# Complex Interactive Networks/Systems Initiative: Final Summary Report

Overview and Summary Final Report for Joint EPRI and U.S. Department of Defense University Research Initiative

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Cosponsor
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# REPORT SUMMARY

The North American power grid faces many challenges that it was not designed and engineered to handle. Congestion and atypical power flows threaten to overwhelm the system, while demand increases for higher reliability and—since September 11, 2001—better protection. The potential ramifications of grid failures have never been greater, as transport, communications, finance, and other critical infrastructures depend on secure, reliable electricity supplies for energy and control. The Complex Interactive Networks/Systems Initiative (CIN/SI), funded equally by EPRI and U.S. Department of Defense (DOD), developed a mathematical basis and practical tools for improving the security, performance, and robustness of critical energy, transport, financial, and communications infrastructure.

## Background

Virtually every crucial economic and social human function of modern society depends on secure, reliable operation of interconnected infrastructures for energy, communications, transport, finance, and more. Robust, reliable operation of these multi-scale, distributed, and highly interactive infrastructures presents unique and growing challenges. No single entity has complete control of networks such as the electric power grid or the Internet, or the ability to evaluate, monitor, manage, and protect them in real time. Moreover, the conventional mathematical methodologies that underpin today's top-down modeling and control paradigm are unable to handle the complexity and connectedness of these infrastructure systems. And new threats of terror attacks on U.S. infrastructure heighten the challenge.

Because modern infrastructure systems are so highly interconnected, a change in conditions at any one location can have immediate impacts over a wide area, and the effect of a local disturbance even can be magnified as it propagates through a network. Large-scale cascade failures can occur—almost instantaneously—with consequences in remote regions or seemingly unrelated businesses. On the North American power grid, for example, transmission lines link all electricity generation and distribution on the continent. Wide-area outages in the late 1990s underscore the grid's vulnerability to cascading effects.

Complex adaptive systems and other emerging sciences provide an attractive bottom-up paradigm for modeling, simulation, control, optimization, and protection of operations—both financial and physical—in complex networks. Practical methods, tools, and technologies based on advances in the these fields are allowing power grids and other infrastructures to self regulate, including automatic reconfiguration in the event of failures, threats, or disturbances.

## Objectives

To create revolutionary self-stabilizing, self-optimizing, and self-healing capabilities for the electric power grid and interconnected communications, transport, and financial infrastructures.

## Approach

CIN/SI was initiated in mid-1998 in response to growing concerns about the vulnerability of national infrastructures. The Initiative was a three-year, $22 million Government-Industry Collaborative University Research (GICUR) program funded equally by EPRI and—through the Army Research Office—the Deputy Under Secretary of Defense of Science and Technology.

CIN/SI aimed to advance basic knowledge in several new sciences—complex adaptive systems, statistical physics, discrete-event dynamical systems, and hybrid layered networks, among others—and to develop practical modeling, simulation, analysis, and synthesis tools providing for robust, adaptive, reconfigurable control of the power grid and other critical infrastructures.

## Results

Six research consortia were funded by the CIN/SI. Five consortia worked for three years, from spring 1999 to spring 2002; one was terminated in early 2001. In all 26 universities took part, along with two energy companies that provided real-world data, staff expertise, and test sites.

These research consortia developed a mathematical basis and practical tools for improving the security, performance, and robustness of critical energy, finance, communications, and transport infrastructures. From the diverse research results, EPRI has extracted 19 technologies for further development. Among others, the technologies include intelligent adaptive islanding, Strategic Power Infrastructure Defense system, wide area protection and control, neuro-fuzzy load forecasting and anticipatory dispatch, context-dependent network agents for real-time system monitoring and control, and mathematical computational foundations for complex networks. CIN/SI research results also have been incorporated in other EPRI programs such as the Consortium for Electric Infrastructure to Support a Digital Society (CEIDS) and the Electricity Infrastructure Security Initiative. CIN/SI results are also being developed in at least five defense programs by the Initiative's DOD cosponsor.

## EPRI Perspective

CIN/SI established a new paradigm enabling more effective design, control, management, and protection for complex interconnected systems, especially for those characterized by high technological content and significant human interaction. For the power grid and other critical infrastructures, CIN/SI results laid the foundation for revolutionary self-stabilizing, self-optimizing, and self-healing capabilities. These capabilities will allow energy companies and other market actors to deliver energy and related products and services with unprecedented stability, reliability, efficiency, and power quality. In addition, more secure, reliable, and efficient operation of national infrastructures will enhance quality of life, economic productivity, and other essential parameters for modern society. See Appendix D.8 for additional detail on research objectives and results or visit EPRI's website for CIN/SI at www.epri.com/targetST.asp?program+83.

## Keywords

Infrastructure modeling, simulation, and control

Complex adaptive systems and intelligent agents

Power system security, robustness, and resilience

Self-healing networks and national infrastructure

# ABSTRACT


This report summarizes the accomplishments in 1999-2002 of the six university research consortia established by the EPRI/Department of Defense-sponsored Complex Interactive Networks/Systems Initiative (CIN/SI). This Initiative was implemented to advance the fundamental understanding of complex interconnected systems in order to improve the nation's ability to ensure the adequacy and security of critical infrastructure systems.

Chapter 1 introduces the research challenges and the Initiative. Work focused on developing the fundamental mathematical underpinnings for robust design, control, and protection of critical infrastructures such as the electric power grid and the Internet and telecommunications systems.

Chapter 2 discusses the critical challenges associated with modern infrastructures, characterizes infrastructure vulnerabilities and the blackout that directly motivated CIN/SI activities, and introduces promising new sciences that CIN/SI consortia drew upon in their research.

Chapter 3 reviews the key results of CIN/SI work by the six university research consortia. The participants and research approach of each consortium are described, and the major results and findings of each team are summarized.

Chapter 4 identifies applications of CIN/SI results to EPRI's 15 "Difficult Challenges" that hinder progress towards the milestones laid out in the EPRI *Electricity Technology Roadmap*. Discussion focuses on applications to Difficult Challenge #3: 'Increasing robustness, resilience and security of the energy infrastructure' and also describes roles for CIN/SI results in addressing other of the Difficult Challenges.

Chapter 5 addresses the next steps. It describes the present state of understanding about complex networks as a result of the CIN/SI program, introduces key technologies and follow-on research projects that grew out of CIN/SI technology transfer, and discusses the research still needed to develop complete modeling, measurement, and management capabilities for complex systems.

The conclusion, Chapter 6, places CIN/SI result in the context of future research challenges and research programs, provides some perspectives about the Initiative and its results, and describes lessons learned.

Four appendixes are included. Appendix A lists the organizations that participated in the CIN/SI. Appendix B discusses the CIN/SI oversight process and lists the Initiative advisors. Appendix C presents thoughts on what makes a large, diverse research initiative successful. Appendix D is a complete reference list of the technical papers resulting from CIN/SI research.

# ACKNOWLEDGEMENTS

The Complex Interactive Networks/Systems Initiative (CIN/SI) was cofunded by EPRI and, through the U.S. Army Research Office (ARO), by the U.S. Department of Defense of the Deputy Under Secretary of Defense (Science and Technology), Office of the Director, Defense Research and Engineering (DDR&E)

Within ARO, key participants include Robert Launer (CIN/SI manager), Jim Chang (ARO director), and Mitra Dutta, as well as Robert Singleton, formerly of ARO.

We gratefully acknowledge the support of many individuals to the formation and successful operation of this Initiative. Important contributors include Delores Etter, former Deputy Under Secretary of Defense; Robert Trew, former Director of Basic Research; and Charles Holland, Deputy Under Secretary of Defense (Science and Technology) and former Director of Information Systems, DDR&E. The Initiative also benefited from the participation of Richard Smith of the Office of Naval Research and U.S. Department of Defense. Other colleagues formerly with DDR&E who were involved with CIN/SI planning include Arthur Diness, Laura S. Rea, George Singley, and James Garcia. Anita Jones of the University of Virginia was the Deputy Under Secretary of Defense, ODUSD(S&T) during the formative stages of the Initiative. Steven Rinaldi and Terry Kelly, both formerly with the White House Office of Science and Technology Policy, also provided essential support.

Governing and oversight for the CIN/SI was provided by a team of ten, appointed jointly by EPRI and the Department of Defense. Their guidance and support were critical to the success of CIN/SI. Members were Chester Carroll, Jim Chang, Marc Jacobs, Gail Kendall, Wendy Martinez, Bruce Renz, Thomas Tanton, Stephen Whitley, Dan Willard, and Vickie VanZandt. (See Appendix B for more information.)

Within EPRI, technical input and other varied assistance have been provided by Chauncey Starr, Gail Kendall, Martin Wildberger, Revis James, Robert Holmes, Ram Adapa, Aty Edris, Paul Grant, Hung-po Chao, Richard Lordan, Steve Gehl, John Stringer, Dejan Sobajic, Peter Hirsch, Steve Lee, Robert Schainker, Alan Gemanis, Bruce Rytkonen, and many others. Valuable administrative assistance was provided by Carolyn Wong, Angelica Kamau, and Karen Larsen..

For this report, principal investigators for the six CIN/SI consortia, and their colleagues at universities and energy companies throughout the United States, provided valuable technical information on research objectives and final results. Participating organizations for each consortium are identified in Section 3 of this report.

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# 1 OVERVIEW

This chapter introduces the final report summarizing the accomplishments of the six research consortia established under the EPRI/Department of Defense-sponsored Complex Interactive Networks/Systems Initiative (CIN/SI).

## 1.1 Introduction

As the world grows smaller and more interconnected, we are becoming surrounded by complex networked systems. These systems consist of numerous components interlinked in complicated webs. As a result of the number of components and their intricate interconnections, complex networked systems are extremely difficult to design, analyze, control, and protect.

Despite the challenge, understanding complex networked systems is becoming critical. Many of our nation's critical infrastructures are complex networked systems, including:

- Electric power grid
- Oil and gas pipelines
- Telecommunications and satellite systems
- Computer networks such as the Internet
- Transportation systems
- Banking and finance systems
- State and local water supply, emergency response, and other services

Secure and reliable operation of complex infrastructure systems such as these is fundamental to our economy, security, and quality of life. Of particular importance is the uninterrupted availability of inexpensive, high-quality electrical power and reliable, high-performance communication networks.

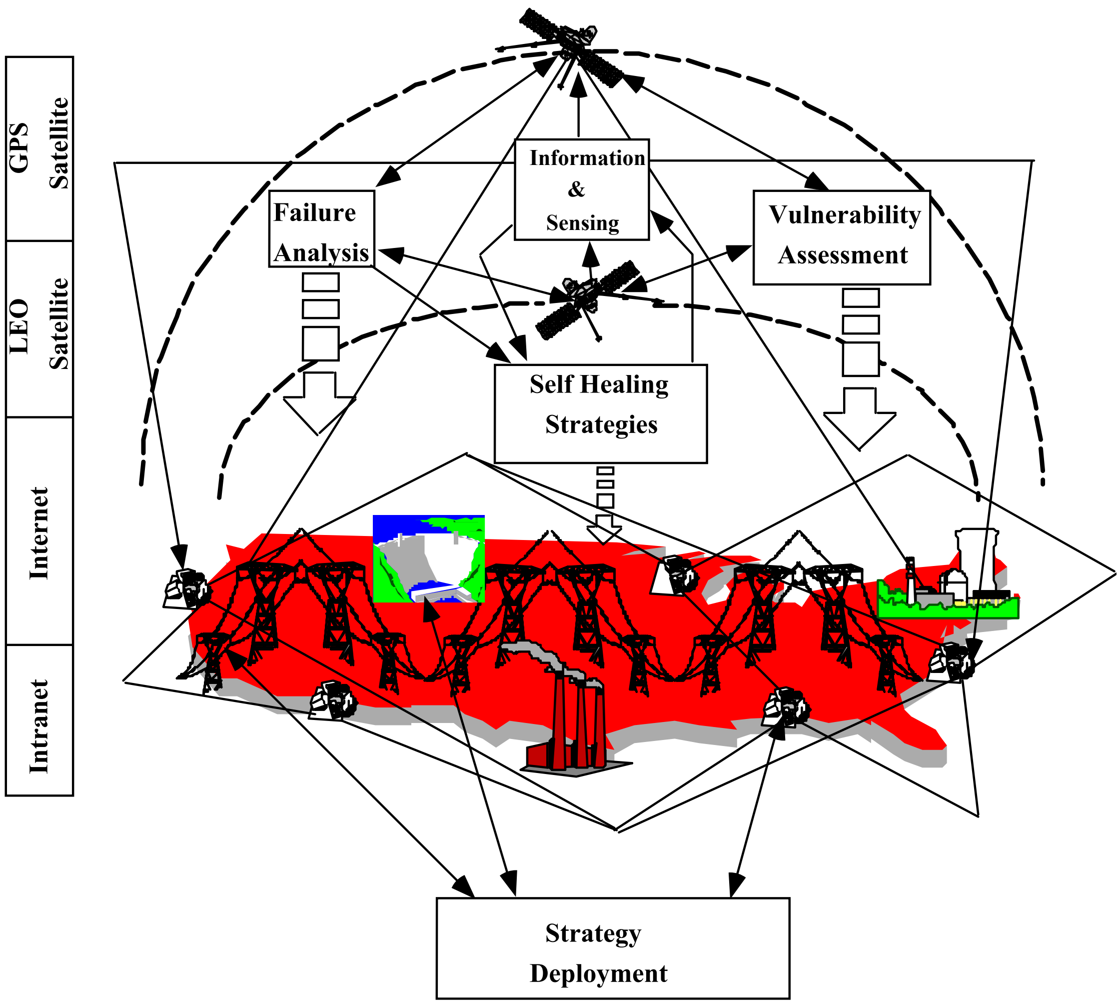



**Figure 1-1**
**U.S. Electric Power Grid as a Complex Interactive Network**
The U.S. electric power system is a leading example of a complex interactive network. Not only does a web of transmission and distribution lines link millions of customers to power plants on a continental scale, but an overlain network of real-time communications and control connects power grid sensors, actuators, and control centers.

