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SIMULATION OF COMMUNICATIONS NETWORKS

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ABSTRACT

This paper discusses how simulation is used to design and analyze communications networks. Topics discussed include: network issues addressed by simulation, simulation software for network modeling, techniques for building valid and credible models, and statistical considerations. A comprehensive example will also be given in the conference presentation.

1 INTRODUCTION

In this paper we present an overview of the use of simulation in the design and analysis of communications networks. A detailed discussion of simulation, in general, may be found in Law and Kelton (1991). A practical discussion of the steps in a sound simulation study is given in Law and McComas (1990). General references on communications are Halsall (1992), Martin and Chapman (1989), Stallings (1991), and Tannenbaum (1989).

It is often of interest to study a proposed or existing communications network to improve its performance. However, it is generally necessary to use a model for this purpose, since experimentation with the network itself is either disruptive, not cost effective, or simply impossible (e.g., the network has not yet been built).

If the relationships that compose the model are simple enough, it may be possible to use mathematical methods (such as algebra, calculus, or probability theory) to obtain *exact* answers to the questions of interest; this is called an *analytic solution*. As a matter of fact, analytic queueing models have been used for years to study performance issues for communications networks and computer systems (see, for example, Kleinrock 1976). However, as network topologies and protocols have become more complex, analytic methods have become increasingly inadequate. Additional shortcomings of analytic queueing models are as follows:

- Only steady-state results are typically possible
- It is difficult to obtain performance measures other than mean values (e.g., the 95th percentile of end-to-end delay)
- Original analytic solutions require considerable mathematical sophistication on the part of the analyst

Because of the drawbacks of analytic methods, there has been a considerable increase in the use of simulation for network analyses during the past five to ten years. This has in turn resulted in the introduction of a number of new simulation products specifically for communications networks. In a *simulation* a mathematical/logical model is numerically evaluated over a time period of interest, and performance measures are *estimated* from model-generated data. Simulation analyses are applicable to systems of almost any level of complexity. Perhaps the only impediment to the use of simulation is the potentially large amount of computer execution time required to process messages for high-traffic-rate networks.

2 OBJECTIVES OF SIMULATION IN COMMUNICATIONS

The following are some of the benefits of using simulation to design and analyze communications networks:

- Determination of the system-wide impact of making "local" changes to the network
- Improved system performance (delays, throughput, etc.)
- Reduced expenditures
- Insurance that performance objectives are met before equipment is bought or leased

- Identification of bottlenecks before system implementation
- Reduced system development time

Simulation has addressed a number of specific communications issues, including:

- How will my network perform when the traffic load increases?
- What are the requirements for number/speed of links, number/speed of switches, and buffer sizes for my wide area network?
- What will be the impact of a link failure?
- What protocols will provide the best network performance?
- What is the best design for my new communications network?
- What will happen when additional PCs or workstations are added to my local area network (LAN)?
- What impact will adding a new application such as image processing have on my LAN?
- Do I need to upgrade my Ethernet to Fiber Distributed Data Interface (FDDI)?
- Should I segment my LAN and, if so, in what manner?
- Do I need another file server for my LAN?
- How many satellites are needed to provide a certain level of service between two earth stations?

The following is a list of performance measures that are commonly used in simulation studies of networks:

- Throughput (e.g., in kilobits per second)
- End-to-end delay
- Delay from point A to point B in a network
- Number of "data units" in a queue or a buffer
- Utilizations of nodes or links
- Probability of a blocked call
- Probability of a lost call (mobile system)
- Number of collisions and deferrals (LAN)

3 SIMULATION SOFTWARE FOR NETWORKS

One of the major tasks in building a simulation model of a communications network is that of converting a system description into a computer program. An analyst may use either a general-purpose programming language (e.g. C or FORTRAN) or simulation software for this purpose. Some advantages of a programming language are as follows:

- Most modelers already know a programming language, but this is often not the case with simulation software.
- C or FORTRAN are available on virtually every computer, but a particular simulation software product may not be available for the analyst's computer.
- Software cost will generally be considerably lower (but not necessarily project cost).

The major advantage of using simulation software is that they automatically provide most of the features needed in programming a simulation model, resulting in a significant decrease in programming time (and usually project cost). Simulation software also provide a more natural framework for system modeling. In general, we believe that an analyst would be prudent to use simulation software to model a communications network.

There are three types of software for simulating communications networks (see Law and McComas 1994). A *general-purpose simulation language* is a simulation package that is general in nature (e.g., it could also be used for modeling manufacturing systems or for combat modeling), but may have special features for communications such as explicit modules for Ethernet or token ring. Examples of simulation languages are Arena, BONeS DESIGNER, GPSS/H, MODSIM II, SES/*workbench*, SIMAN/Cinema V, SIMSCRIPT II.5, and SLAMSYSTEM (only BONeS DESIGNER and SES/*workbench* have communications modules).

A model is developed in a simulation language by writing a program using the language's modeling constructs, which include entities (messages), attributes (message type or destination), resources (nodes or links), and queues (buffers). The major advantage of most languages is their ability to model almost any kind of communications network, regardless of its complexity or uniqueness. Possible drawbacks of languages, as compared to some simulators (see below), are the need for programming expertise and possibly the long time spent coding and debugging that is associated with modeling complex networks.

A *communications-oriented simulation language* is a simulation language that is specifically oriented toward communications networks--OPNET Modeler is such a product. Advantages are possibly reduced programming time and modeling constructs oriented toward communications systems.

