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Recurrent Leaky Bucket

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***Abstract*—In this letter, we propose an extension of the conventional leaky bucket (LB) algorithm which we call *recurrent leaky bucket* (RLB). It is suited for traffic characterized by a recurring cycle, such as variable bit-rate video. RLB extends LB by including a new parameter to describe the recurring cycle: the recurring interval. We show the correctness of our design where we illustrate its impulse response and traffic envelope. The improved efficiency of RLB is also numerically demonstrated.**

***Index Terms*—Leaky bucket, traffic envelope, video traffic, traffic policing**

I. INTRODUCTION

The leaky bucket (LB) algorithm based on its original two-parameter version has been a key fundamental element in a variety of rate control (traffic policing or shaping) algorithms (e.g., [1]–[5]). It has been standardized [6], [7], implemented in routers [2] and given rise to significant research (e.g., [2], [4], [5], [8]–[11]). Moreover, traffic management is key to cloud computing that requires large amount of data to be transported [12]. It is anticipated that the usage of bandwidth-hungry delay-sensitive multimedia applications, such as Video on Demand (VoD) and video conferencing [13], in the cloud will accelerate in the near future [14]. It has led to recent research interest in traffic shaping and policing in the cloud, e.g., LB as traffic regulator in network virtualization for cloud service provisioning [15].

A variable bit rate (VBR) video stream, based on the Motion Picture Experts Group (MPEG) standards, is characterized by bursts (I-frames) occurring at a beginning of each group of pictures (GoP) cycle [4], [5], [10], [16]. Therefore, if a user agrees to conform to a two-parameter LB, the declared sustainable rate must be set higher than the required rate during a light-traffic time-period between two consecutive I-frames as shown in Fig. 1. This causes inefficiency which we aim to overcome by extending the classical LB to the *Recurrent LB* (RLB).

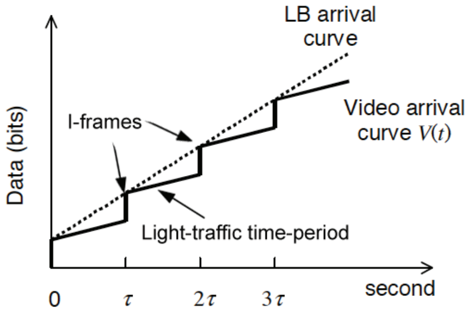

Fig. 1. The LB and the cumulative arrival functions of video streams.

We will use traces of VBR video traffic streams to demonstrate the benefit of RLB over LB. The discussion can be extended to monitor any traffic stream that involves periodic bursts, e.g., streams generated by VoD and video conferencing applications. We will also relate our discussions of LB and RLB to relevant deterministic-QoS network-calculus concepts [17], [18] and present them in Section II. Then we describe the RLB design in Section III and discuss its behavior in Section IV. We illustrate numerically the potential benefit of RLB as policer in Section V. Finally, important conclusions are drawn in Section VI.

II. RELATED NETWORK CALCULUS CONCEPTS

Let the *cumulative arrival process* $R^{in}(t)$ be the number of bits that arrives at a system during the interval $[0, t)$, then the *arrival curve* $A^{min}(t)$ is defined by

$$A^{min}(t) = \sup_{v \geq 0} \left\{ R^{in}(t+v) - R^{in}(v) \right\} \text{ for all } t \geq 0. \quad (1)$$

The function $A^{min}(t)$ specifies the upper bound on the traffic that may arrive during any interval size t. Any $A(t) \geq A^{min}(t)$, for all $t \geq 0$, is called a *traffic envelope* or an *arrival curve* of $R^{in}(t)$.