The importance of these systems was noted in "Critical Foundations—Protecting American's Infrastructures," an October 1997 report by the President's Commission on Critical Infrastructure Protection, and in the subsequent Presidential Directive 93 on Critical Infrastructure Protection, issued on May 22, 1998. The power crisis in California in winter 2000-2001 and the growing prevalence of Internet hacker-attacks and email viruses demonstrate that these key infrastructures are highly vulnerable to failure. Finally the terrorist attacks on September 11, 2001, underscored the critical nature, many vulnerabilities, and importance of protecting the nation's infrastructure systems.

Complex interactive networked systems present unique challenges for robust and reliable operation, let alone protection. These systems are huge—the North American power network has been called the largest machine in the world—and touch almost everyone. They have widely dispersed assets that can never be absolutely defended against a determined attack. And they are more than just gigantic; they are complex and interconnected. Being complex and interconnected means that these systems cannot be reduced to any number—no matter how large—of simple parts that can be considered independently of one another. Rather the fundamental nature of these systems is that their components are interdependent: what affects one component reverberates all throughout the system. Failure of one tiny subsystem can (and has) cause a cascade of failures across a large network, with major consequences.

The ramifications of network failures have never been greater, as our many infrastructure systems are more interlinked now than ever before. In particular, electric power networks constitute the fundamental infrastructure of modern society. A successful terrorist attempt to disrupt electricity supplies could have destructive effects on national security, the economy, and the lives of every citizen.

At the same time, the events of September 11 also demonstrated that the U.S. Department of Defense (DOD) needs new tools and technologies to defend vulnerable infrastructure systems. Powerful weapons are not enough to defend against the myriad dispersed attacks possible from modern military and terrorist forces; coordinated information is necessary to direct these weapons to where they will be effective. The DOD seeks to develop such coordination, both tactically on the battlefield and strategically all around the globe. The vision is one of a "network-centric objective force" where sensors, soldiers, weapons systems, analysts, and commanders, no matter where they may be, are linked together in real time. This vision of the future military is of a highly complex interactive network (CIN) itself, much like a power system or other complex interconnected infrastructure.

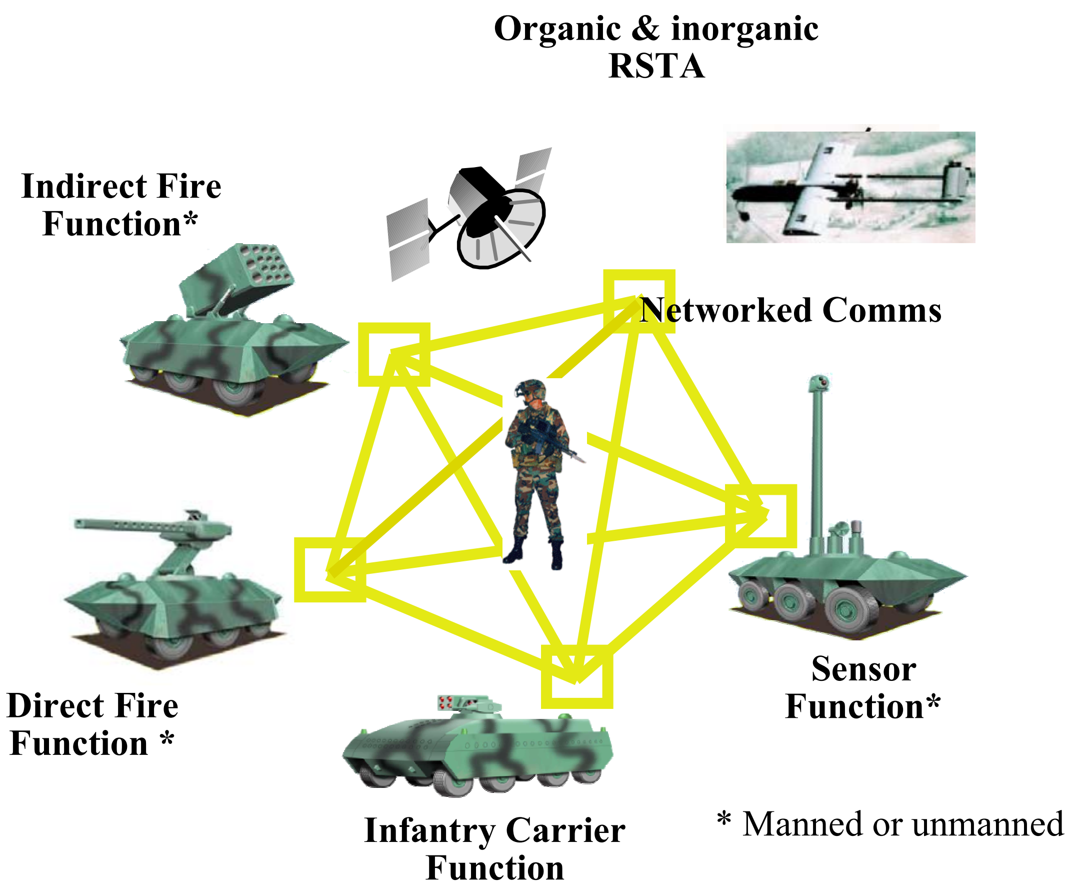



**Figure 1-2**
**Network-Centric Objective Force**
As the world becomes smaller and more interlinked, the opportunities for attack grow larger and defense capabilities need to adapt in order to provide effective protection. In response, the U.S. Department of Defense is developing the concept of a "network-centric objective force" that links remote sensors, soldiers, weapons systems, analysts, and command in real-time for fast, on-line response to any threat. The network-centric objective force concept is based on complex interactive system fundamentals.

## 1.2 Complex Interactive Networks

Secure and reliable operation of CIN, be they modern infrastructure, future defense systems, or something else, poses significant theoretical and practical challenges in analysis, modeling, simulation, prediction, control, and optimization. A few key challenges that must be overcome are listed below:

- Complex networks and systems include several functional, operations, and management layers, and are multi-scale, multi-component, heterogeneous, and distributed in nature.
- They are comprised on a mixture of dynamic, interactive, and often nonlinear entities.

- Uncertain cause and effect relationships, unscheduled discontinuities, and numerous other significant effects influence their behavior.
- They are characterized by many independent points of interactions among a variety of participants—owners, operators, sellers, buyers, customers, data and information providers, data and information users, etc.—and they may interact with their uses and other networks.
- The number of possible interactions rises at a dramatically higher rate than does the number of participants.
- Their behavior is too complex for any single centralized entity to evaluate, monitor, and manage them in real time.
- They are vulnerable to attacks and local disturbances, which can lead to cascading effects through and between them and widespread failure almost immediately.

In addition, today's mathematical models of interactive networked systems typically are vague (if they exist at all). Where models are possible, existing and classical methods of solving them either are not sufficiently powerful to be useful or else are simply unavailable. For the most part, no present methodologies are suitable for understanding the behavior of complex networks and systems.

Foundational mathematical understanding is sorely needed because management of disturbances in all such networks, and prevention of undesirable cascading effects throughout and between networks, requires a basic understanding of true system dynamics, rather than mere sequences of steady-state operations. Effective, intelligent, distributed control is required of such systems so that, after a disturbance, parts of the network will remain operational and even automatically re-configure themselves.

A new science, known as complex adaptive systems, is emerging that may enable us to meet these practical and theoretical challenges. It holds out the hope of distributed control methodologies able to rapidly respond to infrastructure perturbations, intercept cascading failures, and even enable automatic network reconfiguration and self-healing. But this is a science that is still in its infancy and the theoretical underpinnings—along with their practical implementation—require extensive development.

## 1.3 About the Complex Interactive Networks/Systems Initiative (CIN/SI)

In a joint initiative with the Deputy Under Secretary of Defense for Science and Technology, through the Army Research Office (ARO), EPRI worked to develop new tools and techniques, based on the emerging science of complex adaptive systems, that enable large national infrastructures to function in ways that are self-stabilizing, self-optimizing, and self-healing. This effort, launched as the Complex Interactive Networks/Systems Initiative, was a 3-year, $22 million program of Government Industry Collaborative University Research (GICUR) funded equally by the Department of Defense (DOD) and EPRI.

As defined, a GICUR focuses on basic research and breakthrough concepts to address major long-term challenges in complex interactive networks. The CIN/SI was aimed to develop modeling, simulation, analysis, and synthesis tools for robust, adaptive, and reconfigurable control of the electric power grid and infrastructures connected to it. Work began in spring 1999 and was completed in early 2002.

The CIN/SI was a far-reaching program with a timely focus. As such it attracted widespread interest and participation beyond the initial funding organizations and academia. From the U.S. government, the Departments of Commerce, Defense, Energy, State, and Transportation were involved, as well as the Federal Aviation Administration, National Science Foundation, the DOE National Laboratories and Office of Critical Infrastructure Protection, the White House Office of Science and Technology Policy, the Tennessee Valley Authority, and the Western Area Power Administration. At the state level, the National Governors Association and California Energy Commission participated. Government organizations from the European Union and Asia also have been involved. And from the private sector, participants included ABB, CESI, IBM, Intel, Pirelli, Powertech, and Raytheon, among others.

## 1.4 CIN/SI Objectives

The CIN/SI was launched to enable large-scale, interconnected national infrastructures to self-stabilize, self-optimize, and self-heal. In particular, CIN/SI work aimed to develop:

- Methodologies for robust distributed control of heterogeneous, dynamic, widely dispersed, yet interconnected systems
- Techniques for exploring interactive networked systems at the micro- and macro-levels
- Tools to prevent and/or ameliorate cascading effects through and among networks

Many of these new capabilities will need to be developed during the next decade to effectively model, analyze, and operate geographically dispersed networks and systems by operationally interconnected industries, including energy, telecommunications, transportation and distribution, and banking and finance. These capabilities are also required by the military if they are to defend such widely dispersed and interlinked infrastructure systems from attack.

In order to progress towards these capabilities, CIN/SI technical objectives were defined in three broad areas:

Modeling: Understand 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 visualizing 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.

# 2
# CONTEXT FOR CIN/SI

The CIN/SI program was implemented to advance the fundamental understanding of complex interconnected systems in order to improve the nation's ability to ensure the adequacy and security of critical infrastructure systems. This chapter discusses some of the challenges associated with modern infrastructures (with a focus on electric power systems), characterizes infrastructure vulnerabilities and the blackout that directly motivated CIN/SI activities, and introduces complex adaptive systems and other promising new sciences that CIN/SI consortia drew upon in their research.

## 2.1 The Difficult Challenge of Modern Infrastructure

Modern society faces a difficult challenge in designing, operating, and protecting complex interactive infrastructure systems. The challenge must be addressed, for infrastructures such as power, telecommunications, banking and finance, and transportation and distribution grow ever more commonplace and ever more central to modern lifestyles. At the same time, these systems also are becoming more and more congested due to dramatic population growth, particularly in urban centers. Heavy urban growth is taking place both all around the world—more than 30 New York-size megacities (more than 10 million inhabitants) are projected by the EPRI *Electricity Technology Roadmap* to develop by 2020—and within the United States.

Urban growth puts new pressure on local energy systems and other infrastructures. In the United States, for example, during 1988-1998 total electricity demand grew by 30 percent but transmission networks grew by only 15 percent. Electricity demand overall will increase by 50 percent by 2014 if growth continues at around 3 percent, as it did during the 1990s, and in urban areas this increase will be reached before 2008. As a result capacity margins, both for generation and transmission, are shrinking. Other changes add to the pressure on the national power infrastructure as well. Increasing inter-regional bulk power transactions strain grid capacity. New environmental considerations, energy conservation efforts, and cost competition require greater efficiency throughout the grid.

Growth, environmental issues, and other factors contribute to the difficult challenge of ensuring infrastructure adequacy and security. Not only are infrastructures becoming more complexly interwoven and more difficult to comprehend and control, there is less investment available to support their development. Investment is down in many industries. For the power industry, direct infrastructure investment has declined in an environment of regulatory uncertainty due to deregulation, and infrastructure R&D funding has declined in an environment of increased competition because of restructuring. Electricity investment was not large to begin with. Presently the power industry spends a smaller proportion of annual sales on R&D than do the dog food, leather, insurance, or many other industries—less than 0.3 percent, or about $600 million per year. Only railroads of major industries spend less. Electricity R&D, if in proportion to its direct economic value, should be about $5 billion annually, and venture capital investment has not been making up the difference.

