IDEA GROUP PUBLISHING
701 E. Chocolate Avenue, Suite 200, Hershey PA 17033-1240, USA
Tel: 717/533-8845; Fax 717/533-8661; URL-http://www.idea-group.com

ITB12585

This paper appears in the book, *Emerging Trends and Challenges in Information Technology Management, Volume 1 and Volume 2* edited by Mehdi Khosrow-Pour © 2006, Idea Group Inc.

Modeling and Simulation of IEEE 802.11 WLANS: A Case Study of a Network Simulator

Nurul I. Sarkar, School of Computer & Information Sciences, Auckland University of Technology, Private Bag 92006 Auckland 1020, New Zealand, P 64 9 9219999, nurul.sarkar@aut.ac.nz

Roger McHaney, Dept of Management, College of Business Administration, Kansas State University, Manhattan, KS 66506, mchaney@ksu.edu

ABSTRACT
Stochastic discrete event simulation methodology is becoming increasingly popular among network researchers worldwide in recent years. This popularity is due to the availability of various sophisticated and powerful simulation software packages, and also because of the flexibility in model construction and validation offered by simulation. This paper describes our experience in using the ns-2 network simulator, a discrete event simulation package, as an aid to modeling and simulation of the IEEE 802.11 wireless local area networks (WLANs). The paper concludes by discussing the strengths and weaknesses of simulation methodology in general, and the ns-2 in particular.

INTRODUCTION
The use of discrete event simulation packages as an aid to modeling and performance evaluation of WLANs has grown in recent years (Bianchi, 2000; Chen, Jian, & Lo, 2002; Das, Castaneda, & Yan, 2000; Fantacci, Pecorella, & Habib, 2004; Tickoo & Sikdar, 2003). This popularity is due to the availability of sophisticated simulation software packages and low cost powerful personal computers (PCs), but also because of the flexibility in rapid model construction and validation offered by simulation.

A detailed discussion of simulation methodology, in general, can be found in (Carson II, 2004; Law & Kelton, 2000). More specifically, Pawlikowski (1990) in a comprehensive survey of problems and solutions suited for steady-state simulation mentioned the relevance of this technique for telecommunications modeling. This view is frequently supported in the wireless communication and networking literature (Hassan & Jain, 2004; Holloway, 2003; Nicopolitidis, Obaidat, Papadimitriou, & Pomportsis, 2003; N. Sarkar & Pawlikowski, 2002).

A typical WLAN can easily be simulated and its performance evaluated by a software package (i.e., simulator). It is important for researchers to choose a simulator which is easy to use; more flexible in model development, modification and validation; and incorporates appropriate analysis of simulation output data, pseudo-random number generators, and statistical accuracy of the simulation results (i.e., desired relative precision of errors and confidence interval). These aspects of credible simulation studies are recommended by leading simulation researchers (Law & Kelton, 2000; Pawlikowski, Jeong, & Lee, 2002; Schmeiser, 2004).

While various simulators are exist for building a variety of WLAN models, we briefly describe two popular network simulators namely, ns-2 (Fall & Varadhan, 2003) and OPNET (OPNET, 2004). The ns-2 simulator is one of the most commonly used simulators today and is very popular with researchers, including CS and EE students worldwide. The ns-2 is open-source software and provides an environment for rapid model construction and simulation output data collection.

OPNET, developed by OPNET technologies, is another popular commercial software package commonly used by researchers and practitioners for modeling and network simulation. It has a robust and flexible wireless node model which consists of process models of the different layers of the network protocol stack. Like ns-2, OPNET is an object-oriented simulation package. However, unlike ns-2, it is totally menu-driven with easy to use graphical user interface (GUI) for rapid model construction, data collection and other simulation tasks. It is often of interest to study a proposed or existing wireless network to gain insight into the behavior of the network. However, a model is required for this purpose, since experimentation with the live network is disruptive, and not very cost effective.

The remainder of this paper is organized as follows. We first provide an overview of ns-2 simulator and then describe our experiences in using ns-2 simulator as an aid to modeling and performance evaluation of IEEE 802.11 WLANs. Techniques for building credible models and statistical considerations are discussed. The strengths and weaknesses of simulation methodology are highlighted, and a brief conclusion ends the paper.

