MODELING AND SIMULATION TOOLS FOR EMERGING TELECOMMUNICATION NETWORKS
MODELING AND SIMULATION TOOLS FOR EMERGING TELECOMMUNICATION NETWORKS

Needs, Trends, Challenges and Solutions

Edited by

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Springer
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As Chairman of COST Action 285 and co-editor of this book I wish to express my sincere thanks to all the members of the Management Committee for their full and active participation in the studies embraced by the Action including the decision to sponsor this symposium in which they presented the results of their individual research in different aspects of modeling and simulation of communication networks. I would particularly like to mention here Prof Dr Axel Lehmann and Prof Dr Ercan Topuz who, as Deputy Chair and Technical Secretary respectively of the Action 285, made unique contributions to the organisation and success of the Symposium.

The symposium was very much enriched and gained much breadth and depth by the participation of many experts in the field from outside the Action Group, from the United States of America, and Europe who willingly accepted our invitation to attend and contribute to our deliberations. It would be invidious to single out names but I would like to mention Dr Arnold Bragg who played a very important role inside the Committee as well as in the preparation and conduct of the symposium. I owe them all many thanks and much gratitude.

Last but by no means least I would like to express my appreciation to the COST Office Scientific Secretariat for the administrative and financial support given to the Action and to Prof Dr Ulf Schmerl for making the facilities and staff of his Faculty of Informatics at the University of the German Federal Armed Forces in Munich, available for the symposium. Finally It gives me pleasure to acknowledge the support I received from Mr Zerhan Ener and Mr Semih Ener as well as from the staff of Springer Publishers in the production of this book.

Nejat Ince
PREFACE

The papers which appear in this book were written by their authors based on their presentations made at a symposium hosted by The Fakultaet für Informatik of Universitaet der Bundeswehr München on 8-9 September 2005. The symposium was organised under the eegis of COST Telecommunications Action 285 entitled:

Modeling and Simulation Tools for Research in Emerging Multiservice Telecommunications
Needs, Trends, Challenges, and Solutions

COST- the acronym for European COoperation in the field of Scientific and Technical research is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 35 European countries to cooperate in common research projects supported by national funds.

The funds provided by COST- less than 1% of the total value of the projects- supported the COST cooperation networks (COST Actions) through which, with only around 20 million Euro per year, more than 30,000 European scientists are involved in research having a total value which exceeds 2 billion Euro per year. This is the financial worth of the European added value which COST achieves.

A "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "a la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to the scientific communities of countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As precurser of advanced multidisciplinary research COST plays a very important role in the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework
Programmes, constituting a “bridge” towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of “Network of Excellence“ in many key scientific domains such as: Physics, Chemistry, Telecommunications and Information Science, Nanotechnologies, Meteorology, Environment, Medicine and Health, Forests, Agriculture and Social Sciences. It covers basic and more applied research and also addresses issues of pre-normative nature or societal importance.

Currently there are some twenty actions in the Telecommunications and Information Science and Technology area one of which is COST Action 285. The main objective of this action is to enhance existing tools and develop new modeling and simulation tools for research in emerging multiservice telecommunications networks in the areas of:

- Model Performance Improvements,
- Multilayer Traffic Modeling,
- The important issue of evaluation and validation of the new modeling tools.

The studies related to the above activities are carried out by members of the Action Group, with inputs from invited experts/scientists from academia and industry when deemed necessary, and are coordinated at the Management Committee Meetings (MCM) held two or three times a year. Members participate in other related projects and activities nationally and internationally (e.g. COST, IST, ITU, ETSI, ATM Forum) provide opportunities for formal/informal contacts and for dissemination of results.

The Management Committee for COST Action 285 consists of:

Chairman : Prof Dr Nejat Ince (TR)
Deputy Chairman : Prof Dr Axel Lehmann (D)
Technical Secretary : Prof Dr Ercan Topuz (TR)
Other Members : There are up to two representatives from Bulgaria, Denmark, France, Germany, Hungary, Ireland, Italy, Macedonia, Malta, Norway, Slovenia, Spain, Turkey, Switzerland, and The United Kingdom.

The Management Committee decided early in the year 2004 to invite external experts/scientists, specialising on the subjects of interest to Action 285, from other COST Actions, software houses, telecommunications companies, universities and government research institutions of not only the COST Countries but also of other continents. A letter of invitation was
sent out to known experts and institutions to participate in a symposium with the major aim of harnessing ideas and proposals for improved and new languages and tools to enable network designers, developers and operators to model and simulate networks and services of emerging and future telecommunications systems.

