Acknowledgments

The foundation for this work began in 2000, when Jian Yuan, now an associate professor in the department of electronic engineering at Tsinghua University, arrived at the National Institute for Standards and Technology (NIST) to begin four years of collaboration with Kevin Mills. Dr. Yuan introduced to NIST the idea of viewing large communication networks as complex systems, and worked together with Dr. Mills to explore the implications of investigating the Internet as a complex system. During that time, Dr. Yuan developed a cellular automata model of an Internet-like network, which served as the basis from which MesoNet was created. MesoNet is the reduced parameter discrete-event simulator used in the experiments reported in this study. The collaboration between Drs. Yuan and Mills led to creation of two proposals: (1) to develop a project on measurement science for complex information systems and (2) to formulate a complex systems research program within the Information Technology Laboratory (ITL) at NIST.

In 2006, Dr. Mills submitted a project proposal to an internal NIST competition, known as innovations in measurement science (IMS), aiming to gain approval from the NIST director to apply measurement science to complex information systems. William Jeffrey, the NIST director at that time, supported the project proposal, which also found favor with Cita Furlani, director of ITL. In parallel, a group of ITL researchers, including Chris Dabrowski, Fern Hunt, Vladimir Marbukh and Kevin Mills, proposed the creation of an ITL program to study complex systems in general. This second proposal was well received by the management team within ITL, which founded a complex systems (CxS) program and recruited Sandy Ressler as the program manager. Sandy has provided steadfast support to the work documented in this report. In fact, he added resources to the project so that we could explore the use of interactive visualization as a tool to reveal global behavior in large distributed systems. Further, he regularly attended the biweekly project meetings and provided many useful suggestions for improving the content and presentation of the work.

In 2007, while we were exploring potential challenge problems for a measurement science of complex systems, Vladimir Marbukh suggested that we consider the collection of congestion control algorithms being proposed to augment or replace congestion control procedures within the standard transmission control protocol (TCP), which operates within every computer connected to the Internet. Ultimately, Vladimir's suggestion led to the study documented in this report. Through the Internet Congestion Control Research Group (ICCRG) of the Internet Research Task Force (IRTF), we contacted the community of researchers involved in developing future congestion control mechanisms for the Internet. Several members of the ICCRG had performed empirical studies of selected congestion control algorithms operating within a small topology. These empirical results proved invaluable in verifying our models of individual congestion control algorithms. Wesley Eddy and Michael Welzl, co-chairs of the ICCRG, encouraged us to share our work with the group and provided ample agenda time at several meetings for us to first present our methods and later our findings. We also appreciate the general support for our work from researchers within the ICCRG community, as well as several researchers within the Transport Modeling Research Group (TMRG) of the IRTF.

In addition to support from Internet researchers, we also benefited from the work of several colleagues who made temporary visits to NIST. For example, Brittany Devine worked on the project for three months under the Summer University Research Fellowship (SURF) program administered by the National Science Foundation (NSF). Brittany contributed prototype code to make measurements on flow groups, as explained in Chapter 8. Edward Schwartz, one of the study authors, also worked on the project for three months under the SURF program. Ed, now a doctoral student at Carnegie Mellon University, developed the initial models of CTCP, FAST, HSTCP, H-TCP and Scalable TCP that were used within this study. Ed also conducted some preliminary experiments comparing CTCP, FAST and standard TCP under select scenarios. Cedric Houard contributed two years of work to the project as a guest scientist visiting from France. Specifically, Cedric developed DiVisa, an interactive system for visualizing multidimensional data.

Supported by these many valuable contributions, the authors produced the current report to document a set of methods, models, experiments and findings, which were produced largely over the period of 2006-2009. The study encompasses a wide scope and substantial breadth, which could not be documented completely in less than 500 pages. We are indebted to Christopher Dabrowski and Stefan Leigh, two NIST colleagues who made careful, independent readings of the entire report, and who also provided many useful suggestions for improving the manuscript. The review provided by Dabrowski and Leigh upheld the highest standards of NIST requirements for internal review prior to publication. Of course, in a report of such length, scope and depth, errors undoubtedly remain. Responsibility for such residual errors lies squarely at the feet of the authors.