Let $R^{out}(t)$ be the number of bits that departs the system during the interval $[0, t)$, then the system is said to provide a *service curve* $S(t)$ if the following holds

$$R^{out}(t) \geq \inf_{0 \leq s \leq t} \left\{ R^{in}(t) + S(t-s) \right\}, \text{ for all } t \geq 0. \quad (2)$$

For a flow that requires QoS guarantees, the user specifies traffic parameters of its arrival process that conform to an arrival curve $A(t)$ and delay bound d seconds. Then the network will decide whether to admit or reject the flow. If the flow is admitted, the system will provide a service curve to that flow. In the case of a flow with an arrival curve $A(t)$ and delay bound d, service curve $S(t)$ is said to provide service curve scheduling if $S(t) \geq A(t-d)$ for all $t \geq d \geq 0$, where the service curve scheduling provides specific delay bounded data delivery for the flow.

If a traffic stream is *conformant* to an LB with bucket size σ and leak rate ρ, denoted LB(σ,ρ), then its cumulative arrival function is bounded by

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$$R^{in}(t) \leq \sigma + \rho t, \text{ for all } t \geq 0, \tag{3}$$

where σ [bits] and ρ [bits/s] are provided by the user. To meet delay bound requirement of d, a service curve, $S(t)$, that satisfies $S(t) \geq \sigma + \rho(t-d)$, for $t \geq d$, is required.

III. RLB ALGORITHM

Our proposed RLB has three input parameters provided by users, they are: σ (recurrent burst size), ρ' (sustainable rate during light traffic periods) and τ (the cycle duration). While the first two parameters are similar to those in LB, the cycle duration, τ, should be set approximately equal to the burst cycle of the traffic. For VBR videos, it is the same as the period of GoP. RLB allows users to choose a lower sustainable rate for the light traffic periods and obtain extra credit at the end of a cycle called *renewal*. Normally, users will choose a sustainable rate higher than the mean rate during the light traffic period to allow for some traffic variability.

The RLB is based on two LB-like meters LB_1 and LB_2 running in parallel. Let B_i be the credit of LB_i for $i = 1, 2$. They both have a leak rate of ρ' and a bucket size σ. They operate in the same way as a classical LB operates except at renewals. The RLB contains a timer denoted T, which activates flushing of LB_2 (reset B_2 to σ) and check of LB_1 every τ seconds. If and only if $B_1 < \sigma$ at this moment, the RLB will perform a renewal. In this way, we add to the design the flexibility of recognizing large bursts. To describe a video stream, the bucket size is set equal to the largest I frame, and it determines the largest allowed traffic in one cycle along with the leak rate as $\sigma + \rho'\tau$ (refer to Section IV for detailed proof). At renewals, B_1 obtains the value of B_2. Moreover, if there are data arriving at a renewal, and LB_1 has sufficient credit for it, the data can pass through and credit is immediately deducted from B_1 but not from B_2 that retains its new value of σ. At non-renewal times, for each bit of data passes through the RLB, its equivalent credit is deducted from both buckets. At time zero, $B_1 = B_2 = \sigma$. Because the only difference in the operation of LB_1 and LB_2 is at cycling checks $B_2 \Leftarrow \sigma$ and at renewals $B_1 \Leftarrow B_2$, and that burst credit is only deducted from B_1, we always have $B_1 \leq B_2$, so LB_1 dictates conformance. The recurrent burst size of RLB(σ, ρ', τ), therefore, is equal to $B_1 = \sigma$, the same as that of LB(σ, ρ). Algorithm 1 provides pseudo codes for RLB. A self-explanatory flowchart of the algorithm can be found in [19].

LB_2 is used to record the amount of traffic transmitted during the last cycle. By $B_1 \Leftarrow B_2$, RLB deducts the amount transmitted beyond the "normal" $\rho'\tau$ from σ, thus allowing users the flexibility to "borrow" credit during non-renewal times and return at renewals.

