Probabilistic Modeling of Network Congestion and Queue Delay

Course: Fundamentals of Probability in Computing
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Scribe Question 1: Project System and Objective

The probabilistic problem addressed in this project is the modeling of **network congestion and queueing delay** in a distributed communication network. The project examines how randomness in traffic arrivals and service mechanisms leads to congestion and increased end-to-end packet delay.

The system consists of multiple network nodes that generate, forward and transmit packets over shared links. Each node is modeled as an **M/M/1 queue**, where packet arrivals follow a Poisson process and service times are exponentially distributed. The overall network is represented as an open queueing network of interconnected M/M/1 queues. Packets may traverse multiple intermediate nodes before reaching their destination and the total delay is the sum of delays encountered at each node.

The primary objective of the project is to probabilistically analyze the average end-to-end packet delay and study the onset of congestion as traffic load increases.

The main sources of uncertainty in the system are:

- **Packet arrival uncertainty:** Random packet arrivals at each node.
- **Service time variability:** Random transmission and service times.
- **Network interaction effects:** Contention for shared resources among nodes.

By modeling these uncertainties using queueing theory and probability, the project provides insight into network stability and congestion behavior.

Scribe Question 2: Key Random Variables and Uncertainty Modeling

The behavior of network congestion and delay in the project is determined by several key random variables that capture different sources of uncertainty in the system.

- **Packet inter-arrival time:** This represents the time between consecutive packet arrivals at a node. It is modeled as an exponential random variable, assuming packet arrivals follow a Poisson process.
- **Service time:** This denotes the time required by a node to transmit a packet. It is modeled as an exponential random variable, consistent with the M/M/1 queue model assumption.
- **Queue length:** This represents the number of packets waiting at a node at any given time. It is a discrete random variable that evolves based on packet arrivals and service completions.
- **End-to-end delay:** This is the total time experienced by a packet from its arrival at the source to its delivery at the destination. It is a random variable formed by the sum of queueing and service delays across multiple nodes.

Uncertainty in the system is modeled using the M/M/1 queueing framework, where packet arrivals are assumed to be memoryless and independent and service times are random and independent of arrival processes. These probabilistic assumptions simplify the analysis while capturing the essential randomness present in network traffic.

Scribe Question 3: Probabilistic Reasoning and Dependencies

Probabilistic relationships are used in the project to model and analyze uncertainty in network congestion and queueing delay.

Packet arrivals at each node are assumed to be **independent** of each other and follow a Poisson process. This independence simplifies reasoning about traffic flow and allows the use of standard queueing models such as the M/M/1 queue.

Service times at nodes are also assumed to be independent random variables and are not affected by past arrivals or services. This memoryless property supports probabilistic inference about waiting times and system stability.

Dependence arises in the system through network interactions. For example, the queue length and delay at a node depend on the current traffic load and service rate. As the arrival rate increases, queue lengths and delays increase accordingly.

Conditional probability is used when analyzing system behavior under specific conditions, such as determining the expected delay given that the system is heavily loaded or near congestion.

These probabilistic assumptions enable simple reasoning about delay, congestion and stability while keeping the model easy to analyze.

Scribe Question 4: Model–Implementation Alignment

The conceptual implementation of the network system under study fits well with the developed probabilistic model in our project. All the network nodes are viewed as queues which accept packets randomly, process, and send them over the network. This abstraction reflects how packets experience waiting time and delay due to congestion in real communication networks.

It relies on a probabilistic model, which makes certain probabilistic assumptions concerning the implementation to suit the study, such as random arrivals of packets, randomly selected service times, and constant operating conditions. Directly linked to the model-predicted quantities are performance measures that include queue length, waiting time, and end-to-end delay. The assumptions of the probabilistic framework can be applied to the implementation, and it may be utilized to assess congestion behaviour under increasing traffic load without the need to incorporate packet loss or mobility effects.

Scribe Question 5: Cross-Milestone Consistency and Change

The probabilistic model of network congestion and queueing delay is also well defined and internally consistent at the present stage of the project. The main elements of the model include: Random arrivals of packets, stochastic service times, development of queue length, and the delay buildup in two or more nodes are properly developed, the dependencies on the intensity of traffic, node utilization, queue formation and end-to-end delay are well comprehended and form the foundation of the present analysis.

Some of the assumptions are currently clear, such as independent packet arrivals, memoryless service behaviour, constant packet size and adequate buffering at each node. These assumptions make the probabilistic analysis of it rather simpler and address the fundamental sources of randomness causing the congestion.

In the next milestones, the model is anticipated to be changed in some aspects. These include relaxing the assumptions of independent arrivals, the incorporation of more realistic patterns of traffic, as well as the analysis of the impact of limited buffer capacity in addition to increased levels of congestions. These refinements are required in order to make them more realistic and to gain better insight into the behaviour of the system in extreme or non-ideal conditions, as well as to build upon the probabilistic foundation already developed.

Scribe Question 6: Open Issues and Responsibility Attribution

There are certain probabilistic issues that are open at this point in the project. These involve learning about the effect of correlated or bursty arrival of a traffic in terms of the stability of a queue, the effect of large traffic load on delay variation, and the effects of assumptions of independence on outcomes when there is severe congestion. Another area that is unclear is the sensitivity of end-to-end delay to variations in the intensity of traffic in various nodes.

The following milestone of the project will be concerned with these issues. The roles involve ensuring the refinement of the probabilistic assumptions, because the existing model needs to be extended to accommodate more sources of uncertainty and putting the conclusions through numerical analysis or simulations. The solution of these tasks will assist in making the model more reliable and give a deeper understanding of the system of network congestion and queue delays.