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Modele kolejkowe z mechanizmem zawieszenia obsługi typu „multiple vacation” – analiza z wykorzystaniem SD

Streszczenie rozprawy doktorskiej
w języku angielskim
napisanej pod kierunkiem
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Gliwice April 19, 2023

Contents

Introduction

The theory of queues, also called the theory of mass service, has contributed to a significant development of technology in telecommunications, particularly in networks and computer systems, over the last few decades. The essence of this theory is the study of the phenomenon of processing (handling) requests (packets) flowing into the ICT system. In this process, there is an accumulation of requests waiting for handling (i.e. creating a queue of requests), and the handling itself is carried out by the discipline (rules) adopted in the system. The progressing computerization of society translates into the growing importance of this type of system. Demand is met through the development and dissemination of telecommunication devices and services: from computers and the Internet, through smart devices that use mobile networks or the Internet as a medium, to less widespread, operating in the concept of the Internet of Things (IoT) devices for which the medium is wireless sensor networks or the Internet. Each of the devices mentioned above generates network traffic appropriate for the technology used, which directly impacts the process of queuing the sent requests.

The subject matter of this dissertation is part of the research on issues occurring in the theory of mass service, focusing on the analysis of queuing systems applicable in computer networks and telecommunications. In particular, the dissertation's considerations are single-channel queuing models with Poisson input stream, finite queue buffer size, and multiple vacation policy. Queuing models with limited accumulative buffer capacity are the subject of intensive research. Their characteristic properties enable modelling of processes taking place, e.g. in network switches (routers), in which phenomena occur related to the accumulation of packets in the device buffer or their loss due to overflow of this buffer, packet processing by the adopted discipline, or queuing delay resulting from waiting for packets in the buffer. In the case of queuing models with limited access to the server, there is an additional possibility of a more precise description of natural systems in which there may be temporary downtimes in access to the packet processing device. These downtimes may result, i.a., from the need to save energy in a battery-powered device that, under the right circumstances, goes from full standby mode to a mode that consumes less energy. An example of such a circumstance is when the queuing system empties packets. Then the device can switch to a low-energy mode of listening and accumulating incoming packets in the future.

The problem of energy saving in sensor networks was raised, among others, by works [25], [8], [16], presenting various types of queuing models. As it is easy to see, the vast majority of analytical results available in the literature, developed for queuing models with server access restrictions, relate to the system's steady state. The steady-state characteristics illustrate the long-term operation of the system, constituting the necessary basis for assessing the efficiency of its operation. However, sometimes in practice, a transitive (non-stationary) analysis of the characteristics of queuing systems is indicated or even necessary. This results, among others, from the fact that the following phenomena occur in network traffic: *self-similarity* - [1], [26], [41]; *long-range dependence* – [2], [3], [43]; *burstiness* – [7], [33], [35]. These phenomena may contribute to the system's inability to reach a steady state in the short term. Transient analysis of the behaviour of queuing systems allows you to monitor their operation immediately after starting the system, during periods of downtime and destabilization of the server's operation, and when the stabilization of the system takes a relatively long time, e.g. due to irregular input traffic. The general form of the results presented in the dissertation makes it possible to model systems in which any probability distribution carries out packet handling.

The aim and thesis of the dissertation

Aim of the dissertation

The dissertation aims to analyse the essential characteristics of queuing models with the discipline of suspending the service of the "multiple vacation" type in a non-stationary state (transient, at a fixed moment t). The research results presented in the dissertation concerns:

- *precise modelling of network traffic, taking into account the mechanism of suspension of service and the finite size of the buffer of the packet queuing device;*
- *four key characteristics of transient models whose probability distributions have been determined analytically in an explicit form using Laplace transforms;*
- *input stream, including both single and groups of incoming packets;*
- *numerical analysis of the functioning of the considered models;*
- *the use of System Dynamics and the Powell method in selecting the optimized length of vacations occurring in the considered mechanism of suspension of service.*

Dissertation thesis

Mathematical methods based on the concept of an embedded Markov chain, the theorem of total probability law for continuous random variables, systems of integral equations of the Volterra type, Korolyuk's potential method, as well as selected tools and results of mathematical analysis and the renewal theory, enable precise modelling of the behaviour of queuing systems with the multiple vacation policy in the transient state. The dynamics of changes in the characteristics of the considered queuing systems in a transient state can be mapped in a simulation model built based on the System Dynamics methodology. The analysis of these dynamics in the constructed model with the application of the Powell method enables the selection of the optimal length of the vacation time of the service suspension mechanism.

