A Congestion Control Scheme for Continuous Media Streaming Applications *

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Abstract. In this paper a novel congestion control scheme is proposed that aims at providing a smoother and reduced loss rate adaptation behavior compared to that under the basic Additive Increase Multiplicative Decrease (AI/MD) scheme; such a scheme is expected to be more appropriate for continuous media streaming applications. The basic features of the proposed scheme are that: (a) the rate increment is modulated by the distance between the flow's current rate and a targeted maximum rate determined by the streaming application; (b) the multiplicative decrease factor is shaped by the induced packet losses. These features are responsible for a dynamic and self-adjusting rate adaptation behavior that is shown to improve convergence to fairness, the oscillatory behavior and induced packet losses. Numerical results illustrate the good properties and intrinsic advantages of the proposed scheme.

1 Introduction

Internet's stability is due to the congestion control and avoidance algorithm [1, 2] implemented in the Transport Control Protocol (TCP), which belongs in the class of the Additive Increase / Multiplicative Decrease (AI/MD) algorithms [3]. TCP has been designed and successfully used for unicast reliable data transfer. Its window-based congestion control scheme and retransmission mechanism introduce typically end-to-end delays and delay variations, that make TCP unsuitable for the Continuous media (CM) streaming applications. For CM streaming services the User Datagram Protocol (UDP) is used as the base transport protocol, in conjunction with the Real Time Protocol (RTP) and Real Time Control Protocol (RTCP) [5]. Applications that use the UDP transport protocol should also implement end-to-end congestion control to retain the stability of the Internet otherwise all supported applications will suffer (UDP flows will get most of the bandwidth) and eventually the network will collapse [6]. The main requirements of the CM streaming applications are that their adaptation behavior should be as smooth as possible, and the induced losses be controlled and kept low. These requirements are taken into consideration in the design of the rate adaptation scheme proposed in this paper.

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A rate adaptation scheme needs to be communicated the network state through a feedback mechanism. The feedback mechanisms that have been proposed are typically either RTCP-based [7]-[12] or ACK-based [14, 15]. In the first case the feedback delay is about 5 sec (± 1.5 randomly determined), whereas in the second case it is equal to one round trip time. Most rate adaptation schemes for multimedia communication use the current packet loss rate to infer whether the network is congested or not, and thus adjust the rate in response. The increase function is either additive increase or multiplicative increase [15], whereas the decrease function is multiplicative decrease [7, 8, 14]. Alternatively, the rate may be set to a value calculated by an equation-based formula [4] which estimates the equivalent TCP throughput [10-14,16]. The latter schemes aim primarily at inducing a behavior that is TCP friendly.

Independently from whether a rate adaptation scheme is used for data or CM transferring, only a few of them [9, 16] exploit the packet loss rate to determine the new (decreased) rate. In the approach described in the present paper, the introduced loss dependent multiplicative decrease policy is simpler than that in [16] and more meaningful than that in [9], as will be shown later. Furthermore, the simplicity allows for a better understanding of the intrinsic properties of such a loss dependent decrease policy. In addition to this, an innovative aspect of the proposed congestion control scheme is that the associated increase policy takes into consideration the distance between the flow's current rate and a predetermined upper bound. The proposed scheme is compared against the basic AI/MD scheme in terms of smoothness and packet loss rates and its better behavior is demonstrated through a set of simulation results in an environment where only adaptable CM (RTP/UDP/IP) flows are transmitted (i.e., free of TCP flows), as it may be the case under the forthcoming differentiated services.

2 Description of the Distance Weighted Additive Increase and Loss Rate Dependent Multiplicative Decrease Scheme

In this section, a novel congestion control scheme - referred to as the DWAI/LDMD scheme - is introduced. The major characteristics of this scheme are: (a) the rate increment depends on the distance between the current rate and a maximum allowable rate (Distance Weighted Additive Increase (DWAI) policy); (b) the rate decrease depends on the actual value of the reported packet loss rate (Loss rate Dependent Multiplicative Decrease (LDMD) policy).

