they for some time remain constant, will never be completed. Fortunately, the exact identification of the unknown parameters is not necessary for good control. Through the parameters uncertainty the controller expresses its “cautiousness”.

3.2 Backward Explicit Congestion Notification (BECN) Scheme

When the queue length in an ATM switch output buffer exceeds a threshold, the feedback controller will send backward RM cells to the ABR sources currently submitting traffic. Backward RM cells are subject to the same transmission delay as cells in the forward direction. Initially the sources transmit at their peak cell rates (PCR). When a transmitter receives a RM cell it reduces its cell transmission rate to one half of the current rate. Successive RM cells will cause a transmitter to reduce its cell transmission rate to 1/2, 1/4, 1/8, 1/16, 1/32, 1/64 of its PCR after which a further RM cell will cause it to transmit at MCR, because sources are not expected to reduce their ACR to less than MCR. ABR sources seen by the switch as inactive are allocated also MCR only. If no RM cells are received within a recovery time period, the current transmission rate for that source will be doubled, i.e. restored to the previous level once each recovery time period, until it reaches its original PCR. The source recovery period is proportional to the source current transmission rate so that the lower the transmission rate the shorter the source recovery period. The feedback controller transmits no more than a single RM cell to each active source during each control period. To allow the previous RM cell to take effect, the control period is equal to the round-trip delay.

4 Simulation Model and Results

Both flow control algorithms were tested and compared on the same network simulation model (Fig.1), with the same MCRs, the same control threshold and the same time control units. The major shortcoming of BECN scheme - its unfairness in multi-hop networks causing the “beat down problem” did not disadvantage the scheme in these experiments as the simulated network was single-hop. Each source S generates cells that are queued for transmission by the transmitter T. Each of the transmitters T independently removes cells from its source queue and transmits them to the receiver R. R is a point of congestion somewhere in the network, e.g. an output buffer on an ATM switch. The ABR traffic sources Ts transmit at the ACRs, as dictated by the feedback. The VBR traffic sources Ts transmit at the PCR. There is a transmission delay between each transmitter transmitting a cell and the cell being received at the receiver. The transmission delay represents the combination of the propagation delay and the switching delay from the source to the point of congestion. For simplicity all the sources are equidistant to the ATM switch and hence the propagation delay is the same between the ATM switch and all the sources. AS scheme’s and BECN scheme’s control intervals were equal to the round trip delay, i.e. the control rate was matched to the feedback rate. This illustrates a fundamental principle in control theory, which says that the system is unstable when the control is faster than feedback. But the system is unresponsive if the control is slower than feedback. The performance of the model was examined over source -

switch distances (link lengths): 1 km, 10 km, 100 km and 1000 km, with corresponding control intervals 10 μsec, 100 μsec, 1 msec and 10 msec resp. (1 km