Dissertation layout

The results contained in the dissertation are presented in the following order. Chapter 1 describes introductory information on $M/G/1/N$ queuing systems and the used symbols and auxiliary results. Chapters 2 - 5 are the central part of the dissertation. They present the results for transitive probability distributions of characteristics such as queue length, time to the first buffer overflow, queuing delays and departure counting process in $M/G/1/N$ models with the multiple vacation policy. The results apply to the queuing of simple and compound Poisson processes (which, in practice, means considering single and group packet inflow). Chapter 6 describes the use of System Dynamics to simulate the behaviour of the $M^X/D/1/N$ system, with the multiple vacation policy considered in the dissertation, in the dedicated Vensim software. The created simulation model makes it possible to determine the optimal length of vacations occurring in the considered service suspension mechanism. Supplementary information in the form of the program code of the discrete event simulator, which allows simulating the behaviour of the $M^X/G/1/N$ queuing systems with service suspension discipline, is included in Appendix A.

A queuing model with the multiple vacation policy

In the dissertation, we consider $M/G/1/N$ and $M^X/G/1/N$ queuing models, in which the inflow of packets is described by a simple and compound Poisson process, respectively, with the intensity λ. The processing of packets is consistent with the natural discipline of FIFO. The process times of individual packets are independent random variables with the distribution function $F(\cdot)$. The system's maximum capacity (in terms of the number of packets that can be present simultaneously) is equal to N ($N-1$ buffer slots and one slot for a currently handled packet). Each time the packet service ends and the buffer contains no other packets, the server starts the service suspension period. This period consists of consecutive (*multiple*) idle periods (*vacation*), which are independent random variables with equal distributions with the distribution function $G(\cdot)$. After each of the individual vacation time periods ends, the buffer status is monitored. The server does not start another vacation period if it contains at least one queued packet. Otherwise, the next idle period specified by the $G(\cdot)$ distribution is initialized.

One of the first research papers describing the model $M/G/1/N$ with multiple vacations policy considered in the dissertation is [23] by Lee, in which the queue length distribution is studied using embedded Markov chains. Using the supplementary variable technique, a general formula was derived for the distribution of the queue length in a steady state and a formula for the probability of filling the buffer in this state. Occupancy period and waiting time distributions were also obtained using probability-generating functions. The author extends the research by presenting it in another work [24], in which a model is considered with the server starting the service suspension (vacation) period if the queue has been emptied or m packets have been handled during uninterrupted service. The characteristics of the queue length and steady-state occupancy period presented in the paper are also derived for a buffer with unlimited capacity ($N \to \infty$). Another progress in research on the model was presented, among others, by Takagi in [38]. The author used the analysis of the renewal cycle of server busy periods and suspension of service by the server to obtain a measure of system throughput and average wait time for a steady state. He also obtained the Laplace-Stieltjes transform of the function of the virtual distribution of waiting time for service by applying the method of supplementary variables to the joint distribution of queue size and service or suspension time. The work [27] analyzes the transient state of the $M/G^{a,b}/1$ model with group handling of i requests ($a \leqslant and \leqslant b$) and a buffer that allows you to accumulate up to b packets. A minimum of a packets is required to start servicing, and the server starts a vacation period when there are fewer than a pending requests in the buffer. Suppose the server ends the vacation period and again finds less than a pending requests. In that case, it immediately starts the next vacation, and all consecutive periods constitute one continuous multiple vacation period. The authors, using the theory of renewal processes, derived formulas for the time-dependent probability that the system at the time t is in the state (i, j) belonging to the following state space $S = \{(i, j); a \leqslant i \leqslant b, 0 \leqslant j \leqslant b\} \cup \{(0, j); 0 \leqslant j \leqslant b\}$.