From the papers submitted for presentation at the symposium the text of twenty four of them were selected for inclusion in this book. The symposium presentations were made in four sessions as follows;

Session 1 : Multilayer Traffic and Multimedia Behaviour,  
Session 2 : Quality of Simulations,  
Session 3 : Accelerated Simulation Methods,  
Session 4 : Verification, Validation and Credibility of Simulations.

The contributors and their coordinates are given in the list herewith attached.

The symposium covered a wide spectrum of subjects dealing coherently with nearly all the important aspects of simulation modeling and tools for the design and performance evaluation techniques and systems particularly the emerging ones.

It is hoped and expected that this book, which is the proceedings of the symposium, will be found useful as a reference work for practicing engineers and academic researchers.

Nejat Ince,  
Ankara.
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European Concerted Research Action COST 285
Modeling and Simulation Tools for Research in Emerging Multiservice Telecommunications

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Abstract. This paper contains the keynote address given at the Symposium by the Chairman of the COST Action 285. It outlines the studies undertaken by the members of the Action with the objective to enhance existing modeling and simulation tools and to develop new ones for research in emerging multiservice telecommunication networks.

The paper shows how the scope of COST Action 285 has been enriched by the contributions made at the symposium.

1. INTRODUCTION

As a background and introduction to the symposium we shall give here a review of the COST Action 285. The aim is to show how much the Action has been enriched in breadth and depth by the contributions made by the attendants, and particularly by the invited experts.

The main objective of the Action is to enhance existing and develop new modeling and simulation tools for research in emerging multiservice telecommunication networks. To achieve these aims several studies are undertaken in the following three areas identified to be of major importance for the objectives of the Action:
i) Model Performance Improvement
   - Research in the area of new modeling tools based on analytic and hybrid cores for quick solutions of network design and performance evaluation problems.
   - Research in multimedia traffic.
   - Research on how to improve the quality of the statistical analysis tools imbedded in commercial simulation products.

ii) Multilayer Traffic Models
   - Research in the area of multilayer traffic modeling

iii) The important issue of evaluation and validation of new modeling tools.

1.1 Model Performance Improvement

1.1.1 Analytic and Hybrid Cores for Reducing Simulation Time

One of the research objectives of this Action is to investigate the strength and limitations of modeling tools which are based on analytic cores (e.g., Analytic Engines Inc. NetRule) and use steady-state queuing theory formulas and mathematical modeling techniques to produce quick solutions. These tools, which do not capture nuances of protocol behaviors can, however, provide good first-order approximations and may be the only reasonable approach for very large networks.

Another approach to reduce simulation time is the hybrid simulation in which one may focus the simulation on a portion of the network of special interest and model the remainder of the network using the analytic method. It will be interesting to investigate the strength and limitations of hybrids in terms of gain in speed and loss in accuracy.
1.1.2 Statistical Analysis Tools

Experience with available simulation products has shown that the quality and depth of statistical analysis tools embedded in them are rather disappointing and often require the simulation output captured to be analysed in a statistical package like SAS. A more elegant solution would be to have the simulation tool itself "package" the output. This needs therefore to be investigated.

1.1.3 Multimedia Traffic

Multimedia traffic studies carried out in COST 256 [1] and elsewhere give evidence that different protocols behave very differently at different time scales. A study needs therefore to be undertaken of the network behaviour at different time scales, e.g., 1,10,100 second intervals, including the method of validation of simulation results.

1.2 Multilayer Traffic Modeling

1.2.1 Assessment of the State-of-the Art Development

To prepare an exhaustive annotated compilation of teletraffic models which will comment on any applicability to multilayer traffic modeling and analysis and also on how commercial packages (e.g., OPNET) address multilayer modeling.

Some commercial packages handle aggregate "background" traffic quite well via analytical representations and flow models. If and when enhancements such as abstracting lower-layer protocols, perhaps via analytical representations, appear in the literature they may be used as tools for research on multilayer traffic models.

