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QUEUING SYSTEM WITH BULK SERVICE AS A MODEL OF SCTP PROTOCOL FUNCTIONING

The article presents the results of developing a model for the Stream Control Transmission Protocol functioning as a queuing system with bulk service. It constructs a graph of states and transitions for deriving linear and differential equation systems regarding the state probabilities. We obtain explicit solutions to analyse the basic SCTP functioning.

Keywords: *computer network, protocol, probabilistic model, queuing system, bulk service.*

Introduction

One of the modern protocols providing streaming data over a computer network is the TCP/IP stack transport protocol – SCTP (Stream Control Transmission Protocol), which ensures reliable transmission of user data over the network. It is particularly effective at transmitting data related to real-time applications such as speech and video streaming. The quality of functioning of networks that use the SCTP protocol largely depends on the timely delivery and reliability of the transmission of signalling information. Signalling systems manage establishing connections for traditional telephony users while also enabling the provision of 'smart' network services and cellular mobile networks. Transferring data via the SCTP protocol proceeds as follows [1]: data (messages in the SCTP protocol terms) from the user request is encapsulated in data chunks and queued for transmission. In the queue, data chunks form a SCTP packet, which, at the request of the operating device, is selected from the queue for transmission to the IP network. Thus, it is possible to describe transmitting a message over the SCTP protocol in queuing systems with bulk service terms. Indeed, in such a system, it is natural to understand a request as a piece of data, a group of requests as a package, and a service device as an operating device. The characteristics of message flow and packet processing time vary widely and are describable by different distribution laws. The currently available theoretical research results on queuing systems with bulk service do not fully provide applied computational aspects. Applying these results to the problem solution requires the development of existing and new models and methods for analysing probabilistic characteristics.

Literature Review

Queuing systems with bulk service are used in the areas of human activity such as industry, transport, and communications. Research on this queuing systems class began with scientists N. Bailey and F. Downton [2, 3]. Bailey was the first to consider a system with a Poisson incoming flow and a variable bounded above by the size of the group of requests. Using the method of generating functions, he obtained expressions for the average value and variance of the request number in the queue for a Markov chain nested at the moments immediately preceding the end of servicing groups of requests. Work [4] examines queuing systems with bulk service under the assumption of an input flow of requests described by a Markov process. The paper does not derive some characteristics, such as the probability of losing requests. Also, it does not obtain some results in explicit form. The article [5] is devoted to developing a model to provide a way to describe several existing arbitration protocols in a distributed and abstract manner so that their properties and performance can be easily compared and analysed. In [6], the service process operates according to a general bulk service rule, i.e., the service process initiation takes place only if customers are present in the queue at node 1, and the maximum service batch size is b. The service time distribution in each phase is exponential with service rate, which depends on the service stage j, $1 \le j \le k$, and the size of the batch m, $a \le m \le b$. The paper analyses the system behaviour in the steady state and derives some important system characteristics. In the study [7], there was an attempt to review the work done on bulk queues, modelling various phenomena. The goal was to provide sufficient information to analysts, managers, and industry people who are interested in using queueing theory to model congestion problems and want to locate the details of relevant models. [8] presents the analysis of a queue that serves batches of customers with a novel service policy, showing that it is possible to derive a closed steady-state distribution of the number of customers in the queue for a very general setting of its parameters. The paper [9] proposes a procedure to construct the membership functions of the performance measures in bulk service queuing systems with the arrival and service rates as fuzzy numbers. The basic idea is to transform a fuzzy queue with bulk service into a family of conventional crisp queues using the α-cut approach. The paper [10] considers an MX/G(a, b)/1 queueing system with a modified M-vacation policy and variant arrival rate. After service completion, if the number of waiting customers is less than a, the server avails of multiple vacations until the queue length reaches a or consecutively avails of M number of vacations, whichever occurs first. The work [11] obtains expressions of the G/G/1/K queuing model under the popular protocol interference model when adopting CSMA/CA for MAC control. An extensive simulation study results indicate that the proposed G/G/1/K queueing model outperforms M/M/1/K and G/G/1 under a high network load, while it provides competitive results when the network is lightly loaded.

A review of the latest research has shown that the theory of queuing systems with bulk service is developing intensively. It has led to obtaining several results that have practical applications. It is worth noting that most of the works are theoretical; the research results are not tied to specific technical or information systems.