Research outcomes

The research results presented in this dissertation concern the transitive (non-stationary) characteristics of queuing models with a single packet handling server, a finite buffer, a Poisson process input stream, and a service suspension discipline consisting of *multiple vacations*, whose lengths in the general case, are random variables with the same probability distribution. The assumption of buffer finiteness is highly significant in the case of modelling processes taking place in computer networks, particularly in sensor networks of interest to the author, often based on devices with significantly limited processing power and system resources. The analytical results of the queuing characteristics obtained in the dissertation are given as Laplace transforms and Laplace transform generating functions. Detailed results were obtained for the following characteristics: queue length, time to the first buffer overflow, waiting time for service and the process of counting serviced packets. In addition, all the listed characteristics have been determined for both single and group inflow of packets into the system.

The research results described in the dissertation were obtained using analytical methods. They were presented as theorems in which the characteristics mentioned in the previous paragraph are presented as functionals depending on the model parameters (e.g. buffer size) and probability distributions (e.g. input stream intensity, service intensity). The theoretical results are illustrated with numerous numerical examples generated using the Mathematica 12.1 [42] computing environment. The presented considerations' correctness is verified by simulations performed in the OMNeT++ 5.6.1 [39] discrete event simulator and presented in the subsections describing the comparative analysis of numerical and simulation calculations. In addition, due to the specificity of the queuing models examined in the thesis, the concept of using the Powell [34] method for selecting the optimized length of vacation times occurring in the considered service suspension mechanism was proposed. To implement this concept, packet queuing issues were transferred to System Dynamics, and a simulation model was created using the dedicated Vensim [40] software. This model was verified by performing a comparative analysis of the simulation results compared to the expected numerical values. The results of the presented methodology of obtaining (using simulation) the optimal length of the vacation period in the considered queuing models are presented in the graphs presented in the dissertation.

The results contained in the dissertation make it possible to obtain answers to the questions of how the change in the length of vacation periods, as well as changes in the inflow intensity, service intensity, or the initial value of the number of packages present in the system, affect the:

- queue length,
- the probability distribution of the time to the first buffer overflow,
- virtual waiting time for service,
- number of packets served in a given time.

Another issue that can be resolved based on the research results presented in the dissertation is determining the time after the system's operation stabilizes and what impact its initial state has on this stabilization. In addition, it is also possible to determine the degree of transmission conditions occurring in the system on the possibility of selection and the resulting value of the optimal length of the vacation time of the service suspension mechanism.

Summary

The dissertation comprehensively discusses the characteristics of queue length, time to a first buffer overflow, queuing delay, and the departure process of packets for queuing models with a single request handling station, a finite buffer, a Poisson input stream, and a service suspension discipline consisting of multiple vacation periods, whose lengths are, in general, random variables with the same probability distribution. The obtained results concern the queuing of both simple and compound Poisson processes and have been given in the form of Laplace transforms and Laplace transform generating functions. They were obtained using analytical methods that can be successfully used to determine many other characteristics of queuing systems, e.g. packet loss rate, buffer overflow period, and number of requests lost during the overflow period. The applied methodology allows to obtain a transitive description of the most essential characteristics in a compact form, which translates into a reduction of the time necessary for their implementation in the code. In addition, it has been shown that despite the complicated structure of the statistical description of network traffic modelled with the methodology used, it is possible to obtain numerical results on an average-class personal computer. In queuing systems with large queue buffers and complex probability distributions describing service suspension periods or packet processing times, numerical calculations will require correspondingly greater computational resources.

The results of the dissertation prove the possibility of obtaining a mathematical, compact description of the behaviour of queuing systems with multiple vacation service suspension policy, making it possible to effectively model such systems in a transient state. The results of theoretical considerations were supplemented with numerous numerical examples presenting the behaviour of individual characteristics of queuing systems in the context of network traffic. From a practical point of view, the research results achieved in the dissertation make it possible to assess performance and quality assurance in various types of telecommunications services, the functioning of which is based on the queuing theory. In particular, thanks to the use of the Systems Dynamics methodology with the simultaneous application of the Powell method, it is possible to select the optimal length of the vacation time of the service suspension mechanism. In addition, the paper cites two computational algorithms for numerical inversion of the Laplace transform and transform-generating functions, allowing insight into the practicality of their use and the results achieved.

