Effective Frequency Range of Rate-Based Closed-Loop Congestion Control for ABR Service [*]

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Abstract

The Available Bit Rate (ABR) service class has been defined by the ATM Forum. Closed-loop rate-based congestion control has been adopted by the ATM Forum as the standard approach for supporting ABR service in ATM networks. This paper examines congestion control mechanisms for ABR service and presents fundamental performance results for rate-based traffic management schemes under varying available bandwidth conditions. We show the frequency range where a rate-based congestion control scheme can operate effectively. Our results contribute to the fundamental understanding of closed-loop traffic management mechanisms for ABR service and provide guidelines for the future development of effective congestion control algorithms.

Key Words: Frequency Range, Congestion/Flow Control, ABR Service, ATM Networks.

1 Introduction

Available Bit Rate (ABR) service has been defined by the ATM Forum [1]. ABR service will support applications that allow the ATM Source End System (SES) to adjust the information transfer rate based on the bandwidth availability in the network. Such applications include LAN interconnect, file transfer, Frame Relay, etc. By definition, on the establishment of an ABR connection, the user shall specify to the network both a maximum bandwidth and a minimum required bandwidth, designated as Peak Cell Rate (PCR) and Minimum Cell Rate (MCR), respectively, for the requested connection. The available bandwidth from the network may vary, but MCR is always guaranteed. A generic closed-loop rate-based traffic management mechanism is shown in Fig. 1. Resources Management (RM) cells are inserted periodically among ATM data cells to convey network congestion and available bandwidth information to the SES. RM cells contain important information such as the source's Current Cell Rate (CCR) or Allowed Cell Rate (ACR), Minimum Cell Rate (MCR) requirement, Congestion Indication (CI) bit and Explicit Rate (ER). A transit node and Destination End System (DES) may set the CI bit and/or ER field in RM cells. All RM cells of an ABR Virtual Connection (VC) are turned back towards its SES after arriving at the DES. Upon receiving backward RM cells, the SES adjusts its cell generating rate accordingly.

With the completion of the traffic management specifications [1], network equipment vendors are working on the implementation of ABR. But it is extremely important to understand how and under what conditions an ABR congestion control algorithm works. This paper investigates fundamental properties of the ABR traffic management schemes. Both binary and Explicit-Rate (ER) based schemes are examined. Our main objective here is *not* introducing a better traffic management algorithm, but rather, to show the effective operating frequency range for a class of traffic management schemes. Here, "frequency" is a generic term referring the variation of network operating condition, i.e., variation frequency of the available bandwidth or the ABR source traffic. Our paper contributes to the fundamental understanding of closed-loop traffic management mechanisms for ABR service, and provides essential guidelines for the future development of such congestion control algorithms.

The remainder of this paper is organized as follows. Section 2 examines and defines both binary and ER traffic management schemes. The performance results for these algorithms are presented in Section 3. Section 4 concludes this paper.

2 Rate-Based Congestion Control

There are different approaches and extensive studies of closed-loop rate-based traffic management [3, 4, 6, 8, 9, 10, 11, 12]. These proposals fall into two broad categories, "binary feedback" congestion indication [3, 9, 10, 12] and "explicit rate setting" schemes [4, 6, 8, 11]. For binary schemes, a single bit feedback from the network is used to indicate congestion. For ER schemes, a calculated or estimated available bandwidth information is contained in the feedback RM cell to inform the SES. Binary schemes preserve backward compatibility with EFCI-marking switches [2], while the newer ER-based schemes promise higher efficiency and stability with additional implementation cost.

