IS HIGH-SPEED WIRELESS NETWORK TRAFFIC SELF-SIMILAR?

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ABSTRACT

It has been well established by now that high-speed wireline traffic exhibits self-similar behavior. In this paper we study the propagation of self-similarity as the wireline traffic is sent through a gateway to the wireless network. We employ a commonly used model for buffering and repacking performed at the gateway, and study the statistics of the output traffic. Both analysis and simulations reveal that the buffer system can produce traffic that has different degree of self-similarity as compared to the incoming traffic, or even traffic that is no longer self-similar.

1. INTRODUCTION

With the increasing demand for wireless internet access and the fast evolution of wireless techniques, (e.g., third generation systems and wireless LAN), high-speed services are provided via wireless networks. Over the past decade it has been established that wireline traffic generated by multimedia applications has distinctly different characteristics from traditional circuit-switched voice traffic. In particular, it exhibits self-similarity and burstiness [8]. Several models have been proposed to capture the aforementioned characteristics [7], [9], [10], [11], [2]. Self-similarity implies a non-trivial structure for traffic, which can be exploited for data analysis. Recently, there have been some works suggesting that wireless traffic may also exhibit self-similarity [6]. It is true that recent advances in wireless networks can enable high speeds, and it is also true that both wireless and wireline users need to access the same multimedia applications. However, does this mean that the wireless traffic will have the same characteristics as the wireline traffic? To answer this question, we here provide a study of the effect on self-similarity of the buffering which is performed at the gateway that interconnects the wireline to the wireless network. In general, packet sizes are different over a heterogeneous collection of networks, and the gateway should provide a means by which packets can be fragmented and reassembled [4]. Compared to the wireline case, transmission over wireless networks is susceptible to the fading nature of the wireless link. To improve throughput, automatic repeat request (ARQ) and/or forward error correction (FEC) are incorporated to wireless data transmission. A two-state Markovian channel model was proposed in [3] for the radio channel that incorporated ARQ and FEC.

2. SYSTEM MODEL

Let us consider the buffering system of Fig. 1 that serves a single user. The traffic stream from the wireline network is first unpacked into bit streams, denoted as $S(t)$. The system repacks those bits into new packets and sends them via the wireless link. Let the outgoing packet traffic be denoted by $T(t)$. The wireless channel is here modelled based on the two-state Markovian model of [3]. According to this model, the channel strictly alternates between *good* and *bad* states, which correspond to two deterministic service rates: c_g during *good* states and c_b during *bad* states. The periods of both states are independently and identically exponential distributed with means $1/\beta$ and $1/\gamma$ respectively. Let us assume that $S(t)$ follows the model of [11], i.e., it is an ON/OFF process with Pareto distributed ON-/OFF-state durations, denoted here by $\{X_{S,n}\}$ and $\{Y_{S,n}\}$, respectively, and cut-off Pareto distributed ON-state rates, denoted here by $\{A_n\}$ $(n = 1, 2, ...)$. The complementary distribution function (CDF) of the Pareto distribution is:

$$\bar{F}(x;\alpha,K) = P(X \geq x) = \begin{cases} (\frac{K}{x})^{\alpha}, & x \geq K, \\ 1, & x < K, \end{cases} \quad (1)$$

where K is a positive constant and $0 < \alpha < 2$. The survival function of a cut-off Pareto distribution is:

$$\begin{aligned} \bar{F}_L(x;\alpha,K) &= P(X \geq x) \\ &= \bar{F}(x;\alpha,K)(1-u(x-L)) \\ &= \begin{cases} (\frac{K}{x})^{\alpha}, & K \leq x \leq L, \\ 1, & x < K \\ 0, & x > L \end{cases} \end{aligned} \quad (2)$$

where $u(.)$ is the unit step function, and L represents a rate limit imposed to the wireline user. Traffic streams $S(t)$ from one or more connections are fed into a finite buffer of size B, until the buffer overflows, in which case the excess data are discarded. Let us assume that the service time is time-slotted with time slot denoted by τ. In the sequel we will use the notation $S(n)$, $T(n)$ instead of $S(t)$, $T(t)$, where n is the slot index. During each time slot, at most one packet can leave buffer. Since the incoming traffic is assumed to be continuous bit flow, the server needs to repack bits into equal-sized packets and send them out via wireless link. Let P denote the packet size. It is assumed that $P = c$, where c is the instant channel capacity within one time slot, which alternates between c_g and c_b. For the packing operation, we here consider the following model:

- *Server Model*: If the data in the buffer is less than the packet size, the server takes no action and waits until there is enough data to form a packet.