THE NS-2 SIMULATOR
The ns-2 simulator is one of the most popular and powerful simulators, which can be used for modeling and performance analysis of various networks including the IEEE 802.11 WLAN. It is a discrete event simulator originally developed at Lawrence Berkeley Laboratory at the University of California, Berkeley, as part of the Virtual InterNetwork Testbed (VINT) project. Berkeley released the initial code that made wireless network simulation possible in ns-2. The Monarch project at Carnegie Mellon University (Monarch, 2004) has extended the ns-2 with support for node mobility, a realistic physical layer, radio network interfaces and an implementation of the IEEE 802.11b distributed coordination function (DCF) media access control (MAC) protocol.

The ns-2 simulator is written in C++ and uses OTcl (object-oriented Tcl) as a command and configuration interface (Fall & Varadhan, 2003). The OTcl scripts are used to set up simulation scenarios in the simulator. One of the main benefits of OTcl scripts is that there is no need to recompile the simulator between different simulation scenarios. This feature is particularly useful (in terms of saving recompilation time) to study the impact of various influencing factors on the network performance. By using OTcl scripts, one can easily set up network topologies, specific protocols, link bandwidths, traffic sources and applications to be simulated (these behaviors are already defined in the compiled hierarchy) and the form of the output required.

The ns-2 has a rich library of network and protocol objects called ns objects. These objects include nodes, classifiers, links, queues, etc. All objects are derived from a class called NsObject, which is the base for all classes. There are two class hierarchies: the compiled C++ hierarchy and the interpreted OTcl, with one to one correspondence between them.

However, the compiled C++ hierarchy provides a greater efficiency in simulation runs in terms of faster execution times. This is particularly useful for detailed analysis of network protocol's behavior.

In ns-2, the timing of events is determined by a scheduler. The scheduler keeps track of simulation time and fires all events in the event queue scheduled for the current time.

The influence of network traffic load distribution on network performance is an important observation that interests many researchers. For this task, a variety of traffic generator is needed for automatic traffic creation according to a desired pattern and load. The ns-2 supports several traffic generators, e.g., Exponential ON-OFF, Pareto ON-OFF, and Constant Bit Rate (CBR). More details about the ns-2 simulator can be found in the ns manual (Fall & Varadhan, 2003).

CASE STUDY

We have been using ns-2 simulator for a number of years and our experiences are generally favorable. The ns-2 provides an excellent environment for easy simulation model development and performance evaluation of wireless communication networks. Figure 1 shows a simple framework in which we develop and execute various simulation models under ns-2 simulator to study the delay-throughput performance of the IEEE 802.11 WLAN. In addition to modeling wireless network protocols, ns-2 simulator also supports various propagation modeling (Fall & Varadhan, 2003).

Our current research focuses on developing a framework for estimating as well as improving the capacity of WLANs by integrating wireless network protocols and propagation modeling (N. I. Sarkar, 2004). We believe that our work contributes substantial extensions to ns-2 simulator and provides insights into the simulator.

One of the main issues in network simulation is the statistical accuracy of simulation results. A model must be validated and used in a 'valid experiment', which requires suitable sources of 'randomness' as well as appropriate means of analyzing simulation output data.

Fortunately, ns-2 simulator takes care of simulation output-data analysis and statistical accuracy of simulation results. Therefore, researchers can focus on developing and validating simulation models for various performance measures without worrying about controlling the simulation itself e.g., length of simulation runs (to get steady-state analysis), number of each independent simulation runs, and use of appropriate random number generators.

Example: Simulation model of IEEE 802.11 b

In this section we present two simulation scenarios based on ns-2 simulator, namely, IEEE 802.11 ad hoc and an infrastructure networks. Figure 2 illustrates the basic concept of a simulated ad hoc wireless network with 50 mobile stations. Stations communicate without any infrastructure or centralised control.

Figure 1: A framework for developing and executing simulation models under ns-2.

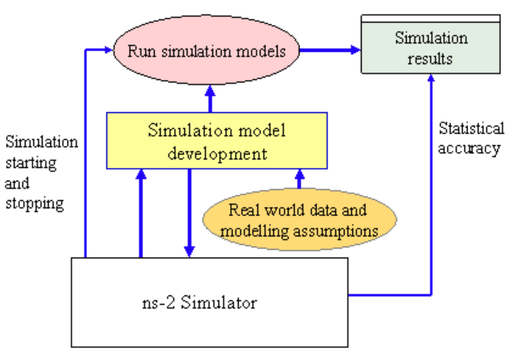

Figure 2: Simulation scenario of the IEEE 802.11b ad hoc network with 50 mobile stations (176 m X 176 m grid).