A *communications-oriented simulator*, in its most basic form, is a simulation package that allows one to simulate a network in a specific class of communications networks with no programming. Examples of basic simulators are BONeS PlanNet, COMNET III, L•NET II.5, and NETWORK II.5. The particular network of interest (in the domain of the package) is selected for simulation by choosing items from menus (typically using a point-and-click approach), by filling in dialogue boxes (forms), and by the use of graphics. Typical modeling constructs for a LAN simulator are LAN types (Ethernet, token ring, etc.), stations on a LAN (PCs or work stations), LAN interconnection devices (bridges and routers), and traffic (message) generators. The major advantage of a simulator is that "program" development time may be considerably less than for a simulation language. This may be very important given the tight time constraints in many business environments.

Another advantage is that simulators have modeling constructs closely related to the components of a communications network, a very desirable feature for someone like a network manager. Also, people without programming backgrounds and those who use simulation only occasionally often prefer simulators because of their ease of use.

The major drawback of basic simulators is that they are limited to modeling only those network configurations allowed by the package's standard building blocks. Thus, if a communications system has some unique features, they might have to be modeled in an approximate manner when using certain simulators. This difficulty can be largely overcome in the Developmental Version of COMNET III, which allows existing modeling constructs to be modified and new constructs to be added. Also, the built-in modules (e.g., Ethernet) in BONeS PlanNet can be modified if the user also has BONeS DESIGNER.

Note that an important feature for simulation software to be used for network modeling is fast model execution speed, because in some networks a very large number of messages will need to be simulated.

4 DEVELOPING VALID AND CREDIBLE SIMULATION MODELS

A simulation model is a surrogate for actually being able to experiment with a communications system. Thus, an idealized goal in building a simulation model is for it to be *valid* enough so that any conclusions drawn from the model would be similar to those derived from physically experimenting with the system (if this were possible). It is also important for a model to be *credible*; otherwise, its results may never be used in the decision-making process, even if the model is valid.

The following are some important ideas/techniques for deciding the appropriate level of model detail, for validating a simulation model, and for developing a model with high credibility:

- State definitively the issues to be addressed and the performance measures for evaluation at the beginning of the study.
- Collect information on the network topology and protocols based on conversations with all important people associated with the system.
- Delineate all information and data summaries in an "assumptions document."
- Interact with the manager on a regular basis throughout the study.
- Perform a structured walk-through (before programming) of the conceptual simulation model as embodied in the assumptions document before an audience of all key project personnel.
- Use sensitivity analyses (see Law and Kelton 1991) to determine important model factors.
- Compare performance measures (e.g., average end-to-end delay and throughput) for the existing network (if there is one) to comparable performance measures for a simulation model of the existing network.

5 STATISTICAL ISSUES IN NETWORK SIMULATION

Since random samples from input probability distributions (e.g., the distribution for interdeparture times of messages) are used to "drive" a simulation model through time, basic simulation output data (e.g., end-to-end delays of messages) or an estimated performance measure computed from them (e.g., average end-to-end delay from the entire run) are also random. Therefore, it is important to model the random inputs to a simulation model correctly and also to design and analyze simulation experiments in a proper manner. These topics are briefly discussed in this section.

5.1 Modeling System Randomness

The most important source of randomness for network simulations is usually that associated with message traffic. In general, one should model *messages* not packets. Note also that messages may not be independent of each other (e.g., there are often acknowledgement messages). The following methods of generating traffic are often used, with the first approach generally being the most statistically valid:

- Message departure times and message sizes for a particular node are application based (file transfer, word processing, E-mail, etc.), and may depend on the receipt of an acknowledgement message
- Message interdeparture times and message sizes for a particular node are each independent samples from respective probability distributions (usually

exponential for interarrival times)
- Traffic data are read into the simulation model from a network analyzer

Because network components are generally quite reliable, equipment breakdowns are not typically modeled in a simulation. An exception is where one is interested in the transient response of the network, e.g., the ability of the network to reconfigure itself after a link failure. In such cases, the operational status of a component can be modeled as an "up" period of random duration followed by a "down" (or repair) period of random duration.

5.2 Design and Analysis of Simulation Experiments

Because of the random nature of simulation input, a simulation model produces a statistical estimate of the (true) performance measure not the measure itself. In order for a simulation estimate to be statistically precise (have a small variance) and free of bias, the analyst must specify for each network configuration appropriate choices for the following:

- Length of each simulation run
- Number of independent simulation runs
- Length of the warmup period, if one is appropriate

We recommend always making at least three to five independent runs for each configuration, and using the average of the estimated performance measures from the individual runs as the overall estimate of the performance measure. (Independent runs mean using different random numbers for each run, starting each run in the same initial state, and resetting the model's statistical counters back to "zero" at the beginning of each run.) This overall estimate should be more statistically precise than the estimated performance measure from one run.

When simulating certain types of communications systems, we are often interested in the long-run (or steady-state) behavior of the system, i.e., its behavior when operating in a "normal" manner. On the other hand, simulations of these kinds of systems often begin with the system in an empty and idle (or some other unrepresentative) state. This results in the output data from the beginning of the simulation not being representative of the desired "normal" behavior of the system. Therefore, simulations are often run for a certain amount of time, the *warmup period,* before the output data are actually used to estimate the desired measure of performance. Use of these warmup-period data would bias the estimated performance measure.

A comprehensive treatment of simulation output-data analysis can be found in Law and Kelton (1991).

6 SIMULATION ANALYSIS OF A COMMUNICATIONS SYSTEM

In the actual conference presentation, we will give a detailed simulation analysis of a wide area communications network. The following performance issues will be addressed:

- Is the performance of the existing network satisfactory?
- What impact will a link failure have on system performance?
- How much can the traffic rates be increased before the system "blows up"?
- What impact will changing the message-size distribution and the form of the traffic have on system performance?

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