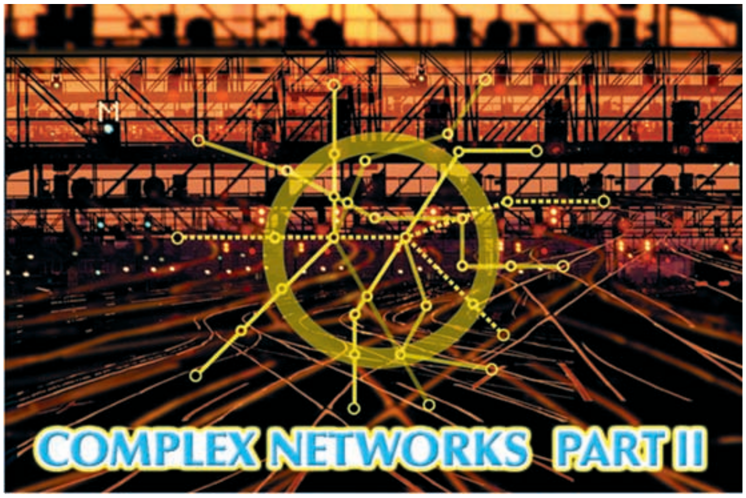

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Modeling and Control of Complex Interactive Networks

By Massoud Amin

Energy, telecommunications, transportation, and financial infrastructures are becoming increasingly interconnected, thus posing new challenges for their secure, reliable, and efficient operation. All of these infrastructures are themselves complex networks, geographically dispersed, nonlinear, and interacting both among themselves and with their human owners, operators, and users. No single entity has complete control of these multiscale, distributed, highly interactive networks, nor does any such entity have the ability to evaluate, monitor, and manage them in real time. In fact, the conventional mathematical methodologies that underpin today's modeling, simulation, and control paradigms are unable to handle the complexity and interconnectedness of these critical infrastructures.

Virtually every crucial economic and social function depends on the secure, reliable operation of infrastructures. Indeed, they have provided much of the good life that the more developed countries enjoy. With increased benefits, however, come increased risks. As these infrastructures have grown more complex to handle a variety of demands, they have become more interdependent. The Internet, computer networks, and our digital economy have increased the demand for reliable and disturbance-free electricity; banking and finance systems depend on the robustness of electric power, cable, and wireless telecommunications. Transportation systems, including military and commercial aircraft and land and sea vessels, depend on communication and energy networks. Links between the power grid and telecommunications and between electrical power and oil, water, and gas pipelines continue to be a lynchpin of energy

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supply networks. This strong interdependence means that an action in a part of one infrastructure network can rapidly create global effects by cascading throughout the same network and even into other networks.

A growing portion of the world's business and industry, art and science, entertainment, and even crime are conducted through the World Wide Web and the Internet. But the use of these electronic information systems depends, as do the more mundane activities of daily life, on many other complex infrastructures, such as cable and wireless telecommunications; banking and finance; land, water, and air transportation; gas, water, and oil pipelines; and the electric power grid.

With these timely issues and considerations as background, we are pleased to present a special section of the *Magazine* on the control of complex networks. The section spans two issues—the first set of articles appeared in December 2001. The first article, by Rinaldi, Peerenboom, and Kelly, defines a framework and taxonomy for a system of infrastructure networks and their interdependencies. Pertinent areas considered include technological, economic, and regulatory aspects, along with couplings and characteristic failure modes and responses. This article builds a framework for describing infrastructure interdependencies in six dimensions. It then introduces the fundamental concepts of infrastructures, infrastructure dependencies, and infrastructure interdependencies. Third, it discusses the interrelated factors and system conditions that collectively define the six dimensions. Finally, it addresses the research challenges involved in modeling, simulation methodologies, and tools.

Modeling interdependent infrastructures in a control theory context is especially pertinent since the current movement toward deregulation and competition will ultimately be limited only by the physics of the domains and the network topologies. In addition, mathematical models of complex networks are typically vague (or may not even exist) and classical solution methods—where they exist—are not sufficiently powerful. For the most part, no present methodologies are suitable for understanding the behavior of complex networks.