Note: the document cover and chapter dividers contain images generated from the study text with http://www.worldle.net/

Executive Summary

When first introduced in the early 1980s the Internet appeared to be an interesting engineering curiosity, providing resource sharing and data communication services to support scientific researchers. Beginning with the introduction of the World Wide Web (circa 1995), the fundamental data communication services provided by the Internet transformed into a global infrastructure for commerce, education and entertainment. Later developments (circa 2005) built upon so-called Web Services to provide innovative social networking technologies that citizens the world over can use to organize and collaborate around collective interests. Along the way, innovative cell phones and other handheld devices were introduced and integrated with the Internet and the Web to extend available information and interaction services to people anytime, anywhere. The future promises a globe interconnected by large, distributed information networks, where people routinely interact in new and unexpected ways. Realizing this future relies in large part on our ability to understand and engineer globally distributed systems of interconnected hardware and software components, including their use by people. At present, society is technologically capable of building such systems but lacks the fundamental knowledge required to understand and predict macroscopic behaviors that may arise from complex interactions as such systems evolve with the addition of new technologies and new patterns of use. A similar lack of knowledge may impede progress with respect to other large systems engineered by society. For these reasons, researchers in the Information Technology Laboratory (ITL) of the National Institute of Standards and Technology (NIST) embarked upon a measurement science based program of research for complex systems. The NIST Complex Systems Program aims to investigate and evaluate methods and tools that system designers might adopt to improve scientific understanding of large distributed systems, such as information networks, electric grids and transportation webs.

As part of the NIST Complex Systems Program, this special publication investigates and evaluates modeling and analysis methods that can be applied to predict and understand macroscopic behavior and variations in user experience that may arise as engineers introduce changes in software components into a large information network, such as the Internet. The Internet consists of millions (someday billions) of interconnected components that may be changed independently. For example, every time vendors of major operating systems introduce software updates, millions of users download new software modules into computers connected to the Internet. As another example, users may download software to support new functions, such as social networking or distributed gaming. At the current state of the art, system designers lack techniques to predict global behaviors that may arise in the Internet as a result of interactions among existing and altered software components. Similarly, hardware faults and unexpected usage patterns may occur within the Internet. Engineers have insufficient methods and tools available to forecast global behaviors and resulting effects on individual users. The study described in this special publication aims to improve existing knowledge about a range of methods and tools that could be applied to understand and predict behavior in such complex information systems.

To give our study a concrete context, we selected a challenging problem of current interest and relevance for the Internet at large. Specifically, we study the likely consequences for macroscopic behavior and for individual users should any of several

proposed mechanisms be introduced to augment or replace congestion control procedures in the standard transmission control protocol (TCP), which is currently deployed to regulate the rate of information transfer among computers connected to the Internet. Congestion control procedures allow individual computers to measure available capacity on network paths and to attempt to transfer information as quickly as possible. Because conditions vary with time, congestion control procedures also enable detection of congestion that may arise as too many computers attempt to use a network path. Upon detecting congestion, TCP first substantially slows a computer's rate of transfer and then attempts to slowly increase the rate. Researchers have predicted that the standard TCP congestion control procedures will inhibit users from realizing increased transfer speeds as capacity expands in the Internet backbone from the current rate of 10 Gigabits per second (Gbps) to 100 Gbps and beyond. For this reason, various researchers have proposed changes to the congestion control procedures implemented in standard TCP. At the current state of the art, such proposed changes have been studied on individual long-lived flows using analytical methods and also studied using simulation and empirical measurements in small topologies with limited types of data traffic. Though researchers and engineers would like to predict the effects of such changes on macroscopic behavior and on individual users, no techniques are currently available to make such extrapolations to large, fast topologies transporting hundreds of thousands of simultaneous data transfers of various sizes under a wide range of network conditions. The study documented in this special publication describes and evaluates modeling and analysis techniques applied to make such extrapolations for seven proposed alternatives to standard TCP congestion control procedures.