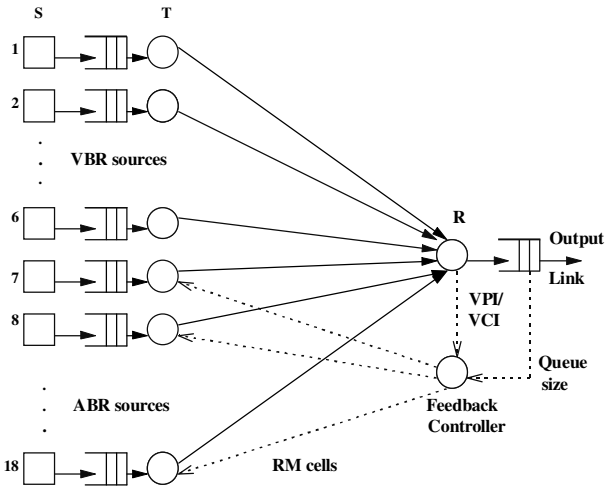

Fig. 1. The simulation model

implies 5 μsec propagation delay). The terminals are connected to the switch through links running at 155 Mbps (365566 cells/s). The switch receives traffic from terminals that are attached to its input ports. All input ports have traffic flowing to a common output port operating at 155 Mbps. The input to the ATM switch is a superposition of streams from 18 (12 ABR and 6 VBR) different ON/OFF sources, also referred to as Interrupted Bernoulli Process (IBP) which alternate active periods, transmitting at their peak cell rate (PCR) and idle periods, transmitting at zero bit rate. Both periods of burst and silence are exponentially distributed with constant average lengths during a simulation. Each burst in average contained 100 cells. The switch server rate is assumed to have a fixed ratio with respect to the long term mean arrival rate. The switch target utilization parameter was set at 0.95 where ABR traffic sources were given 60% and VBR traffic sources 35% bandwidth. In order to have more than a million cells generated, a simulation run time was 3 seconds. The higher priority (VBR) traffic was generated by the sources 1, 2, 3, 4, 5, 6 with PCR 50 Mbps, 40 Mbps, 30 Mbps, 20 Mbps, 10 Mbps, 5 Mbps resp., totally 155 Mbps , therefore equal to the switch server rate and with source utilizations 0.4, 0.5, 0.2, 0.2, 0.3, 0.25 resp.. The lower priority (ABR) traffic was generated by the sources 7, 8, ..., 18 with PCR 155 Mbps each, what means that each ABR source was capable of filling the entire server capacity of the switch. The ABR sources' utilization was 0.10 for sources 7 and 13, 0.08 for sources 8 and 14, 0.05 for sources 9 and 15, 0.04 for sources 10 and 16, 0.02 for sources 11 and 17, 0.01 for sources 12 and 18. The aggregate peak rate of the total traffic thus was 2015 Mbps. The purpose of the experiment was to examine how successfully the two compared schemes can

cope with such stressful conditions when arrival rate to the switch output buffer can exceed 13 times the server capacity, while preserving the design goals. The output buffer threshold value employed by both schemes was 50 cells. Opposite to the initial CAC setup where the MCR was specified as zero, two MCR > 0 values were used: PCR/100 (1% link bandwidth) and PCR/1000 (0.1% link bandwidth) - in practice, it is desirable to allow some minimum capacity for processing aggregate ABR traffic when there is contention. As all ABR sources had the same PCR = 155 Mbps, in AS scheme experiments each of the active ABR traffic sources received periodically the same amount of the feedback equal to u(k)/(number of currently active ABR traffic sources). In the case of different PCRs, the formula above could be easily adjusted. In AS scheme as well as in BECN scheme experiments, inactive ABR traffic sources were allocated MCR only, for two reasons mainly: in order to drain out their queues and because of the transmission delay the sources which may seem as inactive, could be in fact, active. The forgetting factor equal to 0.96 was used in examining AS scheme; initial estimates were $S_{a0} = S_{b0} = 1$ and $a_0 = b_0 = 0.1$.

Performance evaluation of the schemes showed that AS scheme achieved average utilization (Fig. 8) for MCR = PCR/100 on 1 km link 0.86% lower, on 10 km link 1.9% higher, on 100 km link 1.7% lower, on 1000 km link equal and for MCR= PCR/1000 on 1 km link 8.4 % lower, on 10 km link 16.8% higher, on 100 km link 2.4% higher, on 1000 km link 0.75% higher. However, the utilization metric gives only a partial picture of efficiency. Ideally, an efficient scheme should also control queuing delays within acceptable limits. The delay varies according to load, but there is always a non-zero queuing delay. AS scheme achieved shorter mean queuing delay in the switch output buffer (Fig. 2) - from 1.5 times (1 km link) to 55 times (1000 km link) when MCR = PCR/100 and from 3.3 times (1 km link) to 80 times (1000 km link) when MCR = PCR/1000. In other words, for the higher MCR the difference between BECN scheme's and AS scheme's mean queuing delay in the switch output buffer, on 1 km link was 46.5μs what equals 9.3 km propagation delay and on 1000 km link 20 ms what equals 4000 km propagation delay. For the lower MCR that difference on 1 km link was 73.5 μs what equals 14.7 km propagation delay and on 1000 km link 28.4 ms what equals 5700 km propagation delay. Queuing delay variance disproportions (Fig. 3) between the two schemes were even larger - from 2.1 times (1 km link) to 327 times (1000 km link) when MCR = PCR/100 and from 1.9 times (1 km link) to 665 times (1000 km link) when MCR = PCR/1000. AS scheme's maximum queue length in the switch output buffer (Fig. 4) was also much smaller - from 4.1 times (10 km link) to 7.9 times (100 km link) when MCR = PCR/100 and 3.9 times (1 km link) to 12 times (100 km link) when MCR = PCR/1000. Comments are not made here on mean queue lengths (Fig. 5) because results correspond to those for mean queuing delays. On the other hand, mean queuing delay, queuing delay variance, maximum and mean queue size in the buffers of sources generating ABR traffic increased as expected, but on much smaller scale (due to limited space these simulation results are not displayed here). An interesting effect was noticed in AS scheme and BECN scheme alike: the smaller of the two MCRs (PCR/1000) created a bottleneck what caused larger queues in ABR traffic sources' buffers and lower utilization due to lower ABR utilization (Fig. 6). The number of VBR traffic cells received (Fig. 7) for both schemes was almost

