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Распределенные компьютерные и телекоммуникационные сети: управление, вычисление, связь (DCCN-2021) = Distributed computer and communication networks: control, computation, communications (DCCN-2021) **:** материалы XXIV Междунар. научн. конфер, 20–24 сент. 2021 г., Москва / под общ. ред. В.М. Вишневского, К.Е. Самуйлова; Ин-т проблем упр. им. В.А. Трапезникова Рос. акад. наук Минобрнауки РФ – Электрон. текстовые дан. (1 файл: 24,9 Мб). – М.: ИПУ РАН, 2021. – 1 электрон. опт. диск (CD-R). – Систем. требования: Pentium 4; 1,3 ГГц и выше; Acrobat Reader 4.0 или выше. – Загл. с экрана. – ISBN 978-5-91450-258-1. – № госрегистрации 0322103543. – Текст : электронный.

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Analysis of the Amount of Information in Semi-Markov Flow

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Abstract

In this paper, we consider semi-Markov flow as a model of bit-level traffic. Each request of the flow brings some arbitrary distributed amount of information. The current paper aims to investigate the amount of information received in semi-Markov flow. We use the asymptotic analysis method under the limit condition of growing time of observation to derive the limiting probability distribution of the amount of information received in the flow and build its approximation.

Keywords: semi-Markov flow, asymptotic analysis, Gaussian approximation

1. Introduction

In telecommunication systems, the models of arrivals usually capture the structure of traffic from a packet-level point of view. Despite the interest in traffic models, few studies take into account packet length. Traffic modeling is focused on capturing such properties of telecommunication flows as burstiness, self-similarity and long-range dependence [1, 2, 3].

The idea of modeling arrivals together with the size of packets described in paper [4]. Authors use batch Markovian arrival process (BMAP) to model packet size as a size of the batch. In paper [5], authors build the model of traffic based on discrete-time BMAP model using two counting processes: the number of arriving packets and the number of bytes in those packets. Both processes in the model are affected by the state of the underlying Markov chain. More ideas of using packet size in traffic modeling are described in [6].

We propose semi-Markov flow as a model of bit-level traffic, which allows us to take into account the length of packets in telecommunication systems. In our model, packets arrivals are driven by the semi-Markov process and the lengths of packets follow the arbitrary distribution. To research the model, we use the asymptotic analysis method under the limit condition of the growing time of the flow observation. We build a Gaussian approximation of the cumulative distribution function of the amount of information received in the flow.

We have organized the paper as follows. In section 2, we present a mathematical model of semi-Markov flow. Section 3 is devoted to the derivation of the balance equation for the probability distribution of the process describing the amount of information received in the flow. In section 4, we investigate the model using the asymptotic analysis method under the limit condition of growing time and build a Gaussian approximation. Section 5 is dedicated to the concluding remarks.

2. Mathematical Model of Semi-Markov Flow

Semi-Markov flow is determined by semi-Markov matrix $\mathbf{A}(x)$. Elements $A_{k\nu}(x)$ of the matrix has the following from:

$$A_{k\nu}(x) = P\{\xi(n+1) = \nu, \tau(n+1) < x|\xi(n) = k\}. \tag{1}$$

We also take into account that

$$\mathbf{P} = \mathbf{A}(\infty), \tag{2}$$

where $\mathbf{P}$ is the transition matrix of embedded Markov chain $\xi(n)$ at the moments of state changes of the semi-Markov process. Moments t_n of arrivals in semi-Markov flow we determine as follows:

$$t_{n+1} = t_n + \tau(n+1).$$

Further, we use semi-Markov process $k(t)$, which is defined by equality

$$k(t) = \xi(n+1), \text{if } t_n < t \le t_{n+1} = t_n + \tau(n+1). \tag{3}$$

Each request of the flow brings some random amount of information with arbitrary distribution given by cumulative distribution function $B(x)$.

We denote $S(t)$ as the amount of information received in semi-Markov flow during time t. The problem is to derive the probability distribution of process $S(t)$.

We also denote $z(t)$ as the residual time of next arrival in the flow and consider three-dimensional process $\{k(t), S(t), z(t)\}$.

3. Balance Equation for the Probability Distribution of the Flow State

Three-dimensional process $\{k(t), S(t), z(t)\}$ is Markovian. Thus, we consider the function

$$P_k(s, z, t) = P\{k(t) = k, S(t) < s, z(t) < z\}$$

and derive balance equation

$$\frac{\partial P_k(s,z,t)}{\partial t} = \frac{\partial P_k(s,z,t)}{\partial z} - \frac{\partial P_k(s,0,t)}{\partial z} + \sum_{\nu=1}^{K} \int_0^s \frac{\partial P_k(s-x,0,t)}{\partial z} dB(x) A_{\nu k}(z), \quad (4)$$

where $\frac{\partial P_k(s,0,t)}{\partial z} = \frac{\partial P_k(s,z,t)}{\partial z}\Big|_{z=0}$.