A discrete time network model that consists of n users (flows) is considered ; Let $\{\ldots, t-1, t, t+1, \ldots\}$ denote the discrete time instants which are assumed to coincide with the times at which all users receive feedback from their peer entities (synchronized feedback assumption). Let $f_i(t)$ denote the feedback received by user i at time instant t; $f_i(t)$ specifies the packet loss rate that the corresponding flow i experienced over the preceding time interval $(t-1, t)$. The propagation delays between the peer entities are assumed to be zero. Under the assumption that the total network losses are distributed to all flows in proportion to their rate, it is implied that either all flows will experience packet losses or none (see Proposition 1). This implies - as determined by the proposed scheme described bellow - that all flows will react in the same manner: they will all either increase (under zero losses) or decrease (under non-zero losses) their rate. Such rate increases and decreases are subject to the constraint that the resulting rate remain in the range $[m, M]$, that is a minimum (m) and a maximum (M) allowed rate be respected.

Let $x_i(t)$ denote the transmission rate of user i over the interval $(t-1, t)$. The proposed DWAI/LDMD scheme is determined by the following function describing the next rate ($x_i(t+1)$) in terms of the current ($x_i(t)$) and the reported packet losses $f_i(t)$

$$x_i(t+1) = \begin{cases} \min\{M, x_i(t) + \frac{M-x_i(t)}{M-m} I_{\mathrm{DW}}\} & \text{if } f_i(t) = 0 \text{ (DWAI policy);} \\ \max\{m, x_i(t)d(1-f_i(t))\} & \text{if } f_i(t) > 0 \text{ (LDMD policy) ;} \end{cases} \quad (1)$$

where, I_{DW} is the base increase step ($M - m > I_{\mathrm{DW}} > 0$), and d is a constant which is less than one ($d < 1$). Notice that the normalized distance between the current rate and the maximum allowable rate M is taken into consideration when the rate is increased; the normalization quantity is equal to the distance between the maximum and the minimum allowable rates. The increment to the rate is maximized (equal to I_{DW}) when the rate is equal to the minimum allowable (m) while the increment to the rate is minimum (equal to 0) when the rate is equal to the maximum allowable (M). For a rate between the minimum and the maximum, the increment is a linear function of the distance of the current rate from the maximum allowable (equal to $I_{\mathrm{DW}}\frac{M-x_i(t)}{M-m}$). Regarding the decrement of the rate when packet losses are reported, notice that the associated decrease factor ($d(1 - f_i(t))$ is not constant - as in the case of the basic AI/MD scheme - but depends on the reported packet loss rate $f_i(t)$, ($0 \le f_i(t) \le 1$).

Let $\boldsymbol{x}(t) = \{x_1(t), x_2(t), \ldots, x_n(t)\}$ denote the rate vector at time instant t associated with n supported users (flows) and let $X(t)$ denote the total network load associated to $\boldsymbol{x}(t)$. That is, $X(t) = \sum_{i=1}^{n} x_i(t)$. Let X_{eff} denote the targeted maximum total load which is typically equal to the network capacity. Let $L(t)$ and $l_i(t)$ denote the number of packet losses for the network and user i, respectively, associated with time instant t (that is, occurred over $(t-1, t)$). Since the length of the interval $(t-1, t)$ is equal to 1, $L(t) = 1|X(t) - X_{\mathrm{eff}}|^+$, where $|w|^+ = w$ if $w > 0$ and 0 otherwise. Let $f(t)$ and $f_i(t)$ denote the packet loss rate for the network and user (flow) i, respectively, associated with time instant t.

Proposition 1. *Under the assumption that the packet losses experienced by a flow i, are proportional to its rate, that is, $l_i(t) = L(t)\frac{x_i(t)}{X(t)}$, the resulting packet loss rates are identical for all flows and are given by*

$$f_i(t) = \frac{l_i(t)}{x_i(t)} = \frac{L(t)}{X(t)} = \frac{|X(t) - X_{\mathrm{eff}}|^+}{X(t)} = f(t)$$

Since $f_i(t) = f(t)$, $f_i(t)$ will be used instead of $f(t)$ only when the association with flow i is to be emphasized.

