OTKA K-123914 project
Scientific report
2017.10.01-2022.03.31

Our research efforts were focused on the following three main subjects:

- Performance evaluation of computer systems,
- Stochastic modelling,
- Communication systems.

Below we summarize the yearly achieved project results in these fields.

1. Scientific results in 2018

Performance evaluation of computer systems:

- Miklos Telek and Benny Van Houdt: Response Time Distribution of a Class of Limited Processor Sharing Qeues, Performance Evaluation Review, 2017 mtmt: 3328891

  The paper studies the effect of imperfect task parallelization mentioned in the project plan. Imperfect parallelization means that for n parallel threads processed in a server, the power experienced by each thread is a special function of n that is less than $1/n$. The main result of the reported analysis is the calculation of the response time distribution, based on which its tail behavior can be optimized.

- Marco Gribaudo and Illes Horvath and Daniele Manini and Miklos Telek: Modelling large timescale and small timescale service variability, Springer LNCS 10932, 2018 mtmt: 3418916

  At a given modeling level, the performance fluctuations of computer systems must be taken into account on several time scales, so that the behavior on different time scales can be described by different models. In the paper, short-term behavior was described using a diffusion model, while long-term behavior was described using a linear Markov modulated model.

- Imre Kocsis and Andras Pataricza and Miklos Telek and Attila Klenik and Florian Dee and David Cseh: Systematic Performance Evaluation Using Component-in-the-Loop Approach, International Journal of Cloud Computing (IJCC), 2018 mtmt: 3372612

  In the framework of the cooperation with the Department of Measurement and Information Systems of BME, the paper presents the performance analysis of the block chain, which is a very popular distributed trust guarantee system nowadays.

Stochastic modeling

- Zsolt Saffer, Miklos Telek, Gabor Horvath: Fluid polling system with Markov modulated load and gated discipline, Springer LNCS 10932, 2018 mtmt: 3406299

  Modeling of polling systems for the analysis of discrete queues is a long-researched field, while there have been no results for the polling-like service of fluid queues recently. One of the first steps in this direction is this conference paper, in which we analyze one of the simplest methods of service, the gated service discipline.

- Qi-Ming He and Gabor Horvath and Illes Horvath and Miklos Telek: Moment bounds of Phase type distributions based on the steepest increase property, Proc of European Conference on Queueing Theory, 2018 mtmt: 3418924

  Research on Markov chains has provided many interesting but rarely used properties over the past 50 years. One of these is the steepest increase property, which limits the rate of leaving groups of states. Based

on this property, we were able to find previously unknown momentum constraints on the family of phase-type distributions.

- Mindaugas Brazenas, Gabor Horvath, Miklos Telek: Parallel algorithms for fitting Markov Arrival Processes, Performance Evaluation, 2018 mtmt: 3390080

  The efficient application of tools with parallel computing capabilities, which are widespread today, poses continuous research challenges for computational tasks that inherently require serial processing. One such tasks is to fit Markov arrival processes based on data. In the paper, we proposed efficient algorithms for fitting Markov arrival processes utilizing parallel computing capacity.

- Illes Horvath and Zsofia Talyigas and Miklos Telek: An Optimal Inverse Laplace Transform Method Without Positive and Negative Overshoot – An Integral Based Interpretation, Electronic Notes in Theoretical Computer Science, 2018 mtmt: 3329947

  All of the numerical inverse Laplace transform (ILT) methods common today are characterized by "overshoot," which means that the probabilities calculated with numerical ILT can be less than zero or greater than one. The proposed approach is free from these errors.

- Nam H Do, T V Do, A Melikov: Equilibrium customer behavior in the M/M/1 retrial queue with working vacations and a constant retrial rate, OPERATIONAL RESEARCH, 2018 mtmt: 3329606

  Consideration of retrial users is of great importance in the modeling of today's call center. In this paper, we present a performance analysis of a queuing system that can be used to model call centers.

Communication systems:

- Andrea Abrardo and Gabor Fodor and Marco Moretti and Miklos Telek: MMSE Receiver Design and SINR Calculation in MU-MIMO Systems with Imperfect CSI, IEEE Wireless Communications Letters, 2018 mtmt: 3418934

  Knowledge of the communication channel is essential for effective wireless radio communication. The paper presents a model in which users gather as much information as possible about the channel from so-called pilot signals.

- Peiyue Zhao, Gabor Fodor, Gyorgy Dan, Miklos Telek: A Game Theoretic Approach to Setting the Pilot Power Ratio in Multi-User MIMO Systems, IEEE Transactions on Communications, 2018 mtmt: 3392194

  Based on the pilot signals and the transmit power of the other users, the transmit power of each user can be set centrally or distributed. To perform the distributed setup, we introduced a game theoretical algorithm and examined its main properties.