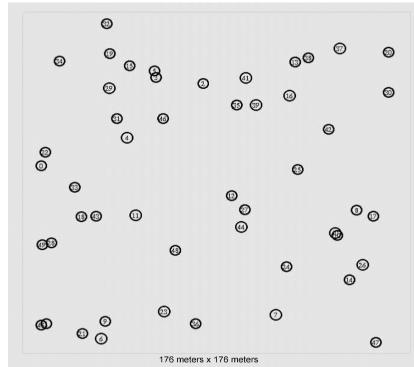

Figure 3: Simulation scenario of IEEE 802.11b infrastructure network with 50 mobile stations, one AP and 50 fixed stations (176 m X 176 m grid).

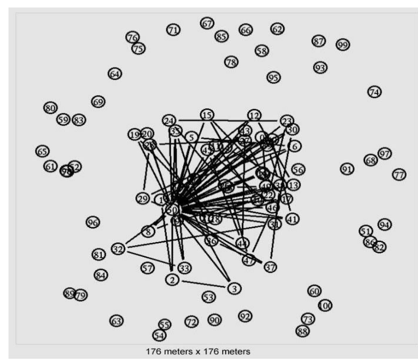

Figure 3 shows the simulated infrastructure-based wireless LAN with 50 mobile stations and one wireless access point (AP) linked to wired backbone with 50 fixed stations. In the infrastructure network, data traffic travels from mobile stations to wired stations via the AP. Both Fig. 2 and 3 are captured from animation output using ns-2's network animator (NAM) utility.

Both the ad hoc and the infrastructure network are based on the IEEE 802.11b with a maximum bandwidth of 11 Mbps. Mobile stations are simulated by setting up a grid of size 176m x 176m in which the longest distance between any two stations is 250m. This is also the maximum transmission range of two simulated stations.

Table 1 lists the parameter values that we used in the simulation of the IEEE 802.11b. Each simulation run lasts for 50 seconds simulated time in which the first 10 seconds is the transient period. The observations collected during transient period are not included in the final simulation results.

We consider two important network performance metrics, namely, 'mean packet delay' and 'throughput' performance, for both individual stations and overall network. The mean packet delay at station i (i = 1, 2, ..., N) is defined as the average time (measured in seconds or slots) from the moment the packet is generated until the packet is fully despatched from that station. A packet arriving at station i experiences several components of delay including queuing delay, channel access delay (i.e., contention time) and packet transmission time. The throughput (measured in bps) is defined as the fraction of the total channel capacity that is used for data transmission. We extracted both mean packet delay and

Table 1: Simulation parameters

Parameter	Values
Bandwidth	11 Mbps
Basic Rate	2 Mbps
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
Simulation time	50 seconds
Packet/Traffic type	UDP
Application	CBR
RTS/CTS	Off
PHY modulation	Direct Sequence Spread Spectrum
CWmin	31
CWmax	1023

throughput from the simulation output trace file generated by ns-2 simulator.

BUILDING VALID AND CREDIBLE MODELS

A main concern in any simulation effort is to ensure the model is credible and represents reality. If this can't be guaranteed, the model has no real value and can't be used to answer desired questions (McHaney, 1991; Sargent, 2004).

Validation is the process of determining the real-world system being studied is accurately represented by the simulation model. Not only does this process provide assurance that the conceptual approach is correct, it establishes an acceptable level of confidence in the conclusions drawn from running the simulation and provides insight as to the true operating characteristics of the modeled system. This confidence, called face validity, is important to both developer and model user.

The validation process begins during the initial stages of a simulation project and continues throughout. Simulation inputs, both qualitative and quantitative, must be examined and validated. Qualitative inputs include underlying assumptions, rules, and other non-numeric data that will be used in the simulation. Several techniques can be used for this including: (1) observation of an existing system followed by a statistical comparison with the model; (2) expert's reviews of assumptions and rules; and (3) intuition and experience of the simulation analyst.

Quantitative or numeric inputs to the simulation can also be tested for validity. Widely accepted method(s) include: (1) statistical comparisons of theoretical input data distribution to collected empirical data using chi-square or Kolmogorov-Smirnov goodness of fit tests; and (2) sensitivity analysis where model input is slightly altered and effects on the outputs are observed and measured. In addition to analyzing model inputs, outputs also need to be validated. This is often believed to be a more crucial form of validation. If the model's output closely represents expected values for the real-world system, a sense of confidence in the model's results is developed.