The study of the properties of the proposed DWAI/LDMD scheme (presented in the next sections) is facilitated by re-writing the rate adaptation equation (1) as follows

$$x_i(t+1) = \begin{cases} \min\{M, a_{\mathrm{I}} + b_{\mathrm{I}} x_i(t)\} & \text{if } f_i(t) = 0; \\ \max\{m, a_{\mathrm{D}} + B_{\mathrm{D}}(f(t)) x_i(t)\} & \text{if } f_i(t) > 0; \end{cases} \qquad \text{where} \quad (2)$$

$$a_{\mathrm{I}} = cM, \;\; c = \frac{I_{\mathrm{DW}}}{M-m}, \;\; 0 < c < 1; \;\; b_{\mathrm{I}} = 1-c, \;\; b_{\mathrm{I}} < 1; \tag{3}$$

$$a_{\mathrm{D}} = 0; \;\; B_{\mathrm{D}}(f(t)) = d(1-f(t)), \;\; B_{\mathrm{D}}(f(t)) < 1; \tag{4}$$

For comparison purposes (to be used occasionally in the next sections), the rate adaptation equation for the basic AI/MD scheme is given by

$$x_i(t+1) = \begin{cases} \min\{M, I_{\mathrm{AI}} + x_i(t)\} & \text{if } f(t) = 0; \text{ where } I_{\mathrm{AI}} > 0 \\ \max\{m, b_{\mathrm{D}} x_i(t)\} & \text{if } f(t) > 0; \text{ where } 0 < b_{\mathrm{D}} < 1. \end{cases} \tag{5}$$

Notice that the decrease factor $B_{\mathrm{D}}(f(t))$ (under the LDMD policy) is shaped by the induced packet losses, unlike the factor b_{D} (under the basic MD policy) which is unaffected by the reported packet losses. Thus, it is expected to apply a large decrease factor when losses are high (caused, for instance, by the initiation of a new high rate flow), which should help avoiding congestion soon and reduce the losses and a small decrease factor when losses are low, preserving thus the smoothness of the rate adaptation. Also notice that the rate increment $I_{\mathrm{DW}} \frac{M - x_i(t)}{M-m}$ under the DWAI policy is variable, takes into account the current rate $x_i(t)$ of the flow and is always equal to or less than the rate increment I_{AI} under the basic AI policy (assuming that $I_{\mathrm{DW}} = I_{\mathrm{AI}}$). Thus, it is expected that the total and per flow rate increment will be less than that under the basic AI policy, therefore the rate adaptation will be smoother and the induced packet losses lower under the DWAI policy, whereas the resulting load allocation among the flows will be more fair since the rate increment for a lower rate flow will be larger than that of a higher rate flow. These claims are also supported by the results of Section 4.

3 Analysis of the Behavior of the DWAI/LDMD Policy

It is easy to show, by employing approaches and definitions as in [3], that the proposed scheme converges to the efficiency line X_{eff} and fairness. Details as well as the proof of Proposition 2 may be found in [17].

In the sequel the responsiveness to BW availability (convergence time to efficiency) under the DWAI policy is quantified by determining the number k_{DW} of successive rate increases (steps) required in order for the network to reach the efficiency line X_{eff}, from an initial total load $X(t)$. BW may become available due to (a) initial startup, (b) flow termination(s), and (c) rate decrease actions after congestion detection.

Proposition 2. *Under the DWAI policy, the rate $x_i(t+k)$ of flow i after k successive increase steps, starting from some initial rate $x_i(t) \in (m, M)$, statifies the following: (a) $x_i(t+k) = x_i(t)(1-c)^k + M(1-(1-c)^k) = M - (M - x_i(t))(1-c)^k$ and (b) $x_i(t+k) < M$ for any $k \geq 1$.*

The following corollary is self-evident in view of Proposition 2.