2. Scientific results in 2019

Performance evaluation of computer systems

- Tien Van Do, Nam Hoai Do, Hai Tuan Nguyen, Csaba Rotter, Attila Hegyi, Peter Hegyi: Comparison of scheduling algorithms for multiple mobile computing edge clouds, Simulation Modelling Practice and Theory, 2019 mtmt: 30308638

  One of the keys to the efficient use of modern distributed computing systems is the optimal allocation of computing tasks and computing resources over time and space. In this topic, a number of procedures have been proposed, but their the performance evaluation is not complete at all. In our work, we analyzed the efficiency of some promising resource assignment procedures assuming different physical resources and task types.

Stochastic modeling

- Andras Meszaros and Miklos Telek. Infinite Markov decision processes with decision independent subset of states. Queueing Models and Service Management, 2(1):1–31, 2019. mtmt: 30814207

  The theory and solution methods of Markov decision processes are available for finite state models. There are no solution procedures for infinite state models. For the special case where decisions in the infinite state of Markov decision processes can only be made in a finite number of states, we have developed a methodology with which one can calculate the optimal policy for these types of systems.

- Illés Horváth, Gábor Horváth, Salah Al-Deen Almousa, and Miklós Telek. Numerical inverse Laplace transformation by concentrated matrix exponential distributions. In MAM10, Febr 2019. mtmt: 30446578

  In terms of potential general-purpose use, perhaps our most promising result is a numerical inverse Laplace transform method that, according to previous studies, shows better properties in general use than all numerical inverse Laplace transform methods proposed so far. The essence of the method is that, unlike the methods resulting from the series approximation of a complex integral which was used so far, we approached the problem as a function fitting problem, which fortunately resulted in much better numerical properties than all the alternative methods.

- Illés Horváth, Gábor Horváth, and Miklós Telek. High order low variance matrix-exponential distributions. In MAM10, Febr 2019. mtmt: 30446564

  In the numerical inverse Laplace transform method mentioned in the previous point, we approximate a unit impulse function with non-negative matrix exponential functions. The solution of this approximation has already been available for a small degrees ($n < 23$), but for applications of practical interest much higher order approximations are required. By developing an efficient transformation procedure between different representations of matrix exponential functions and an intuition based on low-degree results, we created non-negative matrix exponential functions that approximate unit impulse with degree up to $n = 1000$.

- Qiming He, Gábor Horváth, Illés Horváth, and Miklós Telek. Moment bounds of PH distributions with infinite or finite support based on the steepest increase property. Advances in Applied Probability (AAP), 51(1):168–183, March 2019. mtmt: 30756233

  The steepest growth rate is a little-known property of continuous-time Markov chains that describes the relationship between the dominant self-value and the rate of change of the process. However, this property can be used to obtain additional features. In our work, we have shown a consequence of the sojourn time in the transient state group of Markov chains. We have presented momentum constraints on the lower and upper estimates of certain characteristics of Markov chains.

Communication systems:

- Peiyue Zhao, Gabor Fodor, Gyorgy Dan, and Miklos Telek. A game theoretic approach to uplink pilot and data power control in multi-cell multi-user MIMO systems. IEEE Transactions on Vehicular Technology, pages 8707–8720, 2019. mtmt: 30814184

  In multi-cell systems, setting the optimal pilot data power ratio is even more complicated than in a single-cell case due to intercell interference. Continuing the previous year's research, we proposed a game theory algorithm to perform distributed pilot-data power sharing in a multi-cell environment and demonstrated its effectiveness with numerical studies.

- L. Lakatos, L. Szeidl, and M. Telek. Introduction to Queueing Systems with Telecommunication Applications, 2nd edition. Springer, 2019. mtmt: 30711727

  The second, extended edition of our 385-page monograph, published in 2013, was proposed by Springer in 2017. After more than two years of development, the 559-page 2nd edition of the monograph was published, in which new stochastic modeling methods and exercises with solutions help the readers to gain familiarity in the field.

3. Scientific results 2020

Performance evaluation of computer systems:

- Gribaudo Marco, Horváth Illés, Manini Daniele, Telek Miklós Modelling large timescale and small timescale service variability ANNALS OF OPERATIONS RESEARCH 293 pp. 123-140., (2020) mtmt: 31041584, IF: not available, IF for 2019: 2.583

  The performance of service units may depend on various randomly changing environmental effects. In this paper, we consider small and large scale (short and long term) service variability, where the short term variability affects the instantaneous service speed of the service unit and a modulating background Markov chain characterizes the long term effect. The main modelling challenge in this work is that the considered small and long term variation results in randomness along

different axes: short term variability along the time axis and long term variability along the work axis. We an explicit analytic formula for the service time distribution in the double transform domain that allows e.g., for the efficient computation of service time moments.

