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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. Вишневого, 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. – № государственной регистрации 0322103543. – Текст : электронный.

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В материалах научной конференции DCCN-2021, подготовленных к выпуску к.ф.-м.н. Козыревым Д.В., обсуждены перспективы развития и сотрудничества в этой сфере.

Сборник материалов конференции предназначен для научных работников и специалистов в области управления крупномасштабными системами.

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Содержание / Contents

1. Nazarov A.A., Samorodova M.V. WAITING TIME ASYMPTOTIC ANALYSIS OF A M/GI/1 RETRIAL QUEUE SYSTEM.....	1
2. Дудин А.Н., Дудин С.А., Дудина О.С. СИСТЕМА ВМАР/Р Н/1 С НАГРЕВОМ И ОХЛАЖДЕНИЕМ ПРИБОРА	7
3. Дудин А.Н., Дудин С.А., Дудина О.С. СИСТЕМА МАР/РН/1 С АВТОНОМНЫМ ОГРАНИЧЕННЫМ ОБСЛУЖИВАНИЕМ БЕЗ ПРЕРЫВАНИЯ	15
4. Sztrik J., Szilágyi Z., Kólcse Cs. SOFTWARE PACKAGES FOR TEACHING QUEUEING THEORY	21
5. Namiot D., Ilyushin E., Chizov I., Gamayunov D. ON THE APPLICABILITY AND LIMITATIONS OF FORMAL VERIFICATION OF MACHINE LEARNING SYSTEMS	26
6. Melikov A., Shahmaliyev M., Sztrik J. ALGORITHMIC APPROACH TO STUDY THE MODEL OF PERISHABLE INVENTORY SYSTEM WITH REPEATED CUSTOMERS.....	35
7. Shchetinin E.Yu., Sevastianov L.A., Demidova A.V., Blinkov Yu. A. DETECTION OF CARDIAC ARRHYTHMIA BASED ON THE ANALYSIS OF ELECTROCARDIOGRAM USING DEEP LEARNING MODELS	41
8. Полин Е.П., Моисеева С.П., Моисеев А.Н. АСИМПТОТИЧЕСКИЙ АНАЛИЗ НЕОДНОРОДНОЙ СМО $M GI _{\infty}$, ФУНКЦИОНИРУЮЩЕЙ В МАРКОВСКОЙ СЛУЧАЙНОЙ СРЕДЕ, В УСЛОВИИ ЭКВИВАЛЕНТНОГО РОСТА ВРЕМЕНИ ОБСЛУЖИВАНИЯ НА ПРИБОРАХ	48
9. Sztrik J., Tóth Á., Pintér Á., Bács Z. THE SIMULATION OF FINITE-SOURCE RETRIAL QUEUEING SYSTEMS WITH TWO-WAY COMMUNICATIONS TO THE ORBIT AND IMPATIENT CUSTOMERS	58
10. Tóth Á., Sztrik J., Bérczes T., Kuki A. SIMULATION OF TWO-WAY COMMUNICATION RETRIAL QUEUEING SYSTEMS WITH NON-RELIABLE SERVER, IMPATIENT CUSTOMERS TO THE ORBIT AND BLOCKING	66
11. Rusilko T.V. ASYMPTOTIC ANALYSIS OF A CLOSED EXPONENTIAL QUEUEING NETWORK WITH UNRELIABLE NODES.....	74
12. Nekrasova R. S. STABILITY CONDITIONS FOR A MULTI-ORBIT RETRIAL SYSTEM WITH GENERAL RETRIALS UNDER CLASSICAL RETRIAL POLICY.....	80
13. Mondal M., Shidlovskiy S.V., Shashev D.V., Okunsky M.V. AUTONOMOUS INFRARED GUIDED UAV PRECISION LANDING SYSTEM.....	86
14. Zverkina G.A. ON POLYNOMIAL CONVERGENCE RATE FOR RELIABILITY SYSTEM WITH WARM STANDBY.....	94

