Expanding Confidence in Network Simulations

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Abstract

Networking engineers increasingly depend on simulation to design and deploy complex, heterogeneous networks. Similarly, networking researchers increasingly depend on simulation to investigate the behavior and performance of new protocol designs. Despite such widespread use of simulation, today there exists little common understanding of the degree of validation required for various applications of simulation. Further, only limited knowledge exists regarding the effectiveness of known validation techniques. To investigate these issues, in May 1999 DARPA and NIST organized a workshop on Network Simulation Validation. This paper reports on discussions and consensus about issues that arose at the workshop. We describe best current practices for validating simulations and for validating TCP models across various simulation environments. We also discuss interactions between scale and model validation and future challenges for the community.

Keywords*:* network simulation, experiment validation, protocol specification and verification, discrete event simulation

Networks continue to grow more complex as industry deploys a mix of wired and wireless technologies into large-scale heterogeneous network architectures and as user applications and traffic continue to evolve. For example, increased complexity already affects Department of Defense combat networks, the Internet, and industrial wireless networks. Faced with such growing complexity, network designers and researchers almost universally use simulation in order to predict the expected performance of complex networks and to understand the behavior of existing network protocols not originally designed to operate in today's networks. Simulation is also increasingly used to predict the correctness and performance of new protocol designs. In addition, the use of simulations now appears as a strict requirement in processes leading to international standards, such as the IMT-2000 standard for third-generation, wireless, cellular telephony.

This growing reliance on simulation raises the stakes with regard to establishing the correctness and predictive merits of specific simulation models. Yet no widely accepted practices and techniques exist to help validate network simulations and to evaluate the trustworthiness of their results. Early work in networking research and engineering involved both experimentation and mathematical modeling to prove feasibility and to establish bounds on expected performance. In the past ten years, as networks have grown too large to allow easy experimentation and too complicated to admit easy tractable mathematical analysis, network simulation[1] has filled an increasingly important role, helping researchers and designers to understand the behavior and performance of protocols and networks. Today simulation is often used:

- to predict the performance of current networks and protocols in order to aid technology assessment and capacity planning and to demonstrate fulfillment of customer goals,
- to predict the expected behavior of new network protocols and designs through qualitative or quantitative estimates of performance or correctness, and
- to quickly explore a range of potential protocol designs through rapid evaluation and iteration.

For any of these purposes, the results produced from simulation, analytical, or hybrid models must

[1] Of course, modern simulation models often also include analytical sub-models. Such hybrid models can be more effective than either simulation or analysis alone.

be understood. *Validation* is the process of assuring that a model provides meaningful answers to the questions being investigated. (See Sidebar for a discussion of verification, validation, and accreditation.) Models often involve approximations or abstractions from reality; validation provides confidence that these approximations do not substantially alter the answers to the questions being posed. This implies that each set of questions can require a distinct validation because a simulation might be valid for answering one question, while invalid for another. Modeling is not unique in requiring validation. Laboratory experiments also can prove invalid when they encompass unexpected effects, such as measurement artifacts, or when experiment results are extrapolated into inappropriate regions, such as predicting performance of a million-node network based on a hundred-node experiment.

Further, different situations can require different levels of validation; the level of validation required for a network simulation is influenced by the questions being asked and by the systems being used. Answers to qualitative questions (are lost packets recovered?) often require less complete validation than quantitative questions (how quickly are lost packets recovered?). Some domains seem more amenable to abstraction, as well. For example, simple models of delay, bandwidth, and statistical errors can often replace detailed physical and link layer simulations for high-speed wired networks with low bit error rates. On the other hand, a wireless network, which suffers the effects of fading, interference, and mobility, can show significant transmission losses and medium access delays. This variation can produce significant differences between expected and observed performance measures and so wireless systems may require a more complex model to reflect these kinds of interactions between protocols for the transport and physical/radio layers. Increasing use of simulation in the networking research community, along with the need to understand protocols in more complicated environments (for example, mixed wireless and wired networks), has raised the stakes with regard to validating network simulations.

