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An Introduction to
Network Modeling and Simulation for the Practicing Engineer

Jack Burbank
William Kasch
Jon Ward

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CONTENTS

PREFACE

This book provides an overview of the current state-of-the-art in modeling and simulation (M&S) tools and discusses many of the pitfalls most commonly encountered by network engineers. A bottom-up approach is taken in describing network M&S, following the Transport Control Protocol / Internet Protocol (TCP/IP) modified Open System Interconnect (OSI) stack model**.** While applicable to network M&S in general, there is particular emphasis placed on wireless network M&S. This book first decomposes the wireless network M&S problem into a set of smaller scopes: 1) radio frequency (RF) propagation M&S (Chapter 2), 2) physical layer (PHY) M&S (Chapter 3), 3) Medium Access Control (MAC) layer (Chapter 4), and 4) higher layer M&S (Chapter 5). After considering each of these smaller scopes somewhat independently, the book then revisits the overall problem of how to conduct M&S of a wireless networking system in its entirety.

No specific assumptions are made on the type of network being modeled in any particular layer of the protocol stack. Instead, the building blocks are presented to address the common challenges of modeling any wireless network. The reader is also directed to resources that provide more detail on specific topics. Resources are chosen from generic studies of wireless networks and from the Mobile Ad Hoc Network (MANET) and ad hoc sensor network communities. This book is written with particular emphasis placed on specific topics at the different layers of the protocol stack, with the intention of bridging gaps between the computer science and electrical engineering communities. Historically, the higher layers of the protocol stack are often considered research subjects for computer scientists and the lower layers for electrical engineers. In fact, accurate simulations must capture the cross-layer interactions and higher layer simulations must consider the impacts of the lower layer conditions on results. The authors hope that this book will educate the reader in simulation topics that may have not otherwise been considered and will ultimately lead to improved simulation results in the wireless networking research community.

This book can improve the reader's background knowledge on the key components of successful wireless network simulations. But, ultimately, the reader must learn to validate his or her own simulation since they alone will know all specific details and assumptions that lead to a specific result. In general, the output of a simulation should not be a surprise to the designer, and, it if is, sufficient research into the underlying protocol must be conducted to explain any unanticipated results. Because there are so many variables present in a model and therefore so many potential locations where errors are introduced, a model output should not be taken as ground truth without other methods of verification. Results may be compared with results from other researchers, but as some papers [1–4] note, results between two equivalent scenarios simulated on two different simulators may not match. In this case, the designer must not only validate whether or not his or her simulation is correct, but also what led to results not matching the other simulation. Results should not be published until the simulation designer has confidence in the model, the results have been validated to the best of the designer's ability, and, once published, should contain all model parameters, assumptions, and simulation source code.

In this book only a select set of simulators have been considered as the most popular commonly used by academic and industrial researchers. These include OPNET, NS-2, GloMoSim, and QualNET. There is no single, all-purpose simulator that is best for all scenarios. Additionally, budget constraints often force researchers to choose open-source simulators over commercial solutions. Custom simulation solutions (i.e., homebrew simulations) are certainly too numerous to be considered. Note that the risk of citing specific simulators is that these tools are continually evolving. This means that statements about a given product's current capabilities may no longer be valid, as subsequent releases enhance a tool's capabilities. Care has been taken by the authors to focus on principles and practices that assist the simulation designer in improving wireless network simulations while remaining independent of a particular simulator, and hence topics and results are not as limited to an expiration date.

Jack Burbank
William Kasch
Jon Ward

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CHAPTER 1

Introduction

Communications systems continue to evolve rapidly. Users continue to demand more high-performance networking capabilities. Service providers respond to this demand by rapid expansion of their network infrastructure. Network researchers continue to develop revolutionary new communications techniques and architectures to provide new capabilities commensurate with evolving demands. Equipment vendors continue to release new devices with ever-increasing capability and complexity. Technology developers rapidly develop next-generation replacements to existing capabilities to keep up with demand. These rapid developments in the network industry lead to a large, complex landscape.

The network designer and developer wants (and needs) to satisfy the demands of the users. This is difficult, as it is often complicated for the typical network engineer to fully understand this rapidly evolving communications landscape. This challenge is exacerbated by the nature of emerging technologies and techniques that are often extremely complex compared with their legacy counterparts. This leaves the typical network engineer with more questions than answers. The network engineer tasked with maintaining an operational network might ask the following: What is the right approach to solving my problem? Do I buy the latest device from company X that claims to solve all my problems? Do I replace the underlying technology of my system with the latest generation? How do I know whether a technology is mature enough to survive the rigors of my application? How do I know how my already existing network system will respond if I add this device? The network engineer researching next-generation networking techniques might ask: How do I know how this new approach will interact with already-existing protocols? or How do I build confidence in the utility of this approach without producing and deploying the technology? The network engineer developing a particular product might ask: How do I ensure that this design will satisfy requirements

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An Introduction to Network Modeling and Simulation for the Practicing Engineer, First Edition.
Jack Burbank, William Kasch, Jon Ward.

before I go to production? or How can I assess the utility of a design choice compared to its envisioned cost? This book aims to help answer these questions.