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3. PERFORMANCE ANALYSIS OF THE UNDERLYING BUFFER SYSTEM

Considering a slow-varying wireless channel, the alternation of channel states is slower than that of the incoming traffic $S(n)$. This implies that the channel rate of the buffering system can be taken as constant within several ON-/OFF-periods of $S(n)$. Thus, we can first study the simpler case where the service rate of the buffer system is constant and equal to c. The operation of the gateway can be approximated as the statistical multiplexing of two buffer systems: one has service rate c_g and the other has service rate c_b, both system sharing the same buffer with finite buffer size B as shown in Fig. 1. Let us view $T(n)$ as an ON/OFF process. $T(n)$ is in ON state if $T(n) > 0$, and is in OFF state if $T(n) = 0$. Let $X_{T,n}$, $Y_{T,n}$ (n=1,2,...) denote the ON and OFF durations of $T(n)$. We next compute the distributions of $X_{T,n}$ and $Y_{T,n}$ based on the statistics of $S(n)$. Let $b(n)$ denote the buffer content at the slot n, with initial value $b(0) = 0$. Based on our server model, $T(n)$ and $b(n)$ are updated on a slot-by-slot basis as follows:

$$T(n) = \begin{cases} c, & if\ S(n) + b(n-1) \geq c \\ 0, & if\ S(n) + b(n-1) < c \end{cases} \tag{3}$$

$$b(n) = \begin{cases} < S(n) + b(n-1) - c, 0 > \wedge B, \\ \qquad\qquad if\ S(n) + b(n-1) \geq c \\ < S(n) + b(n-1), 0 > \wedge B, \\ \qquad\qquad if\ S(n) + b(n-1) < c \end{cases} \tag{4}$$

where $< \alpha, \beta >= max(\alpha, \beta)$ and $\alpha \wedge \beta = min(\alpha, \beta)$. Both update equations guarantee that the buffer content can only take value within the range $[0, B]$. Let N_j denote the so-called regeneration point of $S(N)$, i.e., the beginning of the j^{th} ON-period of $S(n)$. It holds: $N_j = \sum_{i=1}^{j-1} X_{S,i} + \sum_{i=1}^{j-1} Y_{S,i}$. We next study two cases, one for $B > c$ and the other for $B = c$. We should note that we do not consider the case $B < c$ as it would be impractical for real networks.

Buffering system with $B = c$ Unless the buffer is full (i.e. $b(n) = B$), the amount of data in the buffer isn't enough to form a packet, so no packet will leave buffer. During all OFF-periods of $S(n)$, it holds that $T(n) = 0$. During the ON-periods of $S(n)$, as new bits come into the buffer with rates A_j (j=1,2,...), $b(n)$ will change according to (4), and thus $T(n)$ will change according to (3). The buffer system will not keep one-to-one mapping between X_S and X_T, Y_S and Y_T. Instead, the buffering model considered here combines some consecutive ON-/OFF-periods of $S(n)$ as $\{X_{S,i}\}_{i=j}^{j+M-1}$ and $\{Y_{S,i}\}_{i=j-1}^{j+M-1}$ to form a bigger OFF-period $Y_{T,k}$, i.e., $Y_{T,k} = Y_{j-1} + \sum_{i=j}^{j+M-1}(X_{S,j} + Y_{S,j})$. We will refer to such action as *combining action*. We next consider the following cases:

- **Case 1**: For all A_j such that $A_j \geq c$. Let us define two sets: $D1 = \{j : A_j > c\}$ and $D2 = \{j : A_j = c\}$. For $n \in [N_j, N_j + X_j)$ (where $j \in D1 \bigcup D2$), i.e. the j^{th} ON-period of $S(n)$ belonging to case 1, we have $b(n-1) + S(n) = b(n-1) + A_j > c$, and thus $T(n)$ will also be in ON state. Let us denote the ON (OFF) durations belonging to case 1 by $X_{T,k}^1$ $(Y_{T,k}^1)$ $(k = 1, 2, ...)$. In this case we have $X_{T,k}^1 = X_{S,j}$ $(j \in D_1 \bigcup D_2)$.
- **Case 2**: $A_j < c$ for all A_j. Let us define the set $D3 = \{j : A_j < c\}$. Let us consider the buffer content, $b(n)$, at the regeneration points N_j. For infinite buffer, the stationary distribution of $b(n)$ is asymptotically heavy-tailed with tail index $\alpha_1 - 1$ (where α_1 is the tail index of ON durations of $S(n)$) [11]. For a finite buffer fed by self-similar traffic, the result is rather intractable. Since in this subsection we assume single buffer, the ON/OFF duration of $T(n)$ can change by at most 1 time slot at a time. While $X_{S,j}$ and $Y_{S,j}$ are Pareto distributed and might take very large value with nontrivial probability, for single buffer, $b(n)$ has small impact on the distributions of X_T and Y_T and can be ignored. Thus we can approximate eq. (3) by setting $b(n) = 0$ for all n, i.e.,

$$T(n) = \begin{cases} c & S(n) \geq c \\ 0 & S(n) < c \end{cases} \tag{5}$$

In the simulations section we will provide some results in support of the above approximation. Since $\forall j \in D_3$, we have $A_j < c$, $T(n) = 0$ within that period. In other words, the underlying buffer system virtually converts the j^{th} ON-period of $S(n)$ into an OFF- period for $T(n)$, which results in $T(n)$ staying in OFF state for a larger duration, i.e., $Y_{S,j-1} + X_{S,j} + Y_{S,j}$. The combining action can be applied to more ON-/OFF-periods of $S(n)$ to produce a bigger OFF-period in $T(n)$, i.e., $Y_{T,k}^2 = Y_{S,j-1} + \sum_{i=j}^{j+M-1}(X_{S,j} + Y_{S,j})$ given that $j, j+1, ..., j+M-1$ all $\in D_3$, i.e. M consecutive ON-periods of $S(n)$ which satisfy that $A_i < c$ $(i = j, ..., j_M - 1)$. So that $P(M = m) = P(A < c)^m P(A > c)^2$.

The complementary distribution functions (CDF) of X_T and Y_T can be obtained as follows:

$$\begin{aligned} P(X_T > x) &= P(X_T > x | A \geq c) P(A \geq c) \\ &+ P(X_T > x | A < c) P(A < c) \end{aligned} \tag{6}$$

and

$$\begin{aligned} P(Y_T > y) &= P(Y_T > y | A \geq c) P(A \geq c) \\ &+ P(Y_T > y | A < c) P(A < c) \end{aligned} \tag{7}$$

Based on our assumptions, the ON-state rate A is cut-off Pareto distributed according to $\bar{F}_L(x; \alpha, K)$ with parameters $\{\alpha_A, K_A, L\}$ where $\alpha_A \in (1, 2)$. Thus, $\frac{P(A<c)}{P(A>c)} = \frac{1}{P(A>c)} - 1 > 10^{\alpha} - 1 > 9$ given that $10K_{A_1} < c < L$. The ratio $\frac{P(A<c)}{P(A>c)}$ becomes even larger if $c > L$. So we conclude that $P(Y_T > y | A < c) P(A < c)$ is the dominant term in (7), while $P(X_T > x | A \geq c) P(A \geq c)$ is the dominant term in (6). Based on the above, we have

$$P(X_T > x) \approx P(X_S > x) \tag{8}$$

and

$$\begin{aligned} P(Y_T > y) &\approx \sum_{m=1}^{\infty} P\Big(\sum_{i=1}^{m} X_{S,i} + \sum_{i=1}^{m+1} Y_{S,i} > y \Big) \\ &\times P(A < c)^m P(A > c)^2 \end{aligned} \tag{9}$$