In May 1999, the National Institute of Standards and Technology (NIST) and the Defense Advanced Research Projects Agency (DARPA) co-sponsored a workshop to discuss approaches to validate network simulations. The workshop brought together leading simulation practitioners from companies, such as AT&T, Lucent, ITT, Raytheon, Telcordia, and SAIC, as well as researchers from universities, including Carnegie-Mellon, Dartmouth, George Washington, Rutgers, UC Berkeley, UCLA, and USC/ISI. Workshop attendees submitted position papers addressing key issues with regard to simulation validation (see the acknowledgments section for a URL pointing to the papers). Discussions at the workshop represented the state-of-the-art in network simulation and collected many approaches to validation currently pursued by practitioners and researchers.

This paper summarizes some of the conclusions of that workshop, offering insight into how validation applies to networking. We offer guidelines to simulation users and developers about what levels of validation are appropriate for different purposes, and about what techniques may prove helpful in specific circumstances. Finally, we suggest guidelines to the community about how to appropriately characterize and improve the validity of simulation studiessuch studies are of limited interest if the validity of their results cannot be understood. This paper captures the essence of the workshop (to the best of the authors' abilities), and so we thank workshop attendees for their contributions to these conclusions.

A. Background on Network Simulation

Several network simulators have arisen to meet the need for evaluating network scenarios before deployment. Four widely used simulators today include OPNET, ns-2, Parsec, and SSF. At a high level, all of these simulators are similar: they focus on packet-level discrete-event simulation and they model a wide range of protocols in the traditional

Internet protocol suite. Each simulator has a slightly different focus. OPNET is a commercial simulator with strong customer support, while the others are targeted primarily at the protocol design and networking research communities. Ns-2 emphasizes support for a wide range of wired and wireless protocols (but also provides research variants of TCP) and for multiple levels of abstraction [Breslau00a]. Parsec provides high performance parallel simulation and focuses primarily on wireless simulation [Bagrodia98a]. SSF also provides parallelism, but it emphasizes support for routing protocol simulation and for very large scale [Cowie99a]. In addition to these simulators, a number of more specialized simulators exist, and researchers today continue to explore new approaches to network simulation, approaches such as fluid flow models of network traffic (for example, [Nicol99]).

B. ISSUES TO CONSIDER WHEN VALIDATING NETWORK SIMULATIONS

Regardless of the particular simulator employed, the user must understand whether the results of the simulation will be valid for the question at hand. When considering how to validate a particular simulation, the user must first clarify what represents "ground truth". One obvious approach is to compare the simulation results to results from a particular real-world implementation of a network. This allows direct comparison of simulation results against live experiments. Direct comparison can work for small networks, especially given well-specified protocols. When network topologies are large or when protocols are under-specified, validation through direct comparison can prove difficult.

Comparing Specifications vs. Implementations. Traditionally, protocols have been specified only to the level necessary to ensure successful communication between nodes, and to obtain reasonable performance. This implies that many engineering decisions and optimizations may be left to protocol implementers. In most cases, different decisions lead to differences in performance, but without compromising the basic behavior encoded in the specification. For example, the details of acknowledgment timing are left as implementation decisions in the specification for TCP (see Request For Comments 1122). Such implementation decisions must be empirically determined or assumed when constructing a model for a specific protocol. As a result, protocol models typically embody behavior associated with specific implementations.

Comparison to particular protocol implementations might not be ideal in all cases, since a very accurate simulation can become outdated as protocols evolve or as traffic mixes change. In these cases simulations may need to be validated against future, rather than current, implementations and traffic. Simulation users need to understand both what is provided in a simulator and what is appropriate for their experiments.

TCP provides an example where the specification admits a range of implementations with very different performance. Details of the acknowledgement algorithm and parameters such as window size and scaling can alter initial or steady state throughput by a factor of 2-10. In such cases, simulations may be validated against a specific implementation or against the performance envelope of the specification.

Comparing Simulations as Protocol Designs Evolve. Protocol designs also evolve, and deployed implementations necessarily lag current research versions; simulations may track either. For example, the Reno implementation of TCP has known performance problems when multiple packets are lost in a single round-trip. This performance problem, since corrected in the selective acknowledgement TCP option, could produce large throughput differences between Reno TCP and other variants of TCP. The validity of such comparisons depends on their interpretation: they are valid at comparing specific implementations, but they misrepresent obtainable TCP performance using known techniques not included in the model.

