A Dynamic Real-Time Traffic Management Scheme with Good Throughput and Jitter Characteristics*

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Abstract: Typical rate-based traffic management schemes for real-time applications attempt to allocate resources by controlling the packet delivery to the resource arbitrator (scheduler). This control is typically based only on the characteristics of the particular (tagged) traffic stream and would fail to optimally adjust to non-nominal network conditions such as overload. In this paper, a Dynamic Regulation scheme is proposed whose function is modulated by both the tagged stream's characteristics and some information capturing the state of the coexisting applications. The performance of the proposed scheme – as well as the equivalent Static Regulation scheme – is investigated under overload traffic conditions and the substantially better throughput / jitter characteristics of the Dynamic Regulation scheme are established.

1 Introduction

A secure solution to the problem of guaranteeing the QoS of real-time applications will typically require the reservation of the maximum amount of needed resources. Because of the anticipated low - due to resource requirement fluctuation - network utilization, alternative solutions are being considered based on "over allocation" of resources to a group of applications (multiplexing).

Because of the stringent QoS requirements of real-time applications, it is expected that "traditional" statistical multiplexing schemes, such as FCFS, will not be effective for such applications. It is well understood that some tighter control should be exercised on input, output as well as in the internal processes of a multiplexing scheme which impact on its efficiency. Through (a) sophisticated call admission schemes or other types of "weak" resource reservation at the larger time scale and (b) proper traffic regulation and service scheduling mechanisms at the smaller time-scale, statistical multiplexing will potentially provide for increased network utilization while delivering

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the more stringent QoS associated with real-time applications. This paper is focused on the control approaches at the smaller time scale, namely regulation and scheduling.

Typical QoS metrics shaped by regulation and scheduling schemes are described in terms of the induced cell loss/delay and the allocated bandwidth. In principle, a target value of such QoS metric may be possible to achieve through either tight traffic regulation (typically referred to as rate-based approach), or sophisticated scheduling (typically referred to as scheduler-based approach) only. In most practical cases though, some scheduling will be needed to resolve transmission conflicts among rate-based controlled applications, and vice versa. In addition to the supporting role of regulation in a scheduler-based approach, and scheduling in a rate-based approach, higher multiplexing gain may be achieved by allowing for some coordination between the two functionalities which will typically co-exist and be designed to achieve a common goal.

Substantial effort has been directed toward the development of regulation and scheduling schemes for real-time applications. Examples of regulation and scheduling schemes for real-time applications include : D-EDD (Delay-Earliest Due Date) [1]; J-EDD (Jitter Earliest Due Date) [2], [3]; HRR (Hierarchical Round Robin) [4]; S&G (Stop and Go Queuing) [5]; WFQ (Weighted Fair Queuing) [6]; PGPS (Packet Generalized Processor Sharing) [7]; RCSP (Rate Controlled Static Priority) [8]; LIT (Leave In Time) [9]; MRTS (Multi Rate Traffic Shaping) [10]; VC (Virtual Clock) [11].

The traffic management scheme for real-time applications investigated in this work may be viewed as an enhancement of the Rate Controlled Static Priority (RCSP) scheme proposed in [8]. Under the RCSP scheme each traffic stream passes through a regulator which restores the traffic, completely or partially, based on the traffic description and the type of regulator used. The restored traffic is handed over to the respective priority queue and is scheduled in FCFS order. The rate jitter regulator employed in [8] is based on cell eligibility times (ET) defined as follows: $ET_1 = AT_1$; $ET_k = max\{ET_{k-1} + T + \tau_k, AT_k\}$, $k > 1$ where AT denotes the cell arrival time, and τ_k is a term used to provide the average rate; subscripts indicate packets. T is the minimum cell inter arrival time specified by the source. The idea is to hold cells so that minimum inter departure time is enforced. Clearly the functions of the regulator and scheduler are separated in the RCSP scheme.