There is reasonable concern that national and international energy and information infrastructures have reached a level of complexity and interconnection that makes them particularly vulnerable to cascading outages, initiated by material failure, natural calamities, intentional attack, or human error. The potential ramifications of network failures have never been greater, as the transportation, telecommunications, oil and gas, banking and finance, and other infrastructures depend on the continental power grid to energize and control their operations. Although there are some similarities, the electric power grid is quite different from gas, oil, or water networks—phase shifters rather than valves are used, and there is no way to store significant amounts of electricity. Providing the desired flow on one line often results in "loop flows" on several other lines.

At the time of this writing, in the aftermath of the tragic events of September 11, there are increased national and international concerns about the security and robustness of critical infrastructures in response to evolving spectra of threats. Secure and reliable operation of these networks is fundamental to the national and international economy, security, and quality of life.

Electricity Infrastructure

The electricity infrastructure, faced with deregulation and increased demand for high-quality and reliable electricity for our digital economy, and coupled with interdependencies with other critical infrastructures, is becoming more and more stressed. The occurrence of several cascading failures in the past 40 years has helped focus attention on the need to understand the complex phenomena associated with these interconnected systems. Widespread outages and huge price spikes during the last five years have raised public concern about grid reliability at the national level. According to data from the North American Electric Reliability Council (NERC), outages from 1984 to the present affected nearly 700,000 customers annually, with smaller outages occurring much more frequently and larger outages affecting 7 million customers per decade (Fig. 1).

The article by Kendall, "Power Outages During Market Deregulation," extends this analysis by examining outages before and after deregulation in these countries. The author explores potential linkages between outages, their root cause, and market deregulation. A new study reveals that power outages and disturbances cost the U.S. economy more than $100 billion annually (see the Web site at http://ceids.epri.com/ceids/Resources/Press.html).

In the electric power industry and other critical infrastructures, new ways are being sought to improve network efficiency and eliminate congestion problems without seriously diminishing reliability and security. The question is

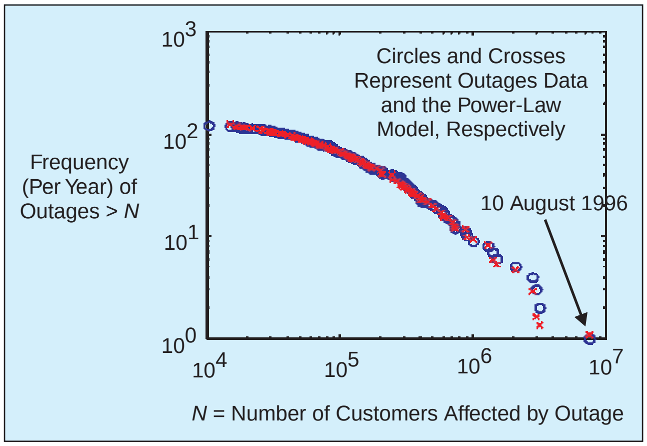


Figure 1. *Major U.S. electric power outages and power law distribution. (Data from NERC http://www.nerc.com/dawg; log-log plot courtesy of Prof. John Doyle, California Institute of Technology.)*

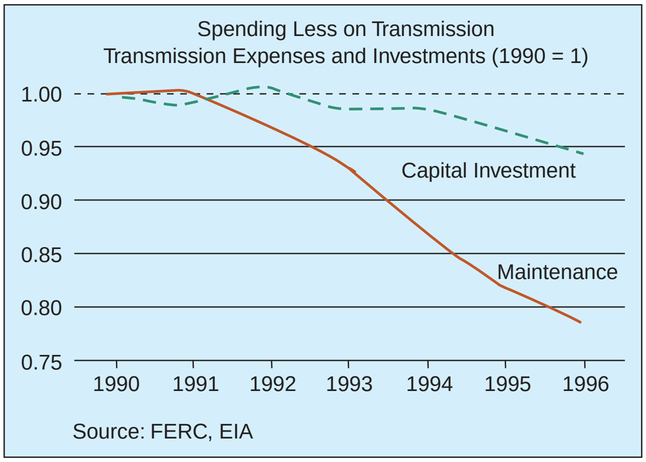


Figure 2. *Declining infrastructure investment.*

raised as to whether there is a unifying paradigm for the simulation, analysis, and optimization of time-critical operations (both financial transactions and actual physical control) in these multiscale, multicomponent, and distributed systems. The article by Asavathiratham, Roy, Lesieutre, and Verghese describes "The Influence Model," comprising a network of interactive Markov chains to unveil the essential roots of the global behavior and to represent the underpinning dynamics of the network.