1.2.2 Multilayer Traffic Models

Some recently proposed models for TCP and their potential in addressing multilayer traffic modeling needs to be investigated. Some of these models (e.g., those proposed by Chadi Barakat, Inria France) focus on window sizing and network issues separately but not independently, and if they can be coupled with a source level-model the outcome might be a valuable step toward multilayer modeling. It would be interesting to try combining good
source and lower-layer models into two-layer or three-layer traffic models and to begin studying the convolutional and confounding effects.

1.3 Model Verification, Validation and Credibility (VVC)

1.3.1 Model Verification

The fundamental building blocks of a simulation are the real-world problem entity being simulated, a conceptual model representation of that entity and the computer model implementation of the conceptual model.

Conceptual model validity, software verification, and operational validity along with data validity are the technical processes that must be addressed to show that a model is credible. The technical experts of the Action, as well as experts from other institutions may be consulted to review the conceptual model to judge if it is valid. This activity – called face validity analysis – is performed to support the technical process of conceptual model validity.

Verification is the process of determining that a model operates as intended. Verification process is also referred to as “debugging”. The aim is to find and remove unintentional errors in the model’s logic and in its implementation.

Verification involves performing test runs in which a comprehensive set of tests are devised to generate ideally all errors and that all error generated during test runs are recognized.

Test cases that explore non-typical operating conditions are most likely to expose modeling errors (increase arrival rate and/or reduce service rate; increase the rate of infrequent events, etc.). Verification of the model should start at the module level. It is paramount that the programming language used presents facilities such as an interactive debugger and the capability of performing a localised “trace” of the flow of events within and between modules.
1.3.2 Model Validation

Validation is the process of assessing an acceptable level of confidence that the inferences drawn from the model correctly represent the real-world system modeled. The aim is to determine whether or not the simplifications and omissions of detail knowingly made in the model introduce unacceptably large errors in the results.

Validation focuses on three questions [1]:

   i) Conceptual Validity: Does the model adequately represent the real-world system?
   ii) Operational Validity: Are the model-generated behavioural data characteristic of the actual system?
   iii) Credibility: Does the user have confidence in the model’s results?

Three variations of the real-world system have to be distinguished:

- The system exists and its outputs can be compared with the simulated results
- The system exists but is not available for direct experimentation.
- The system is yet to be designed; validation here is in the sense of convincing others and ourselves that observed model behaviour represents the proposed reference system if it is implemented.

The methods used for model validation are testing for reasonableness, for model structure and data and model behaviour. Model’s validation will be based on comparison of the results obtained from different analytical and simulation models and, where they exist, measurements in real telecommunication systems.

2. COST 285 INTERIM STUDY RESULTS

Study of the problems and issues outlined above is being performed by the members of the Action Group. They are expected to complete their programme of work in the time frame assigned to the Action (2003-2007) by utilising their own potential which may be augmented, where necessary, by external contributions from symposia organised by the Group as well as from other sources. In this regard it should be mentioned that a formal association has been established with the Center for Advanced Network Research of RTI International Inc., USA, for cooperative research in the areas of mutual interest.
We give below a summary of the studies so far achieved with appropriate pointers to the papers in the present book.

3. MODEL PERFORMANCE IMPROVEMENT

3.1 Existing Design Tools

Simulation and modeling for research and design accounts for a substantial fraction of engineering computation. With valid and credible models, simulation is often dramatically more cost-effective than are real experiments, which can be expensive, dangerous, or, in fact, impossible because a new system may not yet be available.

Scientists and engineers deal with the complexity of the real world in terms of simplified models. There are however techniques that may be used for deciding on an appropriate level of model detail, for validating a simulation model, and for developing a credible model.

One of the basic questions is "Can network design tools help one to find the combination (complicated mix of application, protocols, device and link technologies, traffic flows and routing algorithms) that is right for the problem in hand?". The most challenging decision is to determine how accuracy can be traded off with speed considering the user's role (network designers, sales/marketing, network managers) in the design process.

From a preliminary review and evaluation made of this topic it is clear that the network design tools available on the market are either general-purpose or special purpose tools. The first and most important decision to make for the user is to select the right tool to use. This implies a challenging decision to determine how much accuracy to sacrifice for simulation speed which, depending on the application, can span four orders of magnitude, from tens of seconds to days.