Comparing Simulations as Network Traffic Changes. Finally, the Internet has experienced dramatic changes in traffic mixes (for example, the growth of the web and possible growth of streaming real-time data). Validations against yesterday's traffic mix may miss the current situation, and validation against today's traffic mix may misrepresent future patterns.

Choosing Appropriate Metrics for Comparisons. Given a choice of ground truth, either a specification or a particular implementation, validation methods must define metrics to compare simulation model results against that truth. A first step is to compare expected phenomena in the protocol. For example, TCP consists of several algorithms (such as windowed data transmission, slow-start, and fast retransmit). Testing these algorithms in simulation is akin to behavioral testing of a real-world implementation, and many of the same approaches can apply. In addition, time/event plots, packet animations, and trace comparisons are often useful tools in this process; however, finding general approaches to quantify differences among similar but not identical time/event plots remains an open research question. Successful behavior testing increases confidence that a simulated protocol will operate to specification.

Increasingly, model developers rely on visual comparisons among model outputs. While helpful, visual comparisons are limited in effectiveness because timing and behavioral differences are difficult to quantify visually, thus making it difficult to evaluate similarity.

Aggregate statistical measures, such as packets sent, throughput, and time-to-completion can provide an alternate useful picture. Aggregate measures should be chosen with care and used in conjunction with other approaches, though, since an improperly chosen metric can mischaracterize a comparison. For example, comparing average data sent over a period of time fails to capture differences in protocol burstiness.

Evaluating the Sensitivity of Simulations. Once a simulation has been validated under one set of conditions, sensitivity analysis helps understand how varying configurations change the accuracy of the simulation. For example, variations in how retransmission is handled may not be apparent if a TCP simulation is evaluated only under conditions of low loss. When considered on a large scale, network simulation presents an additional challenge, not addressed by sensitivity analysis, to verify that a simulation model exhibits specified behaviors regardless of variations in network topology, size, and traffic patterns. Such behaviors are sometimes called model invariants. Tools to assist the process of sensitivity analysis are an area for future research.

Assessing Cost-Benefit Tradeoffs. Finally, the extent, and therefore cost, of validation must be considered against the likely benefits. In some cases, detailed, expensive validation may be appropriate. Yet, in specific situations, it might prove impossible to achieve the desired level of validation no matter how much is spent. In other cases, extensive validation, while achievable, might well prove unnecessary. We have already described cases where comparison against an implementation is impossible or inappropriate. In general, more stable protocols, for which designs do not vary frequently or significantly, permit more specific validation. Ultimately, one must consider validation in the context of the research, and operational questions being investigated. Validation of a simulation intended to prove to a customer that a shipping product meets its specification might be much more exacting and costly than validation of a research simulation exploring dozens of possible protocol variants.

C. GUIDELINES FOR SUCCESSFUL VALIDATION

Having decided how to resolve the general issues affecting simulation validation, the user must then select a particular approach to validate a specific simulation. The workshop provided an understanding of the best current practices the community is using to validate network simulations. As input to the workshop, one of the industry practitioners contributed a concise summary of recommended practices [Lubachevsky99], which we expand upon here.

1. Various forms of models and implementations can emphasize different aspects of a networking system. For this reason, modelers should compare simulation results with as many alternate representations as possible. This might include laboratory experiments and field exercises, analytical models, and other, independently developed simulations. Increasing the number of alternative representations against which a model is compared increases the likelihood that errors, inconsistencies, and invalid assumptions will be uncovered.

2. Design in as many means as possible for examining the state of the simulation, and use visual representations to their fullest. While careful statistical analysis is certainly valuable, more often than not, invalid behaviors will be recognized more quickly from viewing animations. Finding effective approaches to examine and visualize very large models (10,000 or more nodes), especially for small but significant differences, remains a research challenge. Such models demand integrated instrumentation with multi-stage filtering and classification of data.

3. Where the model involves interactions over time among various independent entities, be sure to introduce asynchrony where needed to mimic the operation of real systems. For example, each wireless basestation maintains an independent clock. These clocks drift over time. Modeling this behavior is often worth the extra effort.