An apparent drawback of schemes such as the RCSP is that the regulator is *static* in the sense that its function is solely based on the behavior/characteristic of the associated stream. It is clear though that the throughput/jitter of a tagged regulated stream will potentially be substantially modulated at the scheduler by the cumulative activity of the co-existing traffic streams. As a consequence, the effectiveness of the regulator functionality may be compromised significantly. The above problem can be addressed to some extent by allowing for the modulation of the regulator function by some information associated with the state of the other coexisting stream. In other words, by employing a *dynamic* regulation scheme.

In the next section a regulation scheme is described along with a "generic" static one on which the comparative study will be based. By allowing for a proper scheduler state to modulate the regulation function a - very simple to implement - way to engage the recent activity of the co-existing streams (or maybe their regulators) is proposed. In section 3 a simple throughput/jitter study of both the static and the proposed dynamic regulators is presented. Based on this study and the numerical results presented in section 4, the improved throughput/jitter properties of the proposed dynamic regulation scheme are established.

2 The Dynamic Regulation Scheme

The typical primary objective in regulating real-time traffic stream within the network is to control jitter or the instantaneous rate (throughput). This is achieved in the RCSP mechanism [8] by enforcing a minimum spacing at the output of the regulator associated with the traffic stream of interest (tagged traffic stream). Fig.1 (without the feedback loop) shows a block diagram of an architecture implementing a RCSP mechanism where each of the N multiplexed streams is regulated before it is considered for transmission.

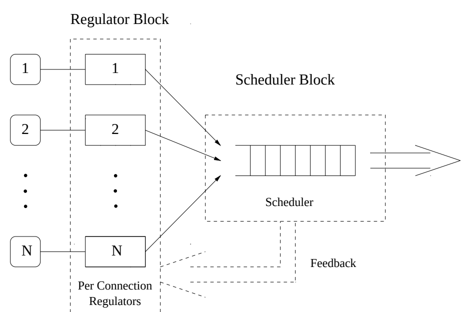

Figure 1: The RCSP (or Static Regulation) and Dynamic Regulation mechanisms

Since scheduling conflicts will arise when more than one regulated applications are present, a scheduler needs to be employed to resolve these conflicts. A consequence of the scheduling conflicts is that the tagged traffic stream at the output of the scheduler will be a distorted version of the target stream enforced at the output of the regulator. For instance, although a minimum spacing between consecutive tagged cells is enforced at the output of the tagged regulator in Fig. 1, this does not hold true for the tagged stream at the output of the scheduler. This clustering is generated due to an increased arrival rate to the scheduler in the immediate past which has pushed back (delayed) earlier tagged cells. Due to the latter, some spreading followed by some clustering of tagged cells is expected to be observed at the output of the scheduler.

The tagged cell spreading mentioned above can be reduced by monitoring the scheduler and releasing a tagged cell before its eligibility time [1] when scheduler queue build ups, which will cause the spreading, are detected. The Dynamic Regulation scheme proposed below attempts to provide for a smoother tagged traffic at the output of the scheduler based on this idea.

Although less commonly stated, another objective in regulating real-time traffic streams within the network is to control (limit) the amount of bandwidth that is

[1] Here defined as T time units following the previous tagged cell release, if a minimum spacing of T is targeted.

demanded by traffic streams. When the arrival rate to the scheduler increases due to (residual) traffic burstiness, or inability of a source(s) to obey to the traffic contract, spreading of the tagged cells at the output of the scheduler is expected to be observed, as indicated again above. This spreading represents an instantaneous reduction in the bandwidth allocated to the tagged traffic stream, as measured at the output of the scheduler. In the context of the bandwidth availability to the tagged traffic stream, the Dynamic Regulation scheme proposed below may be viewed as attempting to provide for a constant bandwidth availability to the tagged traffic stream at periods of excessive total bandwidth demand from the coexisting applications.

