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Research on Aggregation and Propagation of Self-Similar Traffic in Satellite Network

Zhenyu Na[1], Yi Liu[1], Yang Cui[2] and Qing Guo[3]

[1]*Institute of Transport Electronics, School of Information Science and Technology, Dalian Maritime University*
[2]*Institute of Science and Industry Technology, Harbin Institute of Technology*
[3]*Communication Research Center, Harbin Institute of Technology*
[1]*nazhenyu@dlmu.edu.cn,* [2]*ycui@hit.edu.cn,* [3]*qguo@hit.edu.cn*

Abstract

It has already been confirmed that the traffic in high-speed terrestrial network presents self-similarity, but there is little research on self-similarity of traffic in satellite network. Considering time-varying network topology and link status, this paper analyzes the aggregation and propagation of self-similar traffic between nodes in satellite network. Furthermore, a sort of special network node called ground gateway is modeled, based on which the characteristics of the output traffic that the input traffic from terrestrial network passes gateway into satellite network are analyzed. Theoretically analyses demonstrate that after aggregation and propagation between satellite nodes, traffic is still self-similar, and the self-similarity of the output traffic generated by gateway from terrestrial network to satellite network is more often than not weakened.

Keywords: *Self-similarity, traffic, satellite network, gateway*

1. Introduction

With the development of communication technology and industry, current communication network is expanding in broadband, mobility, multimedia, diverse access and the integration of wired and wireless networks, becoming next generation network (NGN). As satellite communication supports global seamless coverage and mobile services, combined with IP technology adapting to different physical links, it will be the most important supplement of NGN to meet demands of future communication in the future.

However, the huge expansion of network size and the explosive increase of multimedia services in recent years result in network congestion that drastically affects quality of service (QoS) of network and quality of experience (QoE) of users. In the early stage of Internet, network traffic can be modeled by Poisson or Markov process. At present, the characteristics of network traffic have sharply changed that traffic shows evident self-similarity [1-2]. Specifically, traffic flows with different characteristics of diverse services aggregate and present high burstiness on wide timescale. It aggravates network node congestion, delay, jitter, packet loss ratio and bandwidth utilization, leading to degraded QoS and QoE.

Over the past decade, self-similar traffic is researched in the field of terrestrial and wired networks [3], but there is little research on self-similar traffic in wireless network [4-5], especially satellite network. According to VoIP (Voice over IP) traffic in terrestrial network, H. Toral [6] analyzes the effect of self-similar traffic on packet loss ratio, delay and jitter. Q. Liang [7] analyzes the influence of wireless gateway on self-similar traffic, but it is one special instance without generality. Based on campus online e-learning network, L. Kaklauskas [8] clarifies the measurement of self-similarity, however, it is only confined to

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wired network. Together with works of [4] and [5], these research results often focus on wired network, almost without research on self-similar traffic in satellite network.

In fact, the time-varying topology, link status and gateway protocols of satellite network are the most important factors which affect aggregation and propagation of self-similar traffic. In this paper, the concept of self-similarity is introduced first, followed by modeling self-similar traffic and channel, and the aggregation and the propagation of self-similar traffic are analyzed. Further, in the light of satellite-terrestrial network, ground gateway model is built, the output traffic of gateway from terrestrial network to satellite network is analyzed in detail, and some constructive conclusions are put forward.

2. Self-similarity and Long Rand Dependence

Consider a wide-sense stationary stochastic process $X = \{X_n, n = 1, 2, 3, \cdots\}$, X_n represents the arriving network entity (for instance, packet or cell) in k-th interval, *i.e.*,

$$X_n = N[nT] - N[(n-1)T] \tag{1}$$

Denote the expectation and variance of X_n as

$$\mu = E[X_n] \tag{2}$$

$$\sigma^2 = E\left[(X_n - \mu)^2\right] \tag{3}$$

The autocorrelation function of X_n is

$$r(k) = \frac{E[(X_n - \mu)(X_{n+k} - \mu)]}{\sigma^2} \tag{4}$$

Following aggregated process $X_n^{(m)}$ is defined

$$X_n^{(m)} = \frac{X_{nm-m+1} + X_{nm-m+2} + \cdots X_{nm}}{m} = \frac{1}{m}\sum_{i=nm-m+1}^{nm} X_i \tag{5}$$

Where, m is positive integer. If the statistical property of $X^{(m)}$ does not change along with m, X is called self-similar process.

Similarly, denote the autocorrelation function of $X_n^{(m)}$ as $r^{(m)}$. If any one of the following three conditions is met, that

$$\mathrm{var}\left[X_n^{(m)}\right] = m^{2H-2}\,\mathrm{var}[X_n] \tag{6}$$

$$r(k) = r^{(m)}(k) = \left[(k+1)^{2H} - 2k^{2H} + |k-1|^{2H}\right]\Big/2 \tag{7}$$

$$f(\lambda) = c(1-\cos\lambda)\left\{|\lambda|^{-(2H+1)} + \sum_{j=1}^{\infty}\left((2\pi j + \lambda)^{-(2H+1)} + (2\pi j - \lambda)^{-(2H+1)}\right)\right\} \tag{8}$$

X is called strict second-order self-similar process. Where, $-\pi < \lambda < \pi$, $0.5 < H < 1$. H is called Hurst parameter which reflects self-similarity high or low. B. Tsybakov [9] proves formulas (6)~(8) are equivalent to each other.