At the core of the power infrastructure investment problem lie two paradoxes of restructuring, one technical and one economic. Technically, the fact that electricity supply and demand must be in instantaneous balance at all times must be resolved with the fact that new power infrastructure is extraordinarily complex, time-consuming, and expensive to construct. Economically, the theory of deregulation to achieve the lowest price must be resolved with the market reality of deregulation to achieve the highest profit. Both the technical and economic paradoxes could be resolved by knowledge and technology.

Similarly, revolutionary developments in both information technology and material science and engineering promise significant improvement in the security, reliability, efficiency, and cost-effectiveness of all critical infrastructures. Steps taken now can ensure that critical infrastructures continue to support population growth and economic growth without environmental harm.

To spur planning for these advances, EPRI's *Electricity Technology Roadmap* provides a vision of future technology needs for the next 25 years and identifies the R&D pathways leading to these technologies. In 2002, EPRI updated the *Roadmap* effort by identifying 15 "Difficult Challenges" that hinder progress towards future technologies in key areas. The Difficult Challenges focus on five areas: 1) power system reliability, 2) revolution in services, 3) economic growth and productivity, 4) electricity supply, and 5) environmental protection. CIN/SI activities directly address these challenges and contribute to the development of advanced infrastructure systems.

## 2.2 Critical Infrastructures and their Vulnerabilities

As a result of demand growth, regulatory uncertainty, and the increasing connectedness of critical infrastructures, it is quite possible that in the near future the ability, for example, of the electricity grid to deliver the power that customers require in real-time, on demand, within acceptable voltage and frequency limits, and in a reliable and economic manner may become severely tried. Other infrastructures similarly may be tested.

Complex interactive infrastructures of all types are vulnerable to both deliberate and accidental disturbances. They are extremely difficult to operate and defend in modern societies because they reach everywhere and everyone: there are many millions of miles of power lines in the United States, for example, and millions of transformers large and small. In addition, the characteristic interconnectedness of major infrastructures means that single, isolated disturbances can cascade through and among networks with potentially disastrous consequences. Large-scale failures can occur in areas geographically remote from the original problem, or in seemingly unrelated businesses.

Because infrastructure networks support critical services and supply critical goods, disturbances can have serious economic, health, and security impacts. Electric power outages and power quality problems, for instance, presently cost the U.S. economy some $120 billion annually, according to a recent study by EPRI. Tens of billions of dollars more are spent each year to repair the damage caused by major computer viruses and other cyber attacks, the documented number alone of which have climbed from about 2000 in 1997 to more than 50,000 in 2001.

Concern about infrastructure disturbances is not new: a major East Coast blackout in 1965 triggered creation of the grid management scheme in use until the past few years. More recently, in 1997, four years before the terrorist attacks on the World Trade Center and the Pentagon, the U.S. Commission on Critical Infrastructure Protection examined the state of U.S. infrastructures, including the electric power grid, telecommunications networks, transportation and distribution networks, and banking and finance systems. The Commission concluded that: 1) the threat to these infrastructures was increasing, 2) deregulation and "Information Age" change afforded timely opportunities to develop new protection capabilities for these infrastructures, and 3) development should be cooperative among government, infrastructure owners/operators, and the nation's research community. Events since only underscore the importance of critical infrastructures, and have brought about a heightened concern for their robustness and security.

At the same time, deregulation and restructuring have added concern about the electric power infrastructure (and other industries as well). This shift marked a fundamental change from an industry that was historically operated in a very conservative and largely centralized way as a regulated monopoly, to an industry operated in a decentralized way by economic incentives and market forces. The shift impacts every aspect of electrical power including its price, availability, and quality. For example, as a result of deregulation, the number of interacting entities on the electric grid (and hence its complexity) has been dramatically increasing while, at the same time, a trend towards reduced capacity margins has appeared. Yet when deregulation was initiated, little was known about its large-scale, long-term impacts on the electricity infrastructure, and no mathematical tools were available to explore possible changes and their ramifications.

It was in this environment of concern that the CIN/SI program was conceived. One event in particular precipitated the creation of CIN/SI: a power outage that cascaded across the western United States and Canada on August 10, 1996. This outage began with two relatively minor transmission-line faults in Oregon. But ripple effects from these faults tripped generators at McNary dam, producing a 500 MW-wave of oscillations on the transmission grid that caused separation of the primary West Coast transmission circuit, the Pacific Intertie, at the California-Oregon border. The result: blackouts in 13 states and provinces costing some $1.5 billion in damages and lost productivity. Subsequent analysis suggests that shedding (dropping) some 0.4% of the total load on the grid for just 30 minutes would have prevented the cascading effects and prevented large-scale regional outages (note that load shedding is not typically a first option for power grid operators faced with problems). In response to this situation, the CIN/SI research program aimed at developing revolutionary new understanding and tools that could protect complex infrastructures from cascade failures and other catastrophic events.

Since the conception of the CIN/SI program, several major failures have impacted critical infrastructures within the United States. Examples include:

- In 1996-97, scheduling and operational difficulties associated with the mergers of major railway companies disrupted deliveries throughout the western United States, leading to billions of dollars in expenses and lost revenue as well as significant delays in redeployment of certain U.S. military assets.

- In January 1998, an ice storm downed transmission lines and cut power to over 3 million people in the northeastern United States and Canada, some for weeks.
- In May 1998, problems with a key communications satellite caused 40 million pagers to fail, shut down National Public Radio, and delayed airline flights nationwide, among other disturbances.
- In summer 1998, huge price spikes due to high temperatures, strong demand, and insufficient transmission capacity increased the cost of power 100-to-200 times.
- In winter 2000-01, high prices and limited supply for natural gas combined with insufficient transmission and dysfunctional markets in California to create 100-to-500-fold price spikes, blackouts, utility bankruptcies, and major economic losses to industries as diverse as aluminum production, cut flowers, and food processing throughout the western United States.

Clearly the time had come for a program such as the CIN/SI.

## 2.3 New Science for Complex Interactive Networks

The majority of the critical infrastructures so important to modern lives (finance, banking, water, electricity, communication, oil and gas, etc.) are very large networks of interacting and interdependent entities. Analysis and design of such systems is extremely difficult. The dynamics that emerge out of the interactions and interdependencies within a complex system cannot generally be anticipated or predicted from the individual behaviors of the component entities: the behavior of the whole is much more than the sum of its parts. As a result the number of possible designs is combinatorially large, the structure of the search space for analysis is generally not well understood, and evaluating the performance of individual designs is often computationally expensive (e.g., it requires numerous and long simulation experiments).

Of course insight is possible, such as the after-the-fact review of the 1996 western grid outages discussed above. Likewise, analysis conducted in late 2001 that examined power grid behavior integrated with power market economics revealed clear deficiencies in the California deregulation scheme implemented in 1996, and connected these deficiencies to the crisis experienced by that market in winter 2000-01.

The challenge for CIN/SI researchers has been to develop capabilities for understanding the true dynamics of a complex interactive system and predict *a priori*, as opposed to afterwards, what kinds of problems may arise from specific types of failures. Related is the challenge of mitigating and localizing the effects of individual failures *in situ.* Overcoming these challenges would give critical infrastructures that abilities to self-diagnose, self-heal, and self-organize at the local level, and thereby mitigate the effects of potential catastrophic disturbances. Several new and emerging sciences promised CIN/SI researchers means to do so.

### 2.3.1 Complex Adaptive Systems

One new science that holds promise for addressing the design, control, and protection of complex infrastructure systems is Complex Adaptive Systems (CAS). When the CIN/SI was planned, CAS was beginning to produce an understanding of the complex overall behavior of natural and human systems. Applications included “artificial life;” decision-making in batch manufacturing, transportation, and logistics; and simulations for condensed matter physics.

The overall behavior of CAS, such as interlinked national infrastructures, emerges through the independent behavior of multiple simple, but adaptive and interacting, components—a phenomenon known as self-organized complexity. The global behavior of a CAS can be influenced by the actions or experiences of individual components. CAS parallels in natural systems include behavior of social insects such as ants and bees; ecologies such as predator-prey relationships; and cellular interactions such as those exhibited by immune and nervous systems. Political movements, business enterprises, financial markets, and the economy itself can also be viewed as CAS, and they all give rise to practical problems that are often mathematically intractable.

A CAS exhibits a number of essential properties and mechanisms:

- emergence of complex, global behavior from the aggregate interactions of many individual relatively simple agents (e.g., Adam Smith’s “Invisible Hand”)
- strategic learning and adaptation (of components, groups of components, or the CAS as a whole) in response to changes in their “environment”
- nonlinearity and a potential for chaotic behavior (i.e., behavior is more than the sum of that of the parts), which make it very hard to model and forecast behavior
- feedback, both negative and positive (e.g., multiplier effect in economics, George Soros’ “theory of reflexivity”)

CAS are attractive for modeling, design, and analysis because they can produce complex emergent phenomenon out of a small set of relatively simple rules, constraints, and relationships, couched in either quantitative or qualitative terms. A CAS model is particularly appropriate for any industry made up of many, geographically dispersed components that can exhibit rapid global changes as a result of local actions. This is characteristic of the industries that make up a national or international infrastructure. The whole combined infrastructure is, itself, a CAS consisting of many individual, and often autonomous, components.

### 2.3.2 CAS and Agents

A useful approach to analyzing CAS-type infrastructures is to model their components as independent adaptive “agents” (in computer programming terms, they are “active objects” that have been defined to simulate parts of the system). The agents in a system interact with each other in their local operations while pursuing global goals set by a minimal supervisory function. This approach is applicable to more than infrastructure industries. The CAS/agent concept has potential to provide a new paradigm for the design, control, operation, and maintenance of any complex interconnected system, especially those that possess significant technological content or in which humans directly participate.

The CAS/agent approach contrasts with the prevailing “top down” paradigm for analysis and optimization of system operations (as well as for the engineering design itself) through mathematical programming. The most common approach uses differential and algebraic-differential equations, the parameters of which approximate phenomenological attributes of the aggregate population that makes up the system under consideration. Top-down modeling requires the explicit specification of all rules and relationships, qualitative or quantitative, internal and external. This enormous task is not possible in any practical case, so the models are simplified, sometimes to the point where they do not adequately reflect any actual situation. Consequently, there are no mathematical models that can create useful top-down models for systems that could be described as CAS.

Scientist working in the CAS field try to develop and test theories by working “bottom up.” They start with the known (or hypothesized) behavior of component agents, hypothesize additional simple rules or relationships, and attempt to reproduce the complex phenomena they have observed in the real world entities made up of these components (for example, flocking behavior in birds can be generated with but two basic rules: 1) stay close to the nearest bird, and 2) avoid collisions with other birds or obstacles). Real-world complexity can be modeled by letting the individual agents interact independently. These agents also can be designed to evolve to adapt to their environment and provide more effective management and control of their system.

Modeling the electric power industry in a control theory context is especially pertinent because movement toward deregulation and competition ultimately will be limited only by the physics of electricity and the topology of the grid. A CAS emulation will test whether any central authority is required or even desirable, and whether free economic cooperation and competition can, by itself, optimize the efficiency and security of network operations for the mutual benefit of all.

### *2.3.3 Statistical Physics*

A complementary approach to CAS science for understanding and managing the behavior of complex infrastructures and systems arises from the power law statistics observed for failure events in large-scale, interconnected networks.

Systems such as infrastructures are optimized, either through “natural selection” over time or through engineering design, to provide robust performance despite uncertain environments. They exhibit a hypersensitivity to certain perturbations that they were not “designed” to handle. As a result, most failure events are small but there exists a “heavy tail” of large events (i.e., more than would be expected based on a classical distribution of failures). For example, the power grid is robust even to very large variations in demand, but it has become extremely sensitive to the loss of specific combinations of power lines and/or generators, such as the August 1996 outage indicated.

It appears that power laws arise in these systems due to tradeoffs among yield, cost of resources, and tolerance to risk. These tradeoffs lead to highly optimized system designs that allow for occasional large events. As a way of providing fundamental understanding of and mathematical underpinnings for complex interactive systems, the statistical distributions for failure events can be investigated to gain insight into the phenomena of cascading disturbances for engineering systems. With this knowledge, engineers can develop a family of models for robust design and control of such systems.

# 3
# CIN/SI CONSORTIA RESULTS, 1999-2002

This chapter reviews the key results of CIN/SI work by the six research consortia. The objectives and activities of the research programs of all six consortia are summarized in brief, and then each program is discussed in some detail.

## 3.1 Overview of Funded Consortia

For the CIN/SI, six consortia (involving 107 professors and 123 graduate students at 26 U.S. universities, as well as staff at two major U.S. energy companies) were funded after a highly competitive source selection process that drew from a pool of more than 98 candidate teams. CIN/SI-funded research was conducted during 1999-2002 by five of the consortia; research by one consortium was terminated in 2001 after two years.

## 3.2 Overview of Consortia Research Results

Brief descriptions of the research for the CIN/SI consortia are given below (identified by lead university), and expanded summaries for each follow. For more detailed information, see Appendix D.8 for the final reports numbers for each consortia.

Of the six consortia, one undertook a statistical physics approach. The other five investigated CIN science, hybrid layered networks, discrete-event dynamical systems, and simulation-based modeling. A total of more than 360 publications and 19 EPRI technologies resulted from the CIN/SI, and the DOD identified several other technologies for future development. The following table (Table 3-1) depicts areas of research investigated by each consortium (lead university shown).