In this paper, we focus on one bottleneck output port of an ATM switch (Fig. 2), also referred to as the bottleneck internodal link. This output port has available bandwidth BW for ABR and is shared by

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ABR VCs from different SES. The cells from these ABR VCs share the bottleneck internodal link with FIFO queueing discipline.[1]

2.1 Binary-Based Feedback Control

Source behavior:

1. A source transmits an RM cell for every N_{RM} data cells transmitted. The CI bit in an RM cell is initially set to 0.
2. The initial ACR is set to ICR.
3. Upon receiving a backward RM cell, the new ACR is set to:
   if $CI = 0$, i.e. no congestion,
   $$ACR \leftarrow min\{(ACR + N_{RM} \times AIR), PCR\}$$
   else ($CI = 1$), i.e. congestion,
   $$ACR \leftarrow max\{(ACR \times MDF), MCR\}$$

Switch behavior:

1. The forward RM cells carry ACR information and update the ACR table at the switch for each VC.
2. The switch sets the CI bit of backward RM cells according to the following rule.
   When the bottleneck link queue length is over QT, the switch selectively marks $CI = 1$ on those backward RM cells whose VCs correspond to larger ACR.
   When the bottleneck link queue length is over DQT, the switch marks all backward RM cells with $CI = 1$.

Destination behavior:

Upon receiving a forward RM cell from the source, the destination simply returns it in the backward direction to the source.

2.2 ER-Based Feedback Control

In ATM networks, CBR, VBR, ABR and UBR share the bandwidth at an internodal link. The available bandwidth for ABR service usually changes with time depending on the variation of other types of traffic in the network. Furthermore, such instantaneous available bandwidth for ABR service may not be known by the internodal link.

2.2.1 Ideal Case: Available Bandwidth Information is Known

When the available bandwidth at an internodal link for ABR service is known, we can calculate ER for each VC.

In section 3, we will present performance results for the idealized situation under which the internodal link has complete knowledge of available bandwidth and the number of active VCs. As we will see, the effective operating frequency range for an idealized ER scheme is determined by the Round Trip Time (RTT) between the SES and bottleneck internodal link. This give us the theoretical limit for an optimal ER scheme.

2.2.2 Bandwidth Information is Unknown

This models a practical scenario at an internodal link where the instantaneous bandwidth available for ABR service is an unknown stochastic process.

Here, an accurate “estimation” of available bandwidth is essential for the ER calculation. The “Intelligent Marking” technique proposed in [11] uses a variable at the bottleneck link, labeled as Mean Allowed Cell Rate ($MACR$), to estimate the optimal cell rate at which a VC can transmit based on the congestion state at the switch. In the following, we present a refined version of the BW-estimator-based ER scheme [11]. In Section 3, we present a performance evaluation of our scheme under various bandwidth operating frequencies. As we will see, the performance of such an ER scheme is only effective in the “low frequency” range, which is determined by the transient response time of the switch variable ($MACR$) to reach steady state, a time scale that is much larger than RTT_{SX}.

Source behavior:

1. A source transmits an RM cell for every N_{RM} data cells transmitted. The ER field in an RM cell is initially set to PCR.
2. The initial ACR is set to ICR.
3. Upon receiving a backward RM cell, the new ACR is set to:
   $$ACR \leftarrow max\{min\{(ACR+N_{RM}\times AIR), ER, PCR\}, MCR\}$$

Switch behavior:

1. The forward RM cells update $MACR$ at the switch according to the flow chart in Fig. 3.
2. The switch sets the ER field of backward RM cells according to the flow chart in Fig. 4.

Destination behavior:

Upon receiving a forward RM cell from the source, the destination simply returns it in the backward direction to the source.

3 Performance of Closed-Loop Feedback Control Schemes

In this section, we present simulation results demonstrating the effectiveness of rate-based closed-loop feedback control algorithms defined in Section 2 for different frequency ranges. Our objective is to identify the frequency range under which a scheme can operate effectively. We choose to use a persistent

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[1] Note that the available bandwidth BW for ABR is a variable throughout our paper.

source (i.e. it always has data to send) under time-varying internodal available bandwidth. Although in practice, most ABR sources are not persistent (but rather, bursty on/off in nature), the operating frequencies for a particular feedback control scheme can be most clearly illustrated by using a persistent source and varying bandwidth. Moreover, by studying the performance of a scheme for a persistent source under varying bandwidth, one can imply similar results for a bursty source (i.e. source profile characterizable in frequency domain [7]) under constant bandwidth, etc.