A simple architecture of the switch for the illustration of the proposed policy is shown in Fig. 1. Similarly to the architecture proposed in [8], each of the N supported real-time applications is regulated at a logically dedicated regulator before it is delivered to the scheduler. In the present work, a simple FCFS scheduling policy is being considered. This scheduling mechanism is the simplest possible, reducing the scheduling complexity to single queue buffering.

Under the Dynamic Regulation policy proposed below, the regulation process is modulated by some scheduler status information. Unlike in past work in the area, appropriate information regarding the status of the scheduler (FCFS queue) is fed back to the regulators, as indicated in Fig. 1 with the feedback arrow. As explained below the time of delivery of the cell from regulator i to the scheduler initiates a cycle of scheduler status monitoring for regulator i; this cycle is completed with the delivery of the next cell from regulator i to the scheduler, initiating the next monitoring cycle. The time at which a tagged cell is shifted from the regulator to the scheduler is determined by the tagged cell release policy described below.

2.1 The Tagged Cell Release Policy: Dynamic Regulation Scheme

Let t_k denote the time slot at which the k^{th} tagged cell is released from the tagged regulator. Let Q_k^r denote the queue occupancy at the regulator upon (following) the release of the k^{th} cell. Let $t_k + B_k$ ($B_k \geq 1$) denote the time slot at which the cumulative number of non-tagged arrivals (releases) to the scheduler following t_k exceeds $T-2$ for the first time. Let a superscript d (s) indicate a quantity associated with the dynamic (static) regulation policy and let

$$W_k = min\{B_k, T\} \quad \text{or} \quad W = min\{B, T\}, \tag{1}$$

where the last expression involves the generic random variables W and B. The $(k+1)$st tagged cell release time t_{k+1} is given by

$$t_{k+1} = t_k + W_k + H_k^d * 1_{\{Q_k^r = 0, A_r^{d,W_k} = 0\}}, \tag{2}$$

where H_k^d denotes the time interval between $\overline{t_k} = t_k + W_k$ and the first tagged cell arrival following $\overline{t_k}$; $A_r^{d,j}$ is the number of cell arrivals to the dynamic regulator queue over j slots; T is a constant positive integer.

If T is equal to the minimum spacing among consecutive tagged cell releases from the regulator in the RCSP scheme [8], then it is easy to see that the above release policy will accelerate the tagged cell releases from the regulator at times when a minimum spacing of T at the output of the scheduler would be violated. This acceleration occurs when $B_k < T$.

It is expected that the tagged cell release acceleration will have a positive impact on the tagged cell delay jitter and availed bandwidth. To quantify such benefits the Static Regulation scheme is considered in parallel in the rest of the paper. As described below its tagged cell release policy is not modulated by any scheduler status information. A simple FCFS scheduler is also considered.

2.2 The Tagged Cell Release Policy: Static Regulation Scheme

By employing the definitions presented above and replacing $W_k = min\{B_k, T\}$ by T, the $(k+1)$st tagged cell release time t_{k+1} is given by:

$$t_{k+1} = t_k + T + H_k^s * 1_{\{Q_k^r=0, A_r^{s,T}=0\}}, \tag{3}$$

where H_k^s denotes the time interval between $\overline{t_k} = t_k + T$ and the first tagged cell arrival following $\overline{t_k}$; $A_r^{s,j}$ is the number of cell arrivals to the static regulator queue over j slots; T is a constant positive integer.

3 Performance Issues

The performance of the Dynamic and Static Regulation policies is evaluated by tagging a specific traffic stream (source or application) and evaluating its characteristics at the output of the scheduler under both policies. The traffic at the output of the regulators associated with the remaining N applications is aggregated and forms the background traffic which competes with the tagged traffic for resources at the scheduler. Let A^k denote the number of background cells delivered to the scheduler over k consecutive slots.