Aim and Objectives

Internet resources, network services, and applications have become integral to the modern information industry. An essential indicator of the quality of network interaction, software, and equipment used is the throughput of transport connections. Accordingly, the performance of most network applications depends on the performance of the transport layer protocol. Mathematical modelling of information processes at the transport layer of the network data transfer protocol makes it possible to analyse the dependence of throughput on the characteristics of the data transfer path and protocol parameters. The object of the study is the data transmission process via the SCTP protocol, carried out in stochastic mode. It accounts for the system functioning as a queuing system with a group selection of service requests. The article aims to examine the processes of information transfer via the SCTP protocol based on queuing systems with a group selection of service requests. The study will consider the Markovian and non-Markovian nature of event flows in such systems.

Discussion of Results

Transmitting a message over the SCTP protocol can be described in queuing systems with bulk service terms. Indeed, in such a system, data chunks at the input of the protocol form an input stream of requests, described by the distribution function $A(t)$. Requests enter the buffer memory, where they form a packet. The operating device carries out the packet sampling from the buffer memory. The sampling time is subject to the distribution $B(t)$.

First, we consider the case when the input flow of requests is Poisson with the parameter λ, and the access of the operating device to the buffer memory obeys the exponential law with the parameter μ: $B(t) = 1 - \exp(-\mu t)$. Fig. 1 shows the system states and transitions graph for the case when the buffer memory volume is 3.

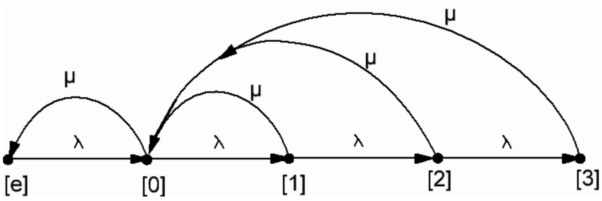

Fig. 1. Graph of system states and transitions.
[e] is the state of the system when the operating device is idle; [i], i = 0, 1, 2... are the states when the operating device processes the next batch of requests in the buffer memory of i requests

Let us denote through p_e the stationary state probability [e], and through p_i the stationary state probability [i], i = 1, 2, ..., k.

Using the graph of states and transitions per the methodology of [12], we will compose a system of linear equations for the probabilities of system states as:

$$\begin{aligned} &-\lambda p_e + \mu p_0 = 0, \\ &-(\lambda+\mu)p_0 + \lambda p_e + \mu\sum_{i=1}^{k} p_i = 0, \\ &-(\lambda+\mu)p_i + \lambda p_{i-1} = 0,\ 1 \le i < k, \\ &-\mu p_k + \lambda p_{k-1} = 0. \end{aligned} \tag{1}$$

From system (1), we will successively obtain the next:

$$\begin{aligned} &p_0 = \frac{\lambda}{\mu} p_e, \\ &p_1 = \frac{\lambda}{\lambda+\mu} p_0 = \frac{\lambda}{\mu}\left(\frac{\lambda}{\lambda+\mu}\right)^1 p_e, \\ &p_i = \frac{\lambda}{\lambda+\mu} p_{i-1} = \frac{\lambda}{\mu}\left(\frac{\lambda}{\lambda+\mu}\right)^i p_e,\ 1 \le i < k, \\ &p_k = \frac{\lambda}{\mu} p_{k-1} = \left(\frac{\lambda}{\mu}\right)^2\left(\frac{\lambda}{\lambda+\mu}\right)^{k-1} p_e. \end{aligned} \tag{2}$$

Using the normalisation condition

$$p_e + \sum_{i=0}^{k} p_i = 1\ , \tag{3}$$

we will get that:

$$p_e = \left\{1+\frac{\lambda}{\mu}\left[1+\sum_{i=1}^{k-1}\left(\frac{\lambda}{\lambda+\mu}\right)^i+\frac{\lambda}{\mu}\left(\frac{\lambda}{\lambda+\mu}\right)^{k-1}\right]\right\}^{-1} = \\ = \left\{1+\frac{\lambda}{\mu}\left(1+\frac{\lambda}{\mu}\right)\right\}^{-1}. \quad (4)$$

Thus, we found all the probabilities.