The rate specified by LB(σ, ρ) to govern the credit accumulation of a conforming VBR video stream may be higher than the actual rate transmitted during recurrent periods of light traffic as illustrated in Fig. 1 that presents the two curves. The first is the cumulative arrival function $\sigma + \rho t$ of a stream conformant to LB(σ, ρ) and the second is a cumulative arrival function $V(t)$ of a cyclic VBR video stream where in each cycle of length τ seconds, I-frame bursts up to σ bits may be transmitted, and B and P frames at a smaller rate ρ'. For $n = 0,\ 1,\ 2,\ \ldots$, the function $V(t)$ is given by

$$V(t) = (n+1)\sigma + t\rho' \text{ for all } n\tau \leq t < (n+1)\tau. \tag{4}$$

Algorithm 1 RLB algorithm

```
**Initialization:**
Set $B_1 = \sigma$, $B_2 = \sigma$ (in bits) and $T = 0$;
while packet(s) arrive do
  Move packet(s) to buffer;
  Set $T_p$ = time passed since last arrival;
  while $T_p \geq \tau - T$ do ▷ Cycling check(s) since last arrival
    Set $B_1 = min(\sigma, B_2 + \rho'(\tau - T))$ and $B_2 = \sigma$;
    Set $T = 0$ and $T_p = T_p - (\tau - T)$;
  end while
  Set $B_1 = min(\sigma, B_1 + \rho' T_p), B_2 = min(\sigma, B_2 + \rho' T_p)$;
  Set $T = T_p$;
  if $T = 0$ and $B_1 < \sigma$ then                ▷ Arrival at renewal
    while A packet of size $L$ waiting in buffer do
      if $L \leq B_1$ then
        Set $B_1 = B_1 - L$;
        Release packet;                           ▷ Burst release
      end if
    end while
  else                                 ▷ Arrivals at non-renewal times
    while A packet of size $L$ waiting in buffer do
      if $L \leq B_1$ then
        Set $B_1 = B_1 - L$;          ▷ "Borrow" credits if needed
        Set $B_2 = B_2 - L$;
        Release packet;                          ▷ Normal release
      end if
    end while
  end if
  Drop remaining packets in buffer;
end while
```

Clearly, $V(t-d) \leq \sigma + \rho(t-d)$. The difference between the two curves is well known [2], [4]. To guarantee a bounded delay d will require service curves to be greater than or equal to $V(t-d)$ and $\sigma + \rho(t-d)$ for $V(t)$ and $\sigma + \rho t$, respectively; also there is a scope to increase efficiency if the network needs to provide a service curve $V(t-d)$ instead of $\sigma + \rho(t-d)$. All these arguments follow through to dual LB.

If we aim only to design a policer that has $V(t)$ of Fig. 1 as its minimal arrival curve, then one simple way is to use the Time Division Multiple Access (TDMA) principle. Namely, to consider a TDMA frame of duration τ subdivided into many slots, and allow a burst of σ in the first slot and a rate of ρ' in the other slots. However, it is too rigid. Another possible solution to improve utilization is to use multiple (σ, ρ) pairs, each corresponds to one of cascading LBs [4]. However, n cascading LBs have $2n$ parameters and can only accommodate a maximum of n bursts. Therefore, system complexity would significantly increase when more bursts need to be accommodated. Our RLB, as proposed above, offers minimal arrival curve of $V(t)$ for up to $n+1$ periodic bursts with size up to σ during a time interval of duration $t = n\tau + \xi$ with 3 parameters only. Proof will be shown in following texts.

IV. RLB IMPULSE RESPONSE AND ENVELOPE

Consider the RLB operation and its conformant traffic process subject to an impulse input process made of an infinite size continuous burst starting at time $t = 0$, i.e., we have a greedy source that from $t = 0$ onwards has data to transmit and we only allow conformant data to pass through the RLB.

Let $B_i(t)$, $i = 1, 2$, be the credit of LB_i at time t. At $t = 0^-$, RLB is initialized: $B_1(0^-) = B_2(0^-) = \sigma$, $T = 0$. At $t = 0$, a burst of size σ passes through the RLB, so σ is deducted from B_1 but not from B_2, thus $B_1(0^+) = 0$ and $B_2(0^+) = \sigma$. Then within $(0, \tau)$, traffic passes through at rate ρ' using credit obtained at ρ' rate, so $B_1(\tau^-) = 0$ and $B_2(\tau^-) = \sigma$. Then at renewal $t = \tau$, we perform $B_1(\tau) \Leftarrow B_2(\tau)$ and $B_2(\tau) \Leftarrow \sigma$, so $B_1(\tau) = B_2(\tau) = \sigma$. A burst of size σ passes through which again results in deducting σ from B_1, so $B_1(\tau^+) = 0$ and $B_2(\tau^+) = \sigma$, etc. so a conformant stream made of a burst of σ passes through every τ seconds and data at rate of ρ' in all other times.