4. Simulation results must be reproducible. Many factors are important to promote reproducibility, including deterministic algorithms to generate pseudo-random number sequences, and mitigation of rounding errors from floating-point representations. Rounding errors can affect event concurrency, especially where optimistic synchronization is used when simulations are executed on parallel computer systems. In general, care must be taken to ensure that both time and causality are modeled accurately when parallel processing systems are used to execute simulations. Validation will prove impossible without the existence of appropriate reproducibility within a simulation.

5. Validation is much easier when the model is focused on comparative, rather than absolute, behaviors. This is natural in many cases, where a new proposal is being compared against an existing scheme, already deployed.

6. Where the size of the simulation must be reduced to execute within memory and CPU cycle limitations, care must be exercised to avoid introducing artificial boundaries into the model. For example, transient startup effects or an artificial physical topology can introduce inaccuracies.

Beyond these validation guidelines for network simulation practitioners, the workshop attendees discussed steps that could be taken to improve validation with respect to published research results. As an important step toward improving the quality of validation in the research community, simulation results should be reproducible. A paper employing simulation studies should be accompanied by a link to a publicly available and well-instrumented model (in either source or binary form) in order to allow independent confirmation of the results. Public availability of simulation source code and model protocol libraries is also important to allow examination for correct operation, and to permit modification for use in additional situations.

Although these recommendations are most important to network simulation developers, they are also applicable to simulation users who must evaluate the validity of their own conclusions. Just like a developer, a user must select an analysis technique (point 1), insure that that approach does not introduce additional error (points 2-5), that the results are interpreted appropriately (point 5), even at different scales (point 6).

D. SCALE AND VALIDATION

If validation of small simulations seems challenging, validating large simulations always proves even more difficult. Given the scope of today's Internet, understanding protocol behavior with large numbers of nodes, varied traffic levels, and with more or less detail, remain important questions. Another dimension of scale is the number of independently developed components within a model. We next look at how these two kinds of scale affect validation.

Scaling to Large Numbers of Nodes. Two approaches to large-scale simulation -- parallel execution and abstraction -- are complementary. Several simulators support parallelism [Bagrodia98a, Cowie99a]. The use of machines with multiple CPUs or clusters of workstations brings more horsepower and memory to bear on a given problem, allowing 10-100 times larger simulations. A complementary approach is the use of abstraction to factor out details unimportant to the simulation at hand [Huang98a]. Abstraction has been used to provide 100-1000 times increases in possible simulation size for particular research questions. That said, abstraction must be applied with care because, in the absence of an explicit mathematical derivation, an abstracted model must still be validated against a more detailed model running at slower speed, or against field experiments of sufficiently large scale. Further, new phenomena might emerge from interactions as networks increase in size.

Scaling with Heterogeneous Model Elements. Large-scale simulations can also build upon small-scale validated sub-models. One approach is recursive composition: begin with well-validated components, and a well-validated composition framework; then generate large models using hierarchical composition [Cowie99a]. Another approach is to compare detailed and abstract simulations at small scales, then generate large abstract scenarios [Huang98a]. Both construction and abstraction assume that potential inaccuracies in small-scale scenarios are not magnified at larger scales. This assumption must still be validated on a case-by-case basis. Preliminary research results suggest that detailed simulations can accurately reproduce Internet-like traffic, as described below in the section on “validation of aggregate statistics”.

E. CASE STUDY: TCP MODELS

As an example of the validation process we next look at how several simulators validate TCP models. As a mature protocol, TCP over wired networks provides a showcase for several validation alternatives. By contrast, validation in other domains remains challenging. For example, in wireless networking there is not yet consensus on how to represent radio propagation effects, or about how radio-based loss affects higher-level protocols.

The TCP models in simulators, such as *ns* [Breslau00a], represent an instructive case study of the validation of network simulations within the networking research community. Unlike many simulation models, the one-way TCP models included in *ns* do not attempt to model a particular TCP implementation or specification, but instead model a simplified protocol supporting one-way data transfer without message fragmentation. These models do however represent the details of the algorithms that make up TCP, including slow-start and fast retransmit. This design was chosen to support easy experimentation with TCP variants. These models have been validated in several different ways.