There are many tools available to the network engineer that can assist in answering these questions, including analysis, prototype implementation and empirical testing, trial field deployments, and modeling and simulation (M&S). It should be stated now that no one tool is typically sufficient in understanding the performance of a network; unfortunately, there is no "silver bullet" answer to all our questions. The complex nature of emerging systems also introduces significant complexity into the effective evaluation of these systems and how these various tools can be employed. Evaluation is often conducted through the coordinated usage of analysis, M&S, and trial deployments in closely monitored environments. Due to the costs and complexities of deployments, analysis and M&S are often used to determine the most sensitive performance areas that are then the focus of trial deployments. This limits the scope of the trial deployment to a realistic level while focusing on the important cases to consider.

Because of the increasingly interconnected nature of communications systems, and the resulting interdependencies of individual subsystems to operate as a whole, it will often be the case that individual subsystems cannot be tested in isolation. Rather, multiple systems must be evaluated in concert to verify system-level performance requirements. This increases the required scale of trial deployments and adds significant complexity as now several different types of measurements will often be required in several different locations simultaneously. This increases the required support for a deployment in terms of required resources, including personnel and measurement equipment, further limiting the realistic amount of trial deployments. Thus, this will place a premium on analysis and M&S to perform requirements verification and to form the basis of any performance evaluation. In many cases, M&S may provide the only viable method for providing insight into the behavior of the eventual system prior to full-scale deployment.

Once the importance of M&S is established, many additional questions still arise: How does the network engineer properly employ M&S? What are the most appropriate M&S tools to employ? While networking technologies continue to evolve rapidly, so too do M&S tools intended to evaluate their performance. The M&S landscape is indeed a complicated space with a multitude of tools with a variety of capabilities and pitfalls. Furthermore, there is often a poor understanding of the proper role and application of M&S and how it should fit within the overall evaluation strategy. There is even confusion surrounding the term M&S itself. Before we continue, let us provide some basic definitions that will be used throughout the book.

Modeling and simulation (M&S) are often combined as a single term. However, a model is quite different than a simulation. This book defines these two entities as:

Model: A logical representation of a complex entity, system, phenomena, or process. Within the context of communications and networking, a model is often an analytical representation of some phenomena (e.g., a mathematical representation for the output of a system component) or a state machine representation. This analytical representation can either be in a closed form or an approximation obtained through assumptions.

Simulation: An imitation of a complex entity, system, phenomena, or process meant to reproduce a behavior. Within the context of a communications network, a simulation is most often computer software that to some degree of accuracy functionally reproduces the behavior of the real entity or process, often through the employment of one or more models over time.

Emulation: An imitation of a real-world, complex entity or process meant to perfectly reproduce a behavior or process. Emulation can be thought of as perfect simulation of something such that it is equivalent to the original entity.

To illustrate the difference between a model and a simulation, consider a simple signal detection circuit. A simulation of this device would imperfectly mimic the various actions of the detection circuit to determine a likely outcome for a given input. A model of this same device would generally take the form of a mathematical algorithm that would produce (either perfectly or imperfectly) an output for a given input.

Unfortunately, the terms *model* and *simulation* are often incorrectly used interchangeably. Generally speaking, the term simulation has wider scope than the term model, where a simulation is typically a compilation of models and algorithms of smaller components of the larger overall entity or process. This book generally uses the combined term *M&S* to generically refer to the employment of models, simulations, and emulators to approximate the behavior of an entity or process.

There are numerous types of computer models and simulations. A computer model or simulation can generally be classified according to several key characteristics:

- Stochastic vs. Deterministic: Deterministic models are those that have no randomness. A given input will always produce the same output given the same internal state. Deterministic models can be defined as a state machine. Deterministic models are the most common type of computer model. A stochastic model does not have a unique input-to-output mapping and is generally not widely employed, as it leads to unpredictability in execution. A simulation can be made to act in a pseudo-random manner through the employment of random number generators to represent random events. However, the particular models governing the behavior of each component within the simulation are generally deterministic.

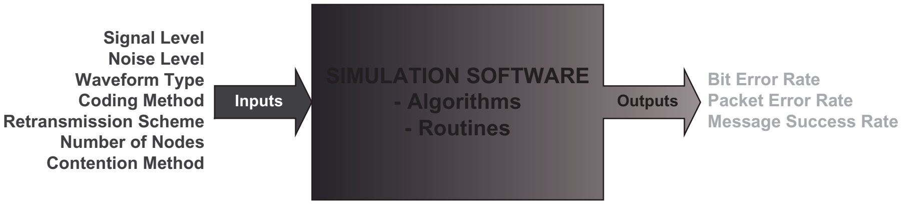

FIGURE 1-1. A block diagram of a wireless communications system simulation.