3.1 Regulator Behavior

The basic operational difference between the Dynamic and Static Regulation schemes is captured by the tagged cell interdeparture process from the regulator $\{V_k\}_{k\geq 1}$, where $V_k = t_{k+1} - t_k$. In view of (2) and (3) it is easy to establish that the evolution of the tagged cell process $\{V_k\}_{k\geq 1}$ is described by

$$V_k^s = T + H_k^s * 1_{\{Q_k^r=0, A_r^{s,T}=0\}} \quad \text{(Static Regulation scheme)} \tag{4}$$

$$V_k^d = W_k + H_k^d * 1_{\{Q_k^r=0, A_r^{d,W_k}=0\}} \quad \text{(Dynamic Regulation scheme)} \tag{5}$$

The maximum achievable regulator throughput under the two policies is easy to determine and it is given by the next proposition.

Proposition 1 *: The maximum throughput (output rate) of the tagged regulator is given by :*

$$R_{max}^s = \frac{1}{T} \tag{6}$$

$$R^d_{max} = \frac{1}{\sum_{j=1}^{T-1} j * Pr\{A^j \geq T-1, A^{j-1} \leq T-2\} + T * Pr\{A^{T-1} \leq T-2\}} \quad (7)$$

under the Static and the Dynamic Regulation policy, respectively. [2]

In view of (6) and (7), the following corollary is self-evident.

Corollary 1 *:* $R^d_{max} \geq R^s_{max}$ *with equality only when the background traffic process can never deliver more than* $T-1$ *cells over* $T-1$ *consecutive slots (typically, a zero probability event).* □

The above discussion establishes that the Dynamic Regulation scheme will respond to a sudden increase of the background load [3] by increasing its rate above the targeted rate of $1/T$, in an effort to ensure that the targeted tagged rate at the output of the scheduler is achieved. The impact of such a reaction (which is not possible under the Static Regulation scheme) on the scheduler output process is investigated next.

3.2 Scheduler Behavior

First, the case in which the scheduler queue is stable is considered. That is $\rho < 1$. Assuming sufficiently large buffer capacity at the scheduler (no overflows), it is clear that the following will hold :

$$R^d_{max} = S^d_{max} \quad \text{and} \quad R^s_{max} = S^s_{max} \quad (8)$$

In view of the above and corollary 1 the following corollary is self evident.

Corollary 2 *:* $S^d_{max} \geq S^s_{max}$*, where* S_{max} *denotes the maximum tagged cell output rate from the scheduler, or the maximum tagged cell throughput.*

The case in which the scheduler queue is unstable is considered next. That is, $\rho > 1$. Although the scheduler queue capacity is again assumed to be infinite and, for that matter, no overflow will occur, the relationship in (8) will not hold since traffic will accumulate in the infinite queue. This ever increasing queue built up will represent a difference between input and output traffic, making it hard to assess the precise throughput achieved by the tagged or background streams. For this reason, a more careful study of the throughput in terms of the observed departure process at the output of the scheduler is carried out next.

It should be noted that although the call admission control function will attempt to minimize the occurrence of temporary overload at the network nodes, due to traffic burstiness and the desire to improve resource utilization through statistical multiplexing, it is expected that temporary overload will be unavoidable. It is under such conditions that traffic management mechanisms should not only not collapse, but rather minimize the impact of the overload on the QoS.

[2] For proofs of the propositions in this paper point your web browser to `http://www.cdsp.neu.edu/info/netgroup/pub.html`

[3] which would result in an instantaneous reduction of the tagged throughput at the output of the scheduler

In addition to determining the tagged stream throughput at the scheduler by employing the associated tagged cell interdeparture process, the latter will also be used to determine the smoothness properties of the two regulation schemes. The quality of a regulator is typically evaluated in terms of its ability to generate a smooth traffic, often measured in terms of cell clustering and cell spreading. If X_k denotes the kth tagged cell interdeparture time interval from the scheduler, then $X_k < T$ and $X_k > T$ will represent clustering and spreading, respectively. The following proposition establishes the smoothness properties of the Dynamic and Static Regulation policies in a comparative manner.

