An Integrated Regulation and Scheduling Scheme for Real-Time Traffic Management *

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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, an integrated Regulation and Scheduling (dynamic-R&S) scheme is proposed whose regulation function is modulated by both the tagged stream's characteristics and some information capturing the state of the co-existing applications as provided by the scheduler. The performance of the proposed scheme – as well as that of the equivalent static one – is investigated under both underload and overload traffic conditions – both analytically and through simulation – and the substantially better throughput / jitter characteristics of the dynamic-R&S 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). Over allocation aims at improving the resource utilization, at the expense of failing to accommodate at certain times peak resource demands from a number of the grouped applications. Grouping of applications and "over-allocation" of resources are the key aspects of non-degenerate statistical 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 traffic handling. In principle, a target value of a 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. Similarly, some traffic filtering (regulation) will be needed to eliminate extreme traffic realization which would be hard to manage even by a sophisticated scheduler under a scheduler-based approach. 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 cooperation between the two functionalities which will typically co-exist and be designed to achieve a common goal. Such a dynamic policy is investigated in the present paper.

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]; HRR (Hierarchical Round Robin) [3]; S&G (Stop and Go Queuing) [4]; WFQ (Weighted Fair Queuing) [5]; PGPS (Packet Generalized Processor Sharing) [6]; RCSP (Rate Controlled Static Priority) [7]; LIT (Leave In Time) [8]; MRTS (Multi Rate Traffic Shaping) [9]; VC (Virtual Clock) [10].

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 [7].

2 The Proposed Dynamic R&S Policy

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 [7] by enforcing a minimum spacing

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at the output of the regulator associated with the traffic stream of interest (tagged traffic stream). Fig. 1 (without the feedback arrow) 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.

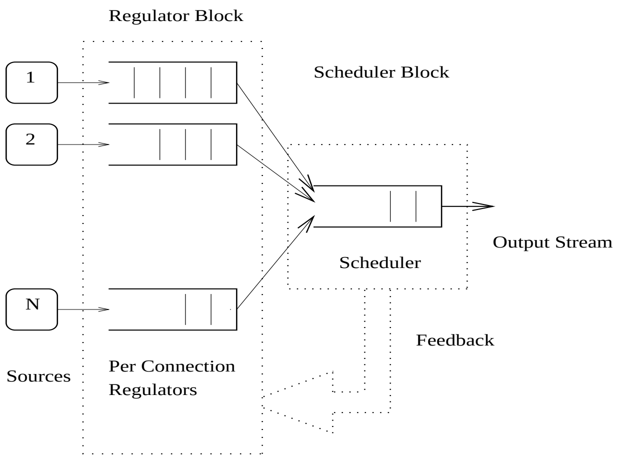

Figure 1: The Regulation and Scheduling architecture.

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 corresponding 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 and Scheduling (dynamic-R&S) scheme proposed below attempts to provide for a smoother tagged traffic at the output of the scheduler based on this idea.

Under the dynamic-R&S 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. The proposed cell release scheme is explained next.

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-R&S (static-R&S) policy and let

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

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

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

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

If T is equal to the minimum spacing among consecutive tagged cell releases from the regulator in the RCSP scheme [7], 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 $B_k < T$.

The tagged cell release of the (equivalent) static R&S policy can be easily described in terms of that of the dynamic R&S by replacing W_k by T.

3 Study of Regulator Behavior

The behavior of the R&S schemes is evaluated by investigating their impact on a specific stream (tagged stream). The traffic at the output of the regulators associated with the remaining $N-1$ applications is aggregated and forms the background traffic which competes with the tagged traffic for resources at the scheduler.

The improved performance of the dynamic-R&S policy over the static-R&S policy is established by evaluating the cell interdeparture process at the output of the scheduler. Since the input process to the scheduler is the output process from the regulator, it is important that the latter be investigated to both gain insight into the combined system (regulator plus scheduler) behavior, as well as evaluate the output process at the scheduler.

The basic operational difference between the dynamic-R&S and static-R&S 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 order to decouple the intrinsic behavior – to be investigated in this paper – of the R&S schemes from the source load, the heavy traffic source assumption will be made throughout the paper. This assumption is consistent with standard ones made in order to determine the throughput capabilities of a scheme as well as the throughput fluctuations (jitter), without the noise introduced by

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

source inactivity periods. In view of (2) and under the heavy traffic source assumption, it is easy to establish that:

$$V_k^d = W_k \text{ (dynamic-R\&S) and } V_k^s = T \text{ (static-R\&S)} \quad (3)$$

since the indicator function in (2) is always zero. The probabilistic description of V_k^d may be found in [11] along with the detailed derivations involved in the following proposition establishing the comparative behavior of the two policies.