Another abstraction for networked systems is discussed by DeMarco in "A Phase Transition Model for Cascading Network Failure." The author presents a special structure of dynamical systems that allows tractable inclusion of element failures, potentially providing an alternative to time-domain simulation to prove the stability and robustness of power systems.

The effects of deregulation and economic factors and the impact of policies and human performance must be considered as well. The electric power grid was historically operated by separate utilities, each independent in its own control area and regulated by local bodies, to deliver bulk power from generation to load areas reliably and economically—as a noncompetitive, regulated monopoly; the emphasis was on reliability (security) at the expense of economy. Power grids must now work economically to 1) get power from low-cost producers and 2) deliver power to the loads at the lowest cost. Competition and deregulation have created multiple energy producers who must share the same regulated energy distribution network—such that this network now lacks the carrying capacity or safety margin to support anticipated demand. In the U.S. electrical grid, investments in maintenance and R&D have continued to decline (Figs. 2 and 3). Similar trends are also evident in long-term R&D investment in related areas.

Increased use of electronic automation raises significant issues regarding the adequacy of operational security: 1) reduced personnel at remote sites makes them more vulnerable to hostile threats; 2) interconnection of automation and control systems with public data networks makes them accessible to individuals and organizations from any worldwide location using an inexpensive computer and a modem; 3) use of networked electronic systems for metering, sched-

