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Содержание / Contents

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Markov-modulated Arrival Processes and Their Application to the Analysis of Active Queue Management Algorithms

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Abstract. The article is devoted to the application of Markov modulated arrival processes (Markov modulated Poisson process — MMPP, Markov modulated Bernoulli process — MMBP and Markov modulated fluid flow — MMFF) models to the analysis of Active Queue Management (AQM) algorithms (Random Early Detection (RED) family, for example). The main ideas and properties of Markov modulated arrival processes (MMAP) are presented as the brief description of RED-type AQM algorithms. A review of the main results obtained with the help of MMAP processes in the analysis of AQM algorithms models is made. The authors formulated problems that also can be solved with the help of MMAP processes when analyzing the systems with RED-like algorithms.

Keywords: Markov modulated arrival processes, Markov modulated Poisson process, Markov modulated Bernoulli process, Markov modulated fluid flow, active queue management, random early detection (RED).

1. Introduction

This article introduces a brief overview of Markov modulated arrival processes (Markov modulated Poisson process (MMPP), Markov modulated Bernoulli process (MMBP) (the discrete analogue of MMPP) and Markov modulated fluid flow) and their application to active queue management (AQM) algorithms.

The structure of the paper is follows: the first section is Introduction, the second part is a brief overview of Markov modulated arrival processes, the third part is devoted to active queue management algorithms. The fourth section introduces the review of the main results obtained with the help of MMAP processes in the analysis of AQM algorithms models. And the last section — Conclusions — a brief summary of the content and purposes of the paper.

2. Markov modulated arrival processes

If one wants to construct a mathematical model considering a heterogeneous character of incoming traffic (for example, burstiness) or service (failures, breakdowns, different modes of service) the point processes whose arrival (service) rates vary randomly over time are needed.

The first works concerning queueing models with heterogeneous arrivals and service are the works of M. Eisen and M. Tainiter [1], U. Yechiali and P. Naor [2], M.F. Neuts [3] and P. Purdue [4]. In [1, 2] the same M/M/1 queueing system (with heterogeneous arrivals and service in terms of [2]) was under investigation (we should note that the term «Markovian environment» and its general form — «random environment» are still used and relevant [5–7]). The rates of arrival and service change their values due to transition of external Markov process from one state to another.

In [1,2] the similar results (system characteristics) were obtained by the probability generating function (PGF) method. In [1] the exact solution for PGF and mean waiting time were obtained only for infinite service rate case. In [2] the level independent customers probability distribution was derived when ratios of incoming and service rates are the same for states of governing Markov process. In [3] the M/G/1 system with extraneous irreducible Markov chain with m states was considered.

In [4] for M/M/1 system with m-state irreducible continuous-time governing Markov chain the busy period, equilibrium conditions and probabilities of system being empty (for each state of Markovian environment) were obtained with the help of analytic matrix functions.

The further works are [8–11]. In [9, 11] the matrix analytical method for such systems analysis was suggested.

Markov modulated Poisson process (MMPP). The term «Markov modulated Poisson process» was introduced by M.F. Neuts in [10].

The MMPP is the doubly stochastic Poisson process whose arrival rate is defined by an m-state irreducible Markov process. When the Markov chain is in state i, arrivals occur according to a Poisson process of rate λ_i. The MMPP is parameterized by the m-state continuous-time Markov chain with infinitesimal generator Q and the m Poisson arrival rates $\lambda_1, \lambda_2, \ldots, \lambda_m$.

The work [12] is an excellent survey about Markov-modulated Poisson processes theory and queues with Markov-modulated input and gives a lot of references for more detailed information.

Markov modulated Bernoulli process (MMBP) is a discrete time analogue of MMPP, where a time is discretized in slots (with fixed length) and the number of time slots spent by arrival process in each state of m-state irreducible Markov chain follows geometric distribution. The MMBP is defined by Bernoulli process $X = \{X_i; i = 1, 2, \ldots\}$ where each X_i is a binary random variable which arrival probability p depends on Y_n state of Markov chain (Y_n, $n = \overline{1, m}$, m — number of states of Markov chain) with transition matrix P (the elements of P define the change of Bernoulli process arrival probabiliry) on a discrete state space E. The theory and analysis of MMBP are presented in [13]. Also the theory of MMBP may be found in [14, 15] as well as examples of application.

Markov modulated fluid flow — the rate of incoming flow (represents the incoming traffic as a stream with a finite rate) is modulated by external continuous time Markov process [15]. The fluid flow models are consider to be appropriate approximation to systems (real-life models) where the number of arrival customers is relatively large (the arrival traffic has to be heavy with system load greater than 90%).

One of the first works concerning MMFF is [16] with superposition of several incoming flows with arrival rates governed by two-state Markov chains with application to computer network analysis. The work [17] suggests the matrix-analytical approach, based on the theory of quasi birth-death processes, for steady-state analysis of MMFF.

The MMFF queue approach may be applied for modelling of peer-to-peer file sharing [18], optical burst switching [20], ad hoc networks [19], Internet of Things (IoT) [21].