It is deduced formula (6), the aggregated process $X^{(m)}$ has slow decaying variance because of $-1 < 2H-2 < 0$ that the decaying speed of variance is slower than m^{-1}. It means that self-similar process can hold high burstiness on very wide timescale, while Poisson process tends to flat.

For formula (7), $r(k) = r^{(m)}(k)$ demonstrates that the aggregated stochastic process $X_n^{(m)}$ has the same autocorrelation function as the original stochastic process X. The following expression holds when $k \to \infty$

$$\lim_{k\to\infty} r(k) = H(2H-1)k^{2H-2} \tag{9}$$

From formula (9), when k increases, the autocorrelation of X is power-law decaying. In contrast, the autocorrelation of Poisson process is decaying exponentially and close to zero. As above, it is called long-range dependence (LRD) that the autocorrelation function of self-similar stochastic process has slow decaying speed.

H is the parameter describing self-similarity of self-similar process. When $0< H <1/2$, it is called negative correlation, but when $1/2< H <1$, it is called positive correlation. If $H =1/2$, it means no correlation. In fact, since real network traffic is positive correlative, the range of H value is (1/2, 1). The larger H is, the higher similarity is. High self-similarity is correlated to LRD and strong burstiness on wide timescale.

Generally, self-similar traffic can be modeled through heavy-tailed distribution. If the complementary cumulative distribution function (CCDF) of a random variable is power-law decaying, that

$$P(X \geq x) \sim x^{-\alpha}, \quad \text{when } x \to \infty \text{ and } \alpha > 0 \tag{10}$$

X is called heavy-tailed distributed [10-11].

Common heavy-tailed distribution is Pareto and Weibull distributions. Considering the following analyses, only Pareto distribution is briefly introduced. The probability density function (PDF) of Pareto distribution is given below:

$$f(x;\alpha,K) = \begin{cases} \frac{\alpha}{x}\left(\frac{K}{x}\right)^{\alpha}, & x \geq K \\ 0, & x \leq 0 \end{cases} \tag{11}$$

$$F(x,\alpha,K) = 1 - \left(\frac{K}{x}\right)^{\alpha} \tag{12}$$

Where, α is shape parameter; K (>0) is the minimum value of random variable x. Mean value and variable can be expressed as

$$\mu = \frac{\alpha}{\alpha - 1} K \tag{13}$$

$$\sigma^2 = \frac{\alpha K^2}{(\alpha - 1)^2(\alpha - 2)} K \tag{14}$$

Apparently, when $0 < \alpha < 2$, Pareto distribution has infinite variance; when $0 < \alpha \leq 1$, it has infinite mean value and variance simultaneously.

3. Analysis on Aggregation and Propagation of Self-similar Traffic in Satellite Network

According to Ad hoc network, S. Yin [4] and Q. Liang [5] set up test bed and collect traffic trace, after statistical analysis, they conclude that the traffic in Ad hoc network has self-similarity. Based on the research fruits about self-similar traffic of other researchers in both wired and wireless networks, this paper tentatively analyzes self-similar traffic in satellite network. In this section, based on a simplified satellite network model, the aggregated self-similar traffic in single satellite node is analyzed, and in the light of node mobility and link status, the aggregation and the propagation of self-similar traffic through multiple nodes are analyzed in detail.

On one hand, for convenience, satellite network is called satellite backbone in this paper. Other terrestrial networks and terminals (Internet, handset, etc.) on the ground and in the air which communicate with satellite network can be abstracted as sources or sinks of traffic. On the other hand, network transmission protocols and link interferences do not taken into consideration mainly because the analytical key point is laid to traffic self-similarity.

Specifically, from the perspective of receiving and forwarding traffic, we investigate whether the aggregated and propagated self-similar traffic through multiple hops is still self-similar.

First, we consider the aggregation of self-similar traffic only through one hop, in other words, multiple sources send traffic to a node through one hop. Consider an ON/OFF traffic source with Pareto-distributed ON and OFF durations, it can be represented by a two-state time series $\{W(t), t \geq 0\}$. When $W(t) = 1$, it means a packet is generated at time t; when $W(t) = 0$, it means the source does not send any packet. Further, suppose there are M independent and identically distributed (IID) sources of which each source sends packet independently. So, the number of received packets at the sink node can be expressed by $\{W^{(m)}(t), t \geq 0\}$, and then the number of received packets from M sources at the sink node can be formulated below

$$N_l^M(t) = \sum_{m=1}^{M} W^{(m)}(t) \tag{15}$$

For formula (15), timescale is reset to Tt, the number of aggregated packets in $[0, Tt]$ can be given below

$$N_l^M(Tt) = \int_0^{Tt} \left(\sum_{m=1}^{M} W^{(m)}(u) \right) \mathrm{d}u \tag{16}$$

For formula (16), J. Hong [12] proves that when M and T are large enough, $N_l^M(Tt)$ is statistically self-similar. Thus, the aggregation of a large number of self-similar traffic sources is still self-similar through only one hop.