identical, excepting BECN scheme's worse performance on 1000 km link with MCR = PCR/1000. As any MCR > 0 contradicts the initial stipulation that VBR traffic can take the entire server capacity whenever it needs it, both MCRs employed in this experiment caused conflicting demands by VBR and ABR traffic classes, as VBR traffic class, albeit able to fill the entire server capacity (if all VBR traffic sources are simultaneously transmitting), was guaranteed only 98.8% (when MCR = PCR/1000) or only 88% of it (when MCR = PCR/100). The competition between the two traffic classes using the higher MCR brought about the higher utilization. Obviously, although the MCR was guaranteed to all 12 ABR traffic sources, due to their bursty nature they did not use it all the time and not all of them at the same time what allowed the VBR traffic to have enough bandwidth to flow smoothly and unabatedly. Therefore, MCR = PCR/100 should be recommended and MCR = PCR/1000 should be dropped. With the sort and configuration of traffic generators employed throughout these experiments the ABR service class whose capacity and demand thus varied dynamically, was always in a transient state. For such a case there is currently no known model for quantifying fairness. Hence the issue of fairness could not be addressed in this study and for the issues that were addressed, the simple network model (Fig. 1) was appropriate. It should be pointed out that the above cited fundamental principle in control theory is not practically applicable on 1 km link, because 10 μs control interval means that RM cells' share in the total number of generated cells (data and RM cells together) is 27.4% whereby data cells utilization of the server and output link falls to about 70 %. Therefore, in order to prevent such huge number of RM cells being generated, a sort of trade-off should be made by replacing the 10 μs interval with a longer one, e.g. 50 μs or 100 μs (as it is on 10 km link) with RM cells' share in the total number of generated cells 5.4% and 2.7% resp.. The total numbers of ABR and VBR cells received as well as the server/output link utilization would be lower, but the numbers of ABR and VBR data cells much higher and data cells utilization of the server and output link could reach and even exceed 90%.