Phenomenon validation: The model and algorithms implemented in *ns* one-way TCP are described in a paper by Fall and Floyd [Fall96a]. To insure *ns* correctly implements this model, *ns* developers regularly validate the current implementation against this model. Initially a human expert compared current output (in the form of time/event graphs) to the model. Today this output is compared automatically (byte-for-byte) against saved output. The first approach is robust to minor simulator changes but requires expert analysis, the second is automatic but brittle.

These tests have also been applied to the independently written implementations of Tahoe and Reno TCP in the Scalable Simulation Facility (SSF) [Cowie99a]. Validation of SSF TCP has been patterned after the testing scenarios developed for use with *ns*. Although completely different in design and implementation, SSF TCPs produce identical results as *ns*. Because SSF shares no code with *ns*, these results provide increased confidence that the TCP implementations in both simulators can be regarded as trusted building blocks for inclusion in larger models. The success of this approach illustrates the importance of widely accepted test scenarios that include expected reference results.

Kernel validation. A subset of the *ns* TCP models has been ported to run over the Parsec simulation engine [Bagrodia98a] in addition to the native *ns* simulator. When all external services are held constant (including, for example, the random number generator), the two simulation kernels generated nearly identical outputs running the same scenario. Such similar results from independent simulations argue against bugs in the exercised portions of the two simulator kernels (an example of n-version programming).

End-to-end statistical validation. Two examples illustrate the use of end-to-end statistics to validate TCP simulation modules. Ya Xu has made small-scale comparisons of TCP throughput and traces in *ns* and on CAIRN, a high-speed network testbed. One result of these experiments is a better understanding of the care that must be taken when conducting real-world experiments. The expected throughput, as predicted by the simulation, was achieved only after iterations addressing a range of bugs and details in the end-node operating system, link configurations, and test applications deployed on CAIRN. In effect, in this case the experimental network had to be corrected to conform to the expected results from simulation and analysis. This example illustrates the need to validate experimental systems as well as simulation models.

In another validation experiment, within the challenging domain of wireless communications, the Monarch project compared simulated and emulated versions of *ns* TCP traffic operating over wireless and ad hoc routing simulation modules developed at CMU. In the comparison, identical end-to-end throughput was achieved; however, the temporal behavior of individual packets was not identical [Johnson99a]. So, in this case, the simulation proved valid for addressing questions of throughput, but invalid for addressing detailed questions of packet delay.

Validation of aggregate statistics. Finally, researchers at AT&T have reproduced ISP-like traffic in *ns* and compared it to real-world traces using wavelet analysis [Feldmann99a]. The technique of wavelet analysis shows similarity between simulated and real traffic across a wide range of time-scales and for reasonably large scenarios (400 nodes and 10,000 or more web requests). More importantly, their simulations are accurate enough to investigate what aspects of TCP influence aggregate network behaviors, an experiment impossible to undertake in the real world.

F. SIDEBAR: WIRELESS SIMULATION

Interest in wireless simulations is growing as researchers investigate next generation cellular telephony, wireless LANs, ad hoc routing, and sensor networks. Our examination of simulation validation focuses on TCP and wired networks because of the breadth of experience there. Validation of wireless simulations poses several new challenges. For example, wired data propagation and queueing are well understood and easily abstracted, while radio propagation is expensive to model (in both development and run-time) and difficult to abstract. In addition, node mobility raises similar questions. No well-accepted procedures exist to validate wireless propagation models, user mobility models, and the relationships between these models and derivative models, such as traffic models and matrices. As research in this area is ongoing, we refer interested readers to recent work in this area [Ho94, Short95, Fasafi96a, Johnson99, Ramanathan00, Heidemann01] rather than summarizing it here.

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G. Sidebar: Verification, Validation, and Accreditation

The Department of Defense has a long-standing interest in methods and techniques for the verification, validation, and accreditation (V, V, & A) of simulation models [Balci94, Page97]. Although there is debate about the exact definition of these terms, general agreement exists surrounding the intent of the methods and techniques associated with each term.