3. Active queue management, RED-type algorithms

According to RFC 7567 [22] active queue management (AQM) is considered as a best practice of network congestion avoidance (reducing) in Internet routers. The active queue management is a based on some rules (algorithms such as random early detection (RED), Explicit Congestion Notification (ECN), or controlled delay (CoDel)) technique of intelligent drop of network packets inside a buffer associated with a network interface controller (NIC), when that buffer becomes full or gets close to becoming full.

We will consider only the case of RED algorithm and some its modifications. RED has the ability to absorb bursts and also is simple, robust and quite effective at reducing persistent queues.

The classic RED [23] is a queueing discipline with two thresholds (Q_{min} and Q_{max}) and a low-pass filter to calculate the average queue size $\hat{Q}$. RED monitors the average queue size and drops (or marks when used in conjunction with ECN) packets based on statistical probabilities $p(\hat{Q})$ [23].

RED is more fair than tail drop when the incoming packet is dropped only if the buffer is full. Also RED does not possess a bias against bursty traffic that uses only a small portion of the bandwidth. But, as shown in [24], RED has a number of problems, one of which is that it need tuning and has a little guidance on how to set configuration parameters.

The more information about RED and its modifications, as other AQM algorithms (Random Exponential Marking (REM), Blue and stochastic fair Blue (SFB), Adaptive virtual queue algorithm) is available in [25–27].

4. The application of MMAP theory to the AQM

In this part the brief overview of articles with Markov modulated arrival processes application (since Internet traffic is known to be bursty and exhibits Long Range Dependence (LRD) characteristic, Poisson and Bernoulli processes failed to model bursty and correlated traffic in adequate manner) to AQM algorithms will be presented.

Markov modulated Poisson process approach. Markov Modulated Poisson Process (MMPP) is used for bursty and correlated traffic modelling due to the simplicity of its mathematical model [28–30]. It was shown that superposition of MMPP can be used to model variable packet traffic with Long Range Dependence [28]. In [28] superpositions of two-state Markovian sources is suggested as a very versatile tool for the modelling of variable packet traffic with LRD. In [29] the queueing model for GRED-I (Gentle RED with instantaneous queue length) algorithm with different classes of bursty traffic was investigated. The aggregate traffic in proposed queueing model is defined by the superposition of 2-state MMPP. For each traffic class two individual thresholds are assigned in order to differentially control traffic injection rate. In [30] the analytical model for priority-based AQM with heterogeneous bursty traffic (MMPP) and non-bursty traffic (Poisson process) with individual thresholds was discussed. The expressions of the aggregate and marginal performance characteristics of the priority-based AQM system are obtained.

Even MMPP approach is considered to be less complex, some scientists [34] consider MMPP models to disagree with the digitalised communication world, so Markov modulated Bernoulli process approach is more appropriate.

Markov modulated Bernoulli process approach. The methodology of bursty traffic sources modelling by the Markov Modulated Bernoulli Process with two states (MMBP-2) is presented in [31]. The proposed technique can be extended to an MMBP with m states.

In works [32–34] the Markov modulated Bernoulli process is applied to AQM modelling and analysis. The [32, 33] consider analytical model proposed for a single MMBP-2 arrival process. In [32] a discrete-time stochastic queueing model for the performance analysis of congestion control mechanism based on RED methodology with bursty and correlated traffic by using a two-state MMBP-2 as the traffic source was presented. Two traffic classes were modelled by two-dimensional discrete-time Markov chain (each Markov chain dimension corresponds to a traffic class with its own RED parameters). The authors computed such performance characteristics as the mean system occupancy and mean packet delay, throughput and the probability of packet loss. In [33] the model for multiple-class traffic with short range dependent traffic characteristics was considered.

Since the analytical models proposed in [32, 33] were not able to represent traffic flows with different characteristics and precedence, the model based on superposition of multiple MMBP-2 sources (for aggregated Internet traffic from multiple traffic classes) for RED and WRED queue management schemes performance evaluation was introduced in [34].

Markov modulated fluid flow approach. It is commonly used to apply fluid models to AQM analysis, for example, for the first time the fluid models for TCP and RED analysis were applied in [35, 36]. In [35] the fluid analysis of TCP and other TCP-like congestion control mechanism was described. The authors modelled the window size behaviour as a Poisson Counter driven Stochastic Differential Equation and performed analysis. And in [36] the authors designed an AQM control system using the RED scheme by relating its free parameters such as the low-pass filter break point and loss probability profile to the network parameters. The guidelines for designing linearly stable systems subject to network parameters like propagation delay and load level were presented.

The fluid flow model approach for AQM analysis was also used in [37, 38] and developed for Wiener fluid process governed by Poisson process (Poisson counter). The method of stochastization (randomisation) of one-step processes (birth-death processes) [39] is proposed for active queue management analysis in before mentioned model.

5. Conclusions

The brief overview of MMAP processes and their applications to the modelling and analysis of AQM algorithms was presented in the article.

The authors consider that not only MMAP processes may be applied to the AQM modelling and analysis (as shown before), but the queueing systems with renovation (general renovation) [40–42] may also be applied (as shown, for example, in [43]) coupled with Markov modulated arrival or service processes.

At the end, it is worthy of mention that there is another approach to the analysis of behaviour of networks with burst traffic (for overload (congestion) control) — the method based on hysteretic thresholds load control [44].

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