- Do, N.H., T.V Do, , L. Farkas, C. Rotter: Provisioning Input and Output Data Rates in Data Processing Frameworks. J. Grid. Computing 18: 491–506 (2020). mtmt: 31039517, IF: not available, IF for 2019: 2.096

  This paper is motivated by the need of deadline-bounded applications in live mobile network environments to obtain the guarantee and the appropriate share of an input and output (I/O) data rate. However, data processing frameworks only support the request of memory and the computing capacity at present. In this paper, we propose a solution that allows the control of disk I/O and network I/O for data processing applications in YARN and Mesos frameworks. Experimental results show that our tool can provision the I/O data rate sharing of competing data processing applications.

Stochastic modeling:

- Horváth G., Horváth I., Telek M. High order concentrated matrix-exponential distributions COMMUNICATIONS IN STATISTICS - STOCHASTIC MODELS 36 : 2 pp. 176-192., (2020) mtmt: 31400240, IF: not available, IF for 2019: 0.4

  This paper is an extended version of the conference publications: Illés Horváth, Gábor Horváth, and Miklós Telek. High order low variance matrix-exponential distributions. In MAM10, Febr 2019. mtmt: 30446564
  The goal of this work was to obtain non-negative matrix exponential functions with very low coefficient of variation also for relatively high orders. Preceding results provided such functions for order n$<$23, but the applied analysis approach could not be extended beyond that order limit. Based on an efficient iterative transformation procedure between the different representations of matrix exponential function we developed an efficient optimization procedure which provides non-negative matrix exponential functions with very low coefficient of variation up to

n=1000. The obtained results indicate that the coefficient of variation of order n matrix exponential function is less than one over n square.

- Nam H. Do, Tien Van Do, Agassi Melikov: Equilibrium customer behavior in the M/M/1 retrial queue with working vacations and a constant retrial rate. Oper. Res. 20(2): 627-646 (2020) mtmt: 3329606, IF: not available, IF for 2019: 1.758

  In this paper, we investigate the M/M/1 retrial queue with working vacations and a constant retrial rate. In the queue, customers decide about the entry based on the information upon their arrival instants. Scenarios regarding the availability of information (i.e., the server is occupied or not, and the server is on the vacation or not) for customers are compared. We derive the closed form solution for the stationary probabilities of the queue. Social optimizing and Nash equilibrium strategies for joining the system are also investigated.

- Horváth Gábor, Telek Miklós Markovian Performance Evaluation with BuTools In: Puliafito, Antonio; Trivedi, Kishor S. (szerk.) Systems Modeling: Methodologies and Tools Cham (Németország), Németország : Springer International Publishing, (2019) pp. 253-268. , 16 p. mtmt: 30883389

  BuTools 2 is collection of computational methods that are useful for Markovian and non-Markovian matrix analytic performance analysis. It consists of various packages. There are packages to obtain, analyze, transform and minimize discrete and continuous time phase-type (PH) distributions and Markovian arrival processes (MAP); to fit empirical measurement data and to evaluate the result; to solve many performance measures of various Markovian queueing systems; and to solve block-structured Markov chains. All three major mathematical frameworks are supported: BuTools is released for MAT-LAB, Mathematica and NumPy/IPython as well, with the same features, with the same call interfaces. Every function is documented, the documentation is supplemented by many examples and the related citations. BuTools uses the state-of-the art algorithms and apart of the basic functionalities it contains several unique, difficult to implement procedures as well.

- Horváth Illés, Mészáros András, Telek Miklós Numerical Inverse Trans-

formation Methods for Z-Transform MATHEMATICS 8: 4 p. 556 (2020) mtmt: 31332503, IF: not available, IF for 2019: 1.746

This paper compares the abilities of the most widely used NIZT methods, and proposes a new variant of a classic NIZT method based on contour integral approximation, which is efficient when the point of interest (at which the value of the function is needed) is smaller than the order of the NIZT method. We also introduce a vastly different NIZT method based on concentrated matrix geometric (CMG) distributions that tackles the limitations of many of the classic methods when the point of interest is larger than the order of the NIZT method.