Corollary 1 *Given an initial n-dimensional rate vector $\boldsymbol{x}(t)$ with total network load $X(t)$, the total network load $X(t+k)$, after k successive increases is given by*

$$X(t+k) = (1-c)^k X(t) + nM(1-(1-c)^k) = nM - (nM - X(t))(1-c)^k$$

Let $k_{\mathrm{DW}}(X(t))$ denote the number of successive increase steps required in order for the network load to reach X_{eff} starting from $X(t)$. Then

$$X_{\mathrm{eff}} = (1-c)^k X(t) + nM(1-(1-c)^k) \Leftrightarrow (1-c)^k = \frac{nM - X_{\mathrm{eff}}}{nM - X(t)} \Rightarrow$$

$$k_{\mathrm{DW}}(X(t)) = \left\lceil \log_{(1-c)} \frac{nM - X_{\mathrm{eff}}}{nM - X(t)} \right\rceil \tag{6}$$

where $\lceil w \rceil$ is the smallest integer exceeding w. $k_{\mathrm{DW}}(X(t))$ determines the responsiveness to BW availability and is independent of $\boldsymbol{x}(t)$.

In the sequel it is established that following the first application of the LDMD policy (that occurs when the total load exceeds X_{eff} for the first time and packet losses are reported) the rate adaptation behavior is periodic. That is the total load fluctuates between fixed levels below and above the efficiency line in a periodic fashion.

Let t_j denote the j^{th} overload time instant, that is the j^{th} time in which the total load $X(t)$ exceeds X_{eff} (that is, $X(t_j) > X_{\mathrm{eff}}$), $j \geq 1$. The following proposition determines the behavior of the total load in the next time instant $X(t_j+1)$ and the resulting oscillation below the efficiency line, $S^-(t_j+1)$, defined below.

Proposition 3. *If t_j is the j^{th} overload time instant then: (a) $X(t_j+1) = dX_{\mathrm{eff}}$ and, thus, the total load in the next time instant always falls below the efficiency line and this new total load is always the same, independent of $X(t_j)$. (b) $S^-(t_j+1) = X_{\mathrm{eff}} - X(t_j+1) = (1-d)X_{\mathrm{eff}}$ which is independent of $X(t_j)$ and, thus, the size of the oscillations below the efficiency line caused by decrease actions are constant.*

Proof. Since $X(t_j) > X_{\mathrm{eff}}$ and $f_i(t_j) = f(t_j) > 0$, the total load will be decreased according to the LDMD policy at time instant t_j+1. The new total rate at t_j+1 is given by (see Proposition 1)

$$X(t_j+1) = \sum_{i=1}^{n} x_i(t_j+1) = d(1 - \frac{X(t_j) - X_{\mathrm{eff}}}{X(t_j)})X(t_j) = dX_{\mathrm{eff}}$$

which proves (a) and (b). □

It is obvious that the value of parameter d should be less that 1 to ensure that the total load will fall below the efficiency line. For video streaming applications it is suggested that d be set very close to 1 (e.g. 0.99) since this value preserves both the smooth adaptation behavior of the flows (small rate decrease) and the throughput of the network.

After a decrease step, the total load $X(t)$ will start increasing from an initial load dX_{eff} until it exceeds the efficiency line; let k^{T} denote the required number of increase steps. k^{T} is a metric of the responsiveness to small BW availability (due to a rate decrease action(s) as a reaction to congestion) in the sense that captures the required number of intervals (increase steps) to reach the efficiency line after such a rate decrease. In view of Proposition 3, after k^{T} increase steps the total load $X(t)$ will be reduced again to dX_{eff} in the next time instant and thus the total load adaptation behavior will be periodic: the total load will be at the overload level $X(t_j)$ at time instant t_j, $j > 1$, then will fall at the level dX_{eff} in the next time instant and then climb up to the same level $X(t_j)$ after k^{T} steps always in the same manner (reaching time instant $t_{j+1} = t_j + 1 + k^{\mathrm{T}}$ from which the process will be repeated). Thus, the function of the total load $X(t), t > t_1$ is periodic with period $T = k^{\mathrm{T}} + 1$. It should be noted that $X(t_j), j > 1$, is independent of the initial total load $X(0)$ and fixed. The size of the oscillations above X_{eff}, S^+, below X_{eff}, S^-, and the induced packet loss rates f^{c} (during the periodic adaptation period) are given by