Proposition 2 *: Under overload conditions at the scheduler the Dynamic Regulation policy will potentially reduce the tagged cell spreading (while it will never increase it) compared to the Static Regulation policy. That is,*

$$Pr\{X_k^d > m\} \leq Pr\{X_k^s > m\} \qquad \textit{for } m \geq T$$

The tagged cell clustering will be identical under both policies, that is,

$$Pr\{X_k^d < m\} = Pr\{X_k^s < m\} \qquad \textit{for } 1 \leq m < T.$$

The above proposition establishes the better jitter characteristics of the Dynamic Regulation scheme, compared to those of the Static Regulation scheme. The following proposition provides for the precise description of the tagged stream interdeparture distribution at the output of the scheduler under overload conditions.

Proposition 3 *Under the overload conditions at the scheduler queue ($\rho > 1$) and infinite scheduler buffer capacity, the distribution of the tagged cell interdeparture at the scheduler, X_k, under the Dynamic Regulation policy, is given by:*

$$Pr\{X_k = l\} = \sum_{m=1}^{T} Pr\{A^m = l-1, A^{m-1} \leq T-2\} * 1_{\{T \leq l \leq N+T-1\}} +$$
$$+ Pr\{A^T = l-1\} * 1_{\{1 \leq l \leq T-1\}} \quad \textit{for } 1 \leq l \leq N+T-1;$$

the distribution under the Static Regulation policy is given by :

$$Pr\{X_k = l\} = Pr\{A^T = l-1\} \quad \textit{for } 1 \leq l \leq N*T+1$$

Proposition 3 can be employed in deriving the instantaneous throughput of the tagged application as summarized in the following corollary.

Corollary 3 *: Under overload conditions at the scheduler, the probabilistic description of the instantaneous tagged cell output rate Y_k, where $Y_k = 1/X_k$, can be derived by employing the probability distribution of X_k given in Proposition 3.*

Although the throughput and interdeparture process from the scheduler of a tagged application can be calculated as indicated above, the following proposition establishes some insightful relationships between the moments of interdeparture and the background traffic process.

Proposition 4 : *Under overload conditions at the scheduler the following can be shown :*

$$
\begin{array}{ll}
(a) & E\{X_k^s\} = T * E\{A^1\} + 1 = T * N * p_b + 1 \\
(b) & VAR\{X_k^s\} = T * VAR\{A^1\} = T * N * p_b * (1 - p_b) \\
(c) & E\{X_k^d\} = E\{W\} * E\{A^1\} + 1 = E\{W\} * N * p_b + 1
\end{array}
$$

Where the last part of the above equations is derived for a binomial random variable A^1 with maximum value N and success probability p_b; $VAR\{x\}$ denotes the variance of random variable x.

The following interesting conclusions may be drawn from Proposition 4. This result establishes the magnitude of the difference in throughput under severe overload conditions achieved by the tagged traffic stream under the two policies.

Corollary 4 : *The throughput gain of the Dynamic Regulation scheme over that of the Static Regulation scheme under overload conditions increases as the load increases and its asymptotic value is equal to T. That is :*

$$
\frac{1/E\{X_k^d\}}{1/E\{X_k^s\}} = \frac{T + 1/E\{A^1\}}{E\{W\} + 1/E\{A^1\}} \overset{E\{A^1\}\to\infty}{\rightarrow} T
$$

4 Numerical Results

In this section, some numerical results are presented to quantify the behavior of the Dynamic and Static regulation schemes. The results are derived under heavy traffic load at both the regulator and the scheduler. Although such conditions are not the dominant ones in a well designed system, they will be present if substantial statistical multiplexing gain is to be achieved. And while simple regulator schemes - such as the Static one - may be adequate under nominal (under loaded) traffic conditions, it is important that their behavior under less frequent - but QoS compromising - overload conditions, be investigated. The results shown here indicate that the Dynamic Regulation scheme proposed in this paper can cope with (temporary) overload conditions better than the Static one.