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

$$R^d_{max} = \frac{1}{E\{W\}} \quad \text{and} \quad R^s_{max} = \frac{1}{T} \quad (4)$$

Notice that $R^d_{max} \geq R^s_{max}$ with equality only when the background traffic process can never deliver more than $T-2$ cells over $T-1$ consecutive slots.

The above establish that the dynamic-R&S scheme will respond to a sudden increase of the background load [2] by increasing its regulator's output rate above the targeted rate of $1/T$, in an effort to ensure that the targeted rate at the output of the scheduler is achieved. The impact of such a reaction (which is not possible under the static-R&S scheme) on the scheduler output process is investigated in the next section.

4 Study of Scheduler Behavior

The tagged cell interdeparture process $\{X_k\}_{k\geq 1}$ from the scheduler has been derived in order to evaluate the throughput / jitter properties of the R&S schemes. Since the deliverability of the QoS of the tagged application (which is considered to be a measure of the induced throughput / jitter) is expected to be decreased under high load conditions at the scheduler, such conditions – both within the stability and instability regions of the system – will be considered at the scheduler.

Under underload conditions ($\rho < 1$) the scheduler queue is stable and since no cell overflow is possible (assuming infinite buffer at the scheduler), the following relationships between the maximum regulator (R_{max}) and scheduler (S_{max}) throughputs hold:

$$R^d_{max} = S^d_{max}\ , \quad R^s_{max} = S^s_{max} \quad \text{and} \quad S^d_{max} \geq S^s_{max} \quad (5)$$

The Probability Mass Function (PMF) of X_k has been derived under both policies by formulating appropriate queuing systems, assuming infinite buffer capacities at the regulator and scheduler and heavy traffic conditions at the regulator. The derivations – under both underload ($\rho < 1$) and overload ($\rho > 1$) – can be found in [11]. Finally it can be shown that under overload conditions at the scheduler the dynamic-R&S policy will potentially reduce the tagged cell spreading (while it will never increases it) compared to the static-R&S policy.

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

5 Numerical Results

The analytical 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 $N - 1 = 8$ and success probability p_b. The background load or utilization is denoted by ρ_{back} (Back Util).

Figure 2 presents the regulator throughput vs ρ_{back} under both policies. As ρ_{back} increases, the dynamic-R&S 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. The scheduler throughput S_{max} vs ρ_{back} is shown in Fig. 3 for both policies under underload conditions ($\rho < 1$). S_{max} is calculated as $1/E\{X_k\}$. As expected from (5), $S^d_{max} = R^d_{max}$

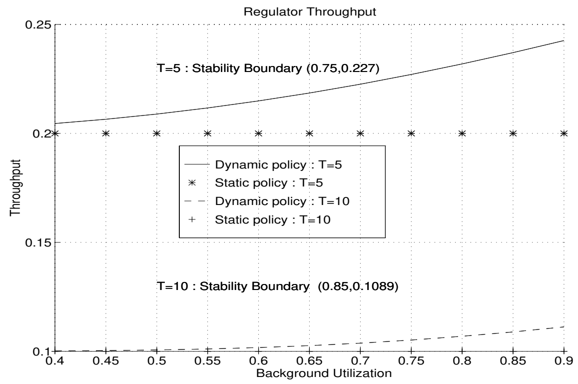

Figure 2: Regulator Throughput VS background utilization ρ_{back} ($\rho_{back} < 1$).