We apply techniques often used by scientists at NIST when studying physical systems. First, we propose an abstract simulation model, representing a data communications network (including TCP) with only 20 parameters, as compared with the hundreds of parameters typically used in detailed Internet simulators. Second, we adopt 2-level-per-factor experimental designs, which consider each parameter at only two values, as compared with the billion or so values that each parameter could possibly take on. Third, we leverage orthogonal fractional factorial (OFF) experiment designs that enable us to model a sparse but balanced set of parameter combinations spread widely throughout the space of possible combinations. Reducing the number of parameters, parameter levels and combinations enables feasible simulation of large networks under a wide range of conditions. Third, we use a variety of statistical analysis and visualization techniques designed to explore multidimensional data sets. Fourth, we use detailed analyses of time series as required to supplement findings from statistical analyses. We demonstrate that our proposed combination of modeling and analysis techniques allows us to predict the influence of seven proposed congestion control mechanisms on macroscopic network behavior and individual user experience.

In summary, this special publication contributes to current knowledge about modeling and analysis techniques for complex information systems and also contributes to the body of knowledge surrounding proposals for improving congestion control mechanisms considered for deployment in the Internet. Six specific contributions improve current knowledge regarding techniques to understand and predict behavior in complex information systems. First, we summarize the current state of the art in modeling and analysis of communication networks and we identify several hard problems that inhibit the study of large, fast networks. Second, we propose an approach to construct simulation models with a reduced parameter space. As a corollary contribution, we identify and explore some alternative, promising modeling approaches, including fluid flow models and hybrid models, which combine quantized time calculations with discrete events. Third, we describe and demonstrate how two-level OFF experiment designs can be applied to reduce the number of parameter combinations that must be considered, while yielding maximum information from available simulation resources. Fourth, we describe and apply a variety of analysis and visualization techniques for interpreting multidimensional data. We first use these techniques to conduct sensitivity analyses of our simulation model and then apply the techniques to compare congestion control mechanisms. Fifth, we evaluate our proposed modeling and analysis techniques, discussing the strengths and weaknesses of various methods and identifying those methods that proved most effective for our study. Sixth, we outline future research needed to improve upon the methods we evaluated. Our six contributions enhance understanding of methods and tools available to designers of complex systems.

Four specific contributions add to the body of knowledge surrounding proposals for improving Internet congestion control. First, we characterize likely macroscopic behavior and user performance for seven proposed alternatives to TCP congestion control procedures. In doing so, we reveal that proposed improvements to TCP congestion control would benefit individual users under a specific combination of circumstances unlikely to arise very often in the general Internet. We also identify some cautionary findings with respect to various congestion control mechanisms we study. Second, we identify key behavioral characteristics to be considered when comparing congestion control mechanisms. We found these characteristics through analyses of experiment data, rather than through a priori analyses. Part of our method was to collect as much measurement data as possible and then to use statistical techniques (e.g., correlation and principal components analyses) to identify those measures representing different facets of system behavior. Then, given selected measures, we could determine the key factors influencing macroscopic behavior and user experience. Previous studies of congestion control mechanisms did not reflect these key factors. Third, we identify and compare the main differences among the congestion control mechanisms we studied. We show that, for the key behavioral factors we identify, one of the seven mechanisms we studied fares better than the others. Fourth, we suggest some future research directions related to Internet congestion control. Our four contributions should help researchers to better understand the problem space surrounding congestion control in the Internet.

While the current study is quite comprehensive with respect to the study of large distributed systems, we have certainly not covered every method and technique that might prove useful. For example, a related project in the NIST Complex Systems Program is investigating how Markov models, coupled with perturbation analysis, Eigenanalysis and graph theory, can be used to identify specific aspects of system designs that might significantly degrade performance when subjected to failures. Further, while some of the methods we applied appear quite effective in the context of Internet congestion control, we also need to demonstrate effectiveness in other applications. In summary, this study makes substantial contributions to methods for modeling and analyzing complex information systems and also provides significant information to the community of researchers studying Internet congestion control.