The results presented below have been obtained for two values of the target interdeparture time T - or desirable throughput $1/T$ - equal to $T = 5$ and $T = 10$. The background traffic is modeled as an independent per slot, batch process with binomially distributed batch size of maximum value $N = 8$ and success probability p_b.

In periods of overload, the Dynamic Regulation policy can detect the increased background intensity and release cells earlier, attempting to provide the targeted throughput ($1/T$) and control jitter. As a consequence, the rate by which the packets leave the regulator increases as the background intensity increases (Fig. 2). The traffic smoothness characteristics of the two schemes can be observed in Fig. 3 and 4, where the jitter distribution (or scheduler interdeparture distribution) is plotted for two different values of background load (Back Util). In both cases the jitter probability mass function is highly contained around the target value T under the Dynamic Regulation scheme, and it is spread over wide range of values under the Static Regulation scheme.

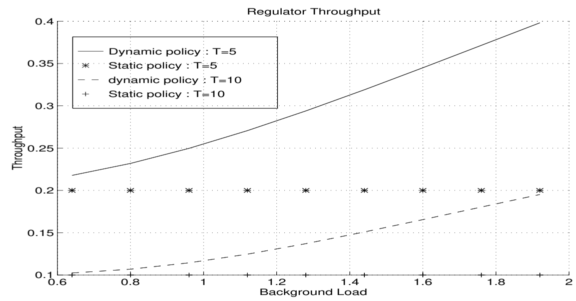

Figure 2: Regulator Throughput VS background utilization ρ_{back}.

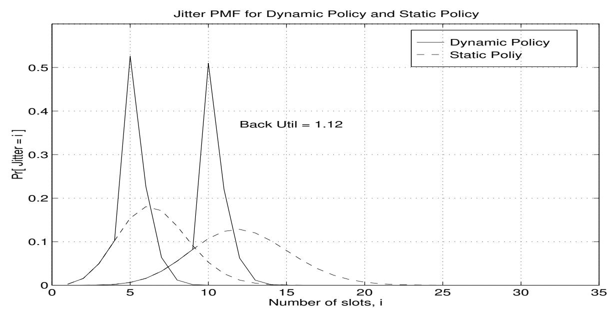

Figure 3: Jitter distributions under moderate overload

The tails of the probability mass function representing spreading ($Pr\{X_k \geq k\}$ for $k > T$), are shown in Fig. 5 and 6 for $T = 5$ and $T = 10$, respectively. The good jitter characteristics of the Dynamic Regulation scheme in terms of reduced cell spreading are clearly observed. Excessive spreading – occurring under network congestion (scheduler overload) – may compromise the QoS of a real-time application by causing starvation at the end user. It is evident that the starvation probability can be substantially lower under the Dynamic regulation scheme.

Results regarding the tagged stream throughput at the scheduler as a function of the background traffic load, ρ_{back}, are shown in Fig. 7; ρ_{back} is such that the scheduler