**Table 3-1**
**A Canvas of Research and Development for Reliable and Robust Operation Versus Solution Components**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Challenges** | **Efficient Operation** | Harvard<br>Purdue<br>U. Washington | Caltech<br>Cornell<br>Harvard<br>Purdue | Carn. Mellon<br>Harvard<br>Purdue<br>U. Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>U. Washington | Carn. Mellon<br>Harvard<br>Purdue<br>U. Washington |
| | **Security and Robustness** | Harvard<br>Purdue<br>U. Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>Purdue | Caltech<br>Carn. Mellon<br>Harvard<br>Purdue<br>Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>U. Washington | Carn. Mellon<br>Harvard<br>Purdue<br>U. Washington |
| | **Cascading Failure - single infrastructure** | Harvard<br>Purdue<br>U. Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>Purdue<br>U. Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>Purdue<br>U. Washington | Caltech<br>Carn. Mellon<br>Cornell<br>Harvard<br>U. Washington | Carn. Mellon<br>Cornell<br>Purdue<br>U. Washington |
| | **Cascading Failure - multiple infrastructures** | Harvard | Caltech<br>Cornell | Caltech<br>Cornell<br>Harvard<br>U. Washington | Cornell<br>Harvard<br>U. Washington | Cornell<br>U. Washington |
| | | **Measurement & Sensing (including visualization)** | **Modeling & Theory** | **Simulation** | **Control System Design** | **Operation & Management** |
| **Solution Components** | | | | | | |

### *3.2.1 University of Washington: Defense Against Catastrophic Failures*

The consortium developed a design and fundamental concepts for an automated system that can defending a wide-area power grid from catastrophic or cascaded disruptions (whether naturally occurring or human-caused) and heal the grid after a disruptive event.

### *3.2.2 Purdue: Intelligent Management of the Power Grid*

Consortium researchers explored implementation of a recent anticipatory control theory by multiple intelligent agents on local area grids (LAGs) within an electric power system as a whole.

### 3.2.3 Harvard: Modeling and Diagnosis Methods

This consortium investigated mathematical substitution techniques that make it less computationally difficult to model complex interactive networks and systems.

### 3.2.4 Cornell: Minimizing Failures while Maximizing Efficiency/Stochastic Analysis of Network Performance

The consortium explored new mathematical techniques for efficiently handling the layered structures and interconnecting links that are common in networks of infrastructures such as the electric power grid.

### 3.2.5 Carnegie-Mellon University: Context-Dependent Network Agents

Research by this consortium aimed to improve the decision-making capabilities of agents by making them aware of the context in which they operate, i.e., to create adaptive, context-dependent network agents (CDNA).

### 3.2.6 Caltech: Mathematical Foundations

This consortium focused research on a new approach for understanding the fundamental mathematical underpinnings governing the behavior of large-scale complex interactive networks and systems.

## 3.3 Innovative Techniques for Defense against Catastrophic Failures of Complex, Interactive Power Networks

### 3.3.1 Consortium Members

Participants: Advanced Power Technologies (APT) Consortium, including University of Washington (lead), Arizona State, Iowa State, Virginia Tech.

Investigators: U. Washington—Chen-Ching Liu (Principal Investigator), M.J. Damborg, M.L. El-Sharkawi, J.N. Hwang, M.T. Sun, S. Tanimoto; Arizona State—G. Heydt, G. Karady, R. Gorur, K. Holbert, F.C. Hoppensteadt, J. Si, D. Tylavsky; Iowa State—V. Vittal, V. Ajjarapu, M.H. Kammash, W. Kleinman, J. McCalley, G. Sheble, L. Tesfatsian, S.S. Venkata; Virginia Tech—A. Phadke, J. De La Ree, Y. Liu, L. Mili

### 3.3.2 Overview

The APT consortium developed a design and fundamental concepts for an automated system that can defending a wide-area power grid from catastrophic or cascaded disruptions (whether naturally occurring or human-caused) and heal the grid after a disruptive event. The system, called Strategic Power Infrastructure Defense (SPID), relies on multi-agent technology combined with other techniques to collect critical and extensive information in real-time, assess system vulnerability quickly, and provide intelligent wide-area protection and reconfiguration capabilities.

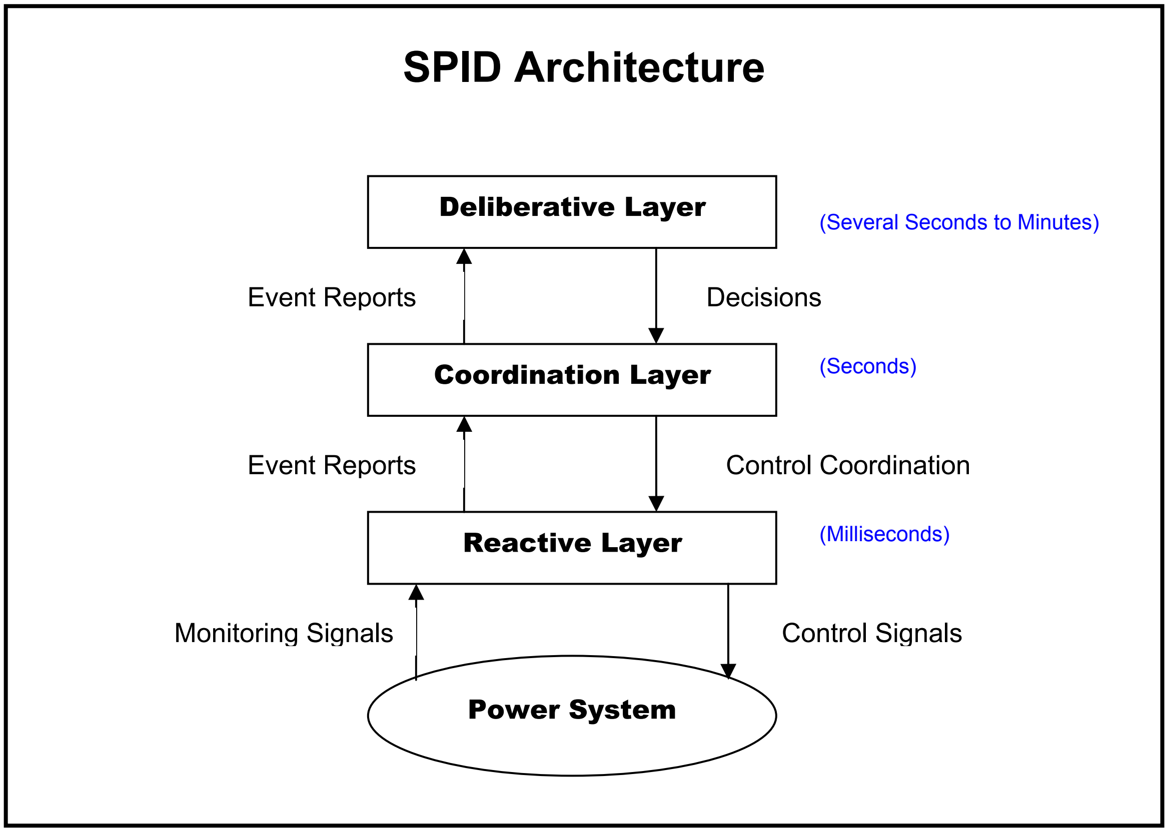



**Figure 3-1**
**Strategic Power Infrastructure Defense System**
The Strategic Power Infrastructure Defense (SPID) architecture devised by APT researchers consists of a three-layer, hierarchical control structure interacting with an electric power system. Each layer consists of numerous computerized "agents," some specialized for reacting quickly to changing conditions and others for analyzing conditions based on previous experience. These agents can communicate both horizontally and vertically, thus providing SPID with the crucial ability to make decisions about threats and responses on both local and system-wide levels.

APT's SPID concept is based on three layers of numerous intelligent, interacting agents. At bottom is a "reactive" layer of agents. These agents exist in every local subsystem (e.g., generator, switch, substation, etc.) and perform pre-programmed self-healing actions that require an immediate response. Simple versions of such agents already are embedded in many systems, such as circuit breakers, fuses, and self-diagnostics. Above this, at the top, is a "deliberative" layer of agents. These agents consider global grid-wide activities to develop long-range, large-scale plans about needs for new infrastructure additions, optimum islanding during emergencies, or direction of outside assistance. In the middle, between these two layers, is a "coordination" layer of agents. These agents constantly communicate with and review the actions of the bottom- and top-layer agents. This middle layer also would be equipped with heuristic knowledge to learn what information needs to be communicated up or down for the effective operation of the other layers.

Research activities of the APT consortium focused on the conceptual, analytical and computational techniques necessary to revolutionize the available technologies to design and develop the SPID system. Particular efforts aimed at methods for wide-area state estimation, vulnerability assessment, and islanding analysis to provide practical capabilities for self-healing and adaptive reconfiguration based on system-wide considerations. Present-day technologies allow only narrowly-focused control actions based on local measurements, e.g., at the substation or line level for a power system.

The major task areas for SPID research were: 1) wide area sensing, measurements and control, 2) adaptive self-healing techniques, 3) system vulnerability assessment tools, and 4) demonstration of prototype defense system.

### *3.3.3 Results*

APT research results under CINSI are summarized in more than 25 publications. Specific accomplishments regarding the conceptual design for a SPID system and in each of the four main task areas are as follow.

A conceptual design has been developed for the adaptive multi-agent SPID system applicable to a deregulated marketplace. The design is based on extensive study of wide-area intelligent, adaptive protection and control systems. It has the abilities to 1) identify hidden failure modes and evaluate the impact of hidden failures on the power system; 2) perform system-wide vulnerability assessment incorporating the power system, protection system, and the communication system; 3) enables the power system to take self-healing actions through islanding and reconfiguration; 4) perform power system stabilization on a wide-area basis; and 5) monitor and control the power grid with a multi-agent system designed to reduce the power system vulnerability.

Specific results in each of the four task areas are as follow.

Wide area sensing, measurements, and control. An effective SPID system will require significant advances in gathering critical data and measurements from a very wide area quickly and efficiently, in using this information to determine the status of the system (which feeds back to provide information about where and what kind of data is important to collect), and in control theory to operate the system securely.

In response, APT researchers devised an Internet-based information structure for the power system and the electricity market and developed its application to wide-area state estimation in a market environment. The effects of communication systems and time delays on data gathering and state estimation were analyzed. For system operation, an intelligent, robust control method was developed that employs wide-area measurements for stabilization of power systems. Also developed were sensors and associated analytical techniques with application of GPS synchronization, as well as agent-based computational economics models for a competitive power market.

Adaptive self-healing techniques. Various adaptive relaying techniques have been developed in the APT program. Adaptive self-healing is an essential part of any functional SPID-type system; because of the massive size of complex systems and the rapid speed with which disturbances can propagate, remedial actions will need to be taken quickly and automatically to prevent wide-area collapse in extreme cases. These actions include islanding that breaks a system into independent units, each capable of functioning on its own, and then prepares the multiple islands for recombination.

For grid self-healing, researchers devised an adaptive remedial action and islanding method with the application of multi-agent systems and temporal difference learning techniques. Results include techniques to determine generation shedding actions that help avoid instability of the system. The adaptation capability allows the system to function under a dynamic environment.

System vulnerability assessment tools. A SPID system at all times must understand the state of the system it is protecting, in particular the key vulnerabilities and threats. New methods are needed to overcome the computational complexity introduced by the massive size and interconnectedness of complex systems.

To address this challenge, APT researchers devised dynamic decision event tree techniques that enable fast system-wide vulnerability assessment. System vulnerability assessment has been defined with respect to various sources of threat. These sources include network and protection failures, communication system failures, sabotage, human errors, and other disruptive events. For use with a SPID system, the impact of these threats has been translated into their effects on a power network and its associated protection systems and communication systems. The hidden failures associated with protective relays have been thoroughly categorized. Appropriate regions of vulnerability, vulnerability indices, and system vulnerability assessment techniques have been developed, including a theory for the region of vulnerability corresponding to hidden failures. The vulnerability assessments are supported by newly developed neural networks and analytical techniques that calculate system margins to avoid vulnerable operating conditions. Additional new techniques quantify the vulnerability of the communication systems as well, and evaluate the impact of communication failures on the power grid.

Demonstration of prototype defense system. SPID relies on advances in theory and application across a variety of disciplines, including communications, control, and state estimation. And all the advances are implemented as agents in a multi-agent framework. Because so much of SPID is new and will be integrated in complex new ways, demonstration of the agents alone and in multiple agent combinations is essential to ensure effective development. Demonstrations also serve as experiments, revealing promising new approaches and concepts.

APT researchers developed a number of software agents under the framework of the multi-agent SPID system. All software algorithms have been validated using the same 179-bus system model. The multi-agent software that integrates all the SPID agents has been demonstrated with the adaptive load shedding capabilities. Proof of concept has been established for an adaptive islanding scheme that reduces the probability of cascading failures and minimizes load lost. Preliminary demonstration results suggest approaches for identifying 1) where to look for signals that indicate the onset of cascading disturbances and 2) how to control failure propagation and perform adaptive islanding.

## 3.4 Intelligent Management of the Electric Power Grid through an Innovative, Anticipatory, Multiagent, High-Performance Computing Approach

### *3.4.1 Consortium Members*

Participants: Consortium for the Intelligent Management of the Electric Power Grid (CIMEG), including Purdue (lead), University of Tennessee, Fisk University, Exelon (Commonwealth Edison Co.), Tennessee Valley Authority.