Publication achievements

Publications in journals

- K. Grochla, A. Strzoda, R. Marjasz, P. Głomb, K. Książek, and Z. Łaskarzewski. Energy-aware algorithm for assignment of relays in LP WAN. *ACM Transactions on Sensor Networks*, 18(4), nov 2022; **140 points**
- A. Strzoda, R. Marjasz, and K. Grochla. LoRa positioning in verification of location data's credibility. *Infocommunications Journal*, 14(4):56–61, 2022; **20 points**
- W. M. Kempa, K. Książek, and R. Marjasz. On time-dependent queue-size distribution in a model with finite buffer capacity and deterministic multiple vacations with applications to LTE DRX mechanism modeling. *IEEE Access*, 9:148374–148383, 2021; **100 points**
- W. M. Kempa and R. Marjasz. Study on transient queue-size distribution in the finite-buffer model with batch arrivals and multiple vacation policy. *Entropy*, 23(11), 2021; **100 points**
- M. Gorawski, K. Grochla, R. Marjasz, and A. Frankiewicz. Energy minimization algorithm for estimation of clock skew and reception window selection in wireless networks. *Sensors*, 21(5):1768, 2021; **100 points**
- W. M. Kempa and R. Marjasz. Distribution of the time to buffer overflow in the M/G/1/N-type queueing model with batch arrivals and multiple vacation policy. *Journal of the Operational Research Society*, 71(3):447–455, 2020; **70 points**
- E. Kasperska, A. Kasperski, R. Marjasz, and E. Mateja-Losa. Some simulation and optimization experiments on prey-predator model. *Zeszyty Naukowe. Organizacja i Zarządzanie, Politechnika Śląska*, (119):111–126, 2018; **11 points**
- E. Kasperska, T. Bajon, and R. Marjasz. Interactive gaming as a support for system dynamics learning with the use of vensim. *Zeszyty Naukowe. Matematyka Stosowana/Politechnika Śląska*, (5):99–110, 2015; **4 points**

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- R. Marjasz. Finding the optimal strategy for employment in conjunction to the mechanism of promotion within the workforce–simulation in Vensim software. *Studia Ekonomiczne*, (234):101–113, 2015; **10 points**
- E. Kasperska, E. Mateja-Losa, T. Bajon, and R. Marjasz. "Did napoleon have to lose the Waterloo battle?": Some sensitivity analysis and optimization experiments using simulation by Vensim. *Studia Ekonomiczne*, (188):97–118, 2014; **10 points**
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Conference proceedings

- A. Strzoda, R. Marjasz, and K. Grochla. How accurate is LoRa positioning in realistic conditions? In *Proceedings of the 12th ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (part of ACM MSWiM 2022 Conference)*, pages 31–35, 2022; **140 points**
- R. Marjasz, K. Połys, A. Strzoda, and K. Grochla. Improving delivery ratio in LoRa network. In *Proceedings of the 19th ACM International Symposium on Mobility Management and Wireless Access (part of ACM MSWiM 2021 Conference)*, MobiWac '21, page 141–146, New York, NY, USA, 2021. Association for Computing Machinery; **140 points**
- R. Marjasz, A. Strzoda, K. Połys, and K. Grochla. Mitigation of LoRa interferences via dynamic channel weights. In *Proceedings of the 35th annual European Simulation and Modelling Conference ESM 2021)*, pages 150–154. EUROSIS, 2021; **70 points**
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- W. M. Kempa and R. Marjasz. Departure counting process in a wireless network node with sleep mode modelled via repeated vacations. In Robertas Damaševičius and Vilma Mikašytė, editors, *Information and Software Technologies*, pages 395–407, Cham, 2017. Springer International Publishing; **20 points**

- E. Kasperska, A. Kasperski, T. Bajon, and R. Marjasz. Visualization for learning in organization based on the possibilities of Vensim. In *Proceedings of Knowledge Management Conference*, pages 21–34, 2014;

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