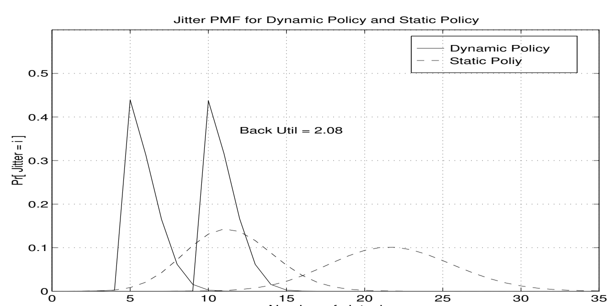

Figure 4: Jitter distributions under excessive overload

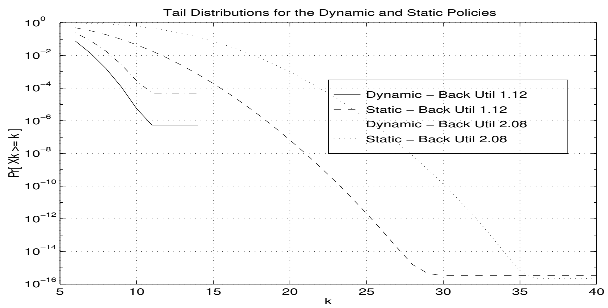

Figure 5: $Pr\{X_k \geq k\}$ for $k > T$, and $T = 5$

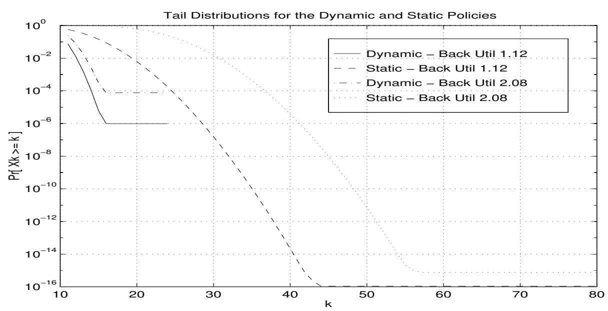

Figure 6: $Pr\{X_k \geq k\}$ for $k > T$, and $T = 10$

is in overload state ($\rho > 1$). The results can be calculated either from parts (a) and (c)

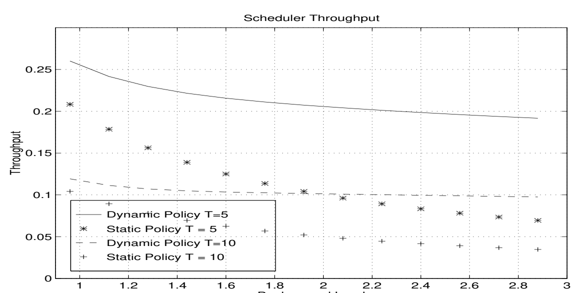

Figure 7: Scheduler Throughput VS utilization ρ.

of Proposition 4, or from the probability mass function of X_k derived in Proposition 3. The improved throughput characteristics of the Dynamic Regulation scheme can be clearly observed. The higher than the targeted throughput for low overload conditions is in accordance with expectations based on the increased regulation throughput and the heavy traffic assumption for the tagged source. As long as $\rho < 1$, the regulator throughput determines the throughput at the scheduler as well, as explained earlier. When $\rho > 1$, some of the regulator traffic is "absorbed" by the infinite buffer built up at the scheduler and a throughput reduction is observed for this reason. Nevertheless, by reducing W the Dynamic Regulator is capable of providing the targeted throughput under severe overload conditions. In the limiting case of very large overload, $W \to 1$ and the tagged throughput reduction below the targeted value is observed, induced by the per slot background batch size. It should be noted that under the Static Regulation scheme the tagged throughput falls dramatically even under low overload conditions. This reduction is directly related to the cumulative over T slots background arrivals, as opposed to that over W slots ($W \to 1$) under the Dynamic Regulation scheme. In

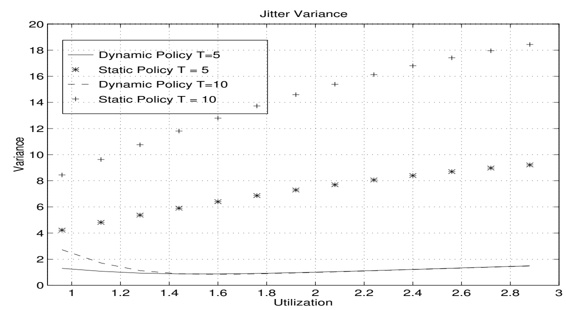

Figure 8: Variance VS background utilization ρ_{back}. $p_b = 0.12 + (k-1) * 0.02$ where k the point of interest ($k = 1, 2, \ldots 13$)

