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We consider two models for a token ring with a general (in particular, non-Poisson) arrival process. In both models the arrival process is characterized by pathwise conditions: in the first case, by the average rate and the burstiness (Cruz bounds) and in the second case by the existence of a long-run average rate. For both types of input process, we show that a sufficient condition for stability is that the rate at which work arrives to the system is smaller than one. We allow the service policy to be quite general, requiring only that the amount of work that leaves the system in a "cycle" is at least the amount of work that was present there in the beginning of the cycle. This includes the standard gated and exhaustive policies. For the first model we obtain deterministic upper bounds on the workload and the cycle times. Our results show that guarantees of no loss and/or service quality can be enforced by shaping the input flows to a token ring using, for example, leaky buckets, without the necessity for additional control mechanisms. We also show that the output process satisfies a Cruz type bound. This is useful in analyzing networks where the output from one token ring can be the input to another element of the network.

The characteristics of input traffic in telecommunications are often quite complex, and the traditional approach of modeling these by Poisson processes is often unrealistic (see Takagi [18],[19]). In this paper we consider two types of arrival processes which are typical for telecommunication. The first, of the type introduced by Cruz [7],[8], is characterized by two parameters: the average rate and the burstiness, and is typical of the traffic at the output of a spacer or a leaky bucket. The second is a very general input process that only satisfies the assumption that a long-run average rate exists.

For both types of input process, we show that a sufficient condition for stability is that the rate at which work arrives to the system is smaller than one. We allow the service policy to be quite general; we require only that the amount of work that leaves the system in a "cycle" is at least the amount of work that was present there in the beginning of the cycle. This includes the standard gated and exhaustive policies. Moreover, we allow for the policy to change in time.

For the first type of arrival process, we obtain uniform upper bounds for several performance measures, such as the amount of work in the system and the cycle duration. The bound for the workload in the system can be used to obtain upper bounds on the length of the buffers required so as to guarantee no losses. The strict bound on the cycle time is also quite desirable, especially in order to guarantee some service quality for synchronous traffic (such as voice or video). Indeed, several token-ring protocols possess some distributed mechanism to enforce a strict upper bound on the cycle time; an example is the *FDDI* protocol. The fact that an upper bound for the cycle times is obtained for the Cruz-type arrival process suggests that previous distributed mechanisms to enforce such constraints can be replaced by shaping the input flows to a token ring using leaky buckets. We also show that the output process satisfies a Cruz type bound. This is useful in analyzing networks where the output from one token ring can be the input to another element of the network. For the second type of arrival process, we also obtain an expression for the average cycle time.

We close this introduction with a brief review of stability conditions that were obtained in the past for different types of polling systems, which have been used to model token-ring protocols. Conditions for ergodicity as a measure of stability were obtained in [2], [5], [6], [10], [11], [16], and [20]. Kroese and Schmidt [13], [14] studied the stability of polling on a graph (i.e. a "continuous" polling model), and Altman and Levy [3] studied the stability of non-cyclic polling in two-dimensional and higher dimensional planes. In [2], and [5] Altman et al. further present sufficient and necessary conditions for stronger notions of stability, namely the geometric ergodicity and the geometric rate of convergence of the moments of several performance measures (embedded at polling instants). Sufficient conditions for Central Limit Theorems and the Law of Iterated Logarithm were given in [5]. In [4], Altman and Liu analyze the stability of the *FDDI* protocol. Conditions for the stability of token rings with spatial reuse were obtained by Szpankowski et al. [12]. All the above references assumed Poisson arrivals and general independent walking and service times. Recently, Altman and Foss [1] obtained sufficient stability conditions for polling systems with a general renewal arrival processes, and Massoulié [15] obtained stability conditions for general stationary ergodic arrival and service processes.

We model the token ring by a polling system consisting of N queues and a single server that moves cyclically among these queues. We define a cycle as a time interval between two consecutive instants that the server arrives at queue 1. The number of packets served in each queue is determined by some polling policy which may be quite general, as long as it satisfies Assumption A1 below. Whenever the server finishes serving customers (transmitting packets) in a queue, it moves to the next queue, incurring some walking time.