Second, we consider the propagation of self-similar traffic through multiple hops. Here, only node mobility and link status are taken into account without other factors considered. The rationality behind it is elaborated as below. First, link disruption (OFF) and connection (ON) due to time-varying topology for satellite network occur definitely, especially for MEO/LEO (Medium Earth Orbit/Low Earth Orbit) satellite networks. This situation is quite different from terrestrial wired network. Second, it is has been proved that self-similarity is unrelated to concrete protocols or applications [1]. Therefore, the premise of analysis below on self-similar traffic in satellite network is more general.

Under condition of multiple hops, satellite nodes can be classified into three types: sending node, intermediate node and receiving node. But in fact, each satellite node can be served as sending node, as well as intermediate node or receiving node. As shown in Figure 1, node A is factually the intermediate node able to receive or send packet. For node B and D, node A serves as sending node. For node C, E, F and G, node A turns to be the receiving node. In view of generality of analysis, this section only discusses intermediate node that it can receive packets as well as send packets.

Suppose $N_l(t)$ denote the number of received packets by node A (serves as receiving node) in time [0, t], $N_f(t)$ denote the number of forwarded packets by node A (serves as intermediate node that the forwarded packets are sent to other nodes). Therefore, the total number of packets $N(t)$ is expressed as below

$$N(t) = N_l(t) + N_f(t) \tag{17}$$

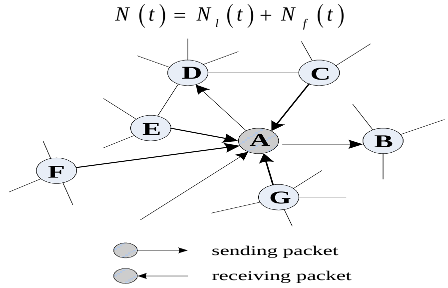

Figure 1. Network Node Types under Condition of Multi-Hops

As analyzed above, $N_l(t)$ is the aggregation of multiple ON/OFF process of heavy-tailed distribution. Each ON/OFF process can be expressed as a stationary two-state time series $\{W(t), t \geq 0\}$, of which definition is the same as in previous section. Let $f_1(x)$, $F_1(x)$, $\bar{F}_1(x) = 1 - F_1(x)$, μ_1 and σ_1^2 denote the PDF, cumulative distribution function (CDF), CCDF, mean value and variance of ON state duration, respectively. Accordingly, $f_2(x)$, $F_2(x)$, $\bar{F}_2(x) = 1 - F_2(x)$, μ_2 and σ_2^2 denote the PDF, CDF, CCDF, mean value and variance of OFF state duration, respectively. When $x \to \infty$, the following two expressions hold

$$\bar{F}_1(x) \sim l_1 x^{-\alpha_1} L_1(x), 1 < \alpha_1 < 2 \text{ or } \sigma_1^2 < \infty \tag{18}$$

$$\bar{F}_2(x) \sim l_2 x^{-\alpha_2} L_2(x), 1 < \alpha_2 < 2 \text{ or } \sigma_2^2 < \infty \tag{19}$$

Where, l_1 and l_2 are constant greater than 0; $L_j(x)\,(j = 1,2)$ is slow decaying function under condition of $x \to \infty$. For any $t > 0$, following expression holds

$$\lim_{x \to \infty} \frac{L_j(tx)}{L_j(x)} = 1 \tag{20}$$

When $1 < \alpha_j < 2$, $\alpha_j = l_j \left(\Gamma(2 - \alpha_j)\right) / \alpha_j - 1,\ j = 1,2$; When $\sigma_j^2 < \infty$, $\alpha_j = 2$, $L_j \equiv 1$, $\alpha_j = \sigma_j^2 / 2$, $j = 1,2$, where the coefficient and the constant are dependent on finite, zero or infinite of $b = \lim_{t \to \infty} t^{\alpha_2 - \alpha_1} L_1(t) / L_2(t)$.

If $0 < b < \infty$, it means that $\alpha_1 = \alpha_2$, $L_1 = L_2$, $b = \lim_{t \to \infty} L_1(t) / L_2(t)$ and $\sigma_{\lim}^2 = \frac{2(\mu_2^2 \alpha_1 b + \mu_1^2 \alpha_2)}{(\mu_1 + \mu_2)^3 \Gamma(4 - \alpha_{\min})}$, and $\alpha_{\min} = \alpha_1 = \alpha_2$ hold.

If $b = 0$ or $b \to \infty$, $\sigma_{\lim}^2 = \frac{2\mu_{\max}^2 \alpha_{\min}}{(\mu_1 + \mu_2)^3 \Gamma(4 - \alpha_{\min})}$ and $L = L_{\min}$ hold.

At time *t*, the number of received packets from *M* traffic sources is expressed as formula (16), while the timescale is reset to *Tt*, the number of aggregated packets is given by formula (17). For large enough *M* and *T*, the statistical behavior of aggregation above converges to the following expression [11]

$$TM \frac{\mu_1}{\mu_1 + \mu_2} t + T^H L^{\frac{1}{2}}(T) M^{\frac{1}{2}} \sigma_{\lim} B_H(t) \tag{21}$$

Where, B_H is fractal Brownian motion.