$$S^+ = X(t_j) - X_{\text{eff}}, j > 1 \text{ fixed for all } j > 1\;; \quad S^- = (1-d)X_{\text{eff}} \tag{7}$$

$$f^{\text{c}} = \frac{S^+}{X(t_j)} = \frac{S^+}{X_{\text{eff}} + S^+} \tag{8}$$

Since f^{c} is fixed due to the periodic oscillatory behavior discussed above, as long as the number n of the flows remains unchanged, it is concluded that the decrease factor $B_{\text{D}}(f(t))$ will also be fixed. Notice that $X(t_1)$, that is the total load when the efficiency line is exceeded for the first time, will in general - be different than $X(t_j)$, $j > 1$, since it would be determined by a sequence of increase steps starting from some initial value $X(0)$ and not dX_{eff}, and therefore depends on $X(0)$.

As discussed earlier, after a decrease step the total load $X(t)$ starts increasing from load dX_{eff} (see Proposition 3). The total load $X(t)$ will exceed the efficiency line after k^{T}_{DW} increase steps, where k^{T}_{DW} is given by (6) for $X(t) = dX_{\text{eff}}$. Since the base $(1-c)$ decreases (increases) as I_{DW} increases (decreases) (see (3), recall that $1 - c < 1$) it is concluded that k^{T}_{DW} decreases (increases) with I_{DW}.

Clearly, k^{T}_{DW} decreases with d, $0 < d < 1$ and $k^{\text{T}}_{\text{DW}} \to 1$ as $d \to 1$. Thus, d affects the number of increase steps required to reach the efficiency line from dX_{eff} and for a value sufficiently close to 1 it will require only one increase step to exceed the efficiency line. The total load $X(t_j), j > 1$ when the efficiency line is exceeded again is determined by the DWAI policy and it is given by (see Corollary 1)

$$X(t_j) = nM - (nM - dX_{\text{eff}})(1-c)^{k^{\text{T}}_{\text{DW}}}, j > 1 \tag{9}$$

In view of (9), S^+ and f^{c} (see (7) and (8)) become

$$S^+ = nM - (nM - dX_{\text{eff}})(1-c)^{k^{\text{T}}_{\text{DW}}} - X_{\text{eff}} \tag{10}$$

$$f^{\text{c}} = 1 - \frac{X_{\text{eff}}}{nM - (nM - dX_{\text{eff}})(1-c)^{k^{\text{T}}_{\text{DW}}}} \tag{11}$$

Proposition 4. *The DWAI/LDMD scheme presents a periodic adaptation behavior. After the first overload time instant t_1 the total load $X(t)$ exceeds the efficiency line every $k^{\text{T}}_{\text{DW}} + 1$ time instants, where k^{T}_{DW} is given by (6) for $X(t) = dX_{\text{eff}}$. Following t_1, the overshoot S^+, the undershoot S^- and the packet loss rate f^{c} are fixed, and given by (10), (7) and (11), respectively.*

4 Numerical Results and Discussion

In this section the better behavior of the DWAI/LDMD scheme compared to the basic AI/MD scheme (see (5)) in terms of smoothness and packet loss rates is discussed and demonstrated through a set of simulation results.

The LDMD policy ensures that after a decrease step the total load will be adapted to a level below the efficiency line after a single action, regardless of the number of flows in the network and the level of the packet loss rate (see Proposition 3). Contrary to the LDMD policy, the basic MD policy cannot ensure such an adaptation because of its fixed multiplicative decrease factor b_{D}. If b_{D} is selected to be relatively large, then the rate decrease under large losses would not be sufficient and thus, more losses would occur in the next time interval(s). On the other hand, if b_{D} is selected to be relatively small, then the rate decrease under small losses would be unnecessarily large with the obvious impact on smoothness and throughput. The DWAI policy induces a typically diverse (for diverse current rates) per flow rate increase, unlike the basic AI policy that induces the same rate increase for all flows independently from their current rate. As a consequence, the resulting rates will come closer after an application of the DWAI policy than of the basic AI policy, leading to a faster convergence to fairness.