3.1 Ideal ER Scheme

This is the ideal case that we discussed in Section 2.2.1. After a SES starts to transmit cells, it takes RTT_{SD} for the first RM cell to return back to the source. This RM cell contains the exact rate at which the source should transmit. After receiving the first backward RM cell, the backward RM cells return periodically to the source and the feedback information from the switch is only delayed by the propagation time between the SES and switch, τ_{SX} or $\frac{1}{2}RTT_{SX}$ (remember that the switch sets the ER field in the *backward* RM cell).

Fig. 5 shows the low frequency case with $N_{VC} = 1$ and available BW variation period $T(= 200$ ms) is much greater than $RTT_{SX}(= 5$ ms). The ACR at source and ACR arriving at the internodal link are delayed waveforms of the available BW by $\frac{1}{2}RTT_{SX}$ and RTT_{SX}, respectively. Fig. 6 shows the instantaneous load, defined as,

$$Load \overset{\text{def}}{=} \frac{\sum_{i=1}^{N_{VC}} ACR_i \, at \, node}{available \, BW}$$

and queue length for the same simulation run. We see that except for short periods (equal to RTT_{SX}) which peak and drop at the time when available BW varies, the load is 1 most of time.

Figs. 7 and 8 show the performance of ER scheme when the available bandwidth variation period T (= 15 ms) is close to RTT_{SX}. We see that the ACR arriving at internodal link can no longer keep up with the available BW variation and the instantaneous load differs from 1 most of the time. Here, even the ideal ER scheme does not work.

We conclude that under ideal case where the bottleneck internodal link has complete knowledge of available BW and the number of active VCs, the operating frequency range for an ER scheme is only limited by RTT_{SX} and should satisfy

$$f \ll \frac{1}{RTT_{SX}} \tag{1}$$

3.2 BW-Estimator-Based ER Scheme

This is the case we discussed in Section 2.2.2. The parameters used in our simulation are listed below.

$PCR = 155$ Mbps
$ICR = 10$ Mbps
$MCR = 0.155$ Mbps
$AIR = 0.03125$ Mbps
$DQT = 1000$ cells
$QT = 500$ cells
$AV = 0.25$
$MRF = 0.5$
$ERF = \frac{31}{32}$
$N_{RM} = 32$
$\tau_{SX} = 1$ ms
$\tau_{XD} = 1$ ms

Fig. 9 shows the ACR arriving at bottleneck internodal link and available BW for one VC in low frequency case with $T = 200$ ms (the first variation period of BW actually starts from $t = 100$ ms in our simulation) and $RTT_{SX} = 2$ ms. The ramp up time as illustrated in Fig. 9 is usually a much larger time period than RTT_{SX} or RTT_{SD}. After reaching steady state, the ACR at the node follows available BW quite closely. Fig. 10 shows the load and queue length for the same simulation run. We see that except for peaks and drops of load at available BW transition points (and a few other points), the load is close to 1 most of the time. This shows that the BW-estimator-based ER scheme works fairly well in the low frequency case.

Figs. 11 and 12 show the performance of the same ER scheme when the available BW variation period decreases to $T = 20$ ms, which is still much greater than $RTT_{SX}(= 2$ ms). We see that such a BW variation is already too fast for our ER scheme to operate effectively. This is due to the response time required for $MACR$ to reach a steady state whenever BW changes value. This response time for $MACR$ is the fundamental limitation to the operating frequency of a BW-estimator-based ER scheme.

We conclude that the effective operating frequency range for ER scheme when BW is unknown should satisfy,

$$f \ll \frac{1}{T_{MACR}} \tag{2}$$

where T_{MACR} is the response time for $MACR$ to reach a new steady state when BW changes between values.

3.3 Binary Scheme

We present simulation results for the binary scheme we defined in Section 2.1. The parameters used in our simulation are listed below.

$PCR = 155$ Mbps
$ICR = 10$ Mbps
$MCR = 0.155$ Mbps
$AIR = 0.03125$ Mbps
$DQT = 1000$ cells
$QT = 350$ cells
$MDF = 0.99$
$N_{RM} = 32$
$\tau_{SX} = 1$ ms
$\tau_{XD} = 1$ ms

Ignoring those parameters used only for the ER scheme, the above parameters are essentially the same as those listed in Section 3.2 for BW-estimator-based ER scheme.[2]

Figs. 13 and 14 show the performance of our binary scheme in low frequency case with $T = 200$ ms.