Verification is a process to evaluate how faithfully the implementation of a model matches the developer's intent, as expressed by conceptual descriptions and specifications, provided either in natural language or a formal notation. In effect, verification is akin to software function testing. While verification does not establish the accuracy of the predictive power of a simulation model, verification can uncover errors in coding and errors in implementation of protocol mechanisms. These errors may or may not invalidate the model. For example, an error might occur in the statistical representation of traffic. If the intent is to compare the performance of different protocols against identical offered load, then this error may have little effect on model validity. On the other hand, if the intent is to establish the absolute performance of a network design given a representative usage scenario, then the same error could well make the model invalid. Still, verification aims to catch programming and coding errors, rather than errors in the accuracy of model results.

Validation is a process to evaluate how accurately a model reflects the real-world phenomenon that it purports to represent. As we discuss, the degree of accuracy required by the validation depends on its specific intended use. For example, if a model is used to compare numerous design choices for new protocols, then the model need only be accurate enough to distinguish effectively between the performance and behavior of the various designs being compared. On the other hand, if a model is used to evaluate engineering alternatives against specific performance objectives and traffic loads, then, for the characteristics of interest, the model might need to exhibit accuracy within a statistically bounded range.

Accreditation, a term often used by government agencies such as the Department of Defense or the Federal Aviation Administration, denotes a process leading to an official declaration that a given software program is fit for its intended use. In the absence of technical solutions that can guarantee that a software model is free from errors and will provide valid predictions, accreditation usually focuses on an external, or third-party, review of the processes used to verify and validate a model. The successful outcome of most accreditation processes is a written certificate signed by a recognized authority that attests that a prescribed set of processes was correctly applied during the development and testing of a simulation model.

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H. SUMMARY OF WORKSHOP CONSENSUS

During the workshop, a consensus developed around several points. Here we present five.

1. Researchers presenting papers based on simulation studies need to consistently present the approach used to validate their models. Ideally, simulations should be made publicly available concurrent with related papers. Tremendous positive community benefits can accrue through sharing knowledge at this level, both in terms of simulation development as well as encouraging the development of widely accepted practices for validation. Such sharing benefits both the private and the public sectors, as new models for traffic, network protocols, and network control emerge in the future. Working with the community, DARPA and NIST plan to create a web-based resource for network simulation modeling knowledge. This resource will be open to everyone working in the network simulation community.

2. Simulation users would benefit from standard approaches to document the model underlying a given simulation software module, including a description of how that software has been validated.

3. The community needs a better understanding of the levels of validation required in different circumstances. For example, validation against a specific implementation can be mandatory or inappropriate, depending on the question at hand. Also, a better understanding of the underlying mathematics related to scaling and model invariants may allow extrapolation of validation to very large networks

4. The community should continue working towards platform-independent data formats (such as, tcpdump) and platform-independent validation tools.

5. Finally, the set of available validation tools should be improved. Smarter tools to compare traces would be valuable, as would more sophisticated (multi-resolution) statistical techniques. A wider set of multi-simulator test scenarios could also prove helpful.

I. CONCLUSIONS

Increasingly, commercial and public organizations deploy large-scale networks incorporating heterogeneous technologies, such as multi-wavelength optical fibers and wireless communications links. In most cases, the Internet protocol suite is used over these diverse networks to provide an infrastructure for distributed applications and network services. To accommodate the growing challenges inherent in connecting diverse network technologies together, while also providing customers with attractive services, industrial and academic researchers continue to explore new network protocols. Whether deploying complex networks or experimenting with new protocol designs, networking engineers and researchers must increasingly turn to simulation modeling. Given their complexity, the networks being designed today may not be amenable to full analysis by mathematical models alone. A more productive approach may be to suitably incorporate mathematical models as subsystems in discrete-event simulations.

The growing role for simulation raises the stakes for validation of the models being developed and used. The workshop discussed in this paper provided a first step toward a larger effort required among the network engineering and research community. The workshop captured the current state of practice, and identified some of the difficult issues that must be resolved before network simulation modeling can reach a mature state. Future funded research that involves simulation modeling of networks should move the community toward the points of consensus identified at this workshop. Also as a concrete step forward, standards-setting organizations, such as the IETF, should encourage the creation of models and suites of test scenarios, together with expected behaviors, to be included as part of the specification of all protocols. The test scenarios should be described in a form that can be applied to simulation models, as well as full implementations.

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