Investigators: Purdue—Lefteri H. Tsoukalas (Principal Investigator), A. L. Bement, A.K. Elmagarmid, T.J. Downar, E.N. Houstis, O. Uluyol; Tennessee—R. Uhrig, A. Gribok, J. Lawlor; Fisk—H.J. Caulfield; TVA—D.T. Bradshaw, R.L. Taylor, K.W. Morris; ComEd (Exelon)—D.C. Schooley, J.P. Crane

### *3.4.2 Overview*

CIMEG researchers explored implementation of a recent anticipatory control theory by multiple intelligent agents on local area grids (LAGs) within an electric power system as a whole. Each LAG, which is a kind of pre-defined island, contains a sufficiently balance of commercial, industrial, and residential loads as well as some standby generating capacity. Within each LAG, adaptive agents dedicated to individual loads and generators predict future local demand and inform a LAG control agency about anticipated conditions in time to do something about potential disturbances.

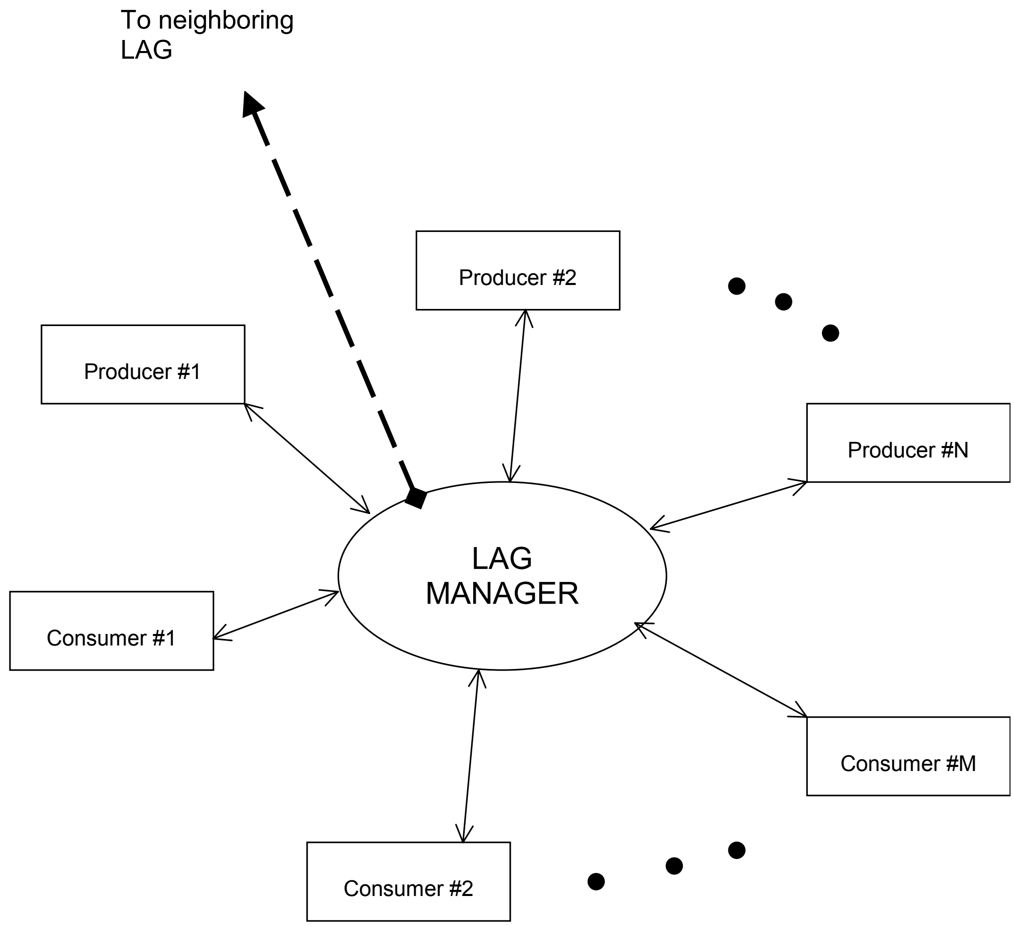



**Figure 3-2**
**Local Area Grid**
Local Area Grid (LAG) diagram shows how CIMEG researchers cluster an electric power grid into small islands each containing a balance of power generation (producers) and load (consumers). Adaptive agents manage each LAG and coordinate its actions with neighboring LAGs based on anticipation of near-term supply and demand.

The focus of CIMEG work under CIN/SI is a simple but potentially powerful idea: *to protect itself from upset events, the power grid, as a complex system, should act proactively, that is, effect local control in anticipation (not just in response) of possible contingencies.* The thesis that anticipation of the future is an integral part of control strategies originated in the field of mathematical biology and ethology by R. Rosen (see *Anticipatory Systems Philosophical, Mathematical & Methodological Foundations*, Pergamon Press, 1985) as a way of explaining how organisms cope with complexity. To apply such an approach for improving security to power systems the consortium investigated a validated anticipatory approach for intelligent management of the power grid. The CIMEG concept calls for the grid to protect itself from local faults (that may be likely to cascade to future global failures) through the use of decentralized anticipatory control strategies implemented by multiple agents in local, small-area grids called LAGs.

Inherent to this approach is a customer-driven model of the deregulated electric power system for security and self-healing purposes. The entire national grid can be thought of as a set of LAGs, each with some autonomy and good neighborly relations that allow for the emergence of a stable and self-regulated whole. Within a LAG, demand would be continuously forecasted and "what if"-type questions pertaining to reliability resolved in a proactive manner by an adaptive agent-based system that CIMEG terms TELOS (Transmission/Distribution Entities with On-Line Self-Healing). TELOS aims to avert power failures by anticipating the changing demands of electricity consumers and automatically adapting to daily fluctuations in electricity consumption. It is expected to function autonomously as well as help making decisions concerning the reliability and efficiency of LAGs. Key requirements for TELOS are 1) accurate prediction of local demand (at appropriate levels of granularity, which may eventually include all power customers) and 2) anticipatory strategies for either dispatching small generating units or (as last resort) demand side management.

Advancing an anticipatory formalism for complex engineering systems such as the power grid presents unique and challenging opportunities for research at the frontiers of modeling, measurement, forecasting, computing, and control. Highly reliable predictive neural networks for short and long-term forecasting; multi-agent modeling of loads, transmission entities, generators and corporate entities; and high-performance computing for simulation, visualization, and online stability analyses are crucial tools that need to be judiciously selected to achieve effective and efficient anticipatory control.

Specific CIMEG task areas include 1) demand forecasting, 2) development of TELOS, 3) anticipatory control theory, 4) modeling and simulation of complex systems, and 5) machine learning and genetic algorithms.

### *3.4.3 Results*

CIMEG research results under CINSI are summarized in more than 20 publications. Specific accomplishments in each of the five main task areas are as follow.

<u>Demand Forecasting.</u> A new neuro-fuzzy methodology has been advanced combining neural network predictors with fuzzy logic-based trend identification. This methodology uses the PROTREN algorithm. It shows great promise in bringing the prediction error on demand forecasting at the customer level to an acceptable range. Predicting electricity demand during "steady-state" or equilibrium-type conditions is adequately addressed by existing statistical and neural approaches, but when customers deviate from steady-state patterns of consumption, the prediction error associated with these approaches becomes intolerably high, in excess of 100% for special events such as baseball world series or unexpected storms. CIMEG's neuro-fuzzy prediction methodology reduces these errors substantially.

Researchers also developed a new neural-wavelet approach for short (minutes)-to-mid (days)-term forecasting that exploits the power of wavelets.

<u>TELOS.</u> A TELOS prototype has been implemented in an agent framework called "Grasshopper" (selected after on evaluation of several popular agent environments), and an alpha

version was demonstrated in off-line simulations. New architecture, as well as a variety of agents and agencies, were developed for this implementation. In addition, a modified optimum power flow procedure was devised for use in the anticipatory agent framework of TELOS, and a metric for power flow stability was defined that includes both cost of operation and voltage stability. Extensive software engineering work ensures that the TELOS structure is modular, highly reliable, and gives high computing-performance. A complete list of TELOS source code is available.

Anticipatory Control Theory. CIMEG has advanced basic anticipatory control theory significantly in several areas. As an example, an anticipatory dispatch and regulation scheme was developed for a small pulverized coal-fired unit. The approach ties the power of neural networks in predicting demand to the scheduling and optimal control of the small generation unit. Study demonstrated that the anticipatory approach results in much reduced control effort which may imply achieving greater reliability and savings due to reduced wear and lower maintenance costs. In addition, anticipatory demand-side management and local dispatch strategies that TELOS agents would employ have been validated on data from the Exelon and TVA power systems.

Modeling and Simulation of Complex Systems. CIMEG research addressed a variety of approaches for modeling and simulation of complex systems. Researchers developed quantitative criteria for defining LAGs, and key findings were made in the area of model selection with particular emphasis on new theoretical work using Rissanen's minimum description length principle and stochastic complexity. A new inferential measurement approach was developed that addresses many challenges of complex environments. For example, it enables physically non-measurable variables to be reliably estimated from measurable ones as well as the selection of variables on the basis of complexity-penalizing considerations.

The concept of Information Complexity (ICOMP) was applied to parameter selection and revealed that use of the ICMOP index could lead to potentially more stable prediction models for power consumption. Researchers also explored support vector analysis of power systems. Findings suggest that the support vector machines approach may help reduce the complexity of power grids. It may also find applicability within the Local Area Grid (LAG) as well as in developing good neighborly relations between LAGs.

Machine Learning and Genetic Algorithms. Anticipatory strategies for dispatching small generating units within LAGs call for new optimal distributed generation approaches. Researchers used a combination of machine learning and genetic algorithms to develop an anticipatory approach that automatically learns the consumption patterns and tracks unexpected demand transients in a LAG. An additional genetic algorithm-based approach was developed that manages optimum power flow, generator dispatch, and the use of energy storage units. Researchers also derived a computational metaphor from cognitive models of consciousness.

## 3.5 Modeling and Diagnosis Methods for Large-Scale Complex Networks

### 3.5.1 Consortium Members

Participants: Harvard (lead); Boston University; MIT; University of Massachusetts, Amherst; Washington University, St. Louis.

Investigators: Harvard—Yu-Chi (Larry) Ho (Principal Investigator), D. Pepyne; BU—C.G. Cassandras; MIT—M. Ilic; UMASS-Amherst—T. Djaferis, W.B. Gong; Washington University-St. Louis—L. Dai, M.V. Hegde, P.S. Min, J. Zaborsky

### 3.5.2 Overview

This consortium investigated mathematical substitution techniques that make it less computationally difficult to model complex interactive networks and systems. In general the techniques simplify computations for complex systems by substituting, where appropriate, qualitative correctness for quantitative correctness. In many important cases such simplification can overcome combinatorial constraints that limit the size of systems that can be studied or the depth of detail to which they may be studied.

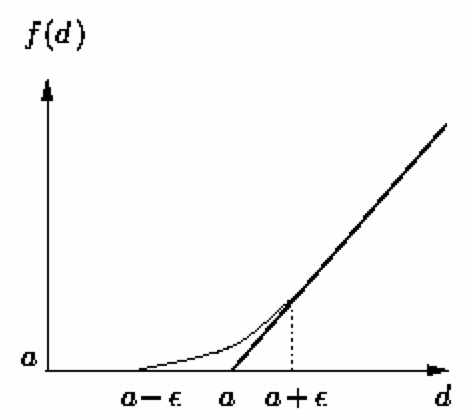



**Figure 3-3**
**Bezier Approximation to the "Max" Function**
Bezier approximation to the “max” function shows how a simple, solvable function (appropriately chosen) can be substituted for a complicated function to yield qualitatively correct solutions. A similar but much more involved substitution approach is at the heart of the Harvard consortium research aimed at reducing the difficulty of modeling and design for complex interactive systems.

The guiding philosophy of the research is the observation that for analysis and design of complex interactive systems, generally it is necessary only to compare competing alternatives rather than to fully characterize the behavior of the system. This means that a model only needs to give the correct performance order (with high probability); there is no need for a model to give the correct performance value. Such models do not need to mimic exactly the real system. They need only to simulate the dominant factors that determine the behavior of interest and not the lesser factors. Because less simulation is needed, the computational burden can be reduced—by orders of magnitude in many cases—even as the range of coverage or degree of understanding is increased.

The techniques explored in this research simplify computations through a combination of brute-force numerical simulation and elegant analytical tools. Two main approaches are used: ordinal optimization and perturbation analysis. Ordinal optimization is a methodology for obtaining quantifiable information about where to find good solutions to large complex design problems in which the range of candidate solutions is poorly understood and the performance of each individual design is difficult to analyze. Most complex interactive systems fall into this category. The concept is to relax solution criteria appropriately in order to obtain a simpler problem to solve that still gives useful information about the original problem. The second approach, perturbation analysis, is a way to extract sensitivity information about system parameters from sample behavior generated either by simulation or by an actual system in operation. The sensitivity information—which factors dominate and where—can be used to reduce the complexity of system analysis and optimization. Together, ordinal optimization and perturbation analysis in combination make it simpler to identify good solution candidates and to compute them.