Following Stidham and El–Taha [17] (see also El–Taha and Stidham[9]) the system is modeled as an *input-output process*, that is, a non-negative real-valued deterministic process, $Z = \{Z(t), t \geq 0\}$ in which $Z(t) \geq 0$ represents the total number of packets in all queues at time t. Specifically, we assume that the state space of Z is $S = R^+$. We assume that $\{Z(t), t \geq 0\}$ is right continuous with left-hand limits, and that

$$Z(t) = Z(0) + A(t) - D(t) \ , \ t \geq 0 \ , \tag{1}$$

where $A(t)(D(t))$ is the cumulative input to (output from) the system in $[0, t]$ and both $\{A(t), t \geq 0\}$ and $\{D(t), t \geq 0\}$ are non-decreasing, right-continuous processes. Thus $Z(t)$ has bounded variation on finite t-intervals. Note that $D(t) \leq Z(0) + A(t)$, since $Z(t) \geq 0$. We shall refer to $Z(t)$ generically as the *work* in the system at time t (i.e., the transmission time that would be required by all of the packets present at time t), with the understanding that it could be some other measure of quantity (e.g., the number of packets).

For $n = 1, 2, \ldots$, define t_n to be the time point at which the n^{th} cycle ends, with the convention that $t_0 = 0$. For ease of notation, define $W_n := Z(t_n)$, the work in the system at the end of the n^{th} cycle. Throughout this paper, we shall make the following assumption:

Assumption A1. For all $n \geq 1$, $D(t_n) - D(t_{n-1}) \geq W_{n-1}$. That is, the output in each cycle is at least as great as the work in the system at the beginning of the cycle.

In general we shall use ρ to denote the rate at which work arrives to the system, in some sense, the exact meaning of which will depend on the context. When the server is busy serving then work leaves the system at a rate of a unit work per unit time. Let $u(t)$ ($v(t)$) be an indicator function for "serving" ("walking") time. That is, $u(t) = 1$ if the server is serving and $u(t) = 0$ if it is walking at time t; $v(t) = 1 - u(t)$. Let $T_n := t_n - t_{n-1}$ denote the duration of the n^{th} cycle. Let $V_n := \int_{t_{n-1}}^{t_n} v(s)\, ds$ be the total walking time during the n^{th} cycle. Finally, we define the "burstiness" of the arrival process during the n^{th} cycle:

$$B_n^A := A(t_n) - A(t_{n-1}) - \rho T_n \tag{2}$$

Thus, B_n^A is the difference between the actual input and the input that would have occurred if the input process had operated at its "average" rate throughout the cycle.

Finally, we shall assume that $t_n \to \infty$ as $n \to \infty$, which is the case, for example, when the walking times, V_n, $n \geq 1$, are bounded below by a positive constant.

Example 1^o. *A Globally Gated Polling System.* In a globally gated polling system a single server attends queues, $i = 1, \ldots, m$, in sequence, serving at each queue all work that was present at the beginning of the cycle. In this setting, a cycle begins each time the server arrives and begins service at queue 1. Assume that the total walking time in each cycle is constant and equal to V. The duration of the n^{th} cycle is $V + W_{n-1}$. If arrivals were at a uniform rate, ρ (with no burstiness), then W_n would equal $\rho V + \rho W_{n-1}$, and also equal $\rho^n W_0 + \rho V \sum_{i=1}^{n} \rho^{n-i}$. Now suppose arrivals are at this uniform rate, except for a single arrival burst of size X in the third cycle. Then for $n > 3$, $W_n = \rho^n W_0 + \rho V \sum_{i=1}^{n} \rho^{n-i} + \rho^{(n-3)} X$. The following is a similar result for our more general system.