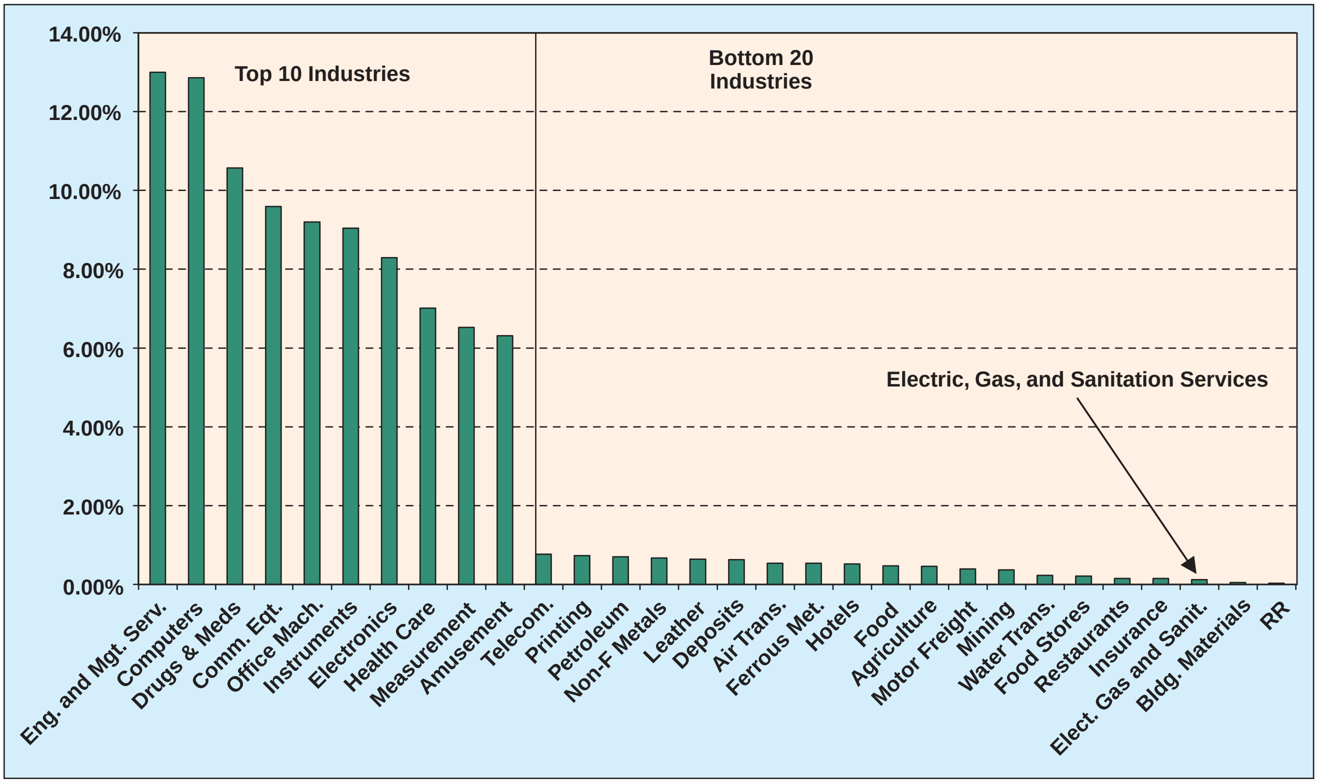


Figure 3. *Percentage of industry R&D expenditures as a portion of net sales.*

uling, trading, or e-commerce imposes numerous financial risks implied by use of this technology. The complex systems used to relieve bottlenecks and clear disturbances during periods of peak demand are now at greater risk of serious disruption—and technological improvements for these systems are needed. A timely issue is merging of sensor-enabled data-based models with derived models from first principles combined with online updating. How can robust controls and observers be developed that can use secure sensing to identify and build realistic models and appropriate responses? Will they be able to adapt, control, and mitigate disturbances to achieve their goals?

The recent California power crisis is only the most visible part of a larger and growing energy crisis in the United States, resulting from a decade of inadequate investment. The most basic problem in the California crisis was that declining investment in these infrastructure components led to a fundamental imbalance between growing demand for power and an almost stagnant supply. This imbalance had been in the making for many years and is prevalent throughout the nation, as shown by Figs. 4 and 5 (source: Western States Power Crises White Paper, EPRI, Summer 2001).

Telecommunications

The globalization of our economy is built on telecommunication networks, including fixed networks (public switched telephone and data networks), wireless (cellular, PCS, wireless ATM), and computers (Internet and millions of computers in public and private use). These networks are growing rapidly and require secure, reliable, high-quality power supplies. This telecommunication infrastructure, like the power grid, is becoming overburdened. The satellite network, just one segment of the infrastructure, is a good example. The satellite network has three main layers:

- Low-earth orbit, at 200 to 2,000 km (“little LEOs” at 750-1500 km), operating at VHF and UHF below 500 MHz with low complexity;
- Medium-earth orbit, at 2000 to 20,000 km (big LEOs/MEOs at 750-11,000 km), operating at L and S microwave (1.6 and 2.5 GHz) with high to very high complexity;
- Geosynchronous orbit (GEO), at 36,000 km, operating at K microwave (19 and 29 GHz) with variable low to high complexity.

Some of the most familiar services are detailed earth imaging, remote monitoring of dispersed locations, and highly accurate location and tracking using the continuous signals of the global positioning system (GPS). Satellite-based business and personal voice and data services are now available throughout much of the world.

In “Internet Congestion Control,” Low, Paganini, and Doyle describe the current congestion control mechanism in the Internet (namely, transfer control protocol (TCP)) and discuss the various analytical models and advances that are currently studied in the networking community. The dynamics of TCP are considered, along with its stability limitations. An optimization-based framework is presented, and the dual model is used to solve the original resource allocation problem. The authors discuss a new protocol that provides scalable stability for Internet applications.

Some utilities are diversifying their businesses by investing in telecommunications and creating innovative communication networks that cope with industry trends toward distributed resources, two-way customer communications, and business expansion, as well as addressing the measurement of complex and data-intensive energy systems via wide-area monitoring and control. Challenges include how to handle network disruptions and delays and manage orbits from the satellite. A major source of complexity is the interdependence of the telecommunication networks and the power grid. (An industry-wide Y2K readiness program identified telecommunications failure as the greatest source of risk of the lights going out on rollover to 2000.) Issues range from the highest command and control level to the individual power stations and substations at the middle level, and then to the devices and power equipment at the lowest level.

Transportation

The backbone of the U.S. transportation system and economy—the road infrastructure system—has continually