Particular application of these simulation simplification techniques was made to electric power systems, power markets, and high-speed data networks. Specific efforts addressed four broad tasks: (1) simulation modeling, (2) efficient analysis methods for cascading phenomena and other abnormal behavior, (3) control, management, and optimization, and (4) mining data for early prediction and detection of abnormal behaviors.

### *3.5.3 Results*

Research results are summarized in 87 publications, including books, scientific journal articles, conference papers, presentations, and dissertations. Major accomplishments in each of the four task areas are as follow:

<u>Simulation modeling.</u> In the area of simulation modeling, the consortium developed an efficient new framework for modeling large-scale, high-speed communication networks. The framework is based on the idea that traffic flow in high-speed networks can be well approximated by stochastic fluid flow models. Packet rates in high-speed networks, particularly the backbones and optical portions, are so high that a fluid model is a very reasonable approximation. Fluid models can provide massive speedup in simulation time because they eliminate the need to simulate each discrete data packet, are inherently amenable to parallel computing implementations, and are generally more analytically tractable than counterpart discrete event dynamic system (DEDS) models. To capture the flow control protocols for data networks in the fluid flow models, the consortium developed a novel stochastic differential equation formulation and time-stepped fluid simulation approach. Also identified were new insights into perturbation analysis for DEDS and fluid models, yielding a powerful means for solving network control and optimization problems.

In addition, a new modeling method was developed to deal with combinatorially complex stochastic optimization problems based on the use of easier to solve "surrogate" problems. This strategy decomposes a complex system into a hierarchy of simpler modules, each with different simulation detail. The outputs of one module become inputs to another module. In a hierarchical setting, low-level detailed simulation modules (e.g., power flows over an electric power grid) generate output data that is then taken as input to a high-level less-detailed simulation module (e.g., transactions in a power market). The essence of the approach is to transform a computationally burdensome integer programming problem into a simpler "surrogate" continuous optimization problem and proceed to solve the latter using standard gradient-based approaches while simultaneously updating both actual and surrogate system states. Researchers developed a clustering approach to preserve stochastic fidelity in such hierarchically structured simulations, and demonstrated the methodology on complex multi-commodity resource allocation problems in manufacturing, communication networks, and mission planning.

<u>Analysis methods for abnormal behavior.</u> Researchers devised a computationally efficient framework, called Interacting Markov Chain (IMC) model, for studying cascading and propagating phenomena in complex large-scale networks. An IMC model consists of a network of interacting and interdependent Markov chains (groups of random variables in which, given the present, the future value is conditionally independent of the past). In the context of electrical power grids the Markov chains may represent generators, buses, and transmission lines. For studies of worms and viruses in the Internet, the Markov chains represent web servers or e-mail clients. In an IMC, the chains interact to capture the interactions and interdependencies between network elements (i.e., the state transition probabilities of each Markov chain is functionally dependent on the states of its neighbors, where a wide variety of dependencies are possible). IMC models are advantageous because they are generally easy to simulate.

The IMC model approach was demonstrated on power systems and Internet simulations. For power grids, it was used to link cascading collapse with system topology, going so far as to identify "weak links" in the North American power grid. Additional studies suggested how IMC models could be used to identify critical power system components to which maintenance and advanced protection strategies could be applied to reduce collapse probability. Similarly, the propagation of malicious software in the Internet (e.g., worms, email viruses, etc.) was modeled to suggest means to combine IMC models with performance models to detect and stop their spread. These preliminary studies suggest IMC can be a powerful tool for understanding cascading phenomena and other critical infrastructure protection issues.

<u>Control, management, and optimization.</u> Consortium researchers extended fundamental theory for the design and optimization of large-scale complex systems. This effort resulted in a framework and strategies for the optimal allocation of computational resources in stochastic optimization problem settings while extending the theory of ordinal optimization. The work also revealed a new, concise, and intuitive explanation of the "No Free Lunch Theorem" of optimization and its implications. The "No Free Lunch Theorem" is an impossibility theorem stating that there does not exist a universal decision-making strategy that outperforms all others on all decision problems, i.e., that the same strategy cannot simply be applied to every design problem with good performance on every problem. Rather, the best strategies are those that exploit the explicit structural properties of the particular design problem at hand. Identifying the relevant structural properties and designing design strategies "matched" to those properties is the essence of systems engineering.

Researchers also developed new control design theory for electric power systems and hybrid time-driven/event-driven systems. This theory led to two new techniques for robust control design. One has application to the design of coordinated Power System Stabilizers (PSS) for generator synchronization in large electrical power grids. Another yielded optimal control algorithms for a class of hybrid dynamical systems, which have applications as diverse as manufacturing systems to power control in wireless communication devices. Researchers proposed and analyzed implementable architectures and protocols for routing, switching, and signaling in wired and wireless data networks, and they developed practical algorithms for obtaining the optimal control policy.

The consortium also explored optimization issues related to power system deregulation, formulating a novel bidding strategy based on Ordinal Optimization techniques for power suppliers. In order to improve bidding and reduce risk, neural networks were applied to the problem of forecasting Market Clearing Prices. Researchers additionally conducted analysis based on game theory to explain price spikes and withholding incentives in the now defunct California power market, and they designed and analyzed dynamic strategies for managing transmission resources under an open-access deregulated environment.

Data mining for early prediction of abnormal behaviors. Ordinal optimization theory was extended to address data mining in complex interactive systems. The objective is to identify which out of multitudinous parameters to monitor in order to predict or quickly detect imminent cascade collapse or other abnormal behaviors in time to stop their spread. In order to do so, important aspects of a system must be modeled in very near real time, which can only be accomplished through massive simplification. Ordinal optimization and other techniques were developed and demonstrated that can simplify a problem and its solution appropriately, and parameter robustness tools were devised for data mining application to interconnected power systems.

## 3.6 Minimizing Failures While Maintaining Efficiency of Complex Interactive Network Systems

### *3.6.1 Consortium Members*

Participants: Power Systems Engineering Research Center (PSERC), including Cornell (lead); University of Illinois; University of California, Berkeley; George Washington University; Washington State University; University of Wisconsin Madison.

Investigators: Cornell—Robert Thomas (Principal Investigator), K.P. Birman, H-D. Chiang, J. Guckenheimer, A. Nerode, F. B. Schneider, S. Strogatz, J.S. Thorp; George Washington—N.D. Singpurwalla, H.G. Abeledo, J. Chandra, A. Eskandarian, T.A. Mazzuchi, R.M. Soland, R. Soyer, D. Ullman, J. Sethuraman (consultant from Florida State University); UC-Berkeley—P. Varaiya, V. Anantharam, S. Oren, S. Sastry; Illinois—P. Sauer, T.M. Basar, J. Bentsman, G. Gross, I. Hiskens, P.R. Kumar, S.P. Meyn, T.J. Overbye, M.A. Pai, A. Vakakis; Washington State—A. Bose, A. Saberi, K. Tomsovic, M. Venkatasubramanian; Wisconsin—R. Agrawal, F. Alvarado, J. Bucklew, C. DeMarco, R. Lasseter.

### 3.6.2 Overview

The PSERC consortium explored new mathematical techniques for efficiently handling the layered structures and interconnecting links that are common in networks of infrastructures such as the electric power grid. The links-and-layers structure of these complex interactive networks creates much of the computational difficultly encountered in attempting to model and analyze them.

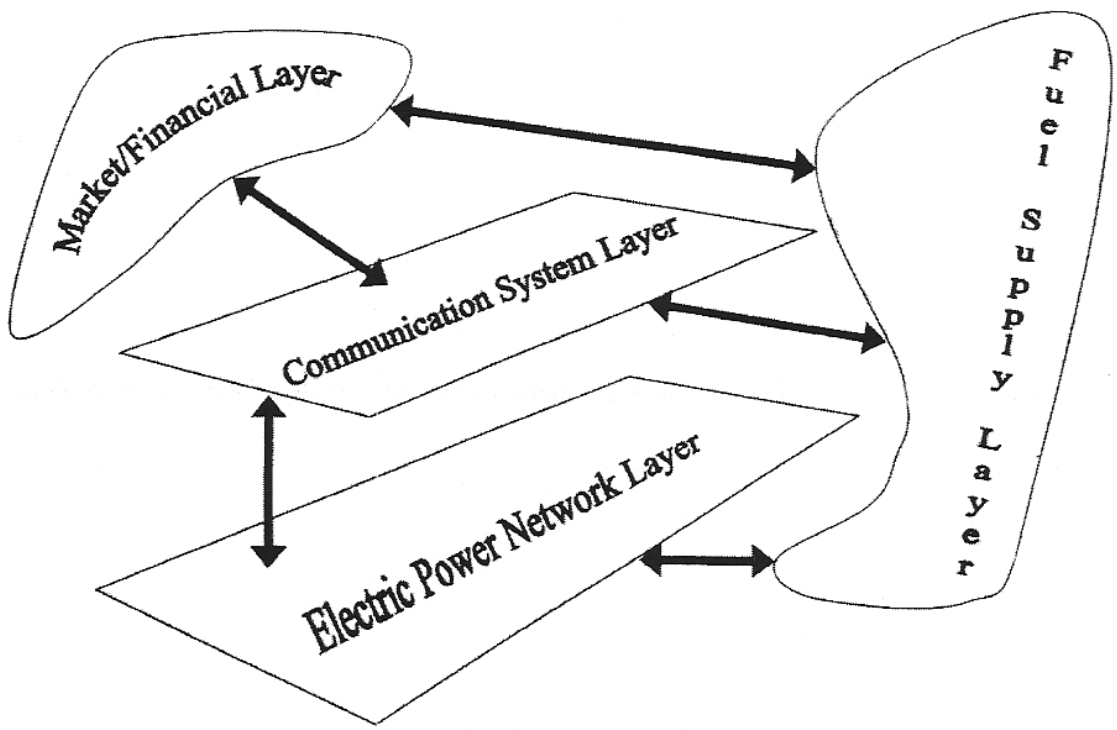



**Figure 3-4**
**Links and Layers in the Electric Power Grid**
The electric power system illustrates the interactive links-and-layers structure common in infrastructure networks, and that contributes to their complex behavior. PSERC research focused on developing software "glue" to handle the computational challenge of real-time control for these linked and layered systems.

The philosophy of PSERC research is that software is the "glue" holding the layers of a complex infrastructure network together. The research goal was to develop a software infrastructure for vigorous network-centric systems, with an emphasis on identifying computer and communication network structures that can provide real-time simulation, control, and decision-making in layered networks. Such tools can help maintain network efficiency while reducing the likelihood of catastrophic failures.

In particular, PSERC work focused on developing link-based mathematical models for the electric power grid and other leading examples of layered infrastructure networks, on characterizing behavior and failure mechanisms for such networks and systems, and on quantifying the impact of uncertainty on analysis. Research aimed at understanding fundamental issues of modeling and analysis in each layer of the power grid and identifying key interface features in the grid's layers. Novel models and approaches were explored for understanding interacting networks as precursor work leading to predictive tools and engineering processes that enable system design for robust and survivable performance.

Specific activities were undertaken in three general task areas: 1) provide a rigorous framework and comprehensive theory for layered networks; 2) develop understanding and models of mechanisms for disturbance propagation and failure in networked infrastructure systems; and 3) devise protective strategy algorithms, engineering procedures, and initial software for increasing the resiliency of such systems.

### 3.6.3 Results

PSERC research under CIN/SI was terminated after the second year of a planned three-year program. Results of study are summarized in more than 80 publications from the first two years of work. Major accomplishments in the three task areas are as follow.

Theory of networked systems. Researchers worked to develop general theories of description, analysis, and control for complex networks in a variety of contexts, such as data networks, wireless communications, and electric power systems. Specific areas of study included hierarchical description of layered networks, characterization of interactions among various layers, and modeling and analysis for inherently hybrid structures.

In particular, theory for layered networks was extended with new link-based models that use a hybrid combination of "top-down" command-and-control and "bottom-up" agent-type approaches. Application of theory to the problem of power system frequency control demonstrated that a hybrid system can be represented by a model consisting of a coupled set of differential, switched algebraic and state-reset (DSAR) equations. Work also was started on abstract models for communications and computer network model compatible with adjacent power system layers and their associated link-based models.

Initial implementation began of MATLAB-based computational tools for the analysis of complex hybrid dynamical systems having a hierarchical structure. A particular focus was on tools to understand stability of an entire system in terms of properties of subsystems. Work centered on developing a computational framework for such a "system-of-systems" approach, which requires a framework supporting components that interact both horizontally (within a layer or hierarchical level) and vertically (between layers or levels).

In the area of computation efficiency, researchers showed for the first time that optimal solutions to control problems for complex hybrid networks can accurately be approximated through the solution of a naïve (simpler-to-solve) fluid model control problem. Such general solutions solve optimal power allocation problem in a power grid, computer scheduling problems, and scheduling and routing in flexible manufacturing systems. Researchers also developed a constructive homotopy-based methodology for reliably finding all or multiple DC operating points of nonlinear circuits and systems and developed theoretical basis for it.

Finally, considerable progress was made on various other fundamental issues for control of complex layered systems including maximizing capacity in data networks and power systems; formulation of decentralized policies for efficient flow control and routing in wireless communication networks that account for uncertainty while minimizing data-sharing; and effective resource-allocation mechanisms for both short- (for agents operating in distributed systems) and long-term (construction of freeways and power system infrastructure) settings.