In addition to the previous, it is expected that the packet losses induced under the DWAI policy would be lower than those under the basic AI policy (assuming that $I_{\mathrm{DW}} = I_{\mathrm{AI}}$) since more conservative increments are applied under the former policy when the per flow rate is away from its minimum, that is likely to be the case when the efficiency line is exceeded by the total load and losses occur. Finally, the DWAI policy results in an overall smoother rate increase compared to that under the basic AI policy (assuming that $I_{\mathrm{DW}} = I_{\mathrm{AI}}$). This is clearly the case since the increase step under the DWAI policy is (typically) lower than that under the basic AI policy.

In the sequel a set of simulation results concerning the rate adaptation behavior of the DWAI/LDMD and the basic AI/MD schemes under different configuration parameters are presented. The objective is to demonstrate the aforementioned relative advantages of the DWAI/LDMD scheme over the basic AI/MD scheme with respect to smoothness and packet losses, as well as point to some intrinsic characteristics of the DWAI/LDMD scheme, such as the dynamic nature of the increase/decrease step. The considered network model is implemented in Matlab. In all simulations the network capacity is set to 8 Mb/s and the number of flows n is equal to 12, 13 and 14 for the time periods [0,700), [700,900) and [900,1000], respectively. The initial rate vector for the first 12 flows is given by $\boldsymbol{x} = \{m + 1 * (M - m)/n, m + 2(M - m)/n, \cdots, M\}$ where $m = 56$ kb/s, $M = 1.2$ Mb/s, $n = 12$ and, thus, the initial total load is $X(1) = 8.108.000$ bps. Flows 13 and 14 are initiated at time instants 700 and 900 with initial loads $x_{13}(700) = x_{14}(900) = 600$ kb/s. In the figures that follow the behavior of flows 1 and 12 (which have the furthest apart initial rates of rates of 151.3 kb/s and 1.2 Mb/s, respectively) are shown. Fig. 1 shows the results under the DWAI/LDMD scheme for parameters $I_{\mathrm{DW}} = 30$ kb/s, $d = 0.99$, $m = 56$ kb/s, $M = 1.2$ Mb/s. Fig. 1 illustrates the convergence of two initially far away rates to a (common) fair rate, the oscillatory behavior both during the transition period ([0,∼200]) as well as during the "steady state" period ([∼200,700]), the response of flows 1 and 12 to the introduction of flow 13 ([700,900]) and to flow 14 ([900,1000]). It is clear that fairness is achieved and the oscillations are fairly low. The latter may be attributed to the dynamic and "self-adjusting" rate increment that assumes a small value when flows are away from their minimum rate m and to the dynamic and "self-adjusting" decrease factor $B_{\mathrm{D}}(t) = d(1 - f(t))$, which assumes a large value (about $d = 0.99$) when losses are low (typical case) leading to a small decrement.

Fig. 2 shows the results under the basic AI/MD scheme with the "equivalent" fixed parameters. That is, $I_{\mathrm{AI}} = I_{\mathrm{DW}} = 30$ kb/s and $b_{\mathrm{D}} = 0.99 = d$; that is, when losses are

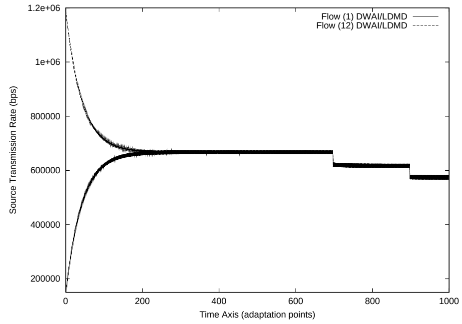

Fig. 1. Rate adaptation of the DWAI/LDMD scheme with $d = 0.99$, $I_{\mathrm{DW}} = 30$ kb/s.