Buffering system with $B > c$ When $B > c$, the previous buffer content $b(n-1)$ has a significant effect on the underlying buffer system. As already stated, the distribution of buffer content $b(n)$ for a finite buffer system is too complicated to derive in closed form. Instead of detailed derivations, we will next provide some intuitive arguments on the behavior of the tails of distributions of X_T and Y_T. In the previous subsection, we approximated $P(X_T > x)$ and $P(Y_T > y)$ with their dominant terms, and so we will focus on the case that all $A_j < c$ due to the same approximation. Let us consider that $S(n)$ is in the j^{th} ON-period, i.e. $n \in [N_j, N_j + X_{S,j})$. Then, if $b(N_j) + A_j < c$, the previous $j - 1^{th}$ OFF-period is extended into this ON-period by excess value δ, for which it holds $\delta = \lfloor \frac{c-b(N_j)}{A_j} \rfloor \wedge X_{S,j}$. Of course, if δ reaches $X_{S,j}$, two consecutive OFF-periods will be connected by this extension δ due to the same combining action as discussed above. If $b(N_j) + A_j < c$ but $\delta < X_j$, or $b(N_j) + A_j > c$, $T(n)$ might alternate between small ON-/OFF-periods within this interval. The buffer system splits a large ON-period of $S(n)$ into several small ON-/OFF-periods of $T(n)$, an action that will be referred to as textitsplitting action. Such action results into X_T and Y_T having a larger portion of small values compared with X_S and Y_S respectively. This implies that X_T and Y_T will have a heavier tail than X_S and Y_S. In summary, the buffer system considered here takes both combining and splitting action on Y_T, but with opposite effects. This can lead to a distribution for Y_T that is similar to that of Y_S. On the other hand, for X_T, only splitting action takes effect, thus X_T has heavier tail than X_S. Although we do not have an rigorous analysis of the above, simulation results to be provided in the simulations section do support our conclusion.

4. SIMULATION RESULTS

In this section, we provide simulations to support the claim that the gateway can influence the statistics of ON-/OFF-periods of self-similar traffic. We first generated the incoming traffic $S(n)$ based on the rated-limited EAFRP model, where the ON- and OFF-durations were Pareto distributed with ($\alpha_1 = 1.6$, $K_1 = 1$) and ($\alpha_0 = 1.4$, $K_0 = 1$), respectively. The data rate during the ON-states was taken from a cut-off Pareto distribution, i.e. $f_L(x; \alpha, K)$ with ($L = 10^{4.64}$,$\alpha_A = 1.19$, $K_A = 48$) and the time unit τ was taken as $\tau = 0.01sec$. The service rates of the wireless channel were alternated between the two states $c_g = 5000$ and $c_b = 500$, with independently exponentially distributed state durations, where the mean of good states was $1/\beta = 0.1sec$ and that of bad states was $1/\gamma = 0.0333sec$. The buffer size was taken $B = 5000$. So, for channel c_g, the buffering system satisfies $B = c$, while for channel rate c_b the system satisfies $B > c$. In Section 3, we assumed that for a single buffer system the value of $b(n)$ can be ignored with minor error. To verify this assumption, the simulation results are shown in Fig. 2. The "real traffic" curve in that figure corresponds to $T(n)$ obtained based on eq. (3) and (4), while the curve denoted as "approximation" is the traffic $T'(n)$ obtained using eq. (5). One can see that the approximation holds well. Based on this assumption, we concluded that OFF-period durations of $T(n)$ (i.e. Y_T) have a heavier tail compared with those of $S(n)$, and the complementary distribution function (CDF) of Y_T can be approximated as (9) where the corresponding buffer system satisfies $B = c$. The ON durations of $T(n)$ (i.e. X_T) has the same CDF as $S(n)$. To support this, the log-log CDFs (LLCD) of ON-/OFF-periods duration of $T(n)$ (solid line), $S(n)$ (dashed line) were plotted in the left/right column of Fig. 3 for $B = c$ ($c = 5000$, $B = 5000$). The analytic approximation of (9) is shown as the dotted-circle curve in the right part of Fig. 3. For the case $B = 5000 > c = 500$, the log-log CDFs (LLCD) of ON-/OFF-periods durations of $T(n)$ (solid line), $S(n)$ (dashed line) are plotted in the left/right column of Fig. 4. Next, we passed $S(n)$ through the buffering system whose service rate alternating between c_g and c_b. The LLCD of ON-/OFF-durations of $S(n)$ and $T(n)$ are plotted in Fig. 5. In this figure, the tail index of ON- and OFF-durations distributions of $T(n)$ are $\alpha_{ON} \approx 3.1$ and $\alpha_{ON} \approx 3.8$ respectively, i.e. both are larger than 2! The Hurst parameter H has been suggested in [5] as a measure of the degree of self-similarity of traffic stream. Since $T(n)$ can be treated as an ON/OFF process with finite reward (limited to channel rate c), H can be calculated as[9]: $H = \frac{3-min(\alpha_{ON},\alpha_{OFF})}{2}$. If both α_{ON} and α_{OFF} are larger than 2, then $H < 0.5$, which means the underlying process $T(n)$ is not self-similar. In other word, $T(n)$ is not a self-similar process while $S(n)$ is self-similar, i.e., the underlying buffering system can influence the degree of self-similarity of traffic and even result in loss of self-similarity when $c_b < B = c_g$.