Models and mechanisms of failure in networked systems. PSERC research efforts in this task area focused on identification, characterization, and quantification of failure mechanisms in complex interactive dynamical systems. The emphasis of study was on fault mitigation, localization, and fundamental understanding of notions of interdependence, coupling, and cascading effects in such systems. Specifically, PSERC stochastic analysis of networked systems aimed at the development of predictive models and control strategies for mitigation or elimination of failures. Progress in this area facilitates design of robust, adaptive, or self-healing network system architectures. Special attention was paid to trade-off between robustness and efficiency, as well as stability analysis of interconnected systems with market dynamics.

Researchers explored several mechanisms that improve detection of disturbances in complex systems. Various observer-based approaches were studied to treat the issue of delay on the measurement set, and also to examine “almost” estimation of fault conditions by relaxing detection requirements. Wavelet techniques, which identify time-varying changes in system structure through mixed time/frequency methods, were studied to provide near-real-time identification of system failure signatures.

To mitigate and localize disturbances, PSERC research showed that nonlinear coupling elements (such as flexible AC transmission elements) designed into networks can introduce passive energy “sinks” that can arrest and confine propagating oscillations introduced by fault events. Theory and designs were developed for a simple class of mechanical oscillators.

Research into procedures for optimal allocation of reliability to the components or nodes of a complex network subject to constraints (such as cost) resulted in a new design strategy that reduces the complexity of collapsing such networks without affecting their reliability. Progress was made on characterizing causal and cascading failures in interacting networks and on understanding the implications of Borel’s Paradox on reliability. Also explored was the key reliability role of warranties in market systems, in particular for commodities such as electric power.

In addition, PSERC work provided the first treatment of complex market-driven systems that incorporates the impact of communication delays in market signals on stability. Examination also was initiated of system vulnerabilities that arise from market allocation of network resources coupled with physical electromechanical response

Software infrastructure and protective strategies for resilient systems. Principle concentration in this task area was on the identification of computer and communication network structures capable of real-time simulation, control, and decision making in large interacting systems. Considerable progress was made in the area of software infrastructure using Spinglass probabilistic communications techniques (specifically Astrolabe, Agent Computing, and Gravitational Gossip) in power grid settings. Spinglass techniques are highly robust to intrusion or disruptions because they allowing fast dissemination of information to many nodes without being hindered by failure or slowdown of a small number of nodes. Progress was also made in using Spinglass and gossip-based approaches to monitor the status of the grid, to gather data at repositories for data mining that might discover intrusion, to address network management problems, or for optimization analysis.

In addition, researchers developed a new Internet/Intranet technology for reliable tracking of the state of a complex network that is robust against failures or disruptions or attack, is completely scalable to load (or size of network), and is rapidly convergent. This approach can be used where simply tracking the picture in real time is good enough, and where small differences between the results seen at different locations are not as important as maintaining the freshness and flow of data.

Researchers also developed a new heuristic search algorithm that speeds up program runtime and improves accuracy for simulations of power systems that generate blackout paths. The algorithm exploits experience with real-world events to minimize computations. It was tested on the 179-bus Western States Coordinating Council (WSCC) system and the 3000-bus New York Power Pool system.

## 3.7 Context-Dependent Network Agents (CDNA)

### *3.7.1 Consortium members*

Participants: Carnegie Mellon University (lead), RPI, Texas A&M, University of Minnesota, University of Illinois.

Investigators: Carnegie Mellon—Bruce Krogh (Principal Investigator), P. Khosla, E. Subrahmanian, S. Talukdar; RPI—J. Chow; Texas A&M—G. Huang, M. Kezunovic; Minnesota—B. Wollenberg; Illinois—L. Sha

### *3.7.2 Overview*

This consortium conducted research designed to improve the decision-making capabilities of agents by making them aware of the context in which they operate, i.e., to create context-dependent network agents (CDNA). For example, a CDNA circuit breaker, knowledgeable about the operating context of the circuit it protects, could make a globally "correct" but locally "wrong" choice of keeping the circuit operating during an overload if large-scale system needs in an emergency situation would outweigh the local damage that might result. Key challenges are 1) to design algorithms and strategies for mapping centralized off-line studies about large-scale system behavior and status (i.e., "context") into local on-line agent implementations, and 2) to devise agent collaboration techniques so that distributed computation and control by individual CDNAs lead to globally acceptable solutions.

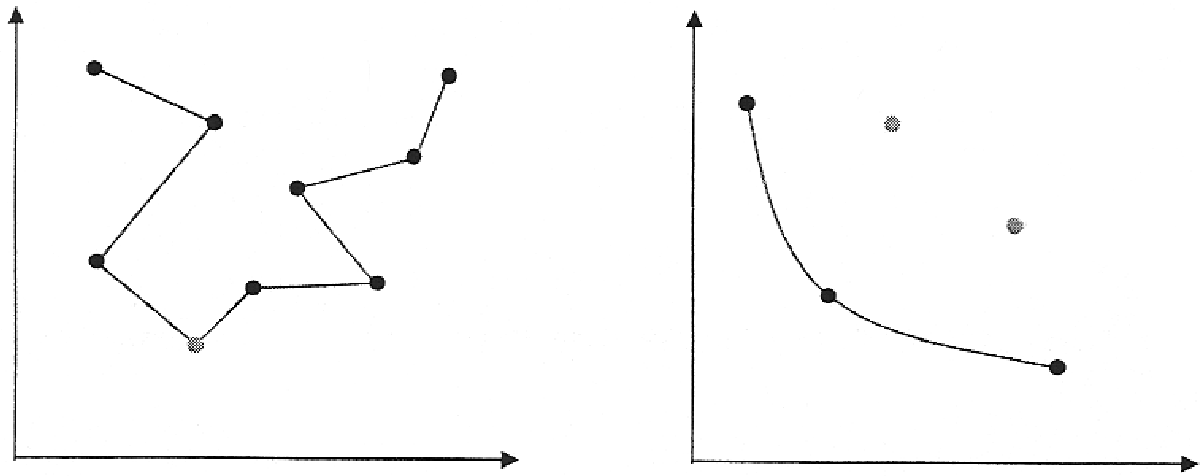


**Figure 3-5**
**Competing Agents vs. Context Dependent Network Agents**
Comparison of the behavior for a complex system as a whole when the system is governed by numerous interacting agents 1) each acting independently of each other (left) and 2) each acting in the context of the whole (right). Research by the CMU consortia aimed to develop effective real-time computation techniques for creating such “context dependent network agents.”

The CDNA project is based on the thesis that the agility and robustness of complex networks can be improved significantly by making some of the agents in the network more *context dependent*. Consortium researchers believe that current design practices in power system networks and other dynamic networks do not take full advantage of memory, computing, and communication technology that is readily available. In many cases on record for the power grid, agents have taken actions that have driven the system into undesirable operating states. The agents acted as programmed, but the pre-designed actions were not the best responses to the actual situation—the context. Typically it would have been possible for these agents to be aware of the context, and at least know that the pre-programmed action was not appropriate had that intelligence been given to the agents. Design and deployment of CDNAs only require appropriate architectures and algorithms (intelligence) for on-line operation.

CDNAs are envisioned as modular, local in influence, self-improving, multi-modal, semi-autonomous, and collaborative. To develop a general CDNA architecture, consortium researchers extended existing methods for system modeling, parameter and state identification, system monitoring, multi-mode (hybrid) control, distributed computations, real-time systems, and learning. Researchers also created a novel real-time host environment to provide realistic simulations to test and evaluate the agent methodologies as they are being developed. One key issue in this work is mapping methods typically used for off-line, centralized studies, into on-line, local implementations. New techniques for agent collaboration are being developed so that distributed computation and control lead to globally acceptable solutions.

Specific CDNA task areas are 1) CDNA cooperation and learning, 2) distributed control theory, 3) CDNA simulation tools, 4) disturbance identification and transmission control, 5) transaction-based power flow analysis, 6) voltage stability and dynamic reserve issues in a deregulated environment, and 7) context-dependent relaying.

### 3.7.3 Results

Research results under CINSI are summarized in 37 publications. Specific accomplishments in the main task areas are as follow.

CDNA Cooperation and Learning. CDNA research has resulted in a number of concepts and models for coordination of agent computations and control actions. These concepts lead to several significant conjectures providing guidelines for design procedures and algorithms, including that 1) competition is a subset of cooperation, 2) all decision-making problems can be represented such that they can tackled by networks of distributed agents, and 3) agent learning is critical in gaining market power (in existing attempts to restructure the electric grid, only large suppliers have been given the opportunity to learn).

Results of these investigations show that distributed decision-making can produce globally optimal results, even though the agents must make decisions with local (incomplete) information about the state of the system. Nevertheless, heuristics are available for agents to make decisions that are close to globally optimal decisions. This result is the first step in obtaining much more effective distributed systems than exist.

Distributed Control Theory. As a strategy to apply CDNAs to the real-time control of power grids and other complex dynamic systems, researchers developed new a decentralized model predictive control (DMPC) scheme. The goal is to create a method that has the same benefits as the conventional strategy of centralized "receding horizon" or model predictive control (MPC), in which decisions are obtained by solving a discrete-time optimal control problem over a given horizon that produces an optimal open-loop control input sequence, but also allows for distributed implementation in applications where centralized control is not desirable or possible for technical or commercial reasons (e.g., CDNA applications to complex systems). The scheme is designed to enable decentralized controllers cooperate by themselves, other than by a centralized coordinator. As an example, researchers successfully applied the DMPC scheme to multi-area load-frequency control in power systems.

CDNA Simulation Tools. In order to explore and test CDNA concepts, the consortium developed a new real-time simulation environment for CDNA studies. This power system simplex tool has been updated over the course of CINSI research. The latest version, known as eSimplex, has been streamlined for embedded systems and ported to Linux. It includes enhancements that support fault-tolerance by dynamically replacing power controllers across the network. In addition, it can dynamically shift between controller sets, each set consisting of multiple controllers. This capability is applicable to scenarios in the power simulation where the controllers being used (both the sophisticated as well as the baseline controllers) are different from those used in other scenarios. Researchers also closed security holes in the simplex tool, making it resistant to software bugs as well as intentional malicious attack.

Disturbance Identification and Transmission Control. Two main aspects of context-dependent control agents were studied. First, feature extractions were investigated for real-tie monitoring of disturbances based on data obtained from a dynamic recording device (DRD) on a power system. Results showed that types of disturbances can be identified from the frequency deviation and the rate of change of the frequency after a disturbance (in regions separated by hyperplanes). Such knowledge is useful in determining when a control action needs to be switched.

The second research activity is to find control variables and obtain insights in power transmission control using FACTS (Flexible AC Transmission System) devices. Although many different control design techniques have been proposed for FACTS devices, achieving more fundamental understanding on control effectiveness and constraints in systems with multiple swing modes is very beneficial. Such insights would aid in both in the planning of new devices as well as real-time control redesign in emergency, if necessary. In particular, sensitivity analysis based on the network admittance matrix could be use to derive modal controllability (torque), modal observability, and inner-loop gain. Consortium work provided a first step toward real-time control applications, with preliminary research results on inner-loop gain.

Transaction-based Power Flow Analysis. Researchers developed a new concept to adapt AC power flow analysis tools to deregulated electricity system where different companies may be responsible for generation, transmission, and distribution functions. Existing AC power flow analysis tools are designed based on the traditional vertical monopoly structure where one company is responsible for all the functions. These tools focus on the total power flow level over particular transmission paths of interest, without concern about which entities were responsible for which flows. This limitation can lead to unrealistic analyses when applied to deregulated grids, and a new 'colored electrons' approach was developed. It begins with a new concept of 'transaction pairs' to substitute the role of the slack bus on matching energy imbalance. Researchers extended the concept to create a new transactions-based power flow analysis (TBPF) that can fairly distribute losses induced by transactions to the selling generators. The TBPF can also decompose the branch flows into transaction components. TBPF demonstrates several advantages over the conventional power flow analysis for the unbundled transmission operating paradigm. Problems such as parallel flow evaluation, transmission congestion management, allocation of available transmission capability (ATC) and flowgates in the system can be easily resolved using TBPF.

Voltage Stability and Dynamic Reserve Issues in a Deregulated Environment. In this area, research was undertaken to clarify dynamic reactive reserve issues for voltage stability in a deregulated electricity market. Addressing resource allocation issues is important because the unbundling of generation and transmission services can reduce voltage security margins in key aspects. Several energy companies and power pools suffered from voltage instability incidences in the 1990s, and some incidents evolved into voltage collapse.

Consortium work examined critical reserve issues using exact dynamic simulations and steady state analysis. Among the areas investigated include the grid-wide effect of reactive power support by generators; impacts of ULTC, switched shunt banks, energy transactions, and load characteristics on voltage stability; and the effectiveness of the steady state analysis approaches in accurately estimating the voltage collapse point. All simulations are implemented with an advanced power system simulation tool called EUROSTAG, developed by Electricite de France, and findings were demonstrated through a small yet realistic power system.

Context-Dependent Relaying. Researchers developed new a new context-dependent strategy for system security and protective relaying in power system networks. Making protective relaying more aware of context (for better recognition of faults, disturbances, alert, and normal states) is a promising way to greatly enhance robustness and agility for the entire system.

