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Transient Markovian and Diffusion Approximation Models for Performance Analysis of Computer Networks and Battery Energy Storage Systems

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Abstract

Quality of Service (QoS), security, energy consumption, and cost (deployment and operational cost) are key constraints in the design and provisioning of computer systems, networks, and ICT (Information and Communication Technology) infrastructures. These metrics are tightly connected. Thus, modern computer systems and networks should be designed and deployed in such a way as to find a reasonable tradeoff between QoS, security, energy consumption, and cost. Queueing theory is a commonly used tool in such studies. Queueing models based on Markov chains and diffusion approximation have been extensively used to model problems in computer systems and networks. One such application of these models is to evaluate the performance of queues (waiting lines of jobs, processes, data packets, energy packets, etc.) in computer systems and networks. Diffusion approximation is well suited for the transient analysis of queueing systems in computer systems and networks. It provides a methodology to perform a time-dependent analysis of the performance metrics (queue size, waiting time, and probability of rejection when the storage memory is full and subsequently arriving customers are rejected) as the parameters of the interarrival and service (processing) times changes over time. Another advantage of the diffusion approximation modelling methodology is the possibility of using realistic distributions of the interarrival and service times obtained from measured data.

The packet sizes generated from access networks vary from a few bytes in IoT and wireless sensor networks to 1500 bytes in Internet Protocol (IP) networks. The transmission of massive amounts of small packets (sometimes with randomly varying sizes) generated by access networks through high-speed Internet core networks to other access networks or cloud computing data centres has introduced several challenges such as poor throughput, underutilisation of network resources, and higher energy consumption. Packet aggregation mechanisms were developed to resolve these challenges. Packet aggregation mechanisms aggregate smaller packets into a larger payload packet, and these groups of aggregated packets will share the same header, hence increasing throughput, improving resource utilisation, and reduction in energy consumption. In Chapter 2, we present a review of packet aggregation applications in access networks (IoT and 4G/5G mobile networks), optical core networks, and cloud data centre networks. We also propose diffusion-based analytical models that can be used to design and evaluate the performance of packet aggregation mechanisms. We also demonstrated the use of measured traffic from real networks to evaluate the performance of packet aggregation mechanisms using simulation and analytical models. Despite its benefits, packet aggregation increases the packets' delays and may not be suitable for traffic belonging to real-time applications.

Queues of packets or jobs are unavoidable in computer network devices (e.g., routers and switches) due to the stochastic nature of the interarrival times of packets, processing and transmission times of packets, and sizes of packets. Queueing also results from sharing limited computational and communication resources. Queueing degrades the quality of service (QoS) experienced by users by increasing packet delays, packet loss probability, and jittering experienced by multimedia traffic. Queueing theory models (e.g., Markovian, fluid flow, and diffusion approximation models) are very useful tools for the analysis of the performance of computer systems and networks. In chapter 3, we present the architectures of hardware and software SDN switches and model the flow matching (lookup) mechanisms used in these switches. We propose a tractable diffusion approximation for both the transient and steady-state behaviour of a network router. Using these results, we show that when SDN switches change the paths of flows frequently, the network's behaviour may often be far from its steady-state behaviour. In chapter 4, we present an overview of flexible routing

in SDN-based networks. We extend the methodology developed in chapter 3 to the time-dependent analysis of multiple SDN switches using diffusion approximations, which are very convenient to analyze in a time-dependent regime.

Markovian, fluid flow, and diffusion approximation models have recently been adapted to model the energy depletion process in battery energy storage systems for computer systems and ICT infrastructures. One of the most important criteria is minimizing energy consumption in designing and deploying battery-powered computer systems (e.g., IoT devices, mobile phones, UAVs). Energy consumption in battery-powered computer systems and network devices can be reduced by using energy-efficient hardware, software, and protocols. If the energy stored in the battery is completely drained, the computer system or network device is shut down. Thus, modelling energy consumption in battery-powered computer systems and networks and modelling the energy depletion process in batteries is essential. In chapter 5, we apply a diffusion or Brownian motion process to model the energy depletion process of a battery of an IoT device. We use the model to obtain the probability density function, mean, variance, and probability of the lifetime of an IoT device. Also, we study the influence of the active power consumption, sleep time, and battery capacity on the probability density function, mean, and probability of the lifetime of an IoT device. We use numerical examples to study the influence of battery depletion attacks on the distribution of the lifetime of an IoT device. We also introduce in our model an energy threshold after which the device's battery should be replaced to ensure that the battery is not completely drained before it is replaced.

The energy-harvesting technologies to harvest energy from external energy sources in the environment such as solar, thermal, wind, and vibration to power computer systems or to replenish the energy drawn from the batteries attached to these systems enable them to operate longer with minimal energy-related interruptions. Thus, an effort to ensure higher efficiency of the harvesting and more economical performance of these devices is necessary. In chapter 6, we present an architecture of a green base station site. We develop Markovian and diffusion approximation models to analyze the steady-state and transient-state performance of battery energy storage systems. We apply the Markovian and diffusion approximation model to derive the time after which the battery energy storage system is completely discharged or fully charged. By assuming that the energy harvesting and the energy consumption processes are exponentially distributed, we compare the result obtained from the Markovian model to those from diffusion approximation models.

Therefore, diffusion approximation is a practical tool for analysing the performance of computer systems and networks as it allows the use of measured packet interarrival times and packet service times (processing and transmission times) distributions. It is useful for analysing the transient behaviour of QoS parameters in SDN-based networks resulting in frequent changes in the flow forwarding rules in the SDN switches. Transient Markovian and diffusion models are suitable for modelling the energy depletion process in battery energy storage systems for computer networks and networks with stochastic energy harvesting and energy consumption processes.