Having shown that the conformant traffic process has exactly $V(t)$ as its minimal arrival curve, we show here that it is also an envelope of any RLB conformant stream. For RLB(σ, ρ', τ), the following claim follows:

Claim 1: Given a time duration t where $0 \leq t < n\tau, n = 1, 2, ...,$ any traffic stream policed by RLB(σ, ρ', τ) experiences 0 to n renewal events during the interval.

Also, during a time interval with no renewals, RLB(σ, ρ', τ) operates like an LB, starting with a credit of at most σ that increases at a rate ρ', having credit ceiling of σ that decreases by L as a packet of size L passes if such credit is available. This behavior leads to the following claim.

Claim 2: Any traffic stream policed by RLB(σ, ρ', τ), that experiences no renewal event during a time interval of duration t, denoted $[t_0, t_0 + t)$, has its cumulative arrival function bounded by $\sigma + \rho' t$.

The following lemma extends Claim 2 to the case that a renewal exists within a time interval.

Lemma 1: Any traffic stream policed by RLB(σ, ρ', τ), that experiences one renewal event during a time interval of duration t, $[t_0, t_0 + t)$, has its cumulative arrival function bounded by $\sigma + \rho' t$.

Proof of Lemma 1: Consider a renewal at time t_R that partitions the time interval $[t_0, t_0 + t)$ into two mutually exclusive periods $[t_0, t_R)$ and $(t_R, t_0 + t)$, called P and Q, of duration d_p and d_q, respectively, that is, $d_p = t_R - t_0$ and $d_q = t_0 + t - t_R$.

Let t_{p1} be the time the first packet is released in P. Let $d_{p1} = t_R - t_{p1}$. Let C_p and D_p be the credits added to and deducted from LB_2 within (t_{p1}, t_R), respectively.

Based on the RLB algorithm, $B_2(t_R{}^-) = B_2(t_{p1}) - D_p + C_p$ and $B_2(t_{p1}) \leq \sigma$. Since LB_2 leak rate is ρ', $C_p \leq \rho' d_{p1}$. Hence, $B_2(t_R{}^-) + D_p = B_2(t_{p1}) + C_p \leq \sigma + \rho' d_{p1}$. Since by definition $d_{p1} \leq d_p$, then we have

$$B_2(t_R{}^-) + D_p = B_2(t_{p1}) + C_p \leq \sigma + \rho' d_p. \tag{5}$$

Assume, without loss of generality, that a burst of size D_R, $0 \leq D_R \leq B_2(t_R{}^-)$, passes through the RLB at the renewal time t_R. Thus, $B_1(t_R{}^+) = B_2(t_R{}^-) - D_R$.

Let D_q be the credits deducted from LB_1 during Q. Let t_{q1} be the time the last packet is released in Q, and $d_{q1} = t_{q1} - t_R$. Since $B_1(t_R{}^+) = B_2(t_R{}^-) - D_R$, with leak rate of ρ' in LB_1, we have $D_q \leq (B_2(t_R{}^-) - D_R) + \rho' d_{q1}$. Rearranging the last expression gives $D_q + D_R - B_2(t_R{}^-) \leq \rho' d_{q1}$. Since $d_{q1} \leq d_q$, we have $D_q + D_R - B_2(t_R{}^-) \leq \rho' d_q$. Combining the latter and (5) yields

$$D_p + D_R + D_q \leq \sigma + \rho' t. \tag{6}$$

As $D_p + D_R + D_q$ is the total data passes through the RLB during the interval $[t_0, t_0 + t)$ consisting of one renewal event, this completes the proof. ■