A check list was developed [2] which addresses the needs of the following four categories of users (in terms of user features such as user interface, modeling paradigm, network topology, network types, supported traffic models, level of customisation, etc.):
i. Researchers and developers want to reduce development costs and risks by testing the effects of new or modified protocols, devices, architectures, components design, and traffic models in the lab or on the workbench. They need complete control of simulated behavior at the programming language level, and want the language to provide a rich set of special-purpose modeling functions. They usually simulate discrete events (packets transiting a router, protocol retransmissions, etc.), and must often simulate billions of events in order to mimic actual behavior. They want accuracy over run-time speed.

However, they also want tools that support rapid and reliable simulations. Simulations in industry are expected to mimic the behavior of a specific product that may still be in the design phase, and whose features depend on ever-changing market forecasts. At the same time, reliability is a must, since business decisions are based on simulation results. (See Chapter 9 for a discussion of the challenges of simulation tool development in the telecommunication industry.)

ii. Network designers specify and build new networks, or overhaul existing ones. They want to reduce design time and improve design accuracy, ensure that designs meet performance requirements without overbuilding, and identify potential bottlenecks and overloads. They need an extensive library of link technologies, devices, architectures, and protocols to build or upgrade the network, and tools to accurately predict its performance.

Low rate high latency data services will coexist with high rate low latency real-time multimedia applications in next generation networks, generating time-varying demands on the quality of service (QoS) and network resources. (See Chapter 2 for a summary of challenges in the design of next-generation networks having dynamic resource reservation schemes and extreme variability in demand patterns and for a potential solution using a learning, prediction and correction (LPC) architecture.)

iii. Network managers and network engineers operate networks, troubleshoot and solve performance problems, and make sure that service-level agreements are met. If the existing network is large, they need to import topology and traffic data from other tools. The
set of alternatives is usually enormous, so they want to evaluate scenarios in tens of minutes rather than hours. (See Chapter 8 for an in-depth discussion of network management issues and requirements for emerging telecommunications networks, and for modeling tools required to move from today's centralized monitoring and management systems to emerging systems that require highly coordinated real-time control capabilities, automated decision making, and an integrated view of end-to-end managed network entities.)

iv. Sales and field staff want to show customers reasonably accurate representations of how a product, service or technology will improve the customer’s network and support customer’s business case. They want an intuitive tool that runs on a laptop computer and can be mastered in 1-2 days. They need fast execution speed (tens of seconds per scenario rather than tens of minutes), and extensive presentation features

3.2 Shortcomings of Existing Tools

Even though many of the features indicated in the list above are common in many of the existing commercial tools used or known by the Action members, most if not all of these tools suffer from the following shortcomings:

i. Adequate information is not given generally about the mathematical models underlying the programming objects (models) and algorithms used in their implementation, nor about the validation and credibility issues of the software.

ii. The quality and depth of statistical analysis tools imbedded in the commercial simulation products are rather disappointing and often require the simulation output to be captured in a separate statistical package [see Section 3.4 below]

iii. Little or no support is provided for open source operating systems. It would be very desirable to have tools to run under Linux, FreeBSD, etc. In the experience of some users Microsoft Windows variants, even XP, lack the resilience and robustness required for long simulation runs.
iv. Little or no run-time debugging capability is provided. Tools that allow viewing (or at least logging and viewing later) the event list, task scheduler, and other dynamic kernel components at run time would be very desirable.

v. Some commercial packages are prohibitively expensive for universities and non-profit R&D institutions. This is not a technical shortcoming per se, but it severely limits the scope of tools available to a large population of modeling and simulation practitioners.

vi. Some open source simulation kernels are unstable, perhaps due to the collegial way in which they are modified, debugged, and supported; two different kernel releases can provide inconsistent results with the same model suite and parameter set. This is considered to be a major limitation of open source simulation systems. (See Chapter 12 for a discussion of compatibility issues and shortcomings, and a summary of potential enhancements for a widely-used open source network simulator.)