Lemma 1 *Suppose that $\rho < 1$, and let N be a non-negative integer. Then*

$$W_n \leq \rho^{n-N} W_N + \rho \sum_{i=N+1}^{n} \rho^{n-i} V_i + \sum_{i=N+1}^{n} \rho^{n-i} B_i^A \ , \ n \geq N + 1 \ . \tag{3}$$

Proof. First note that

$$\begin{aligned} W_n &= W_{n-1} + A(t_n) - A(t_{n-1}) - [D(t_n) - D(t_{n-1})] \\ &= W_{n-1} + \rho T_n + B_n^A - (T_n - V_n) \ , \end{aligned}$$

and hence

$$T_n - V_n - W_{n-1} = \rho T_n + B_n^A - W_n \ .$$

By our assumption that the output during the cycle must be no smaller than the work at the beginning of the cycle, both sides of this equation are non-negative. Noting $\rho < 1$, we subtract ρ times the left side from the right side to obtain

$$W_n \leq \rho W_{n-1} + \rho V_n + B_n^A \ . \tag{4}$$

Beginning with the expression for W_N and iteratively substituting in the expression for W_{n-1} leads to equation (3). ∎

For this section, in addition to the assumptions of Sections 1 and 2, we assume that the input process has a bound that is a special case of those studied by Cruz [7], [8]. Specifically, we assume that

$$A(t) - A(s) \leq \rho(t-s) + \sigma_A \ , \ 0 \leq s < t \ , \tag{5}$$

where σ_A is a non-negative constant. In words, the burstiness of the process in any interval is bounded by a constant independent of the length of the interval. We also assume that the walking time during any cycle is bounded by a constant: $V_n \leq V$, for all $n \geq 1$.

We begin by showing that the sum of the "discounted" bursts in equation (3) has the same bound as the sum of the corresponding "un–discounted" bursts. For this result we shall need the following lemma.

Lemma 2 *Suppose we have two sequences of real numbers, $\{B_i\}_{i=1}^n$ and $\{\rho_i\}_{i=1}^n$, such that $0 \leq \rho_1 \leq \cdots \leq \rho_n$. Then*

$$\rho_1 B_1 + \cdots + \rho_n B_n \leq \rho_n \max\{0, B_n, B_n + B_{n-1}, \ldots, B_n + \cdots + B_1\} \ . \tag{6}$$

Proof. The proof is by induction on n. Suppose (6) holds for n. Since the right hand side is non–negative, we can replace ρ_n with ρ_{n+1} on the right hand side, and add $\rho_{n+1}B_{n+1}$ to both sides, thus obtaining

$$\begin{aligned} &\rho_1 B_1 + \cdots + \rho_n B_n + \rho_{n+1} B_{n+1} \\ &\quad \leq \rho_{n+1} \left(B_{n+1} + \max\{0,\ B_n,\ B_n + B_{n-1}, \ldots,\ B_n + \cdots + B_1\} \right) \\ &\quad = \rho_{n+1} \max\{B_{n+1},\ B_{n+1} + B_n,\ B_{n+1} + B_n + B_{n-1}, \ldots,\ B_{n+1} + B_n + \cdots + B_1\} \\ &\quad \leq \rho_{n+1} \max\{0,\ B_{n+1},\ B_{n+1} + B_n,\ \ldots,\ B_{n+1} + \cdots + B_1\}, \text{ establishing (6) for } n+1. \end{aligned}$$ ∎

Lemma 3 *If $\rho < 1$, we have the following bound for the work at the end of a cycle:*

$$W_n \le \rho^n W_0 + \frac{\rho(1-\rho^n)V}{1-\rho} + \sigma_A \ .$$

Proof. We bound each of the terms on the right-hand side of (3), with $N = 0$. Since the walking times are bounded by V,

$$\rho \sum_{i=1}^{n} \rho^{n-i} V_n \le \rho \sum_{i=1}^{n} \rho^{n-i} V = \frac{\rho(1-\rho^n)V}{1-\rho} \ .$$

Turning to the arrival process, it follows from (2) and (5) that

$$\sum_{i=j}^{k} B_i^A = A(t_k) - A(t_j) - \rho(t_k - t_j) \le \sigma_A \ , \ 1 \le j < k \le n \ , \text{ and using Lemma 2,}$$

$$\sum_{i=1}^{n} \rho^{n-i} B_i^A \le \sigma_A \ , \ n \ge 1.$$

These bounds for the right-hand side terms of (3) with $N = 0$ yield the desired result, (7). ∎