- Steady-state vs. Dynamic: Steady-state models attempt to find the input-to-output relationship of a system or entity once that system is in steady-state equilibrium. A dynamic simulation represents changes to the system in response to changing inputs. Steady-state approaches are often used to provide a simplified model prior to dynamic simulation development.
- Continuous vs. Discrete: A discrete model considers only discrete moments in time that correspond to significant events that impact the output or internal state of the system. This is also referred to as a discrete-event (DE) model or DE simulation. This requires the simulation to maintain a clock so that the current simulation time can be monitored. Jumps between discrete points in time are instantaneous; nothing happens between discrete points in time corresponding to interesting events. Continuous simulations consider all points in time to the resolution of the host's hardware limitations (all computer simulations are discrete to some extent because of the fact that it is running on a digital platform with a finite speed clock). DE methods are the most commonly used for network M&S.
- Local or Distributed: A distributed simulation is such that multiple computer platforms that are interconnected through a computer network work together, interacting with one another, to conduct the simulation. A local simulation resides on a single host platform. Historically, local simulations have been the most common. But the increasing complexity of simulations have increased the importance of distributed simulation approaches.

In general, a simulation can be thought of as a piece of software residing on a computer platform that implements a set of algorithms and routines and takes a set of inputs to produce a set of outputs that represent the behavior of the system of interest. This is depicted in Figure 1-1.

The typical inputs that are important to consider when simulating a wireless network are summarized in Table 1-1. The typical outputs that are often of interest are summarized in Table 1-2.

TABLE 1-1. Typical Inputs to a Wireless Network Simulation

Parameter	Explanation
Signal power	This will influence the received power level and consequently the Bit Error Rate (BER) and Packet Error Rate (PER) performance of the wireless link.
Waveform type	This will influence the BER and PER performance of the wireless link in a given channel.
Forward error control coding (FEC) method	This will influence the BER and PER performance of the wireless link in a given channel.
Retransmission protocol	This will affect the throughput and delay performance of the wireless link.
Contention method	This will influence BER, PER, throughput, and delay performance of the wireless link in a given channel.
Channel model	This will determine the performance of a given wireless link in terms of received power level, BER, and PER.
Mobility model	This will impact the performance of the MAC layer protocol and of the higher layers (e.g., IP routing).
Traffic model	This will impact the performance of the MAC layer protocol and of the higher layers (e.g., IP routing).
Network topology	This will impact the performance of the MAC layer protocol and of the higher layers (e.g., IP routing).

TABLE 1-2. Typical Outputs from a Wireless Network Simulation

Parameter	Explanation
BER	The fundamental performance metric of a digital communications link.
PER	Often considered the most important performance metric in a packet-switched network.
Throughput	The data rate supportable by the wireless network.
Goodput	The useful data rate supported by the wireless network (i.e., data rate as available by the application).
Latency	The end-to-end delay that an application or user will experience across the wireless network.

1.1 ADVANTAGES AND DISADVANTAGES OF MODELING AND SIMULATION

As is the case with any tool, M&S has both advantages and disadvantages. This section provides a tradeoff framework for the designer or developer to consider when choosing to employ M&S. In the following section, M&S is often compared with empirical testing. For the purposes of this book, empirical testing refers to real-world testing of equipment (e.g., physical hardware devices) deployed in a physical environment.

1.1.1 Breadth of Operational Scenario

First and foremost, M&S provides the ability to exercise a wide range of operational scenarios. Empirical testing will exercise a much smaller portion of the possible scenario space than will M&S. This includes the ability to evaluate greatly increased network scale (e.g., number of network nodes), not easily achieved in empirical activities, and more dynamic choice of environmental conditions (e.g., wireless environment). Because of the ability to exercise a wide variety of scenarios, M&S has a clear advantage in this aspect.

1.1.2 Cost

Generally, another advantage of M&S is reduced cost compared with empirical testing and trial deployments. Extensive empirical testing carries a high cost, to the point where extensive empirical-only approaches are largely impossible in the modern wireless networking landscape; however, this advantage is dependent on the scope placed on the M&S development effort.

1.1.3 Confidence in Result

A less obvious advantage of M&S is the amount of precision and control that can be exerted over the scenario in question. In the empirical scenario, measurements are taken and then those measurements are analyzed and understood for their ramifications. However, due to the uncontrolled nature of empirical testing, there are often many variables that affect the measurement. And often the number of uncertain variables is so great that it is impossible to isolate the source of any behavior or to correlate a measurement to its source (i.e., map the effect to the cause). This limits the scientific utility of such measurements, and makes it difficult to associate a high degree of confidence to the measurement. The "the data is what it is" philosophy is rarely justified if the phenomena under observation are not understood. Note, this is much more the case for over-the-air (OTA) empirical activities. Other empirical activities are much more highly controllable (e.g., direct radiofrequency (RF) chain testing).