addition to maintaining a throughput as close to the targeted one under overload, it is important that the variability of the throughput (or interdeparture time X_k) be low. Fig. 8 presents results for the variance of the tagged cell interdeparture process induced by the two policies. These results have been derived by employing the probability mass function of X_k, for various values of ρ_{back} corresponding to success probabilities given by $p_k = 0.12+(k-1)*0.02$ for $k = 1, 2, \ldots 13$. In view of the linear relationship between $VAR(X_k)$ and $VAR(A^1)$ (Proposition 4) the increasing behavior of $VAR(X_k)$ as ρ_{back} increases under the Static Regulation scheme is expected and it is observed in Fig. 8. The results under the Dynamic Regulation scheme are less easy to interpret. For low overload conditions $VAR(X_k)$ decreases until $\rho_{back} = 1.44$ (4th point on the plot) and then increases slightly. X_k depends solely on the background accumulation over W slots (between consecutive tagged cell releases). Therefore, as ρ_{back} increases the condition $A^W \geq T-1$ is expected to be met in fewer slots, and therefore a cell would be released earlier. This implies that a decreasing number of batches would interfere with X_k, reducing $VAR(X_k)$. As ρ_{back} increases the number of batches which interfere with X_k under the Dynamic policy reduces to 1; beyond that point the increased value of $VAR(X_k)$ is due to the increase in $VAR(A^1)$.

5 Some Concluding Remarks

The study of the proposed Dynamic Regulation scheme under overload traffic conditions has clearly established its good throughput / jitter properties. Work is currently in progress regarding a comprehensive evaluation of the proposed Dynamic Regulation scheme. Analytical and simulation approaches are being considered in order to evaluate the behavior of the proposed scheme in the presence of specific traffic sources (relaxing the heavy traffic assumption at the regulator), under underload conditions at the scheduler, and in the presence of multiple streams subject to Dynamic Regulation (refining the background traffic model).

References

[1] D. Verma D. Ferrari. "A Scheme for Real Time Channel Establishment in Wide Area Networks". *IEEE Journal on Selected Areas in Communication*, 8(3):368–379, April 1990.

[2] D. Ferrari. "Delay Jitter Control Scheme for Packet-Switching Internetwork". *Computer Communications*, 15(6):367–373, July-August 1992.

[3] D. Ferrari D. C. Verma, H. Zhang. "Delay Jitter Control for Real-Time Communication in a Packet Switching Network". In *Proceedings of Tricomm '91, Chapel Hill N.C.*, pages 35–46, April 1991.

[4] S. Keshav C. R. Kalmanek, H. Kanakia. "Rate Controlled Servers for Very High Speed Neworks". In *IEEE Global Telecommunication Conference, San Diego California*, pages 300.3.1–300.3.9, December 1990.

[5] S. J. Golestani. "Congestion-Free Communication in High-Speed Packet Networks". *IEEE Transactions In Networking*, 39(12):1802–1812, December 1991.

[6] S. Shenker A. Demers, S. Keshav. "Analysis and Simulation of a Fair Queueing Algorithm". In *Proceedings ACM SIGCOMM '89*, pages 1–12, October 1989.

[7] R. G. Galager A. K. Parekh. "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks : The Single-Node Case ". *IEEE/ACM Transactions in Networking*, 1(3):344–357, June 1993.

[8] D. Ferrari H. Zhang. "Rate-Controlled Static-Priority Queueing". In *Proceedings IEEE INFOCOM '93*, pages 227–236, September 1993.

[9] J. Pasquale N. R. Figueira. "Leave in Time: A New Service Discipline for Real Time Communications in a Packet Switching Nework". In *Proceedings ACM SIGCOMM '95 Cambridge MA*, pages 207–218, 1995.

[10] S. K. Tripathi D. Saha, S. Mukherjee. "Multi-rate Traffic Shaping and End-to-End Performance Guarantees in ATM Networks". In *International Conference on Network Protocols, 1994*, pages 188–195, 1994.

[11] L. Zhang. "Virtual Clock: A New Traffic Control Algorithm for Packet Switching Networks". In *Proceedings of ACM SIGCOMM '90*, pages 19–29, September 1990.

[12] M Sobel D. Heyman. *"Stochastic Models in Operations Research"*, volume Vol.I. McGraw Hill, 1982.