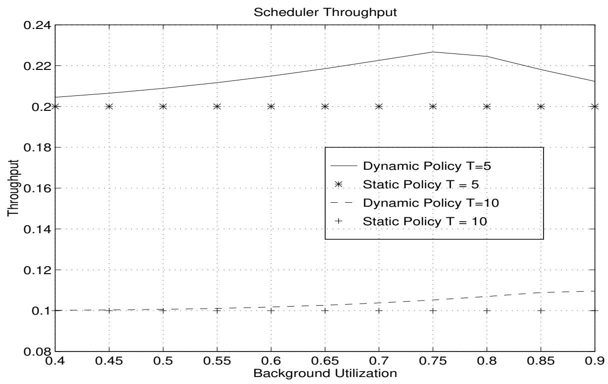

Figure 3: Scheduler throughput vs ρ_{back}

under underload conditions and infinite buffer capacity at the scheduler. Although R^d_{max} continues to increase as ρ_{back} increases (as said earlier), S^d_{max} starts deviating from R^d_{max} and declines beyond some value of ρ_{back} equal to about .78 for $T = 5$. This is due to the fact that the scheduler reaches an overload state ($\rho > 1$) and the dynamics change. Specifically, an infinite scheduler queue backlog is built up under these conditions, resulting in a different than R_{max} output rate from the scheduler, as discussed earlier. Thus, only the results for $R_{max} + \rho_{back} < 1$ are relevant.

The detailed traffic smoothness characteristics of the two R&S schemes are shown in Fig. 4 for underload conditions at the scheduler. Tagged cell clustering ($X_k < T$) is seen to slightly increase under the dynamic-R&S policy, while spreading ($X_k > T$) is substantially reduced and more probability mass is concentrated around T. While

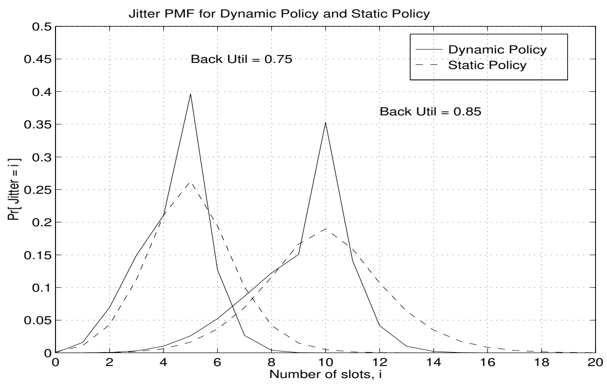

Figure 4: Jitter (X_k) PMF ($\rho_{back} < 1$)

the spreading reduction under the dynamic-R&S policy is expected, the slight increase in the clustering is less obvious. It may be attributed to the higher probability that the scheduler queue is nonempty under the dynamic-R&S policy, due to the higher scheduler load (S_{max}) resulting from a higher regulator throughput (R_{max}).

The traffic smoothness characteristics of the two schemes under overload traffic conditions at the scheduler can be observed in Fig. 5. The jitter PMF is highly contained around the target value T under the dynamic-R&S scheme, and it is spread over wide range of values under the static-R&S scheme.

Finally, a system in which $N = 7$ ON_OFF Markov sources ($src_0 - src_6$) controlled by the R&S policies is considered and is studied through simulations;the parameters of the geometric length of the On and OFF periods are denoted by P_{on} and P_{off}, respectively. The objective of this study is to investigate whether the good characteristics of the dynamic RandS policy are maintained when multiple sources are controlled by such a policy.

The actual cell interdeparture times (X_k) from the scheduler were recorded, after filtering out the gaps caused by the source's OFF periods, Thus the calculated throughput (called the active throughput, S_a) will be higher than

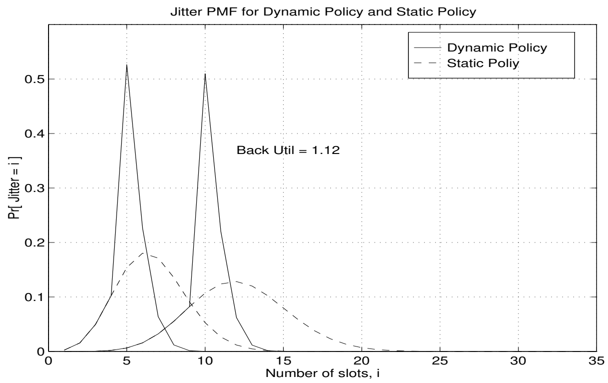

Figure 5: Jitter (X_k) PMF ($\rho_{back} > 1$)

src#	λ_{ave}	S^d_a	S^s_a	$VAR[X^d_k]$	$VAR[X^s_k]$
0	0.397	0.430	0.435	3.122	2.948
1	0.383	0.426	0.431	3.132	2.980
2	0.400	0.432	0.437	3.026	2.913
3	0.043	0.092	0.065	8.262	48.028
4	0.042	0.090	0.063	8.986	51.963
5	0.111	0.157	0.124	11.99	20.319
6	0.111	0.162	0.126	9.825	17.710

Table 1: Simulation results

the actual average throughput. This filtering of the data allows for capturing the effect that the policies have on the sources while they are active, without being obscured by the OFF periods where the policies are ineffective.