3.3 Analytic and Hybrid Cores for Reducing Simulation Time

3.3.1 Hybrid Techniques

Hybrid techniques are being investigated for modeling two types of telecommunications systems that are far too complex for commercial analytical or discrete event simulation tools. These studies are very relevant to the Action because they use a combination of methods to reduce simulation time (DES, analytical models, close-form expressions, emulation, etc.) and because they appear to be a feasible way of modeling the very large and/or very complex infrastructures deployed in emerging multi-service telecommunication networks:

i. The first is ultra high capacity optical networks, which are widely deployed in the core of emerging multi-service telecommunication networks. These networks have aggregate traffic volumes 4-5 orders of magnitude larger than what today’s discrete event and hybrid simulators are able to handle. Modeling them in (near) real time requires a combination of
techniques: emulators to mimic the network’s control plane; an inference engine to deduce data plane behavior and performance from traffic observed in the control plane; analytics to model core network behaviors; a fast hybrid simulator to inject traffic and network impairments; and a supervisory kernel to interconnect and manage the components [3].

ii. The second is computing Grids, which some believe will be the next major computing paradigm. Grids are a major backbone technology in multi-service research testbeds, and are focus areas in at least three COST Actions (282, 283, 291) [4]. Grids are enormously complex dynamic systems. They require new modeling and simulation methods and tools to understand the behavior of components at various protocol layers and time scales, and to decipher the complex functional, spatial, and temporal interactions among the components. A “grid-in-lab” tool is under development, which is scalable modular, configurable, and plug-and-play, for modeling grids and analysing the performance of applications and middleware services offered on Grids (see Chapter 11).

Hybrid techniques can also be used for transmission network design – e.g., using the object oriented paradigms of Cosmos and Nyx tools. Cosmos is used as the support for system and component development, behavior description, and simulation and analytic calculation development. Nyx is used to describe optimization procedures using general heuristic search techniques. The combination of these two development environments and their component approach enables reusability and shortening of the new application development time (see Chapter 17).

3.3.2 Analytic Solution

On the analytic solution front, we have a number of important new results. Markov chains have been used successfully to model burst errors on channels and at the access level for UMTS/DVB-T systems. New channel measurements on indoor environments are being conducted to improve Markov chain methods, and to validate them (see Chapter 16).

This activity is being extended to models on Power Line Communication (PLC) systems which are expected to be used for
communicating over power lines [5]. (The EU is leading the world in the development of PLC-based communications.)

Verification of simulation using a computer and simulation/emulation using DSPs/FPGAs has been studied. Comparison between MATLAB/C simulation programs and real time implementation on DSPs/FPGAs has been performed. The implemented systems are UMTS modems and smart antennas for UMTS. Moreover, the antenna pattern produced by the smart antenna (which includes a UMTS modem and RF transmitters/receivers on it) has been measured, and the mutual coupling effect between RF chains and antennas has been corrected to obtain results close to simulation (see Chapter 21).

A Monte Carlo approach for modeling and simulation of an ultra high performance optical switching network technology – burst switching – has also been proposed. These networks typically present enormously difficult challenges because they lack sufficiently accurate models, and may require excessively large computational resources. New analytical modeling techniques are required to produce results with reasonable run times (see Chapter 15.)

Another novel analytical approach has been proposed to evaluate the end-to-end performance of optical networks that employ slotted (fixed length) optical packets. For a given topology and traffic matrix, one can estimate the end-to-end loss ratio analytically; the approach can also be used to develop a network dimensioning (sizing) method (see Chapter 18). This is impossible with discrete-event simulators because of the very large number of events required to generate a single rare-event loss.

Fluid models of IP networks have been proposed to break the scalability barrier of traditional performance evaluation approaches, both simulative (e.g., ns-2) and analytical (e.g., queues and Markov chains). Fluid models adopt a deterministic description of the average source and network dynamics through a set of (coupled) ordinary differential equations that are solved numerically, obtaining estimates of the time-dependent behavior of the IP network. These models are scalable, i.e., their complexity is independent of the number of TCP flows and of link capacities (see Chapter 6).

An analytical solution for optimal dimensioning of multi-service lines is also proposed. The solution is based on a method to convert recursions for global state probabilities of multi-service models into stable form. The
approach is numerically stable because it deals with normalised values of global state probabilities used for estimating main stationary performance measures (see Chapter 7).

An analytical model is proposed that is sufficiently general for a broad family of virtual circuit switching systems. Virtual circuits are widely used in many telecommunications and networking architectures: wireline and wireless telephony; packet-switched networks; MPLS and ATM networks; optical networks; and in emerging multi-service networks. The model is used to derive analytical expressions for traffic intensity, blocking probability, and quality of service (QoS) dimensioning of resources (see Chapter 24).