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[2] Since our binary scheme does not employ the elaborate time-based congestion detection algorithm used for ER scheme, Queue Threshold ($QT = 350$ cells) is set to be smaller than that in Section 3.2 (500 cells) to make the binary scheme operate properly.

In comparison with Figs. 9 and 10, it is obvious that the zig-zag nature of ACR under binary scheme makes it less desirable than ER scheme. This illustrates that ER scheme outperforms binary scheme in the low frequency case.

Figs. 15 and 16 show the performance of our binary scheme in a higher frequency range with $T = 20$ ms. Here, we have more interesting results. In comparison with Figs. 11 and 12, the obvious advantage of ER scheme over binary scheme in the low frequency case disappears. That is, when the variation frequency of available BW becomes sufficiently high, the elaborate BW-estimator-based ER scheme loses its accuracy and may not perform better than a simple binary bit setting mechanism.

4 Concluding Remarks

Based on our simulation results, we further make a qualitative plot of "Scheme Effectiveness" vs. "Frequency" in Fig. 17 to give fundamental insights on closed-loop traffic management. The "Scheme Effectiveness" is a measure of: (i) how well the ACR at node can follow the available BW at node; and (ii) the fluctuation of buffer occupancy (ideally, we want to keep the buffer content at a steady constant level, i.e., keep load close to 1).

As shown qualitatively in Fig. 17, at the low frequency range ($\ll RTT_{SX}^{-1}$), the ideal ER scheme gives the upper bound of effectiveness for closed-loop congestion control. Its effective operating frequency is only constrained by the Round Trip time (RTT_{SX}) of the feedback loop. The BW-estimator-based ER scheme is better than the binary scheme only at very low frequency range ($\ll T_{MARC}^{-1}$). Once over (T_{MARC}^{-1}), the ER scheme loses its accuracy and may not be better than the binary scheme. At the higher frequency range ($\sim RTT_{SX}^{-1}$), any feedback scheme does not work well. At such a frequency range, the binary scheme may be the most robust scheme because single bit feedback better reflects the congestion state at bottleneck node. Thus, the necessity of implementing ER algorithm (with additional cost) over the simple binary algorithm at an ATM switch has to be carefully justified according to the actual network environment.

The operating frequency range for ER and binary feedback mechanisms were clearly demonstrated above by using a persistent source under frequency varying bandwidth. In practice, the number of ABR VCs at a bottleneck internodal link varies with time as well as each ABR VC source profile (usually on/off). A simple expression showing the operating frequency is not obvious. However, it it expected that equivalent or similar results will hold. As an example, for a BW-estimator-based ER scheme, only when the on/off burstiness of each source as well as number of VCs vary on a much larger time scale than T_{MACR}, will such a scheme operate effectively.

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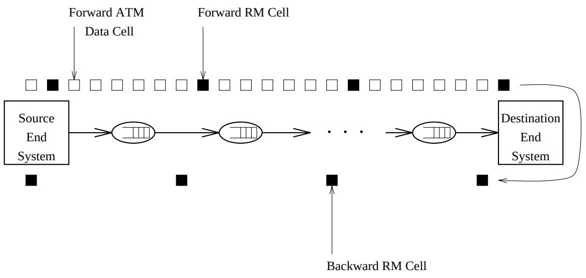

Figure 1: Closed-loop rate-based traffic management for one ABR VC.

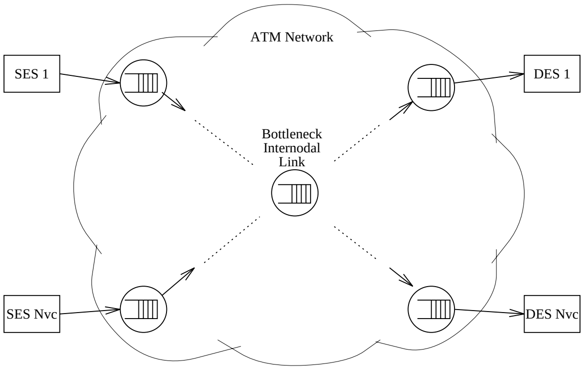

Figure 2: Closed-loop rate-based traffic management for ABR VCs at a bottleneck internodal link.