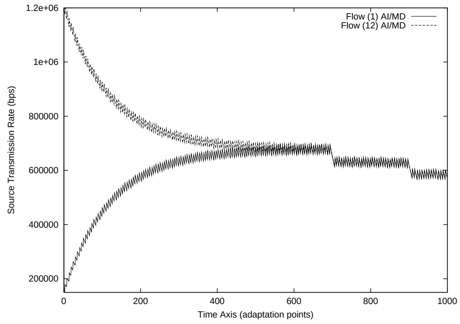

Fig. 2. Rate adaptation of the AI/MD scheme with $b_{\mathrm{D}} = 0.99$, $I_{\mathrm{AI}} = 30$ kb/s.

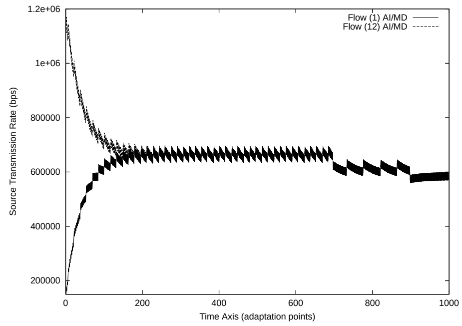

Fig. 3. Rate adaptation of the AI/MD scheme with $b_{\mathrm{D}} = 0.95$, $I_{\mathrm{AI}} = 30$ kb/s.

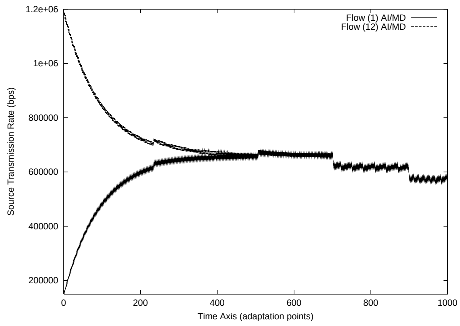

Fig. 4. Rate adaptation of the AI/MD scheme with $b_{\mathrm{D}} = 0.979$, $I_{\mathrm{AI}} = \frac{M - \frac{X_{\mathrm{eff}}}{n}}{M-m} I_{\mathrm{DW}}$.

very low $b_{\mathrm{D}} \approx d(1 - f(t))$ and about the same rate decrement would be in effect for both schemes. The idea here is to show the behavior of a scheme that is equivalent to the above DWAI/LDMD scheme where the increments and decrements are not shaped by the rate distance from M and the induced losses $f(t)$, respectively.

From Fig. 1 and 2 it is observed that both the convergence speed to fairness and the oscillatory behavior is worst under the basic AI/MD scheme. The poor convergence speed to fairness is expected due to the application of the same increment to all flows independently from their rate as well as because of the typically larger decrease factor $b_{\mathrm{D}} = d > d(1 - f(t)) = B_{\mathrm{D}}(t)$. As a consequence, the rates would come closer under the DWAI/LDMD scheme as a smaller increment and a larger decrement would be applied to higher rate flows because of the rate dependent increment size and the smaller decrease factor ($B_{\mathrm{D}}(t)$). The poorer oscillatory behavior under the basic AI/MD scheme during the times that fairness has been reached may be attributed to the larger increment under the basic AI policy, that leads to higher overshoots. These higher overshoots - along with the smaller decrement under large packet losses - is responsible for the induced higher mean conditional packet loss rate under the basic AI/MD scheme. Specifically, these loss rates are 2.22% (1.11%) , 2.61% (1.49%), 2.72% (1.88%) under the basic AI/MD (DWAI/LDMD) scheme, over the periods [0,700], [700,900] and

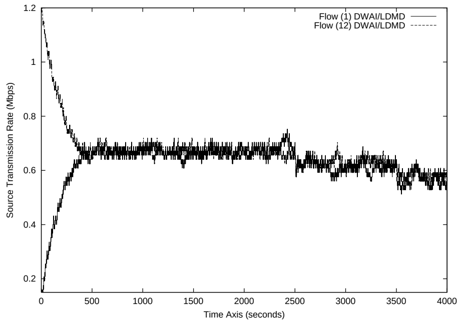

Fig. 5. Rate adaptation of the DWAI/LDMD scheme with $d = 0.99$, $I_{\mathrm{DW}} = 30$ kb/s.