Below, the analysis on $N_f(t)$ will be presented. As MEO/LEO satellite is not stationary relative to the ground (GEO is the simplest situation), the movement of such satellite would change the status of inter-satellite link (ISL) and satellite-ground link, resulting in change of traffic transmission routing. For node A shown in Figure 2, at time t_0, the location coordinate of node A, B, G and H is demonstrated in Figure 2(1) that node A forwards a part of packets from G to B. As shown in Figure 2(2), at time $t_0 + \tau_1$, if the ISL between node A and B fails due to satellite movement and time-varying topology, the link between node A and H is established that node A as the intermediate node forwards packets from node G to B (routing changes). A shown in Figure 2(3), at time $t_0 + \tau_2$, node A forwards packets from node H to G. In other words, routing change has to happen as long as link status changes. Node A would forward data traffic between different node pair (such as G→B, G→H and H→G). Therefore, for node A, $N_f(t)$ contains different fragment of data traffic between different node pair. So-called fragment, it means data flow between node pair is interrupted due to link failure, thus node A only forwards a part of the data flow.

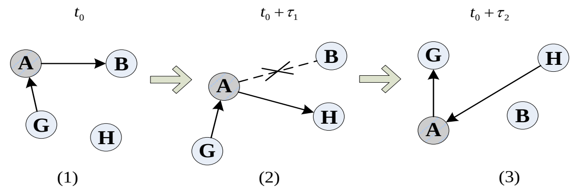

Figure 2. Node Movement and Routing Change

Number data flow as 1, 2, ..., M_f, for instance, G→B: 1, G→H: 2, and so on. Let $p_i(t)$ denote whether data flow i should be forwarded at time t. If $p_i(t)=1$, flow i is forwarded at time t; else if $p_i(t)=0$, flow i is not forwarded at time t. In a sense, $p_i(t)$ can be considered as ON/OFF process because $p_i(t)$ is ON state if flow i is forwarded and $p_i(t)$ is OFF state if no flow i is forwarded. Let λ_1 and λ_2 denote the duration of ON and OFF state, respectively. At time t, the number of forwarded packets received by intermediate node A can be formulated as

$$N_f(t)=\sum_{m=1}^{M_f} p_m(t)W^{(m)}(t) \tag{22}$$

Timescale is reset to *Tt*, the number of aggregated packets in $[0,t]$ can be given below

$$N_f(Tt)=\int_0^{Tt}\left(\sum_{m=1}^{M_f} p_m(u)W^{(m)}(u)\right)\mathrm{d}u \tag{23}$$

Following theorem presents the statistical property of the stochastic process $\{N_f(Tt),t\geq 0\}$ when M_f and T are large enough.

Theorem: for large enough M_f and T, following expression holds:

$$\lim_{T\to\infty}\lim_{M\to\infty}\frac{N_f(Tt)-\dfrac{\lambda_1}{\lambda_1+\lambda_2}TM_f\dfrac{\mu_1}{\mu_1+\mu_2}t}{T^H L^{\frac{1}{2}}(T)M_f^{\frac{1}{2}}}=\frac{\lambda_1}{\lambda_1+\lambda_2}\sigma_{\lim}B_H(t) \tag{24}$$

Where, $H=(3-\alpha_{\min})/2$ and $B_H(t)$ is fractal Brownian motion.

Under condition of large enough M_f and T, the average level of the stochastic process $\{N_f(Tt),t\geq 0\}$ can be derived as below according to formula (17), (21) and (24).

$$TM\frac{\mu_1}{\mu_1+\mu_2}t+\frac{\lambda_1}{\lambda_1+\lambda_2}TM_f\frac{\mu_1}{\mu_1+\mu_2}t=T\left(M+\frac{\lambda_1}{\lambda_1+\lambda_2}M_f\right)\frac{\mu_1}{\mu_1+\mu_2}t \tag{25}$$

The oscillation around average level is factually Fractal Brownian motion which is scale-transformed by low-order factor which is given below

$$T^{H}(L)T^{\frac{1}{2}}M^{\frac{1}{2}} + T^{H}(L)T^{\frac{1}{2}}M_{f}^{\frac{1}{2}}\frac{\lambda_1}{\lambda_1+\lambda_2} \tag{26}$$

Analysis above rationally interprets the propagation of self-similar traffic between satellite nodes. The packets received by a satellite node include two parts: one part is received by the node, while another part is forwarded to the next node, as given in formula (17). Stochastic process $N_l(t)$ and $N_f(t)$ are fractal Brownian motion [11], thus they have self-similarity. The sum of $N_l(t)$ and $N_f(t)$ is still fractal Brownian motion with Hurst parameter given below

$$H = (3 - \alpha_{\min})/2 \tag{27}$$

Two conclusions can be drawn from above analyses: (1) the aggregation of a number of ON/OFF processes has self-similarity; (2) through multiple hops between nodes, the forwarded traffic is still self-similar. The aggregation of two self-similar traffic flows keeps self-similarity. It is can be further deduced that the aggregation of more than two self-similar traffic flows still keeps self-similarity. According to (27), the Hurst parameter of the aggregated traffic is equal to the maximum Hurst value among all original traffic flows. In addition, J. Shi [13] has proves if a self-similar traffic is divided into several flows, these flows are still self-similar with the same Hurst parameter to the original self-similar traffic. When network traffic has self-similarity, it will always be kept regardless of aggregation or division.