5. CONCLUSION

The proposed model can help us to understand and study the effect of the gateway that feeds wireline traffic into the wireless network. The analysis presented here suggests that the gateway can change the degree of self-similarity of traffic due to its reassembling and repacking operations on the incoming self-similar traffic.

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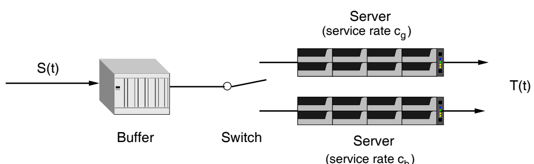

Fig. 1. The buffering system used for analyzing the outgoing traffic.

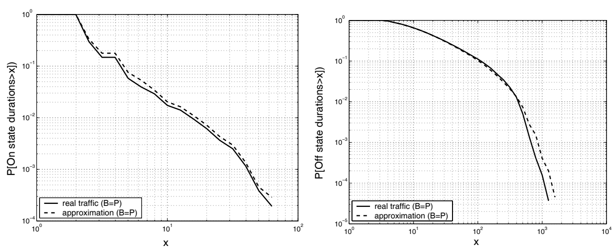

Fig. 2. The LLCDs of ON-periods (left) and OFF-periods (right) corresponding to traffic obtained based on the approximation of (5) (dashed line), and to outgoing process $T(n)$ obtained via (3), (4) (solid line). The underlying buffering system has constant rate c and satisfies that $B = c$.

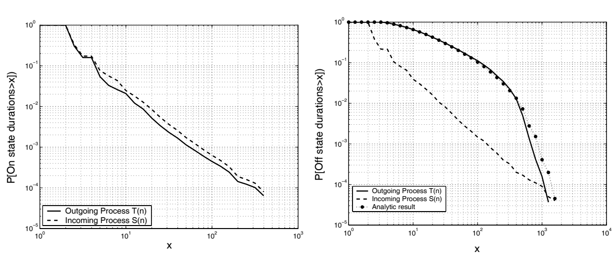

Fig. 3. The comparisons of LLCD of ON-periods (left) and OFF-periods (right) corresponding to incoming process $S(n)$ (dashed line) and outgoing process $T(n)$ (solid line). Also the analytic result of Y_T obtained via (9) is shown (dotted-circle) in the right part of figure. The underlying system satisfies that $B = c_g$.

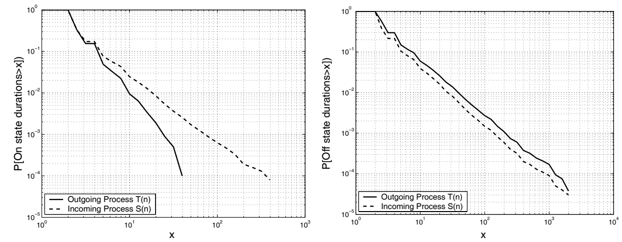

Fig. 4. The comparisons of LLCD of ON-periods (left) and OFF-periods (right) corresponding to incoming process $S(n)$ (dashed line) and outgoing process $T(n)$ (solid line). The underlying buffering system has constant rate c_b and satisfies that $B > c_b$.

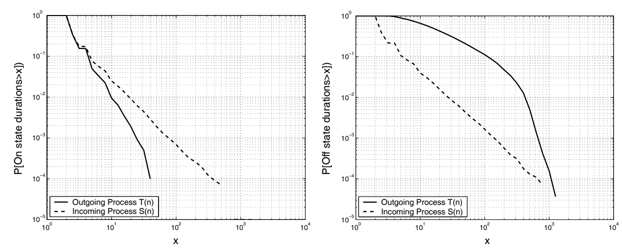

Fig. 5. The comparisons of LLCD of ON-periods (left) and OFF-periods (right) associating with incoming process $S(n)$ (dashed line) and outgoing process $T(n)$ (solid line) where $T(n)$ was obtained by passing $S(n)$ through the buffering system whose service rate alternating between c_g and c_b and satisfying that $c_b < B = c_g$).