15. Shatravin V., Shashev D.V., Shidlovskiy S.V.	
DEVELOPING OF MODELS OF DYNAMICALLY RECONFIGURABLE NEURAL NETWORK ACCELERATORS BASED ON HOMOGENEOUS COMPUTING ENVIRONMENTS	102
16. Kosarava K.U., Kopats D.Y.	
APPLICATION OF A QUEUING NETWORK WITH POSITIVE AND NEGATIVE ARRIVALS FOR MODELING A COMPUTER NETWORK WITH ANTIVIRUS SOFTWARE.....	108
17. Клименок В.И., Дудин А.Н., Семенова О.В.	
НЕНАДЕЖНАЯ СИСТЕМА МАССОВОГО ОБСЛУЖИВАНИЯ С ПОВТОРНЫМИ ВЫЗОВАМИ И РЕЗЕРВНЫМ ПРИБОРОМ.....	114
18. Efimov V.V.	
TARGETED MASSIVE INCIDENT NOTIFICATION SYSTEM FOR A GLOBALLY DISTRIBUTED COMPUTATION NETWORK	120
19. Borevich E.V.	
INFLUENCE OF INFORMATIONAL CONTENT ON FILM FRAME PERCEPTION.....	125
20. Grebeshkov A.Y.	
ONTOLOGY-BASED MODEL FOR SENSOR NETWORK FAULT MANAGEMENT	138
21. Nazarov A.A., Moiseev A.N., Lapatin I.L., Paul S.V., Lizyura O.D., Pristupa P.V., Peng Xi, Chen Li, Bai Bo	
ANALYSIS OF THE AMOUNT OF INFORMATION IN SEMI-MARKOV FLOW.....	143
22. Kuki A., Bérczes T., Tóth Á., Sztrik J.	
MODELING OF NON-RELIABLE RETRIAL QUEUEING SYSTEMS WITH COLLISIONS AND CATASTROPHIC BREAKDOWNS	148
23. Astafiev S., Rumyantsev A.	
DISTRIBUTED COMPUTING OF EMBARRASSINGLY PARALLEL R APPLICATIONS USING RBOINC PACKAGE.....	155
24. Bondarchuk A. S., Shashev D.V., Shidlovskiy S.V.	
BINARY GRADIENT COMPUTATION AND IMPLEMENTATION IN RECONFIGURABLE COMPUTING ENVIRONMENTS	161
25. Bulinskaya E.V.	
RISKS ORDERING AND RELIABILITY OF SOME APPLIED PROBABILITY SYSTEMS	167
26. Daneshmand B.	
SURVEY OF LOAD BALANCING MECHANISMS BASED ON SDN IN 5G/IMT- 2020.....	173
27. Дудин А.Н., Мэй Лю	
МНОГОЛИНЕЙНАЯ СИСТЕМА С РАЗНОТИПНЫМИ НЕНАДЕЖНЫМИ ПРИБОРАМИ И ПОВТОРНЫМИ ВЫЗОВАМИ	185
28. Kim C., Dudin A.N., Dudin S.A., Dudina O.S.	
MULTI-SERVER LOSS QUEUEING SYSTEM WITH THE BMMAP ARRIVAL PROCESS	191
29. Yudin A.V., Grosheva P.Yu.	
INTELLIGENT SYSTEM FOR FORECASTING THE EFFECTIVENESS OF SPACE SERVICES IN SOLVING ECONOMIC PROBLEMS	197