4. Analysis on Propagation of Self-similar Traffic via Gateway in Satellite Network

Analysis in previous section only proves the aggregation and the propagation of self-similar traffic in satellite network which is the homogeneous network, but there is little research on the aggregation and the propagation of self-similar traffic from terrestrial network to satellite network.

Figure 3 presents the schematic of a sort of satellite-ground network where gateway connects terrestrial network with satellite network. Gateway is a bridge connecting and integrating heterogeneous networks. It support physical interface to different networks, flow regulation, congestion control, rate adaptation and protocol conversion. In addition, satellite also supports direct access of other terminals without gateway.

The traffic from terrestrial network (Internet, LAN, Cellular network, and so on) aggregates in gateway. After the process of gateway, traffic is sent to satellite network, as shown in Figure 4. This section will analyze whether the output traffic of gateway from terrestrial wired network to satellite network is still self-similar.

In order to analyze the issue, this section successively presents traffic model, channel model and gateway model.

4.1. Traffic Model

(1) Input traffic analysis

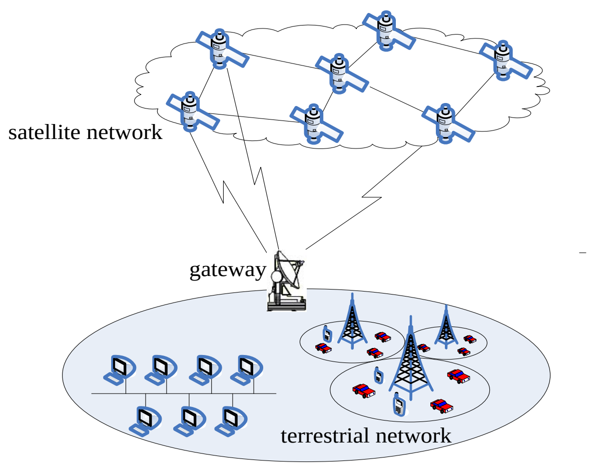

Figure 3. Satellite Network Connects Terrestrial Network via Gateway

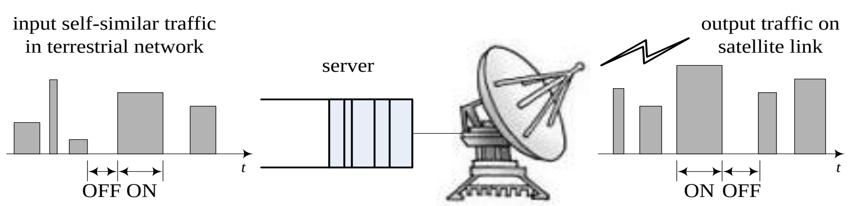

Figure 4. Wired Self-Similar Traffic Goes through Gateway and Enters Wireless Networks

Consider two-state ON/OFF traffic source. In ON duration, traffic source sends data with rate of g_j which can be deemed as constant. In OFF duration, traffic source does not send any data. Let X_j and Y_j denote the duration of ON and OFF state, respectively. The ON/OFF process can be mathematically expressed as below

$$s(t) = \sum_{j=1}^{\infty} g_j \cdot 1_{[s_j, s_j + X_{n+1})}(t), \quad t \geq 0 \tag{28}$$

Where, s_j represents the starting time of j -th ON state, that is

$$s_j = s_0 + \sum_{i=0}^{j-1} (X_i + Y_i), \quad j \geq 1 \tag{29}$$

Where, s_0 is the starting time of the first ON state, for convenience, suppose $s_0 = 0$.

$1_{[t_1, t_2)}(t)$ is defined as below

$$1_{[t_1, t_2)}(t) = \begin{cases} 1, & t \in [t_1, t_2) \\ 0, & t \notin [t_1, t_2) \end{cases} \tag{30}$$

Two rational premises are presented for following analysis.

Premise (1): $\{X_j, j = 1, 2, \cdots\}$ and $\{Y_j, j = 1, 2, \cdots\}$ are IID, and all of X_j and Y_j are Pareto distributed.

The aggregation of M ON/OFF processes can be considered as a new ON/OFF process of which duration of ON and OFF state meets premise above. Suppose $S(t)$ denote the arriving traffic which is the aggregation of M independent traffic flows represented by $S_i(t), i = 1, 2, \cdots, M$. Let X_j^s and Y_j^s denote the duration of ON/OFF state of $S(t)$, respectively. In its ON duration, traffic source sends data with rate G_j . For convenience of mathematical analysis, G_j can be deemed as constant. The expression of $S(t)$ is similar to (28)

$$S(t) = \sum_{j=1}^{\infty} G_j \cdot 1_{[S_j, S_j + X_j^s)}(t), \quad t \geq 0 \tag{31}$$

Let $\bar{F}(x; \alpha_1, K_1)$ and $\bar{F}(x; \alpha_0, K_0)$ denote the CCDF of ON/OFF duration, respectively. Where, $1 < \alpha_1 < 2$ and $1 < \alpha_0 \leq 2$.

The 1-st premise for distribution of $\{X_j^s, j = 1, 2, \cdots\}$ and $\{Y_j^s, j = 1, 2, \cdots\}$ is the same as Premise (1) above.