Consider a time interval of duration $t = n\tau + \xi$, denoted $[t_0, t_0 + n\tau + \xi)$, $n = 0, 1, ...,$ and $0 < \xi \leq \tau$. It can be partitioned into $n+1$ mutually exclusive subperiods $[t_i, t_i + \tau)$, $i = 0, 1, \ldots, n$ each of which of duration τ, and one subperiod of duration ξ. According to Claim 1, the interval $[t_0, t_0 + n\tau + \xi)$ may contain 0 to $n+1$ renewals, each of which may appear in one particular subperiod. Then, based on Lemma 1 and Claim 2, the arrival curve during this interval is bounded from above by $n(\sigma + \rho'\tau) + (\sigma + \rho'\xi) = (n+1)\sigma + \rho' t$ when renewals happen in every subperiod ($n + 1$ renewals) and from below by $\sigma + \rho' t$ if none of the subperiods experiences a renewal. Therefore, the following proposition follows.

Proposition 2: The function $(n + 1)\sigma + \rho' t$ for $n\tau \leq t < (n + 1)\tau$ and $n = 0, 1, ...,$ is the envelope of RLB(σ, ρ', τ).

It proves that the maximum number of bursts that can be accommodated by RLB, within time interval of duration $n\tau + \xi$, is $n + 1$.

V. RLB BENEFIT

Specifying traffic by RLB(σ, ρ', τ) instead of by LB(σ, ρ) enables the network to better schedule its service and achieve a more efficient and cost effective operation. In the previous section, we have proved that the envelope of RLB is the same as $V(t)$ in Fig. 1. Now we demonstrate the benefit for the following two examples.

A. Aggregated streams with bounded delay requirements

Consider two users each transmitting a video stream conforming to LB(σ, ρ) with bounded queuing delay requirements d_1 and d_2, respectively, with $d_1 \leq d_2$. The two streams are aggregated and served at a constant rate r_{LB}. Given (3), the service curve, $S_{LB}(t)$, for the delay consideration must satisfy $S_{LB}(t) \geq U(t - d_1) + U(t - d_2)$. The minimum rate that the network is required to allocate is obtained by solving the following optimization problem:

$$\begin{cases} \text{Minimize} & r_{LB} \\ \text{Subject to} & r_{LB} \cdot t \geq S_{LB}(t), \forall t \geq 0, \end{cases} \tag{7}$$

where $r_{LB} \cdot t$ is the number of bits serviced during time interval t based on the optimal constant rate r_{LB}. Solving it yields the following optimal solution

$$r_{LB}^{*} = \max\left\{2\rho, \frac{\sigma}{d_1}, \frac{2\sigma + (d_2 - d_1)\rho}{d_2}\right\}. \tag{8}$$

Now consider the case where each of the two streams use the RLB(σ, ρ', τ) where $\rho' = \rho - \sigma/\tau$. Similarly, given (4), the service curve, $S_{RLB}(t)$, for the delay consideration must satisfy $S_{RLB}(t) \geq V(t-d_1) + V(t-d_2)$. Using the same approach, the minimum rate required, r^*_{RLB}, is

$$r^*_{RLB} = \max\left\{2\rho, \frac{\sigma}{d_1}, \frac{V(d_2-d_1)+V(0)}{d_2}\right\}. \qquad (9)$$

Fig. 2 presents the optimal rates r^*_{LB} and r^*_{RLB} versus $d_2 - d_1$, where d_1 is fixed at 0.2, for LB$(1,2)$ and RLB$(1, \frac{1}{3}, 0.6)$ and demonstrates that RLB enables lower rate allocation relative to LB.