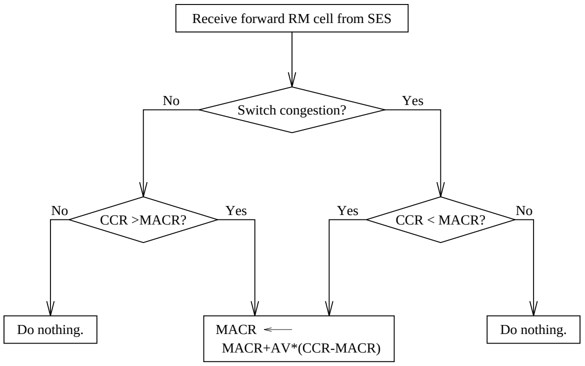

Figure 3: Switch behavior when receiving forward RM cells.

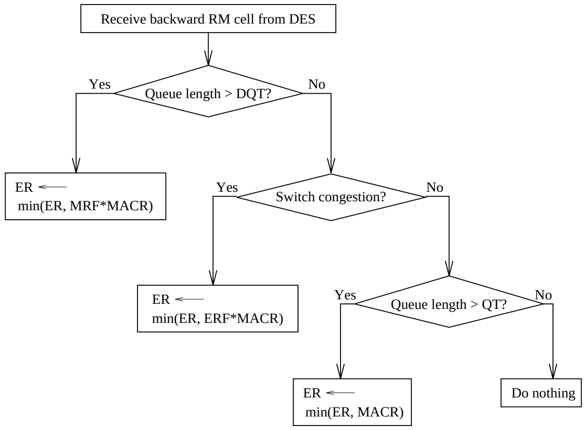

Figure 4: Switch behavior when receiving backward RM cells.

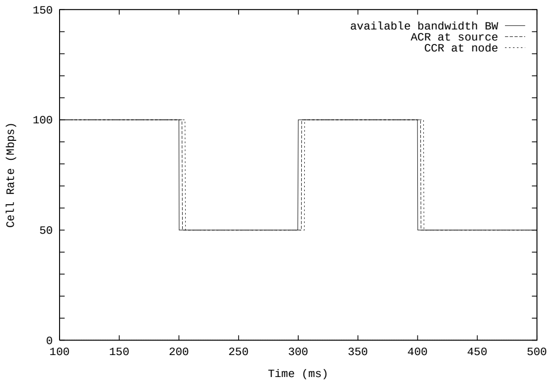

Figure 5: Ideal ER scheme in low frequency case: ACR at source, ACR at node and link BW.

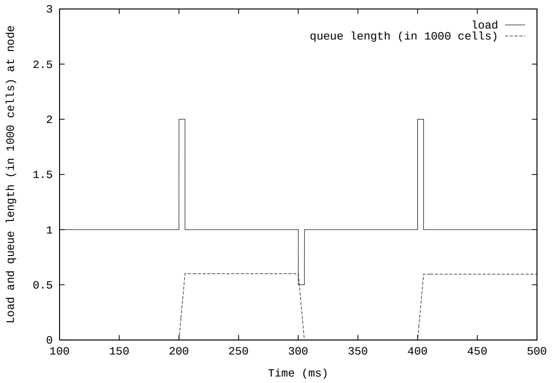

Figure 6: Ideal ER scheme in low frequency case: traffic load and queue length.

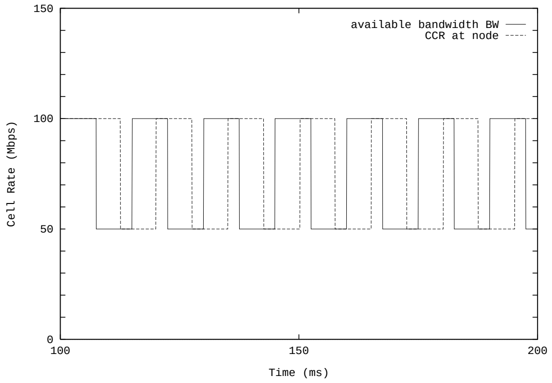

Figure 7: Ideal ER scheme: ACR at node and link BW.