Premise (2): in ON duration, rate $\{G_j, j = 1, 2, \cdots\}$ is two-rate truncated Pareto distribution, and $\{G_j, j = 1, 2, \cdots\}$ is independent of $\{X_j^s, j = 1, 2, \cdots\}$ and $\{Y_j^s, j = 1, 2, \cdots\}$. Its CCDF is given below

$$\bar{\bar{F}}_G(x; \alpha_I, K_I, \alpha_{II}, L, R) = \begin{cases} 1, & 0 \leq x < K_I \\ \left(\frac{K_I}{x}\right)^{\alpha_I}, & K_I \leq x < L \\ \left(\frac{K_{II}}{x}\right)^{\alpha_{II}}, & L \leq x \leq R \\ 0, & x > R \end{cases} \tag{32}$$

Since $\bar{F}_G(x)$ is continuous at the point of $x = L$, then

$$\left(\frac{K_I}{L}\right)^{\alpha} = \left(\frac{K_{II}}{L}\right)^{\alpha} \tag{33}$$

So

$$K_{II} = e^{\frac{1}{\alpha_{II}}\left[K_I^{\alpha_I} \cdot L^{(\alpha_{II} - \alpha_I)}\right]} \tag{34}$$

The PDF according to (30) can be expressed as below

$$\begin{aligned} f_G(x; \alpha_I, K_I, \alpha_{II}, L, R) = {} & f(x; \alpha_I, K_I)[1 - u(x - L)] \\ & + f(x; \alpha_{II}, K_{II})[u(x - L) - u(x - R)] + (K_{II}/R)^{\alpha_{II}} \delta(x - R) \end{aligned} \tag{35}$$

Where $f(\cdot)$ is the PDF of Pareto distribution given by (11).

Given the above, the input aggregated traffic $S(t)$ at gateway is an ON/OFF process. Its distribution of ON/OFF state meets premise (1), while the data rate in ON duration satisfies premise (2). Y. Jie [14] presents the detailed deduction that $S(t)$ is LRD, *i.e.*, the input aggregated traffic is self-similar.

(2) Output traffic analysis

Let $E(t)$ denote the traffic output from gateway into satellite network. From the respective of traffic model, $E(t)$ is also ON/OFF process mainly because sending data is not continuous. Let X_j^E and Y_j^E denote the duration of ON/OFF state, respectively. Suppose $\{X_j^E, j = 1, 2, \cdots\}$

and $\{ Y_j^E, j = 1, 2, \cdots \}$ are stationary stochastic processes. As followed, the statistics of the output traffic X_j^E and Y_j^E will be discussed when the input traffic passes gateway.

4.2. Channel Model

For the sake of convenient analysis and adequate model, two-state Markov model is introduced in this paper, in which channel state alternates between "Good State" and "Bad State". Suppose the bit error rate of "Good State" and "Bad State" is $p_{e,g}$ and $p_{e,b}$, respectively. In general, $p_{e,g} << p_{e,b}$. The duration of "Good State" and "Bad State" is IID that follows exponential distribution with mean value $1/\beta$ and $1/\gamma$, respectively. The output packet uses ARQ (Automatic Repeat reQuest) and FEC (Forward Error Correction). For convenience, block correction code (w, k) is adopted where k is the length of information word and w is the length of code word. Let e denote the maximum number of error bit that can be corrected. If there is uncorrected error in the received packet, the packet transmission can be considered failed. The failure probability is

$$P_{f,state} = \sum_{i=e+1}^{w} C_w^i \cdot p_{e,state}^i \cdot (1 - p_{e,state})^{w-i} \tag{36}$$

Where, $state = \{good, bad\}$, C_w^i is combination.

If packet fails to be transmitted, the packet is cached in the buffer until it is received successfully through ARQ. From formula (36), the probability of the packet sent successfully can be derived as $(1 - P_{f,state})$.

Suppose V is the total data rate, accordingly, the rate of "Good State" and "Bad State" is c_g and c_b, respectively. Thus, c_g and c_b can be expressed as below

$$c_g = V \cdot \frac{k}{W} \cdot (1 - P_{f,good}) \tag{37}$$

$$c_b = V \cdot \frac{k}{W} \cdot (1 - P_{f,bad}) \tag{38}$$

4.3. Gateway Model

The input data packets from terrestrial network to gateway will be unpacked and encapsulated and then sent to satellite link to be wireless data flows. Considering both convenient analysis and appropriate model, gateway should have following functions:

(1) Input traffic is cached and queued in buffer;

(2) The buffered data is encapsulated and then output data packets are formed;

(3) Server sends newly generated packets to satellite link.

In the light of Kendall queuing model, suppose there is only one server in the system. The service system can be represented by G/G/1/B, where the first G stands for arriving time which has a general distribution; the second G means service time which has a general distribution; 1 denotes single server; B means there is a buffer in server.

Suppose gateway sends information every interval τ. For convenience, let $S(n)$ and $E(n)$ substitute $S(t)$ and $E(t)$, respectively, where n is the time index. From n-th interval τ on, a packet from terrestrial network comes into gateway with $S(n)$ bits of information. In gateway, the packet is unpacked into bit flow and stored in buffer. Every interval τ, $c\tau$ bits of information is encapsulated into a new packet to be sent.