Average number of requests in buffer memory is:

$$L_b = \frac{\lambda}{\mu}\left\{\sum_{i=1}^{k-1} i\left(\frac{\lambda}{\lambda+\mu}\right)^i + k\frac{\lambda}{\mu}\left(\frac{\lambda}{\lambda+\mu}\right)^{k-1}\right\}p_e \quad . \quad (5)$$

Probability of losing requests:

$$P_{loss} = \frac{\lambda}{\mu}\left(\frac{\lambda}{\lambda+\mu}\right)^{k-1} p_e . \quad (6)$$

We consider the general case when the service time of a queue group of requests is subject to a general distribution with a distribution function $B(t)$.

We denote by $r(t)$ the instantaneous intensity of reading requests from the drive, defined as $r(t)=B'(t)[1-B(t)]^{-1}$, through μ – the average intensity of reading requests, through $\beta(s)=\int_0^\infty e^{-st}\,dB(t)$ – the Laplace–Stieltjes transform from $B(t)$.

Let $[e]$ be the state when there are no requests in the system and $[n, u]$ – be the state when there are n requests in the storage. The service channel processes the next group of requests, and the time elapsed since the previous access to the storage is equal to u. We denote through $p_e(t)$ the state probability $[e]$ and through $p_n(t)$ – the probability that there are n requests in the drive, and because $p_n(t,u)$ – the probability density u that there were n requests in the drive and the time elapsed after the previous access to the drive (service time) is equal to u_0, $u<u_0<u+\Delta$. , $p_n(t)$ and $p_n(t,u)$ are related to each other by a ratio $p_n(t)=\int_0^\infty p_n(t,u)du$.

Next, we consider the possible transitions of the system from one state to another in an interval $(t, t+\Delta)$. Let us fix the time moment and find the probability $p_0(t+\Delta,u+\Delta)\Delta$ that at the moment $t+\Delta$, the system will be in the state $[0, u+\Delta]$. It can happen only in one case: the system at the moment t was in the state $[0, u]$, and during the time Δ with the probability $1-r(u)\Delta$, the service of a group of requests already being processed has not ended (the probability of this by definition is $p_n(t,u)$) and with a probability of $1-\lambda\Delta$, no new request has arrived in the system. The validity of the second statement follows from the fact that if a request arrives during time Δ, then it will be immediately selected for service, and the system from the state $[e]$ at the time t will go to the state $[0, \Delta]$ at the time $t+\Delta$, but this contradicts the starting position. So:

$$p_0(t+\Delta,u+\Delta)\Delta = \\ = p_0(t,u)\Delta\{[1-r(u)\Delta][1-\lambda\Delta]\}+o(\Delta) \ . \quad (7)$$

Let us find the probability that at the moment $t+\Delta$, the system will be in the state $[n, u+\Delta]$. It can happen in two ways:

– at the moment t, the system was in the state $[n, u]$, and during time Δ, no new request arrived, and the service of the current group of requests did not end;

– at the moment t, the system was in the state $[n-1, u]$, and during the time Δ with the probability $\lambda\Delta$, a request came to the system.

So:

$$p_n(t+\Delta,u+\Delta)\Delta = p_n(t,u)\Delta\{[1-r(u)\Delta][1-\lambda\Delta]\} + \\ + p_{n-1}(t,u)\Delta\lambda\Delta+o(\Delta) \quad . \quad (8)$$

Let us determine the boundary conditions at the point $u=0$. To do this, we will again fix the moment of time t and derive the probability that at the moment $t+\Delta$, the system will be in the state $[n, \Delta]$, i.e., since the start of servicing the next group of requests, the time has passed that does not exceed Δ. We will first derive the equation for the state $[0, \Delta]$. The system can go to the state $[0, \Delta]$ in the time Δ in two ways:

– at the moment t, the system was in the state $[e]$, and in the time Δ with probability $\lambda\Delta$, a new request arrived, which was immediately selected for service;

– at the moment t, the system was in the state $[n, u]$, and with probability $r(u)\Delta$, the service of the previous group of requests ended, which resulted in the storage reset. The probability of this event will consist of probabilities for all possible values of n and all possible values of u.

Therefore:

$$p_0(t+\Delta,\Delta)\Delta = p_e(t)\lambda\Delta + \sum_{n=1}^{k}\int_0^\infty p_n(t,u)r(u)du\Delta . \quad (9)$$

Since the system can receive no more than one request during the time Δ and the drive is reset to zero when accessing it, then:

$$p_k(t,\Delta) \equiv 0 \quad . \qquad (10)$$

We derive the probability that at the moment $t + \Delta$, the system will be in the state $[e]$. It can happen in two ways:

– at the moment t, the system was in the state $[e]$, and with the probability of $1 - \lambda\Delta$, no new request will be received;

– at the moment t, the system was in the state $[0, u]$, and during the time Δ with the probability $r(u)\Delta$, the service of the next group of requests ended.