Theorem 1. *Assume $\rho < 1$ and $W_0 = 0$. Then*

$$W_n \le \frac{\rho V}{1-\rho} + \sigma_A \ , \ n \ge 1 \tag{8}$$

$$T_n \le \frac{V}{(1-\rho)^2} + \frac{\sigma_A}{(1-\rho)} \ , \ n \ge 1 \tag{9}$$

$$Z(t) \le \frac{\rho(2-\rho)V}{1-\rho} + \sigma_A \ , \ t \ge 0 \ . \tag{10}$$

Proof. The first inequality follows from Lemma 3. To prove (9), note that

$$T_n = D(t_n) - D(t_{n-1}) + V_n \le W_{n-1} + \rho T_n + B_n^A + V_n \ ,$$

since the output in the n^{th} cycle is bounded by the work at the beginning of the cycle plus the input during the cycle. Thus,

$$\rho(1-\rho)T_n \le \rho(W_{n-1} + B_n^A) + \rho V_n \ .$$

Using Lemma 1 with $N = 0$ to bound W_{n-1}, we obtain

$$\rho(1-\rho)T_n \le \rho^n W_0 + \rho \sum_{i=1}^{n} \rho^{n-i} V_i + \rho \left(\sum_{i=1}^{n-1} \rho^{n-1-i} B_i^A + B_n^A \right) \ .$$

The term in parentheses on the right-hand side of this inequality is bounded by σ_A by Lemma 2. Applying the other bounds calculated in Lemma 1 leads to

$$\rho(1-\rho)T_n \le \frac{\rho V}{1-\rho} + \rho\sigma_A \ ,$$

from which (9) follows upon dividing both sides by $\rho(1-\rho)$. Now let $0 \leq s < t$ and define $B^A_{s,t} := A(t) - A(s) - \rho(t-s)$. In other words $B^A_{s,t}$ is the burstiness of the arrival process in $(s,t]$. To prove (10), let $t \geq 0$ be given and suppose that $t_n \leq t < t_{n+1}$, where $n \geq 0$. Now

$$Z(t) = W_n + A(t) - A(t_n) - (D(t) - D(t_n)) \; . \tag{11}$$

It follows that

$$D(t) - D(t_n) = t - t_n - \int_{t_n}^{t} v(s)ds \geq t - t_n - V_{n+1} \; ,$$

which, together with (11), implies that

$$\begin{aligned}
Z(t) &= W_n + \rho(t - t_n) + B^A_{t_n,t} - (D(t) - D(t_n)) \\
&\leq W_n + \rho\left(D(t) - D(t_n) + V_{n+1}\right) + B^A_{t_n,t} - (D(t) - D(t_n)) \\
&= W_n + \rho V_{n+1} + B^A_{t_n,t} - (1-\rho)(D(t) - D(t_n)) \\
&\leq W_n + \rho V_{n+1} + B^A_{t_n,t} \; .
\end{aligned}$$

Using Lemma 1 and the fact that $V_i \leq V$ for all $i \geq 1$, one obtains

$$Z(t) \leq \frac{\rho V}{1-\rho} + \rho V + \left(\sum_{i=1}^{n} \rho^{n-i} B^A_i + B^A_{t_n,t} \right) \; . \tag{12}$$

By Lemma 2, we can calculate bounds for the summations in (12) to obtain the desired result, $Z(t) \leq \rho(2-\rho)V/(1-\rho) + \sigma_A$. ▮

Example 1^o (continued). Consider the example of a globally gated polling system introduced in the previous section. If this system operates without bursts for $n-1$ cycles, the work at the end of the $n-1^{st}$ cycle will approach $\rho V/(1-\rho)$ as n increases. If there is an arrival burst of σ_A in the n^{th} cycle, W_n, the work in the system at the end of cycle n, will be arbitrarily close to the bound in (8). If, on the other hand, the system switches to exhaustive service in the n^{th} cycle, then T_n, the length of the n^{th} cycle, will be arbitrarily close to the bound given by (9).

Finally we show that the output from the system also satisfies a burstiness constraint of Cruz type. This is useful in analyzing networks where the output from one token ring can be the input to another element of the network.