Following service model is adopted by server which meets two conditions: (1) buffer size: $B >> c\tau$; (2) service discipline: if the number of stored information is not less than $c\tau$ bits, $c\tau$ bits are removed and formed into a packet and sent out of server; else, if the number of stored information is less than $c\tau$ bits, server waits for more bits to form packet.

The rationality behind selecting such a server with above two conditions is based on these factors. First, small buffer size would result in packet losses if traffic is heavy; however, properly large buffer size could better trade off between packet losses and jitter. It is very important for real-time traffic, such VoD (Video on Demand) and stream trsffic. Second, the interval τ has almost no influence on system delay. For instance, if two user terminals communicate with each other through satellite network (of course via gateway), the typical transmission delay for GEO/LEO satellite is 270ms and 20ms (actual delay is often more than the value because of additional processing delay, queuing delay, etc.), respectively. If the output packet size is 1kB (typical size) and link rate is 2Mb/s, it only takes about 4ms to generate the output packet. Factually, ground gateway has higher link rate such that smaller τ has negligible additional delay. Third, the service discipline can improve bandwidth utilization. When the number of stored information is less than $c\tau$ bits, server waits for more bits to form new packet, as a result, valuable bandwidth can be utilized sufficiently.

Let $Q(n)$ denote the queue length in n -th interval ($0 \le Q(n) \le B$). The relationship between $Q(n)$, $S(n)$ and $E(n)$ is given in formulas (39) and (40)

$$E(n) = \begin{cases} c, & S(n)\tau + Q(n-1) \ge c\tau \\ 0, & S(n)\tau + Q(n-1) < c\tau \end{cases} \tag{39}$$

$$Q(n) = \begin{cases} \left[[S(n)\tau + Q(n-1) - c\tau, 0]^{+}, B \right]^{-}, & S(n)\tau + Q(n-1) \ge c\tau \\ \left[[S(n)\tau + Q(n-1), 0]^{+}, B \right]^{-}, & S(n)\tau + Q(n-1) < c\tau \end{cases} \tag{40}$$

In formula (40), the result of the operator $[a,b]^{+}$ is the larger value of a and b , while the result of the operator $[a,b]^{-}$ is the smaller value of a and b .

In ON duration of $S(n)$, information bit enters buffer and the queue length is undated according to (40). $E(n)$ is updated according to (39).

4.4. Analysis on Output Traffic of Gateway

As server waits for forthcoming information bit to form new packet if the number of stored information is less than $c\tau$ bits, in this interval, $2M$ continuous ON and OFF states correspond to the OFF state of the output traffic $E(n)$, that means

$$Y_m^E = Y_{j-1}^S + X_{j+M-1}^S + \sum_{i=j}^{j+M-2} (X_i^S + Y_i^S), M \ge 1 \tag{41}$$

Following conditional probabilities hold [15]

$$P(X^E > x) = P(X^E > x \mid G \ge c) \cdot P(G \ge c) + P(X^E > x \mid G < c) \cdot P(G < c) \tag{42}$$

$$P(Y^E > y) = P(Y^E > y \mid G \ge c) \cdot P(G \ge c) + P(Y^E > y \mid G < c) \cdot P(G < c) \tag{43}$$

For further analysis, three rational premises are presented:

(1) The minimum rate K_I of ON state in input traffic satisfies $K_I << c_{state}$, where $state = \{good, bad\}$.

Suppose n is a too large integer, set $K_I < c/n$, then $c > nK_I$. Following equations are investigated: $P(G < c)/P(G \ge c) = [1 - P(G \ge c)]/P(G \ge c) = 1/P(G \ge c) - 1$. Referring traffic model in Section 4.1, then $P(G \geq c) < P(G \geq nK_I) = (K_I / nK_I)^{\alpha_I} = n^{-\alpha_I}$. Therefore, $P(G < c)/P(G \geq c) = 1/P(G \geq c) - 1 > n^{\alpha_I} - 1 >> 1$. So, $P(G < c) >> P(G \geq c)$.

Further, formula (42) and (43) can be approximated as below

$$P(X^E > x) \approx P(X^E > x | G < c) \cdot P(G < c) \approx P(X^E > x | G < c) \tag{44}$$

$$P(Y^E > y) \approx P(Y^E > y | G < c) \cdot P(G < c) \approx P(Y^E > y | G < c) \tag{45}$$

Let the mean rate of ON state of $S(n)$ be v_S which can be expressed as [14]

$$v_S = \int_{K_I}^{R} x \mathrm{d}\left(1 - \overline{F}_G(x)\right) = \frac{\alpha_I}{1 - \alpha_I}[K_I^{\alpha_I} \cdot L^{1-\alpha_I} - K_I] + \frac{\alpha_{II} K_{II}^{\alpha_{II}}}{1 - \alpha_{II}}[R^{1-\alpha_{II}} - L^{1-\alpha_{II}}] \tag{46}$$

It is noted that

$$E[S(n)] = \frac{\mu_1 v_S}{\mu_1 + \mu_0} \tag{47}$$

Where, μ_1 is the mean value of ON state, μ_2 is the mean value of OFF state.