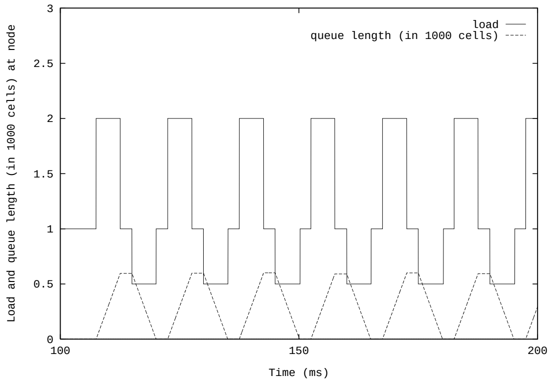

Figure 8: Ideal ER scheme: traffic load and queue length.

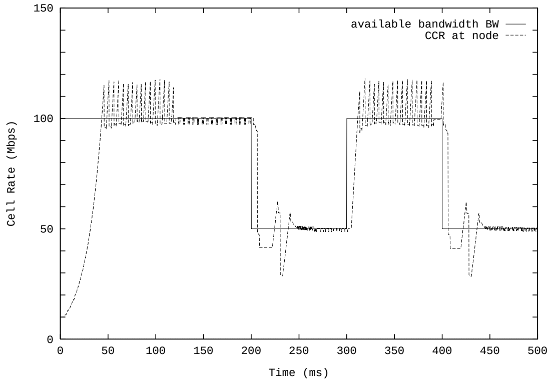

Figure 9: BW-estimator-based ER scheme in low frequency case: ACR at node and link BW.

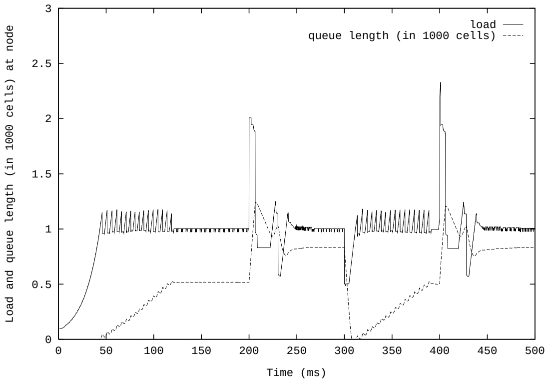

Figure 10: BW-estimator-based ER scheme in low frequency case: traffic load and queue length.

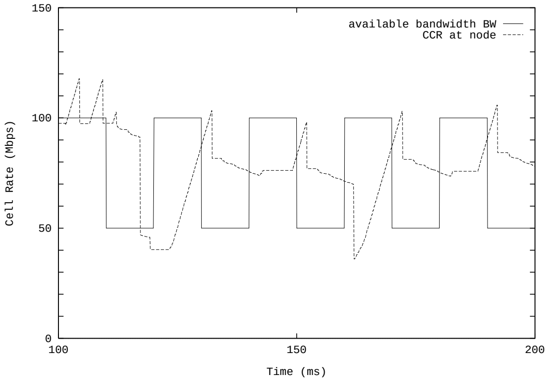

Figure 11: BW-estimator-based ER scheme: ACR at node and link BW.

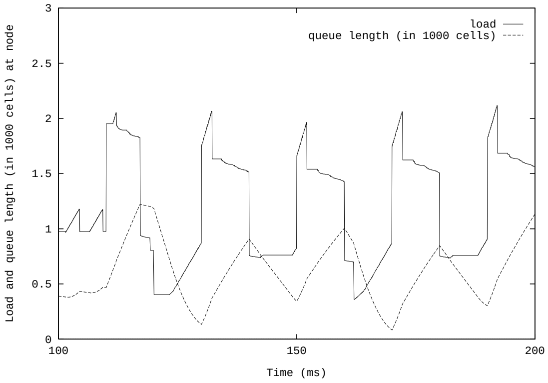

Figure 12: BW-estimator-based ER scheme: traffic load and queue length.