So:

$$p_e(t+\Delta) = p_e(t)[1-\lambda\Delta] + \int_0^{\infty} p_0(t,u)r(u)du\Delta \,. \qquad (11)$$

Let us open the parentheses in expressions (7) and (8), transfer $p_n(t,u)$ in the left part, add here $p_n(t,u+\Delta) - p_n(t,u+\Delta)$, divide everything by Δ, and proceed to the limit at $\Delta \to 0$. We obtain a system of equations:

$$\begin{aligned} &\frac{\partial}{\partial t} p_0(t,u) + \frac{\partial}{\partial u} p_0(t,u) = -[\lambda + r(u)]p_0(t,u), \\ &\frac{\partial}{\partial t} p_n(t,u) + \frac{\partial}{\partial u} p_n(t,u) = -[\lambda + r(u)]p_n(t,u) + \\ &+ \lambda p_{n-1}(t,u). \end{aligned} \qquad (12)$$

Similarly, we can derive the boundary conditions from expressions (9)–(11):

$$\begin{aligned} &p_0(t,0)\Delta = \lambda p_e(t) + \sum_{n=1}^{k}\int_0^{\infty} p_n(t,u)r(u)du \\ &\frac{\partial}{\partial t} p_e(t) = -\lambda p_e(t) + \int_0^{\infty} p_0(t,u)r(u)du \,, \\ &p_n(t,0) \equiv 0 \,,\ 0 < n \le k \,. \end{aligned} \qquad (13)$$

We will take as initial conditions $p_e(0)=1$. The joint system of equations (12) and (13) can be solved numerically on a computer using appropriate software, for example, the grid method.

Let us consider the stationary mode. With $t \to \infty$,

$$p_n(t,u) \to p_n(u), \quad \frac{\partial p_n(u)}{\partial t} = 0. \qquad (14)$$

As a result, we get the following system of equations:

$$\begin{aligned} &\frac{\partial}{\partial u} p_0(u) = -[\lambda + r(u)]p_0(u), \\ &\frac{\partial}{\partial u} p_n(u) = -[\lambda + r(u)]p_n(u) + \lambda p_{n-1}(u), 1 \le n \le k, \end{aligned} \qquad (15)$$

and boundary conditions:

$$\begin{aligned} &-\lambda p_\delta + \int_0^{\infty} p_0(u)r(u)du = 0, \\ &p_0(0) = \lambda p_\delta + \sum_{n=1}^{k}\int_0^{\infty} p_n(u)r(u)du. \end{aligned} \qquad (16)$$

Solving the system of equations (15) step by step, we get:

$$\begin{aligned} &p_0(u) = [1 - B(u)]p_0(0)e^{-\lambda u}, \\ &p_1(u) = \lambda u[1 - B(u)]p_0(0)e^{-\lambda u}, \\ &p_n(u) = \frac{(\lambda u)^n}{n!}[1 - B(u)]p_0(0)e^{-\lambda u}, \ 0 \le n \le k. \end{aligned} \qquad (17)$$

Substituting expression (17) into the first equation of system (16), we find:

$$p_e = \beta(\lambda)p_0(0)/\lambda \,. \qquad (18)$$

So:

$$p_n = \int_0^{\infty} p_n(u)du = \left[\frac{1}{\lambda} - \frac{(-1)^n}{n!}\lambda^{n-1}\beta^{(n)}(\lambda)\right]p_0(0), \qquad (19)$$

where $\beta^{(n)}(\lambda)$ is the value of the n-th derivative of $\beta(s)$ at $s = \lambda$.

Using the normalisation condition

$$p_e + \sum_{i=0}^{k} p_n = 1, \qquad (20)$$

we will get:

$$p_0(0) = \lambda \cdot \{k - \sum_{n=1}^{k}\frac{(-1)^n}{n!}\beta^{(n)}(\lambda)\}^{-1}. \qquad (21)$$

For the m-th order Erlang distribution:

$$\beta^{(n)}(\lambda) = (-1)^n \frac{(m+n-1)!}{(m-1)!}\frac{\mu^m}{(\mu+\lambda)^{m+n}}. \qquad (22)$$

For the hyperexponential distribution:

$$\beta^{(n)}(\lambda) = (-1)^n n! \sum_{i=1}^{m}\frac{b_i\mu_i}{(\mu_i + \lambda)^{n+1}}. \qquad (23)$$

Expressions (5) and (6) determine the main characteristics of the studied system.