30. Tyulin A.E., Chursin A.A., Yudin A.V., Grosheva P.Yu. BASIS FOR THE FORMATION OF A DIGITAL ECOSYSTEM OF AN INDUSTRIAL HOLDING	207
31. Головинов Е.Э., Аминев Д.А., Козырев Д.В., Кулыгин В.Н. ОПРЕДЕЛЕНИЕ ПОКАЗАТЕЛЕЙ ДОЛГОВЕЧНОСТИ РАСПРЕДЕЛЁННОЙ КОММУНИКАЦИОННОЙ СЕТИ МЕТЕОСТАНЦИЙ МИНИМАЛЬНОЙ КОНФИГУРАЦИИ.....	212
32. Markovich N.M., Ryzhov M.S. INFORMATION SPREADING IN NON-HOMOGENEOUS EVOLVING NETWORKS	220
33. Hilquias V.C.C., Zaryadov I.S., Milovanova T. A. SINGLE-SERVER QUEUEING SYSTEMS WITH EXPONENTIAL SERVICE TIMES AND THRESHOLD-BASED RENOVATION	229
34. Razumchik R.V. JOINT STATIONARY DISTRIBUTION IN THE TWO-CHANNEL QUEUEING SYSTEM WITH ORDERED ENTRY, GOVERNED BY ONE QUEUE SKIPPING POLICY	237
35. Stepanov M.S., Stepanov S.N., Andrabi U., Petrov D.S., Ndayikunda J. ENHANCING THE RESOURCE SHARING CAPABILITIES OF A NETWORK BY DEPLOYING NETWORK SLICING PROCEDURE	243
36. Шкленник М.А., Моисеев А.Н, Задиранова Л.А. МЕТОД МАРКОВСКОГО СУММИРОВАНИЯ ДЛЯ ИССЛЕДОВАНИЯ ПОТОКА ПОВТОРНЫХ ОБРАЩЕНИЙ В ДВУХФАЗНОЙ СИСТЕМЕ $MAP GI _{\infty}$	252
37. Borisovskaya A. LINUX NETWORK DEVICE DRIVERS: NAPI POLLING IN KERNEL THREADS	259
38. Жарков М.Л., Казаков А.Л., Лемперт А.Л. К ВОПРОСУ О ПРИМЕНЕНИИ ТЕОРИИ МАССОВОГО ОБСЛУЖИВАНИЯ ПРИ МОДЕЛИРОВАНИИ РАБОТЫ ЖЕЛЕЗНОДОРОЖНЫХ СТАНЦИЙ.....	263
39. Krishtalev N., Lisovskaya E., Moiseev A. RESOURCE QUEUEING SYSTEM $M/M/\infty$ IN RANDOM ENVIRONMENT ...	269
40. Kartashevskiy V.G., Buranova M.A. OPENFLOW-BASED SOFTWARE-DEFINED NETWORKING QUEUE MODEL	275
41. Zatuliveter Yu.S., Fishchenko E.A. THE AUTOMATA-BASED APPROACH TO LARGE SYSTEMS CONTROL IN THE GLOBAL COMPUTER ENVIRONMENT	281
42. Grusho A.A., Grusho N.A., Zabezhaiko M.I., Timonina E.E. STATISTICAL METHOD FOR SUPPORT OF RESPONSIBLE DECISION	287
43. Sabbagh A.A., Shcherbakov M.V. EVALUATION OF REACTIVE ROUTING PROTOCOLS PERFORMANCE UNDER MALICIOUS ATTACKS IN VANET	292
44. Danilyuk E.Yu., Moiseeva S.P., Nazarov A.A. ASYMPTOTIC DIFFUSION ANALYSIS OF AN RETRIAL QUEUEING SYSTEM $M/M/1$ WITH IMPATIENT CALLS	298