Communication systems:

- Toka Laszlo, Szalay Mark, Haja David, Szabo Geza, Racz Sandor, Telek Miklos To boost or not to boost: a stochastic game in wireless access networks In: ICC 2020 - 2020 IEEE International Conference on Communications (ICC) (2020) pp. 1-6. , 6 p. mtmt: 31529413

  In most efficient solutions for resource allocation in wireless access networks central coordination is used for optimizing a specific target aspect of the overall communication. In contrast, in this paper we adopt a distributed solution which provide users with the possibility of resource allocation suggestions. We propose a wireless access sharing framework in which users have a say in optimizing their quality of service on the long term, and we tackle its analysis with the tool set of stochastic game theory. Our findings show that greedy users become polite against their counterparts when the load is relatively low with the goal of preparing for situations with high load.

- Fodor Gábor, Pap László, Telek Miklós Recent Advances in Acquiring Channel State Information in Cellular MIMO Systems INFOCOMMUNICATIONS JOURNAL 11 : 3 pp. 2-12. , 11 p. (2019) mtmt: 30971839, IF: 0.3

  In cellular multi-user multiple input multiple output (MU-MIMO) systems the quality of the available channel state information (CSI) has a large impact on the system performance. Therefore, cellular MU-MIMO systems employ predefined pilot sequences and configure associated time, frequency, code and power resources to facilitate the

acquisition of high quality CSI for data transmission and reception. Although the trade-off between the resources used for pilot and user data transmission has been known for long, the near-optimal configuration of the available system resources for pilot and data transmission is a topic of current research efforts. In this article, we review recent advances in system design approaches that are designed for the acquisition of CSI and discuss some of the recent results that help to dimension the pilot and data resources specifically in cellular MU-MIMO systems.

- Horváth Illés, Attila Horváth Kristóf, Kovács Péter, Telek Miklós Mean-field analysis of a scaling MAC radio protocol JOURNAL OF INDUSTRIAL AND MANAGEMENT OPTIMIZATION 13 Paper: 1547-5816_2017_5_367 (2019) mtmt: 31158429, IF: 1.368

  In this paper, we examine the transient behavior of a positioning system with a large number of tags trying to connect to the infrastructure with an exponential backoff policy in case of unsuccessful connection. Using a classic mean-field approach, we derive a system of differential equations whose solution approximates the original process. Analysis of the solution shows that both the solution and the original system exhibits an unusual log-periodic behavior in the mean-field limit, along with other interesting patterns of behavior.

4. Scientific results 2021

Performance evaluation of computer systems

- Nguyen Hai T., Do Tien V., Rotter Csaba Optimizing the resource usage of actor-based systems JOURNAL OF NETWORK AND COMPUTER APPLICATIONS 190 : 2021 p. 103143 (2021) mtmt: 32073418

  Runtime environments for IoT data processing systems based on the actor model often apply a thread pool to serve data streams. In this paper, we propose an approach based on Reinforcement Learning (RL) to find a trade-off between the the resource (thread pool in server machines) usage and the quality of service for data streams. We compare our approach and the Thread Pool Executor of Akka, an open-source

software toolkit. Simulation results show that our approach outperforms ThreadPoolExecutor with the timeout rule when the thread start times are not negligible.

- Horváth Gábor, Horváth Illés, Almousa Salah Al-Deen, Telek Miklós Numerical inverse Laplace transformation using concentrated matrix exponential distributions PERFORMANCE EVALUATION 137 p. 102067 Paper: 102067 (2020) mtmt: 31031822

  Laplace transforms are widely used in many engineering sciences. The practical application of Laplace transforms are often limited by the difficulties of the inverse transformation of the Laplace domain description. Most practically interesting cases symbolic Inverse Laplace transformation is not possible and numerical Inverse Laplace transformation (NILT) is required. Previously applied NILT methods have several shortcomings (Gibbs oscillation, numerical instability, sign-change, ...), which are caused by the internal mechanism of those NILT methods, namely the use of a weight function with alternating sign. The proposed a new approach is based on concentrated matrix exponential weight functions, which are non-negative by construction. The NILT method with such weight function, referred to as CME method, is proved to avoid to above listed shortcomings.

Stochastic modelling

- Akar Nail, Gursoy Omer, Horvath Gabor, Telek Miklos Transient and First Passage Time Distributions of First- and Second-order Multi-regime Markov Fluid Queues via ME-fication METHODOLOGY AND COMPUTING IN APPLIED PROBABILITY , 27 p. (2020) mtmt: 31397817

  The transient analysis of Markov Fluid Queues is a tremendously hart problem, while there are computational methods for the transient analysis of such models. An approximate transient analysis approach has been introduced with the use of a random clock, whose firing time distribution approximates the deterministic time point of interest. The proposed analysis approach is composed of the following steps.