Fig. 2 shows a graph of packet loss depending on the intensity of the incoming flow of streams and the capacity of the buffer memory.

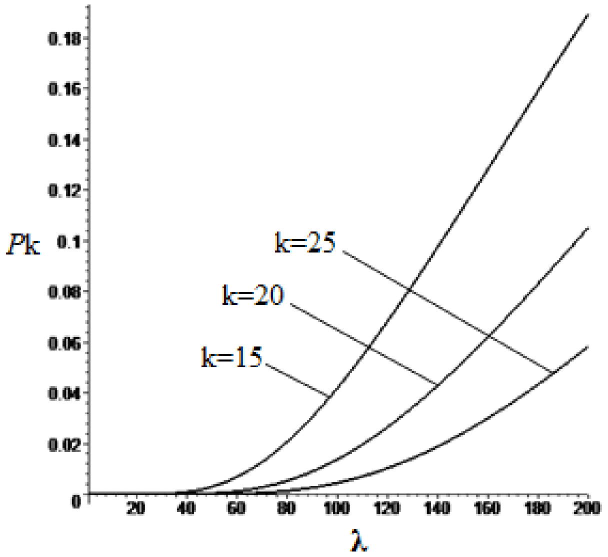

Fig. 2. Dependencies of the probability of losing requests on system parameters

We can see that the capacity of the buffer memory strongly affects this dependence.

Conclusions

By drawing analogies with queuing systems, it is easy to see that transmitting a message via the SCTP protocol can be described in a queuing system with bulk servicing terms. Indeed, in such a system, it is natural to understand a request as a piece of data, a group of requests as a packet, and a serving device as an SCTP stream. Due to the independence of SCTP streams, it is possible to set the operating device number to one. The study constructs a graph of states and transitions used to derive systems of linear and differential equations regarding the probabilities of states. We obtain the solutions of the systems of equations in explicit form, which allows us to use them to analyse the basic functioning of the SCTP protocol.

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СИСТЕМА МАСОВОГО ОБСЛУГОВУВАННЯ З ГРУПОВИМ ОБСЛУГОВУВАННЯМ ЯК МОДЕЛЬ ФУНКЦІОНУВАННЯ ПРОТОКОЛУ SCTP

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Передача інформації через комп'ютерну мережу виконується за певним протоколом. Сучасний протокол SCTP має низку відмінних рис. Зокрема, він передбачає можливість як надійної (TCP), так і ненадійної (UDP) доставки даних з можливістю підтримки порядку передачі всередині кожного з потоків даних (функція Multistreaming). За рахунок цього досягається ефект незалежної передачі незв'язаних даних, наприклад, що належать до різних послуг. Основною перевагою такого підходу є той факт, що виникнення помилки в одному із потоків та можлива втрата якості відповідної йому послуги не впливає на своєчасну доставку даних в інших потоках та на показники якості інших послуг. Потік інформації, що проходить протоколом, має ймовірнісний характер, що вимагає використання ймовірнісних моделей для оцінки якості передачі інформації. Процес передачі даних протоколом SCTP здійснюється наступним чином: дані (повідомлення в термінах протоколу SCTP), що надходять від програми користувача, інкапсулюються в порції даних (chunks), які ставляться в чергу на передачу. У черзі порції даних збираються в SCTP-пакет, який за запитом операційного пристрою вибирається з черги для передачі в IP-мережу. Отже, процес передачі повідомлення протоколом SCTP можна описати в термінах систем масового обслуговування з груповим обслуговуванням. Для випадку пуасонівських потоків подій побудовано граф станів та переходів, за ним виведено систему лінійних рівнянь щодо ймовірностей станів системи. Отримано аналітичні вирази для середнього числа запитів у буферній пам'яті, ймовірність втрати інформації. Для довільно розподіленого часу зчитування інформації з буферної пам'яті виведено систему інтегро-диференціальних рівнянь щодо щільності ймовірностей станів. Її рішення отримано у загальному вигляді. Чисельні розрахунки підкріплені графіками залежності ймовірності втрати інформації від інтенсивності надходження інформації на вході протоколу та ємності буферної пам'яті.

Ключові слова: *комп'ютерна мережа, протокол, імовірнісна модель, система масового обслуговування, групове обслуговування.*