In many cases validity cannot be definitely proven until the modeled system has been implemented. However, until that time several methods can increase the confidence that a model is valid. Among these are: (1) comparison with data from similar systems; (2) experts; and 3) calculations. Like any form of simulation, a simulator plays an important role in building a credible model for the system under study. Therefore, it is important for researchers to use the right simulator which offers flexibility in model construction and validation. A good simulator should have appropriate analysis of simulation output data, pseudo-random number generators, and statistical accuracy of the simulation results.

We have validated our simulation results obtained from ns-2 simulator with empirical measurements using wireless laptops and access points for an IEEE 802.11b WLAN (N. I. Sarkar, 2005). We found that a good match between simulation results and empirical measurements. In short, the ns-2 simulator as reported in this paper has all the characteristics of a good simulator.

STRENGTHS AND WEAKNESSES OF SIMULATION

In this section we focus on the strengths and weaknesses of simulation methodology in general and ns-2 in particular. The use of simulation as an analysis technique has many advantages over other competing options. In systems that already exist, the testing of new ideas may be difficult, costly, or even impossible. For example, experimenting on an active network to test bottlenecks could severely impact users dependent on that system. Simulation can provide a means for doing this without interruption to the actual system.

In another instance, simulation can be used to test concepts prior to installation. Testing may reveal unforeseen design flaws and give designers a tool for improvement. The same flaws discovered after installation could result in increased costs and schedule delays. Another strength of simulation is its ability to increase and collate system knowledge and understanding. At the start of a simulation project, especially in the modeling of complex systems, knowledge is dispersed among different people and groups. Each individual may be an expert in his or her area but doesn't possess knowledge of the overall system.

Simulation also forces system definition and requires those involved to develop complete details of the system under investigation. It enhances creativity and encourages innovative solutions that can be evaluated prior to real world implementation.

In general, simulation's greatest strength is its ability to reduce risk. A network simulator, such as ns-2, offers flexibility in model construction and simulation. For example, one can easily develop a new simulation model of wireless media access control (MAC) protocol by modifying the existing example code (e.g., IEEE 802.11) given in ns-2 simulator. Another important strength of ns-2 simulator is that many researchers are contributing towards further extension of ns-2 since it is an open source software package (Anonymous, 2005). Authors of research papers often publish ns-2 code that they used, allowing other researchers to build upon their work using the original code. Moreover, ns-2 package is freely available at no cost and can be installed on a variety of operating systems (e.g., Linux, FreeBSD, and MS Windows). These features of ns-2 are particularly useful to academics, specifically Masters and PhD students who are looking for a tool for modeling and performance evaluation.

In spite of possessing many strengths, simulation is not always the "silver bullet" that removes all risk from decisions making. It has limitations and disadvantages that must be considered. High on this list are expenses. The creation of computer models can be costly both in terms of software and time. Although lower priced simulation packages are available (Swain, 2003), most large scale simulation languages and their environments represent a major investment. Large-scale simulation projects can represent many years of effort. First time use of simulation in an organization must include extra costs to cover personnel training and the learning curve. For instance, in our experience, many student researchers point out that ns-2 simulator has a steep learning curve.

Developing the model can also be costly. In most cases, data collection, model development, analysis, and report generation will require considerable time and skill. For example, the ns-2 simulator does not have any built-in support for creating sophisticated graphical presentations of simulation output data. The raw data must be processed using scripting languages such as 'awk' or 'perl' to produce data in a suitable format for tools like Xgraph or Gnuplot.

The final result in a simulation study must also be considered within context since modeling only yields approximate answers. The random number generators used to drive most models provide estimated characteristics. Statistics must be used as a tool for interpreting output.

CONCLUSION

Stochastic discrete event simulation methodology has become popular as a network modeling and performance analysis tool. This paper described the use of a network simulator, ns-2 and discusses wireless networking issues addressed by simulation. The models built under ns-2 simulator were validated using empirical measurements from wireless laptops and access points for an IEEE 802.11b WLAN. A good match between ns-2 simulation results and empirical measurements were reported. The paper provides a general discussion on techniques for building valid and credible models, and on the strengths and weaknesses of simulation methodology.

In summary, we want to stress the importance of using a good simulator for modeling and performance analysis of wireless communication networks. The ns-2 simulator offers more flexibility in model construction and validation, and incorporates appropriate analysis of simulation output data, pseudo-random number generators, and statistical accuracy of the simulation results. Without these features, a simulation model would be useless since it will produce invalid results. As Kleinjen (1979) pointed out that "…*instead of an expensive simulation model, a toss of the coin had better be used*".

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