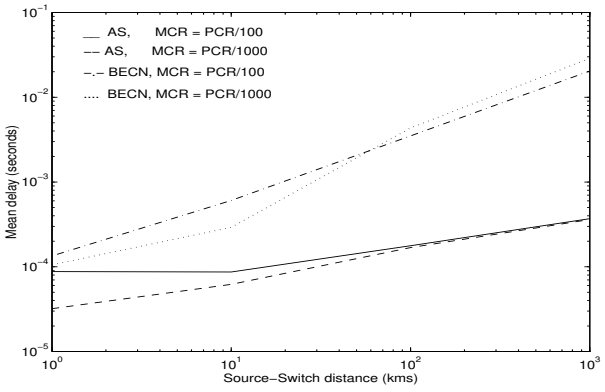

Fig. 2. Mean queuing delay in the ATM switch output buffer

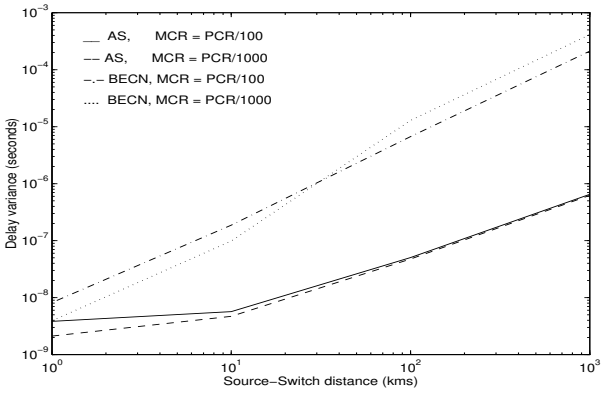

Fig. 3. Queuing delay variance in the ATM switch output buffer

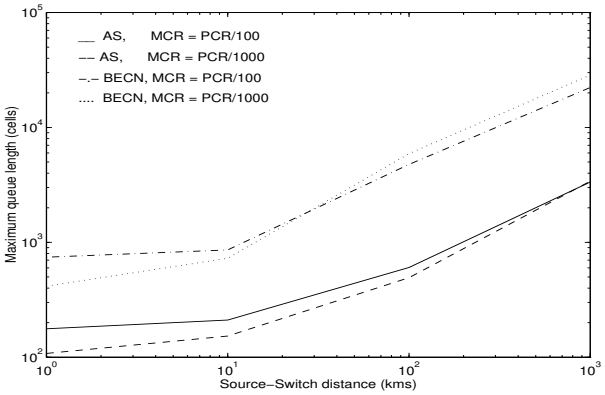

Fig. 4. Maximum queue length in the ATM switch output buffer

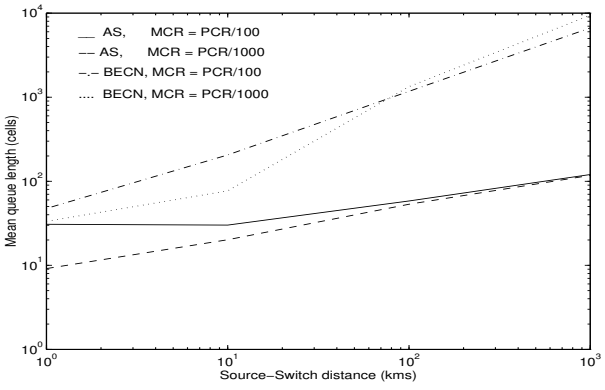

Fig. 5. Mean queue length in the ATM switch output buffer

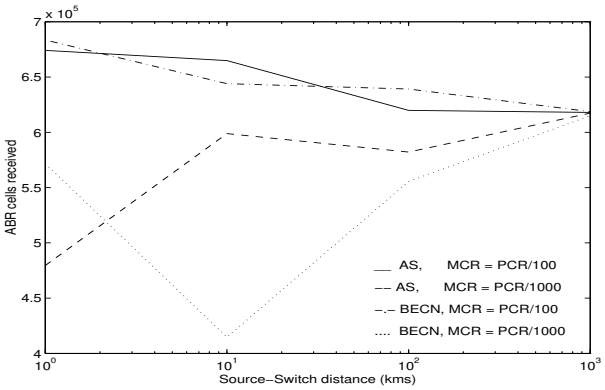

Fig. 6. Number of ABR traffic cells received

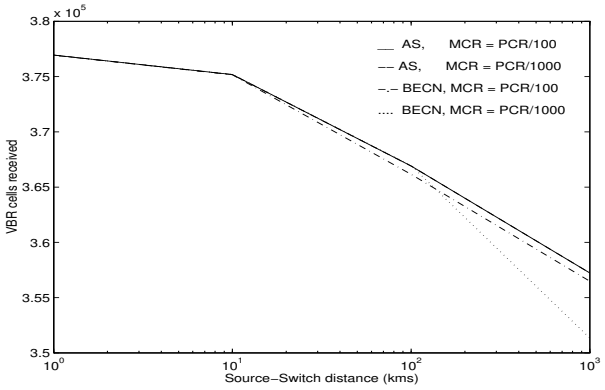

Fig. 7. Number of VBR traffic cells received

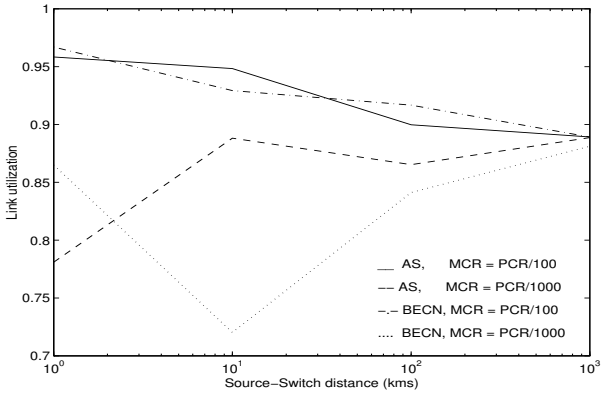

Fig. 8. Server / output link utilization

5 Summary

BECN and proposed AS congestion control schemes for ABR service in ATM networks are compared in the presence of two traffic classes - ABR and VBR, under heavy load conditions exceeding 0.95. The discussion relates to the traffic management at the segment of an ATM network between terminals generating traffic and the switch. By ensuring much shorter queue in the ATM switch output buffer, AS scheme provided for delay sensitive VBR traffic class, while retaining approximately the same utilization, sharply reduced mean queuing delay and queuing delay variance. This disproportions between AS and BECN schemes grew huge on long, i.e. WAN links. At the same time, delay insensitive ABR traffic class experienced either in considerably smaller proportion increased queue size and mean queuing delay or even shortening of queue and mean queuing delay.

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