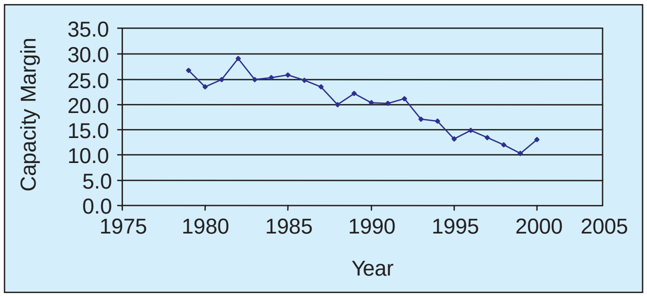


Figure 4. *Generation capacity margin in North America.*

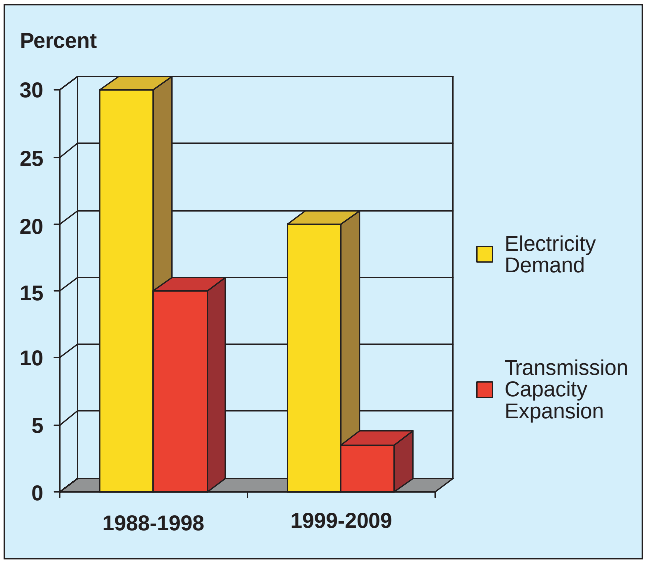
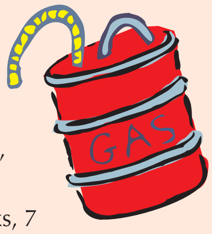


Figure 5. *Transmission additions in the United States.*

Getting Around in America

- Length of public roads: 46,036 miles of interstate highways (1%); 124,467 miles of National Highway System (3%); and 3.76 million miles of other roads (96%)
- Personal travel by mode:
  - 208 million vehicles: private vehicles, 85.9%; public transport, 2.8%; other means, 11.3%
  - About 130 million cars, 69 million light trucks, 7 million commercial trucks, and 700,000 buses (e.g., California has 15.5 million motor vehicles, Florida has 7.3 million,…)
  - About 1.2 million rail cars, 68 ferries, 6,000 aircraft



- Half of the total petroleum consumption in the United States is for highway vehicles and another 18% is for other transportation:
  - Fuel consumption: 148 billion gallons of gasoline, 28 billion gallons of diesel, and about 4 billion gallons other fuels
- Fatalities: 22,416 in cars (50.4%), 9,901 truck occupants (22.2%), 2,160 on motorcycles (4.9%), 1,088 on aircraft (3.1%), and 624 on trains (1.4%)
- Fatal accident types amenable to technological prevention: off-road (36%), angle collision (18%), head-on collision (17%), rear-end collision (5%), sideswipe (2%).

evolved since the 1930s, but the cost to build and maintain it is rising. The U.S. Department of Transportation estimates that the annual cost of congestion in lost productivity alone is more than $100 billion. In addition, more than 40,000 people are killed and another 5 million injured each year in traffic accidents.

Human population centers have grown dramatically in the past century, creating a "trilemma" of sustainability issues: population, poverty, and pollution. The United States, along with many other nations, is seeking a solution to this worsening traffic congestion problem. Such solutions have to be viewed in terms of the economic, social, and political environments, together with the technological capability of the nation. Furthermore, the costs associated with generating and maintaining road infrastructure are increasing, and the impact of inefficiencies can be quantified in terms of lost labor-hours in the workplace, loss of fuel, etc., as well as intangibly in terms of pollution and the general increased stress level of a work force using these transportation channels.

The article by Chen, Jia, and Varaiya, "Causes and Cures of Highway Congestion," presents a timely study of transportation networks and proposes that congestion is caused not just by increase in demand, but also by loss of efficiency. Actual highway data is used to determine performance measures using the equations developed in the article. Empirical analysis supports potentially large gains in efficiency, with dramatic reductions in congestion, through the use of ramp-metering control strategies.

The Bigger Picture

Power, telecommunications, banking and finance, transportation and distribution, and other infrastructures are becoming more and more congested, partially due to dramatic population growth, particularly in urban centers. These infrastructures are increasingly vulnerable to failures cascading through and between them. A key concern is the avoidance of widespread network failure due to cascading and interactive effects. Moreover, interdependence is only one of several characteristics that challenge the control and reliable operation of these networks. Other factors that place increased stress on the power grid include dependencies on adjacent power grids (increasing because of deregulation), telecommunications, markets, and computer networks. Furthermore, reliable electric service is critically dependent on the whole grid's ability to respond to changed conditions instantaneously.