We introduce partial characteristic functions

$$H_k(u,z,t) = \int_0^\infty e^{jus} d_s P_k(s,z,t)$$

and denote vector characteristic function

$$\mathbf{H}(u,z,t) = \{H_1(u,z,t), H_2(u,z,t), ..., H_K(u,z,t)\},$$

identity matrix $\mathbf{I}$ and vector of ones $\mathbf{e}$. After that, we rewrite equation (4) together with additional equation obtained taking the limit by $z \to \infty$

$$\frac{\partial \mathbf{H}(u,z,t)}{\partial t} = \frac{\partial \mathbf{H}(u,z,t)}{\partial z} - \frac{\partial \mathbf{H}(u,0,t)}{\partial z}\{\mathbf{I} - \mathbf{A}(z)B^*(u)\},$$

$$\frac{\partial \mathbf{H}(u,t)}{\partial t}\mathbf{e} = \frac{\partial \mathbf{H}(u,0,t)}{\partial z}\{B^*(u) - 1\}\mathbf{e}, \quad (5)$$

where $B^*(u) = \int_0^\infty e^{jux} dB(x)$ is the characteristic function of the amount of information in one request of semi-Markov flow and $\mathbf{H}(u,t) = \mathbf{H}(u,\infty,t)$.

4. Asymptotic Probability Distribution of the Amount of Information Received in Semi-Markov Flow under the Limit Condition of Growing Time

We introduce the equality $t = \tau T$, where $\tau \geq 0$ and T is an infinite parameter, as the limit condition of growing time. Solving system (5) in the limit by $T \to \infty$, we formulate the following theorem.

Theorem 1. For characteristic function $H(u,t) = \mathbb{E}e^{juS(t)} = \mathbf{H}(u,t)\mathbf{e}$ in the limit condition of growing time the following equality holds:

$$\lim_{t\to\infty} \left\{ H(u,t) - \exp\left(ju\kappa_1 t + \frac{(ju)^2}{2}\kappa_2 t \right) \right\} = 0, \quad (6)$$

where

$$\kappa_1 = \frac{b_1}{\mathbf{r}\mathbf{A}_1\mathbf{e}}, \tag{7}$$

$$\kappa_2 = \frac{b_2}{\mathbf{r}\mathbf{A}_1\mathbf{e}} + 2b_1\mathbf{g}'(0)\mathbf{e}. \tag{8}$$

Here b_1 and b_2 are the first and second raw moments of distribution function $B(x)$, matrices $\mathbf{A}_1$ and $\mathbf{A}_2$ are determined by formulas

$$\mathbf{A}_1 = \int_0^\infty (\mathbf{P} - \mathbf{A}(x))dx,$$

$$\mathbf{A}_2 = \int_0^\infty x^2 d\mathbf{A}(x).$$

Vector $\mathbf{g}'(0)$ is the solution of inhomogeneous system of equations

$$\mathbf{g}'(0)(\mathbf{I} - \mathbf{P}) = \kappa_1(\mathbf{r} - \mathbf{R}),$$

$$\mathbf{g}'(0)\mathbf{A}_1\mathbf{e} = \frac{b_1}{2}\frac{\mathbf{r}\mathbf{A}_1\mathbf{e}}{(\mathbf{r}\mathbf{A}_2\mathbf{e})^2} - b_1.$$

Vector $\mathbf{r}$ is the steady state probability distribution of embedded Markov chain $\xi(n)$, which is the solution of the system

$$\mathbf{r} = \mathbf{r}\mathbf{P}, \quad \mathbf{r}\mathbf{e} = 1.$$

Vector $\mathbf{R}$ is the steady state probability distribution of semi-Markov process $k(t)$, which is given by formula

$$\mathbf{R} = \frac{\mathbf{r}\mathbf{A}_1}{\mathbf{r}\mathbf{A}_1\mathbf{e}}.$$

As we can see, the distribution of the amount of information received in semi-Markov flow is asymptotically Gaussian with mean $\kappa_1 t$ and variance $\kappa_2 t$.

We note that by setting $b_1 = 1$ and $b_2 = 1$, we obtain the case when the amount of information in a packet is deterministic and equal to one. Thus, the obtained result is valid for the number of packet arrivals in the flow.

5. Conclusion

We have considered the bit-level traffic model in form of semi-Markov flow. For the amount of information received in the flow, we have obtained the limiting probability distribution under the limit condition of growing time of observation. We have derived the explicit formula for the mean and variance of Gaussian distribution. Since the distribution of the packet length in the model is arbitrary, the results are applicable for the number of packets arrivals when we set the size of each packet is equal to one.

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