45. Borisov A.V., Mukharlyamov R.G., Kaspirovich I.E. CONSTRUCTION OF DIFFERENTIAL EQUATIONS OF A NONHOLONOMIC MECHANICAL SYSTEM AND PERSPECTIVES OF MOTION CONTROL USING ARTIFICIAL INTELLIGENCE METHODS	306
46. Nazarov A.A., Paul S.V., Phung-Duc T., Morozova M.A. SCALING LIMITS OF A TANDEM RETRIAL QUEUE WITH COMMON ORBIT AND POISSON ARRIVAL PROCESS	315
47. Rogozin S.S. A GENERALIZED LOSS PRIORITY SYSTEM, WITH APPLICATION TO BANDWIDTH SHARING	322
48. Mikhaylov K.I., Abramov A.G. AN INNOVATIVE SOLUTION FOR ANALYZING THE DYNAMICS OF SLOWLY DEVELOPING PROCESSES OF CHANGING THE GEOMETRY OF ENGINEERING STRUCTURES USING THE EXAMPLE OF A SYSTEM FOR STRENGTHENING A ROCKY SLOPE	328
49. Федотов И.А., Ларионов А.А., Михайлов Е.А. ЭФФЕКТИВНОСТЬ РАДИОЧАСТОТНОЙ ИДЕНТИФИКАЦИИ ТРАНСПОРТНЫХ СРЕДСТВ С ИСПОЛЬЗОВАНИЕМ АНАЛИТИЧЕСКОЙ АППРОКСИМАЦИЕЙ И ИМИТАЦИОННОГО МОДЕЛИРОВАНИЯ	336
50. Kochetkov D.M., Birukou A.A., Ermolayeva A.M. THE IMPORTANCE OF CONFERENCE PROCEEDINGS IN RESEARCH EVALUATION: A METHODOLOGY FOR ASSESSING CONFERENCE IMPACT	343
51. Poslavskiy S., Shashev D.V., Shidlovskiy S.V. OBJECT CLASSIFICATION USING NEURAL NETWORKS WITH BINARY INPUT AND BINARY FEATURE EXTRACTION	350
52. Вишневский В.М., Семёнова О.В., Тан З.Т. ИСПОЛЬЗОВАНИЕ МАШИННОГО ОБУЧЕНИЯ ДЛЯ ИССЛЕДОВАНИЯ СИСТЕМ ПОЛЛИНГА С КОРРЕЛИРОВАННЫМИ ВХОДНЫМИ ПОТОКАМИ	357
53. Blaginin A.L., Lapatin I.L. THE TWO-DIMENSIONAL OUTPUT PROCESS OF RETRIAL QUEUE WITH TWO-WAY COMMUNICATION AND MMPP INPUT	369
54. Sabbagh A.A., Shcherbakov M.V. AN EFFICIENT CLUSTER ROUTING PROTOCOL FOR VEHICULAR AD-HOC NETWORK USING BIO-METAHEURISTIC ALGORITHM	376
55. Ageev K.A., Sopin E.S. ON THE CONVERGENCE OF AN ITERATIVE METHOD FOR APPROXIMATE ANALYSIS OF A RESOURCE QUEUING SYSTEM WITH SIGNALS	384
56. Dagaev A.V., Pham V.D., Kirichek R.V., Afanaseva O.V., Yakovleva E.A. AVAILABILITY FACTOR ANALYSIS OF A NETWORK IN MESH STRUCTURE	390
57. Pham V.D., Do P.H., Le D.T., Kirichek R.V. A METHOD FOR LINK QUALITY ESTIMATION IN LORA NETWORK BASED ON SUPPORT VECTOR MACHINE	401
58. Moskaleva F., Lisovskaya E., Lapshenkova L., Shorgin S., Gaidamaka Yu. DEVELOPMENT OF RADIO ADMISSION SCHEME MODEL FOR 5G NETWORK SLICING FRAMEWORK AS A RETRIAL QUEUE	409

59. Houankpo H.G.K., Kozyrev D.V., Nibasumba E., Mouale M.N.B.	
RELIABILITY MODEL OF A HOMOGENEOUS HOT-STANDBY K-OUT-OF-N SYSTEM	415
60. Efrosinin D., Stepanova N., Sztrik J.	
FULL VERSION FOR ALGORITHMIC ANALYSIS OF FINITE-SOURCE MULTI-SERVER HETEROGENEOUS QUEUES	424
61. Рыков В.В., Козырев Д.В., Иванова Н.М.	
ПРИМЕНЕНИЕ ТЕОРИИ РАЗЛОЖИМЫХ ПОЛУРЕГЕНЕРИРУЮЩИХ ПРОЦЕССОВ К ИССЛЕДОВАНИЮ СИСТЕМЫ К-ИЗ-N:F С ЧАСТИЧНЫМ РЕМОНТОМ.....	454
62. Pomogalova A.V., Sazonov D.D., Donskov E.A., Borodin A.S. , Kirichek R.V.	
IDENTIFICATION OF NARROWBAND WIRELESS COMMUNICATION NETWORKS SYSTEMS AND INTERNET OF THINGS DEVICES USING BLOCKCHAIN TECHNOLOGY	461
63. Le D.T., Nguyen T.D., Le L.B., Pham V.D., , Kirichek R.V.	
ANALYSIS OF NETWORK SECURITY ISSUES IN THE JOIN PROCEDURE OF LORAWAN.....	468

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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:

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

We also take into account that

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

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

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

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

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

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 $z \rightarrow \infty$

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

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 $T \rightarrow \infty$, 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:

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

where

$$\kappa_1 = \frac{b_1}{\mathbf{r}\mathbf{A}_1\mathbf{e}}, \quad (7)$$

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

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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