### 3.4 Statistical Analysis Tools

Our discussions on the topic of Statistical Analysis Tools show that no "elegant solution" appears to have been implemented; however, XML may be a solution for data interfacing between network simulation tools (like OPNET, NS) and statistical analysis tools (like SAS, MATLAB) as it is supported by a number of systems/vendors. However XML adds a large amount of overhead to data; HDF5 (Hierarchical Data Format 5) is a far more efficient method which, however, does not appear to support discrete-event simulators and statistical tools (e.g. OPNET and SAS) at this time. Action members have agreed that perhaps a framework/strategy/approach/methodology would be a reasonable deliverable, and that support for two (or more solutions), targeting small- and large-scale simulations, are likely recommendations.

There are several solutions to the problem, each with tradeoffs reflecting the problem’s dimensions (performance, size, deployment, etc.); perhaps one should (1) identify the dimensions and the range of solutions in each, and (2) systematically lay out an approach for presenting the problem at large. The Action concluded therefore that “Structured Formats for Simulation Results” outlined in [6] might be used to build upon for the deliverable. Sometimes an enumeration of alternatives and where each fits (or does not fit) is a more valuable contribution than a so-called ‘point solution’. Helping practitioners understand the issues and build a strategy is perhaps all one can do; there is no “one size fits all” solution.
A software package has been designed and is being implemented that can:

i. Import simulation or measurement results, in the form of trace files, into a common data structure starting with ns2 and tcpdump.

ii. Launch post-processing (i.e. filtering and calculations) applications on the imported data, then complementing the raw data with the results of post-processing, storing results of post-processing separately and then feeding them to other applications (e.g. for presentation).

iii. Export data into various output formats (ASCII, XML, etc.).

Typical input structures are being identified to assess which commercial statistical tools support HDF 5.

### 3.5 Multimedia Traffic

The invariants in network traffic has been investigated [7]. It is concluded that different time scales need to be used at different protocol layers, mathematical formulas are available to describe traffic at different protocol layers, and that one has to be careful to understand and to identify the parameters or the characteristics of the traffic to be used for modeling and simulation purposes. We also have results that show that system performance strongly depends on the incoming workload. Some characteristics, like heavy tail distributions, temporal locality, and frequency of references may depend on certain types of multimedia content (see Chapter 4).

Several multiplicative SARIMA (s, p, d, q) models based on 30 frame-per-second MPEG-4 multimedia traces from TU-Berlin have been developed and their behaviour at different time scales is being examined. Preliminary results suggest that the dominant factor at time scales up to 1 sec. is the seasonal effect induced by the MPEG-4 “group of pictures (GOP)” structure. So-called “scene length” is the dominant factor at longer time scales (see Chapter 3).
IP Network traffic measurement and modeling at the packet level as well as network performance with self-similar traffic has been carried out and discussed [8, 9].

Auto Regressive Integrated Moving Average (ARIMA) models, combined with Generalized Auto Regressive Conditional Heteroscedasticity (GARCH) models, have been used to try to capture both short-and long-range dependence characteristics of the underlying data, especially for highly bursty data (see Chapter 5).

A parameter estimation procedure and an adaptive prediction scheme for the ARIMA/GARCH model has been developed which is capable of capturing the non-stationary characteristics of Internet data [10].

4. MULTILAYER TRAFFIC MODELS

It has been shown that the topics of Multilayer Traffic Models and Statistical Analysis Tools as well as Model Verification/Validation and Credibility are rather intractable problems which do not have elegant universal solutions. Consequently one has to be content with "framework solutions", and with solutions that fit a specific requirement (e.g., HDF 5 for managing large-scale simulation output).

These problems have a large number of dimensions (N-dimensional space) and the so-called solutions we see published represent cases in which someone has fixed most dimensions and solved for only a single point, line, or plane. A particular research result may be important, but it usually does little more than firmly establish one point/line/plane in N-space. Most neither provide insight about the N-dimensional performance response surface, nor attempt to explain how sensitive one parameter might be to other parameters. Another problem is that researchers make limiting assumptions so as to arrive at closed-form expressions. These assumptions ignore the potential convolutional, confounding, and interaction effects among the dimensions, and some of them are of little value because the assumptions are too limiting to be useful.

To demonstrate what can be achieved with multilayer traffic models, Padhye et al.’s [12] TCP Reno analytical model (layer 4), and plus layer 2 and 3 extensions have been used to investigate whether analytical multilayer traffic models might provide credible results in (near) real time.