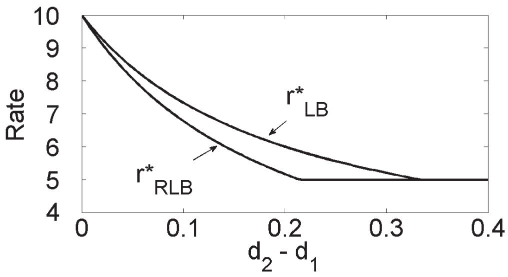

Fig. 2. Illustration of RLB benefits.

Notably, priority scheduling is needed to exploit the difference in delay bounds of the two flows.

B. Envelope test of real video stream

Fig. 3 shows part of the cumulative arrival functions of sample video clips with different contents from YouTube. The figure shows different extents of cyclical bursty characteristic are exhibited for each stream.

We then aggregate the four video clips and test the multiplexing gain by RLB over LB. Table I shows the lowest sustainable rate that can be achieved by LB and RLB when transmitting some of the video streams concurrently. In applications such as VoD and video conferencing, two or three aggregated video streams are reasonably expected [13]. By specifying the traffic by RLB instead of LB, more than 30 percent lower sustainable rate can be achieved to admit the streams. Therefore, less resource is required and more streams can be admitted over a shared channel.

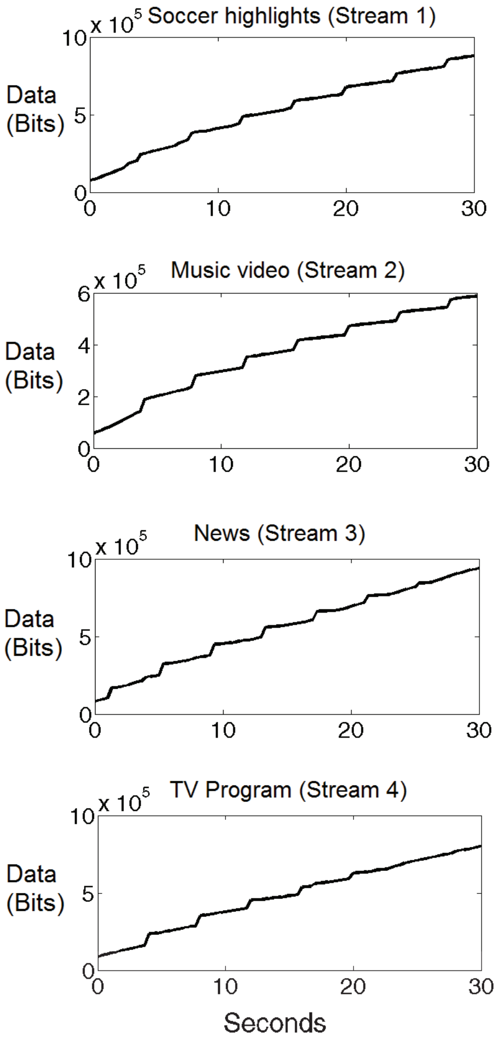

Fig. 3. Cumulative arrival functions of sample video streams.

Table I
SUSTAINABLE RATE BY LB AND RLB OVER A SHARED CHANNEL.

Video streams	r_{LB} (bits/s)	r_{RLB} (bits/s)	**Savings**
1 and 2	25482	19819	22.2%
1, 2 and 3	38326	27873	27.2%
1, 2, 3 and 4	50749	34797	31.4%

VI. CONCLUSIONS

We have proposed a simple, yet flexible policer suitable for the admission of VBR video streams. The new policer is characterized by three parameters, where the first two are the bucket size and the leak rate as in the conventional LB, and the third is the recurring interval. The new parameter describing the recurring period allows it to capture the recurring bursts commonly appeared in many applications. As a result, better resource allocation and scheduling may be applied to achieve more efficient and cost effective operation.

We have studied the characteristics of RLB, particularly its impulse response and traffic envelope. Its potential benefit over the classical LB as a policer in practical applications has also been demonstrated numerically. We leave open the question of maximizing the benefit that can be gained by the RLB as a shaper. Moreover, while we have demonstrated the benefit of a single RLB over LB, performance analysis of multiple RLBs, multiple LBs or combination of both require further study.

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