Theorem 2 *Under the assumptions of Theorem 1, for all* $0 \leq t < t'$,

$$D(t') - D(t) \leq \rho(t'-t) + \frac{\rho(2-\rho)V}{1-\rho} + \sigma_A \; .$$

Proof. For $0 \leq t < t'$, we have

$$D(t') - D(t) \leq Z(t) + A(t') - A(t) = Z(t) + \rho(t'-t) + B^A_{s,t} \; .$$

Suppose $t_n \le t < t_{n+1}$, where $n \ge 0$. Using (12), we obtain

$$D(t') - D(t) \le \rho(t'-t) + \frac{\rho V}{1-\rho} + \rho V + \left(\sum_{i=1}^{n} \rho^{n-i} B_i^A + B_{t_n,t}^A + B_{t,t'}^A \right) .$$

The desired result then follows, again using Lemma 2. ∎

In this section we consider systems in which the input process has a limiting average rate. Specifically, in the same spirit as in Stidham and El–Taha [17], we make the following assumption:

$$\lim_{t\to\infty} \frac{A(t)}{t} = \rho , \tag{13}$$

We also assume that

$$\lim \frac{V_n}{t_n} = 0 . \tag{14}$$

The following lemma, which is analogous to Lemma 3, will enable us to use the results of the previous section to characterize the asymptotic behavior of W_n, T_n, and $Z(t)$.

Lemma 4 *Assume (13), (14), and $\rho < 1$. Let $\epsilon > 0$ be given and suppose N is large enough that*

$$(\rho - \epsilon)t \le A(t) \le (\rho + \epsilon)t , \tag{15}$$

$$V_i \le \epsilon t_i , \tag{16}$$

for all $i \ge N$ and $t \ge t_N$. Then for $n \ge N+1$,

$$W_n \le \rho^{n-N} W_N + \left(\frac{\rho}{1-\rho} + 2(1+\rho) \right) \epsilon t_n \tag{17}$$

Proof. When s and t satisfy $t_N \le s < t \le t_n$, it follows from (15) that

$$A(t) - A(s) \le \rho t + \epsilon t - \rho s + \epsilon s \le \rho(t-s) + 2\epsilon t_n .$$

Thus, imitating the proof of Lemma 3 with ϵt_n taking the place of V and $2\epsilon t_n$ taking the place of σ_A leads to the desired result, (17). ∎

The next theorem is analogous to Theorem 1.

Theorem 3 *Under the assumptions of Lemma 4,*

$$\lim_{n\to\infty} \frac{W_n}{t_n} = 0 \tag{18}$$

$$\lim_{n\to\infty} \frac{T_n}{t_n} = 0 \tag{19}$$

$$\lim_{t\to\infty} \frac{Z(t)}{t} = 0 \tag{20}$$

Proof. The first limit follows immediately from Lemma 4. Now let ϵ and N be given as in Lemma 4. To prove (19), first imitate the proof of (9) in Theorem 1, to obtain

$$\rho(1-\rho)T_n \leq \rho^{n-N}W_N + \rho \sum_{i=N+1}^{n} \rho^{n-i}V_i + \rho\left(\sum_{i=N+1}^{n-1} \rho^{n-1-i}B_i^A + B_n^A\right) ,$$

from which it follows that

$$\rho(1-\rho)T_n \leq \rho^{n-N}W_N + \left(\frac{\rho}{(1-\rho)} + 4\rho\right)\epsilon t_n ,$$

using an argument like that used in the proof of Lemma 4. Dividing both sides by t_n and letting $n \to \infty$ then leads to the desired result, (19), since ϵ was arbitrary. Finally, to prove (20), let t be such that $t_n \leq t < t_{n+1}$, where $n \geq N$. Following the proof of (10) in Theorem 1, we have $Z(t) \leq W_n + \rho V_{n+1} + B_{t_n,t}^A$. Using (1) to bound W_n leads to

$$Z(t) \leq \rho^{n-N}W_N + \frac{\rho V}{1-\rho} + \rho V + \left(\sum_{i=N+1}^{n} \rho^{n-i}B_i^A + B_{t_n,t}^A\right) ,$$

from which it follows that

$$Z(t) \leq \rho^{n-N}W_N + \left(\frac{\rho(2-\rho)}{1-\rho} + 2(1+\rho)\right)\epsilon t_{n+1} , \tag{21}$$

using an argument like that used in the proof of Lemma 4. Let $N(t) := \max\{n : t_n \leq t\}$. Since ϵ was arbitrary, (21) implies that $Z(t)/t_{N(t)+1} \to 0$ as $t \to \infty$. Now

$$\frac{Z(t)}{t} = \frac{Z(t)}{t_{N(t)+1}} \cdot \frac{t_{N(t)+1}}{t} \leq \frac{Z(t)}{t_{N(t)+1}} \cdot \frac{t_{N(t)+1}}{t_{N(t)}} .$$