Secure and reliable operation of complex networks poses significant theoretical and practical challenges in analysis, modeling, simulation, prediction, control, and optimization. To address these challenges, a new research initiative has been undertaken. The Complex Interactive Networks/Systems Initiative (CIN/SI) is a 5-year, $30 million program of Government Industry Collaborative University Research (GICUR), funded equally by EPRI and the United States Department of Defense (DoD), through the Army Research Office (ARO). The objective of this initiative is to produce significant, strategic advancements in the robustness, reliability, and efficiency of the interdependent energy, communications, financial, and transportation infrastructures.

A key concern is the avoidance of widespread network failure due to cascading and interactive effects—threats include intentional disturbances by an enemy, natural disasters, and material failures. Work focuses on advancing basic knowledge and developing breakthrough concepts in modeling and simulation; measurement, sensing, and visualization; control systems; and operations and management. To achieve this goal, technical objectives were defined in three broad areas:

- *Modeling:* Understanding the "true" dynamics"—to develop techniques and simulation tools that help build a basic understanding of the dynamics of complex infrastructures.
- *Measurement:* Knowing what is or will be happening—to develop measurement techniques for visualiz-

ing and analyzing large-scale emergent behavior in complex infrastructures.

- *Management:* Deciding what to do—to develop distributed systems of management and control to keep infrastructures robust and operational.

Many of the contributions to this special section of the *Magazine,* as well as the special section on "Electric Power Systems and Markets" featured in the August 2000 issue, are outputs of the EPRI/DoD CIN/SI. This initiative has developed, among other things, a new vision for the integrated sensing, communications, and control of the power grid. Some of the pertinent issues are why/how to develop controllers for centralized versus decentralized control and issues involving adaptive operation and robustness to disturbances that include various types of failures.

Conclusions

Any complex dynamic infrastructure network typically has many layers and decision-making units and is vulnerable to various types of disturbances. Effective, intelligent, distributed control is required that would enable parts of the constituent networks to remain operational and even automatically reconfigure in the event of local failures or threats of failure. In any situation subject to rapid changes, completely centralized control requires multiple, high-data-rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed (i.e., when the system is stressed by natural disasters, purposeful attack, or unusually high demand). Management of disturbances in all such networks, and prevention of cascading effects throughout and between networks, require a basic understanding of the true system dynamics, as well as effective distributed control functions to enable parts of the networks to remain operational or even to automatically reconfigure themselves in the event of a threat or other potentially destabilizing disturbance.

The control methodology that has probably enjoyed the greatest success for large-scale systems is model predictive control (MPC). However, current MPC formulations assume centralized computation, a shortcoming that adversely affects both scalability and reliability. In "Distributed Model Predictive Control," Camponogara, Jia, Krogh, and Talukdar discuss a distributed optimization algorithm that may be used in MPC. Advantages of distributed MPC over centralized MPC for large-scale interconnected systems are presented.

When failures occur at various locations in such a network, the whole system breaks into isolated "islands," each of which must then fend for itself. With the intelligence distributed, and the components acting as independent agents, those in each island have the ability to reorganize themselves and make efficient use of whatever local resources remain to them in ways consonant with the established global goals to minimize adverse impact on the overall network. Local controllers will guide the isolated areas to operate independently while preparing them to rejoin the network, without creating unacceptable local conditions either during or after the transition. A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure.

Although the immediate and critical goal is to avoid widespread network failure, the longer-term vision is to enable adaptive and robust infrastructure. As expressed in the July 2001 issue of *Wired* magazine: "The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming—and interconnected with everything else."

Achieving this vision and sustaining infrastructure reliability, robustness, and efficiency are critical long-term issues that require strategic investments in research and development. Given economic, societal, and quality-of-life issues and the ever-increasing interactions and interdependencies among infrastructures, this objective offers exciting scientific and technological challenges.

I express my gratitude to all authors, the referees, members of the *CSM* editorial office, and Editor-in-Chief Tariq Samad for their contributions and continued interest in this topic. I hope that this collection will be of interest to many in various fields of science and technology who have a particular interest in the modeling and control of critical infrastructures.

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