Traffic intensity ρ is the ratio of $E[S(n)]$ to service rate:

$$\rho = \frac{E[S(n)]}{c} = \frac{\mu_1 v_S}{\mu_1 + \mu_0} \cdot \frac{1}{c} \tag{48}$$

(2) For actual queue, $L > c$ is constantly tenable [16]。

(3) Queue is stable.

Stable queue means the service rate satisfies: $c > E[S(n)] = \frac{\mu_1 v_S}{\mu_1 + \mu_0}$, equivalent to traffic intensity $\rho < 1$.

Based on premises above, the following results can be deduced [16]

$$P(X^E > x) \overset{x \to \infty}{\sim} C_1 x^{-(\alpha_1 + 1)} \tag{49}$$

$$P(Y^E > y) \approx P(Y^S > y) \tag{50}$$

Formulas (49) and (50) demonstrate that, when the input traffic passes gateway, whether X_j^S and X_j^E or Y_j^S and Y_j^E, they are not one-to-one mapping any longer. α_1 is the tail index of input traffic.

Expression (49) indicates that compared with the tail index of input traffic, the tail index of output traffic increases by 1, that is $2 < \alpha_1' = \alpha_1 + 1 < 3$.

Expression (50) indicates that the tail index of output traffic is the same as the tail index of input traffic, that is $1 < \alpha_0' = \alpha_0 \leq 2$, then following two situations to be discussed:

(1) If $1 < \alpha_0' < 2$, according to (27), the Hurst parameter $H' = (3 - \alpha_0')/2 > 0.5$. Therefore, after input self-similar traffic from terrestrial network being processed in gateway, the output traffic sent to satellite network from gateway is still self-similar.

(2) If $\alpha_0' = 2$, according to (27), the Hurst parameter $H' = 0.5$. Therefore, after input self-similar traffic from terrestrial network being processed in gateway, the output traffic sent to satellite network from gateway is not self-similar.

Intuitively, the rationality behind the tail index of ON state increased is that, since server has to wait for forthcoming input data bit to encapsulate new packet at times, the longer ON state in input traffic would be divided into many shorter ON states due to sampling every interval τ. Therefore, the probability of very long ON state would be decreased, lead to tail index increased.

Through analysis above, a determinate conclusion can be drawn that gateway does change the distribution of ON state in input traffic, resulting in statistical change of the output traffic in satellite network. Further, the change of tail index of ON and OFF state has an impact on self-similarity of output traffic. Specifically, if $\alpha_0 < \alpha_1 < 2$, for input traffic, Hurst parameter $H = (3-\alpha_0)/2$; on account of $2 < \alpha_1^{'} < 3$, the Hurst parameter of output traffic is $H^{'} = (3-\alpha_0)/2$; Apparently $H^{'} = H$, it means that the self-similarity of output traffic is the same as the input traffic. If $\alpha_1 < \alpha_0 < 2$, in the light of (27), for input traffic, Hurst parameter $H = (3-\alpha_1)/2$; however, the Hurst parameter of output traffic is $H^{'} = (3-\alpha_0)/2$; apparently, $H^{'} = H$ holds, it means that the self-similarity of output traffic is decreased compared with input traffic. If $\alpha_1 < \alpha_0 = 2$, due to $\alpha_1 < \alpha_0 = 2$, the Hurst parameter of output traffic is $H^{'} = (3-\alpha_0)/2 = 0.5$, it indicates that the self-similarity of output traffic is disappears.

In conclusion, considering the heterogeneity of input traffic, gateway can weaken the self-similarity of input traffic as a whole.

5. Conclusions

Based on satellite network, this paper analyzes the aggregation and the propagation of self-similar traffic between satellite nodes first. Further, taken gateway into consideration, this paper discusses the processing of input self-similar traffic in gateway and investigates whether output traffic of gateway is still self-similar. The aggregated and propagated self-similar traffic between satellite nodes are still self-similar under the conditions of time-varying topology and link interruption. When self-similar traffic is fed into gateway, self-similarity will be weakened as a whole mainly because gateway unpacks input packet and encapsulates new packet. In general, as the device connecting heterogeneous networks, gateway completes the process of rate adaptation and protocol conversion. In the process, the operations of unpacking and encapsulating packet will change the statistics of input traffic, leading to the change of output traffic in self-similarity.

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Authors

Zhenyu Na, he was born in 1981, Harbin, P.R.China. He received the B.S. degree in communication engineering, M.S. degree in information and communication engineering from Harbin Institute of Technology (HIT) in 2004 and 2007, respectively. In Jan. 2010, he received doctoral degree in information and communication engineering at Communication Research Center of HIT.

Now, he is a lecturer at School of Information Science and Technology of Dalian Maritime University (DMU) with research interests including satellite communications and networks, wireless communications, OFDM communications. Until now, he has published 15 papers as the first author in international journals and conferences.

Yang Cui, he was born in 1982, Harbin, P. R. China. He received the B.S. degree in communication engineering, M.S. degree in information and communication engineering from Harbin Institute of Technology (HIT) in 2005 and 2007, respectively. In 2012, he received doctoral degree in information and communication engineering at Communication Research Center of HIT.

Now, he is an assistant professor at Institute of Science and Industry Technology of HIT. His research interests cover wireless communications and networks, QoS, radio resource management for heterogeneous wireless networks. Until now, he has published more than 10 papers in international journals and conferences.