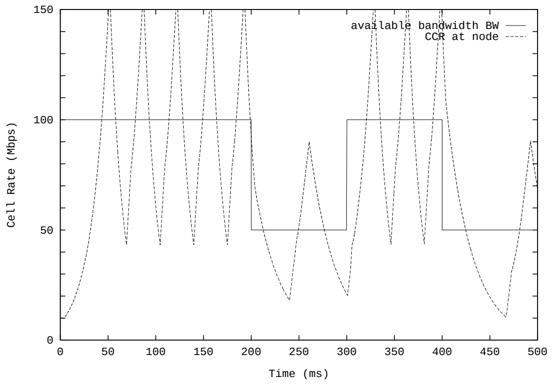

Figure 13: Binary scheme in low frequency case: ACR at node and link BW.

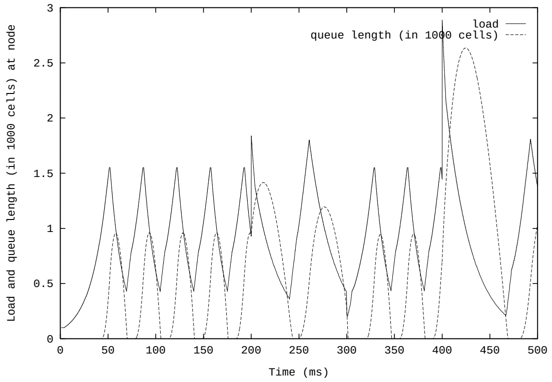

Figure 14: Binary scheme in low frequency case: traffic load and queue length.

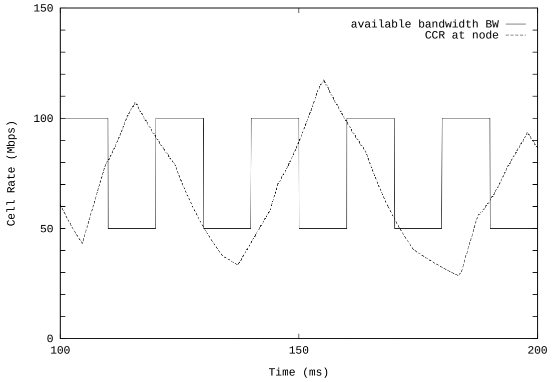

Figure 15: Binary scheme: ACR at node and link BW.

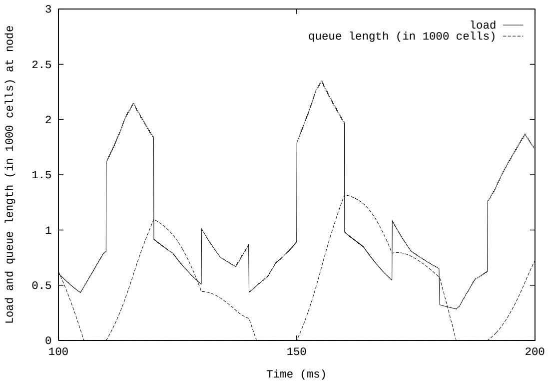

Figure 16: Binary scheme: traffic load and queue length.

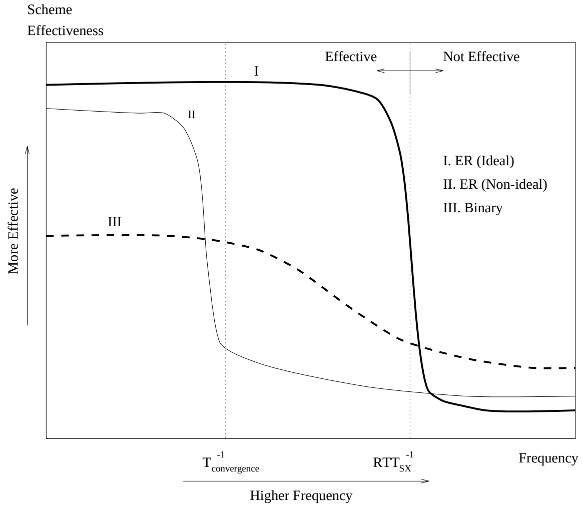

Figure 17: Effectiveness comparison of feedback control schemes.