The desired result, (20), then follows from (19). ▮

Remark. The condition (20) is a kind of pathwise stability condition, called *rate stability* by El–Taha and Stidham [9] (see also Stidham and El–Taha [17]. Given $\lim_{t\to\infty} A(t)/t = \rho < \infty$, it is equivalent to equality of the input and output rates: $\lim_{t\to\infty} D(t)/t = \lim_{t\to\infty} A(t)/t = \rho$. As an elementary consequence, we obtain the following result for the long-run fraction of time that the system is down.

Corollary 1 *Under the conditions of Lemma 4,*

$$\lim_{t\to\infty} \frac{\int_0^t v(s)\,ds}{t} = 1 - \rho . \tag{22}$$

Proof. We have $Z(0) + A(t) = Z(t) + D(t) = Z(t) + \int_0^t u(s)\,ds$, so that $Z(0)/t + A(t)/t = Z(t)/t + \int_0^t u(s)\,ds/t$. Taking limits and using (20), one obtains

$$\rho = \lim_{t\to\infty} \frac{\int_p^t u(s)\,ds}{t} ,$$ from which (22) follows immediately. ▮

In the following theorem we derive an expression for the long-run average cycle length.

Theorem 4 *Under the assumptions of Lemma 4, suppose that* $\lim_{n\to\infty} n^{-1}\sum_{i=1}^{n} V_i = V < \infty$. *Then*

$$\lim_{n\to\infty} \frac{t_n}{n} = \frac{V}{1-\rho} . \tag{23}$$

Proof. Let n and m be positive integers where $n > m$. Then

$$W_m + A(t_n) - A(t_m) = W_n + D(t_n) - D(t_m) ,$$

or, equivalently,

$$W_m + \rho(t_n - t_m) + B^A_{t_m,t_n} = W_n + t_n - t_m - \sum_{i=m+1}^{n} V_i .$$

Rearranging terms, we have

$$(1-\rho)t_n + W_n - B^A_{t_m,t_n} = \sum_{i=1}^{n} V_i + E_m , \tag{24}$$

where $E_m := W_m - \sum_{i=1}^{m} V_i + (1-\rho)t_n$. Now let ϵ and N be given as in Lemma 4 and suppose that $n > m \geq N$. Then Lemma 4 implies that the absolute value of the burstiness term in (24) is bounded by $2\epsilon t_n$. Moreover, from (18) it follows that $0 \leq W_n/t_n \leq \epsilon$ for sufficiently large n. Using these bounds in (24) and dividing by n, we obtain

$$(1-\rho-2\epsilon)\frac{t_n}{n} \leq \frac{\sum_{i=1}^{n} V_i}{n} + \frac{E_m}{n} \leq (1-\rho+3\epsilon)\frac{t_n}{n} .$$

Now fix $m \geq N$ and let $n \to \infty$. Since E_m is constant and ϵ was arbitrary, we conclude that $(1-\rho)\lim_{n\to\infty} t_n/n = V$, from which the desired result (23) follows upon dividing both sides by $1-\rho$. ∎

Remark. Note that the proof of Theorem 4 did not use our basic assumption that $D(t_n) - D(t_{n-1}) \geq W_{n-1}$, for all $n \geq 1$, except implicitly when we invoked Theorem 3 to conclude that (18) holds, that is, $\lim_{n\to\infty} W_n/t_n = 0$. In fact the proof demonstrates that Theorem 3 holds for any system in which (13), and (14) hold, with $\rho < 1$, provided that (18) also holds. In particular, it suffices that the system be rate stable: $Z(t)/t \to 0$ as $t \to \infty$.

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