  - to extend the stochastic model with the model of the clock, such that the overall model is reset to its initial state after every firing of the clock.

  - perform the stationary analysis of the extended model
  - based on the stationary model behaviour, compute the embedded model behaviour at clock firing epochs.

- Almousa Salah Al-Deen, Horváth Gábor, Telek Miklós Transient analysis of piecewise homogeneous QBD process STOCHASTIC MODELS pp. 1-26. , 26 p. (2020) mtmt: 31566233

  Infinite Markov chains with regular block structures are referred to as QBD processes. The analysis of those processes are based on

  - the computation of some characteristic matrices and
  - the evaluation of performance measures based on the characteristic matrices.

  The first step of this analysis was known for time dependent characteristic matrices in Laplace transform domain, but the second step was not available piecewise homogeneous QBD structures. The paper proposes the introduction of a set of level dependent derived measures based on the characteristic matrices and a procedure to compute the performance measure of interests based on the level dependent derived measures.

- Horváth Illés, Razumchik Rostislav, Telek Miklós The resampling M/G/1 non-preemptive LIFO queue and its application to systems with uncertain service time PERFORMANCE EVALUATION 134 Paper: 102000, 13 p. (2019) mtmt: 30931647

  The vast majority of queueing theory results aim at computing the performance measures of queues assuming known arrival and service processes. The effect of uncertain knowledge about the arrival or the service process is hardly investigated, while the strong sensitivity of the performance measures on the arrival and service processes is widely known. In this paper we investigate the effect of uncertain knowledge on the service time distribution and show that a special queueing system, the resampling M/G/1 non-preemptive LIFO queue, can be used to bound the performance measures with uncertain service time.

- Al-Deen Almousa Salah, Telek Miklós Enhanced optimization of high order concentrated matrix-exponential distributions ANNALES MA-

THEMATICAE ET INFORMATICAE 53 pp. 5-19. , 15 p. (2021) mtmt: 32068571

Due to the absence of symbolic construction to obtain the most concentrated ME distributions, non-linear optimization problems are defined to obtain high order concentrated matrix-exponential (CME) distributions. In this work we present an enhanced heuristic optimization procedure, optimizing only 6 parameters independent of the order, which allows to extend the range of available CME distributions until order 20000.

Communication systems

- Fodor Gabor, Fodor Sebastian, Telek Miklos Performance Analysis of a Linear MMSE Receiver in Time-Variant Rayleigh Fading Channels IEEE TRANSACTIONS ON COMMUNICATIONS 69:6 pp. 4098-4112. (2021) mtmt: 31900460

  The performance of the uplink of single and multiuser multiple input multiple output (MIMO) systems depends crucially on the receiver architecture and the quality of channel state information at the receiver. Therefore, several previous works have developed minimum mean squared error (MMSE) receivers and proposed balancing the resources spent on acquiring channel state information and transmitting the payload of data packets. Somewhat surprisingly, the most popular MIMO linear MMSE receivers do not exploit the correlation structure that is present in autoregressive Rayleigh fading environments. Therefore, in this article we develop a new linear receiver that not only takes channel state information errors into account in minimizing the MSE of the received data symbols, but it also utilizes that the subsequent noisy channel coefficients are correlated.

5. Scientific results in 2022

The project has been extended by 6 months. During this extended period we published the following papers:

- András Mészáros and Miklós Telek. Concentrated matrix exponential distributions with real eigenvalues. Probability in the Engineering and Informational Sciences, page 1–17, 2021. mtmt: 32202016

  In some application fields transform functions are not available in complex points, but they can be evaluated in real points. In these cases the application matrix exponential distributions with only real eigenvalues has a special importance. The paper studies the properties of matrix exponential distributions with real eigenvalues and concludes that such distributions are numerically sensitive, but applying the required numerical precision rather concentrated matrix exponential distributions can be obtained. While the squared coefficient of variation of order n matrix exponential distributions with complex eigenvalues is $< n^{-2.1}$ the squared coefficient of variation of order n matrix exponential distributions with real eigenvalues is $< n^{-1.8}$.

- Salah Al-Deen Almousa, Gábor Horváth, and Miklós Telek. Transient analysis of piecewise homogeneous Markov fluid models. Annals of Operations Research, 2020. mtmt: 31797535

  The numerical analysis of Markov fluid models with fluid level dependent fluid rates is a complex analysis problem for which stationary analysis results are available, but transient results are not. We adapted a Laplace transform based analysis approach and presented the transient measures of such stochastic models in Laplace transform domain, based on which numerical inverse Laplace transformation can provide the required performance measures of interest.