Several simulation scenarios were considered with different system utilization factors. Results are shown here for $\rho = 1.49$ (overload).

The results of the simulation scenario are shown in Table 1; $P_{on} = P_{off} = .8$ for src_0, src_1, src_2, $P_{on} = .8$ and $P_{off} = .85$ for src_3, src_4 and $P_{on} = .8$ and $P_{off} = .75$ for src_5, src_6. The target cell spacings (X_{min}) enforced were: $X_{min} = 1$ for $src_0 - src_2$, $X_{min} = 10$ for $src_3 - src_4$ and $X_{min} = 5$ for $src_5 - src_6$. Sources $src_0 - src_2$ are practically unregulated since they are allowed to release cell as soon as they are generated. For each source, the average source rate λ_{ave} is shown in table 1, along with the measured active throughput S^d_a and variance $VAR[X^d_k]$ under the dynamic-R&S and S^s_a and variance $VAR[X^s_k]$ under the static-R&S policies.

The positive impact of the dynamic-R&S policy on the regulated sources ($src_3, src_4, src_5, src_6$) is clearly observed in Table 1: the variance of the interdeparture process under the dynamic-R&S scheme ($VAR[X^d_k]$) is dramatically smaller than the variance under the static-R&S scheme ($VAR[X^s_k]$). At the same time the S^d_a is higher than the S^s_a. This quantifies the ability of the dynamic-R&S scheme to control the delay jitter better than the static-R&S scheme, for all of the regulated sources. The dynamic-R&S scheme manages to serve the regulated sources with a less variable service rate and, as a result, the traffic maintains better the desirable characteristics at the output of the scheduler.

The unregulated sources (src_0, src_1, src_2) experience a slightly higher $VAR[X_k^d]$. Since the target X_{min} for these sources is 1, the two policies are basically ineffective and the variance and active throughput are shaped solely by the background interfering process seen by each of these sources during each slot. The background interfering processes are different under the two policies. It is expected that under the dynamic-R&S policy more cells will be released to the scheduler per slot during the ON period, due to the early releases.

The above results can be viewed graphically in terms of the empirical PMFs shown in Fig. 6 and Fig. 7. The PMF at the target value is substantially higher under the dynamic-R&S scheme. This may be attributed to the reduced spreading. The empirical PMFs for src_0, src_1, src_2 are almost identical under the two policies and they are not shown.

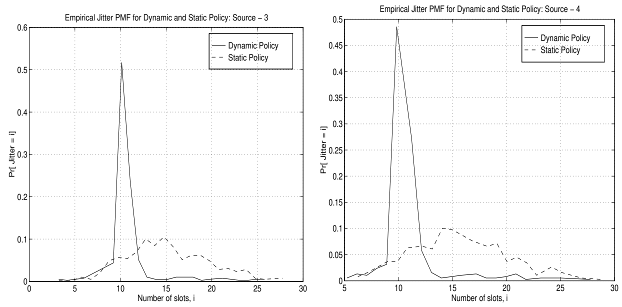

Figure 6: Empirical Jitter PMFs : src_3 and src_4

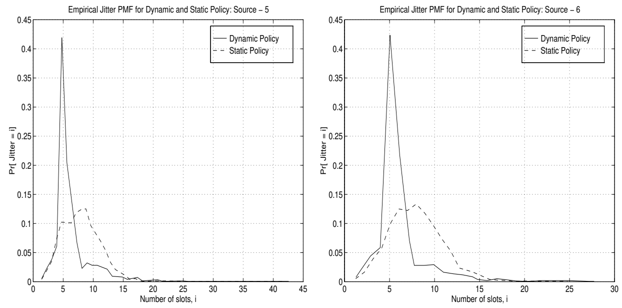

Figure 7: Empirical Jiter PMFs : src_5 and src_6

6 Conclusion

In this paper a dynamic Regulation and Scheduling (R&S) scheme has been proposed and studied through analysis and simulation. The analytical and simulation results clearly have shown that the dynamic-R&S can provide substantially better jitter control – both under underload and overload conditions – than the static-R&S scheme.

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