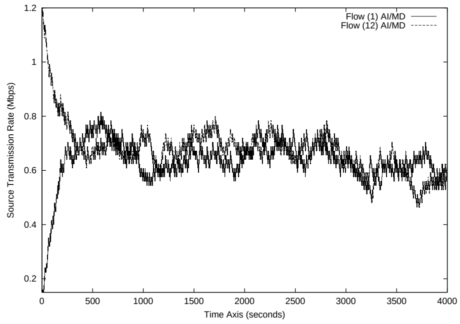

Fig. 6. Rate adaptation of the AI/MD scheme with $b_{\mathrm{D}} = 0.979$, $I_{\mathrm{AI}} = 30$ kb/s.

[900,1000], respectively. The mean conditional packet loss rate is defined as the long term average of the following quantity defined only over periods with non zero packet losses: (number of packet lost over the current loss report period)/(number of packets sent over the current loss report period). The above simulation results point to the advantages of a scheme that adapts dynamically its key parameters in a meaningful way (DWAI/LDMD) over a scheme that does not (AI/MD). The remaining results emphasize some key trade-offs in the selected values of key parameters and the fact that a static parameter cannot effectively balance competing objectives.

Fig. 3 shows the results under the AI/MD scheme with a lower decrease factor $b_{\mathrm{D}} = 0.95$ (and $I_{\mathrm{AI}} = 30$ kb/s). This decrease factor would lead to a larger diversification of the decrements that would be applied to flows of different rates (larger decrement to higher rates) and thus improve the convergence speed to fairness (compared to $b_{\mathrm{D}} = 0.99$). This indeed is observed to be the case. In fact $b_{\mathrm{D}} = 0.95$ brings the convergence speed to fairness under the basic AI/MD scheme to almost match that under the DWAI/LDMD scheme for the parameters considered in Fig. 3 and 1. The price paid for this improvement (wrt $b_{\mathrm{D}} = 0.99$) are larger oscillations (less smooth rates). The induced conditional packet loss rates are higher than those under the DWAI/LDMD scheme. Specifically the former are equal to 2.1%, 2.04% and 4.04% over the periods [0,700], [700,900] and [900,1000], respectively.

In Fig. 4 a lower fixed increment is selected that is about equal to the increment applied by the DWAI/LDMD scheme in Fig. 1 when the flows have reached the fairness line (period [∼200,700]). That is $I_{\mathrm{AI}} = \frac{M - \frac{X_{\mathrm{eff}}}{n}}{M-m} I_{\mathrm{DW}}$. Also, the parameter b_{D} is selected to be equal to 0.979 which is the vaule of $B_{\mathrm{D}}(t)$ that is applied by the DWAI/LDMD scheme in Fig. 1 during the period [0,700]. Therefore, the flows under the basic AI/MD scheme present the same smooth adaptation behavior as the flows under the DWAI/LDMD scheme as the former flows converge to the fairness line.

In the simulation results presented above it has been assumed that the packet loss rate is the same for all the flows; that is, $f_1(t) = f_2(t) = \cdots = f_n(t)$. This is a result of the assumption made in the study of the DWAI/LDMD scheme that packet losses are proportional to the flow's rate (see Proposition 1). As this may not be practically the case, further simulations have been carried out in a more realistic environment based on the ns-2 simulator. RTP/UDP/IP flows and drop tail routers that tend to distribute losses not necessarily in accordance with the flow's rates. The RTCP provides the packet loss rate feedback though the RTCP reports sent every 5 seconds. The round trip time is common for all flows, therefore the feedback is synchronized. The behavior of the DWAI/LDMD and the basic AI/MD schemes is examined in an environment where only adaptive CM (RTP/UDP/IP) flows are transmitted (i.e., free of TCP flows), as it may be the case under the forthcoming differentiated services. The results derived from the ns-2 simulations are in line with the theoretical as reported earlier. Flows under the DWAI/LDMD scheme (Fig. 5) present smoother adaptation behavior than those under the basic AI/MD scheme (Fig. 6) and lower packet losses. Details and comments - omitted here due to space limitations - may be found in [17].

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