This strategy adds system robustness through a more complex decision-making process, in which the patterns of input signals (currents and voltages samples of the three transmission line phases) are recognized as features of the events in the power network. Neural networks are used to implement a pattern recognition algorithm where the prevailing system conditions (context) are taken into account through the learning mechanism; the neural network is applied directly to the samples of voltages and currents measurements. The context classification approach must reliably conclude, in a very short time (about one cycle), whether, where, and which type of fault occurs under a variety of time-varying operating conditions. To do so, researchers aimed at enhancing the existing neural network-based clustering algorithm ('k-nearest neighbor') with a fuzzy-logic enhanced classification algorithm. The enhanced approach improves pattern classification when the neural network is exposed to test patterns. (The test patterns might be very heterogeneous and quite different from the limited number of patterns initially used to train the neural network, for there are many operating states and possible events in the power network.)

## 3.8 From Power Grids to Power Laws: A Mathematics Foundation for Complex Interactive Networks

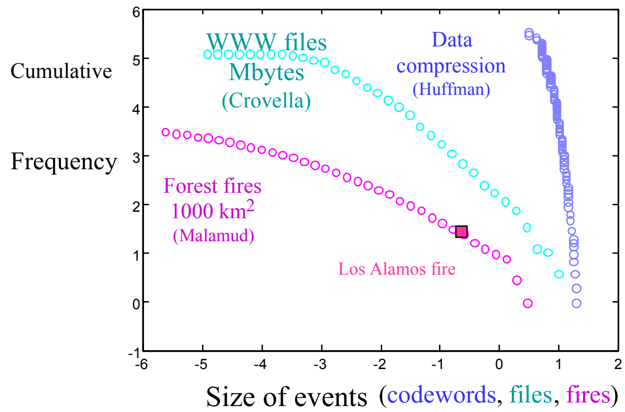
### 3.8.1 Consortium Members

Participants: Caltech (lead); Stanford; MIT; University of California, Los Angeles; University of California, Santa Barbara; University of Illinois, Urbana-Champaign.

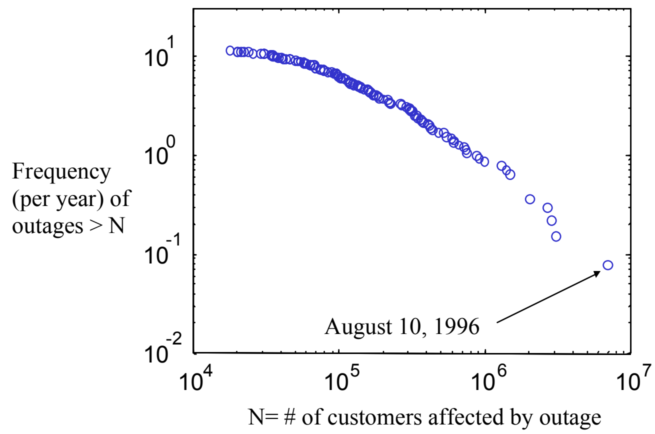
Investigators: Caltech—John Doyle (Principal Investigator), K.M. Chandy, M.C. Cross, J.E. Marsden; MIT—G.C. Verghese, B.C. Lesieutre; UCLA—F. Paganini, R. Bagrodia, M. Gerla; UCSB—J. Carlson, L. Petzold; Illinois—C. Beck; Stanford U.— S. Lall.

### 3.8.2 Overview

This consortium focused CIN/SI research on a new statistical physics-type approach for understanding the fundamental mathematical underpinnings governing the behavior of large-scale complex interactive networks and systems. The objective is to identify common features that complicated systems in engineering and biology share and which can be captured using simple models and general principles. This deeper understanding of complex systems then can be applied to control them more efficiently and strengthen them against failures.




**Decimated data**




***Data from NERC***

**US Power Outages, 1984-present**

**Figure 3-6**
**Highly Optimized Tolerance: Power Law Behavior**
Graph of failure event size vs. frequency shows "heavy tail" power-law behavior (i.e., a larger number of failures than expected from classical analysis) common in diverse complex interactive systems including electric power grids, the Internet, and forest ecosystems. Caltech consortium researchers explored how power law behavior suggests the "robust-but-fragile" nature of these systems and provides insights into their optimum design and management.

The philosophical basis for much of the research undertaken by the Caltech consortium is the mechanism of "Highly Optimized Tolerance" (HOT). HOT is a fundamental new mechanism explaining the pervasive appearance of power-law statistics in the distribution of event-size data from complex system networks, i.e., "robust-yet-fragile" failure behavior dominated by small failure events but having more-than-expected numbers ("heavy tail") of large (catastrophic) failure events. These large failure events occur because of hypersensitivities to disturbances that a given system was not designed to handle and are characteristic of complex systems throughout engineering and biology. HOT concepts directly connect system structure and robustness with power-law statistics.

The HOT approach differs from other concepts for considering complex systems such as Self-Organized Criticality (SOC) and Edge-of-Chaos (EOC) mechanisms or the percolation systems of statistical physics. For SOC and EOC systems, external forces serve only to initiate events and then, once a complex system is off and running, the mechanism that gives rise to complexity is essentially self-contained within that system. By contrast, HOT concepts take into account the fact that infrastructure designs are developed and biological systems evolve in a manner that rewards successful strategies subject to a specific form of external stimulus, i.e., that system complexity arises at least in part in response to external stimuli. And unlike percolation systems, key properties of HOT systems (including robustness to designed-for disturbances, hypersensitivity to unanticipated disturbances and design flaws, highly specialized structures, and power law behaviors), are associated with system design and evolution. As such, the HOT approach provides a fundamental new avenue for research into complex systems of all kinds.

The particular focus of research undertaken by this consortium is the mathematics fundamental to complex systems optimized to be robust despite uncertain environments. HOT characteristics arise in these systems because of trade-offs between resource yield and tolerance to cost and risk. Areas of special study were the electric power grid and the Internet, but other complex systems such as financial systems and biological ecosystems were examined as well.

The major task areas were to (1) develop new understanding of the behavior of large interactive networks based on HOT concepts and (2) apply this understanding to provide tools for efficient modeling, tractable simulation, and robust control of these networks.

### *3.8.3 Results*

At time of publication, CIN/SI research results for this consortium have been presented in some 90 scientific publications and at more than 50 invited presentations. Major accomplishments in the two main task areas are as follow.

Understand the behavior of large-scale interactive networks. An introduction was developed to HOT as a fundamental new mechanism explaining the pervasive appearance of power-law statistics for complex system networks. This mechanism then was applied to explore the behavior of complex networks including power systems, communications networks, and financial markets.

In particular, the Caltech consortium research provided insight into the statistical physics behavior of "designed systems" (i.e., systems that evolve and/or are modified over time in response to external forces, such as occurs in electric power grids, the Internet, and transportation infrastructure in response to demand growth, demographic shifts, and other factors) and the statistical theory of optimal states for such systems. Considerable effort was devoted to examination of phase transitions and critical phenomena that arise in complex distributed systems as a result of optimizing trade-offs between system efficiency and sensitivity to cascading events and failures: in most cases, the more capable and specialized a system becomes for accomplishing any given task, the more susceptible it also becomes to catastrophic upsets stemming from unplanned-for upsets that in themselves frequently appear insignificant. HOT-based trade-off analysis was extended to multiple levels of network design, such as communications networks integrated with a power system. Among other things, these investigations revealed some of the key effects played by the structure of a network or system on its overall behavior, including its robustness to cascade events.

Researchers also explored HOT in the context of coupled map models of population dynamics. Studies of fatal epidemics, biological mutation and evolution, and other systems showed that particular HOT states may emerge in order to give a system the ability to re-grow after catastrophic losses or extinctions. This theory may explain observations of repeatable patterns in the fossil record associated with extinction events triggered by rare environmental disturbances.

Building on the new understanding, researchers generalized a coding problem to explain the origin of power laws in distributed complex systems. They then applied the generalization to simplified models of web layout, Internet congestion, forest fires, ecosystems, and electric power grids to create better understanding of the behavior of these systems. This improved understanding suggests possible improvements in the design and management of designed systems that could harden them against cascade failures with minimum impact on their efficiency.

Particular effort was directed at understanding cascade failures in power systems and their mitigation. Electricity flow on power grids is unlike the flows considered in traditional systems, such as transportation or communication, because flow is driven by potential (by phase-angle differences across edges) and is capacitated (by line length and voltage level). Consortium researchers developed a new algorithm for optimum design of small power systems, and a novel eigenstructure-based partitioning approach for accurately isolating specific system dynamics within geographic areas of a grid. This latter approach was generalized to link grid structure with eigenstructure of the linearized swing equation retaining phase angles. Based on success in extending the classical results from conventional spring-mass characterizations of power networks, the generalized approach was applied to examine swing dynamics of the real-world Western States Coordinating Council (WSCC) power network.

Related explorations of swing dynamics provided a new perspective on the spatio-temporal behavior of a power grid. Researchers built on this improved understanding to develop a unique new approach for stabilizing power systems. The new approach involves controlling boundary generators to make them appear as "matched impedances" that extinguish traveling electromechanical waves in the system. They also investigated a new method for dynamically estimating the swing state of a power system based on highly non-redundant data from a limited number of sensors on the system. In the method, reliable estimates of system state are developed based on a dynamic model that relates measurements taken at any given time to those taken at other times, and relates measured variables at sensor sites to unmeasured variables throughout the system. This dynamic method improves on traditional estimation study approaches that employ quasi-static load flow models and redundant data.

Looking at other complex systems, consortium researchers conducted multi-resolutional simulations of congestion on the Internet and in parallel simulations to study its propagation. Findings suggest theoretical explanations that describe congestion propagation. Also developed were dynamic models of existing TCP protocols for avoiding communications congestion (see "tools for efficient modeling," below).

Researchers applied HOT concepts also to the modeling and analysis of financial markets, and the price dynamics within them. In particular, they examined financial markets as an interaction of heterogeneous agents. The objective is to understand risks in various hedge approaches, lack of which understanding led to the failure of portfolio insurance in the 1980s and the collapse of Long-Term Capital Management in 1998. Results point toward possible "dynamic hedging" techniques for minimizing and controlling risks in these markets. New models were developed that can capture the "heavy tail" property of price distributions and, when combined with dynamic programming, can efficiently determine optimal hedging schemes for such price dynamics. Efficient methods were also developed for characterizing risk in a dynamic hedge. Researchers also began extending this work to construct a mathematically correct and accurate theory of trading to minimize risk, using simulations of stochastic differential equations and discrete time steps.

Provide tools for efficient modeling, tractable simulation, and robust control. In the area of efficient modeling and tractable simulation for complex interactive networks, consortium members developed a variety of model reduction approaches. Robust new control approaches then were developed for complex systems in general and for specific applications in power grids and communications networks.

Substantial effort was aimed at tractable simulation of large-scale modular systems such as the power grid distributed systems. A new method, called Dynamic Iteration using Reduced-order Models (DIRM), efficiently simulates large-scale, modular systems by using reduced-order models of the various modules. For each reduced-order model, the unreduced model of the module or subsystem in question is simulated while it is connected to the reduced models for all of the other subsystems of the overall system. The resulting simulation data are then used to update the reduced model of the particular subsystem under study. Iteration of the process across all subsystems yields high-quality yet efficient modeling of the system as a whole, which was proved in complete convergence and error analysis work that compared DIRM methods with more familiar waveform relaxation techniques. Because of its nested nature DIRM is well suited for parallel computing, and researchers implemented it in a commercial parallel environment for further testing. In addition, researchers extended to differential-algebraic equations the proper orthogonal decomposition (POD) methods used throughout DIRM (application is difficult of POD to these equations, which are characteristic of power grid models), and they developed adjoint methods that provide for sensitivity analysis. A new theory and algorithm (called ADDA) was developed that can do most of the work of generating sensitivity systems for partial differential equation forms as well.

Different model reduction approaches were developed for many other classes of complex interactive systems. Linear fractional transformation representations using structured operators were explored for certain multi-dimensional systems, resulting in complete generalization of minimality, controllability, and observability notions for such systems. Model reduction results, largely based on generalized Gramians, were devised for classes of systems including nonstationary dynamical systems, structured systems, Lagrangian systems, spatially distributed systems, and nonlinear control systems.

Taking an alternative simulation approach, other Caltech consortium researchers developed idealized models that can represent some of the important interactions that occur in complex networks. The focus was a class of stochastic models for network dynamics called “linear stochastic networks.” These models capture key dynamic interactions among nodes or sites in a network, and provide a tractable framework for abstractly studying the behavior of some interesting engineered and natural networks. Researchers formulated, analyzed, and generalized an “influence model” comprising interacting node-based Markov chains, and they explored a particular version that abstractly represents failure propagation in a network to study relations among failure event sizes, repair/replace rates, and network structure. This influence model was also used to study resource allocation problems in networks. A second type of linear stochastic network model also was developed to study flows (of data, vehicles, etc) in networks. In this "flow model," probabilistic flows, rather than influences, represent the interactions among nodes.

In the area of robust control, researchers reviewed distributed control approaches for analysis and design of complex decentralized systems where spatially distributed units (agents) interact dynamically with a coupled physical medium (such as a power grid, internet web, or phone network) and coordinate their real-time actions through a communications substrate (that may have delays). Work focused on a leading challenge of distributed, decentralized control: that of understanding how to design local dynamic laws to produce a desired global behavior in the complex system as a whole. Consortia researchers devised new methods for local/global control design that are computable even for very large-scale networks. These methods are based on spatial transforms among uniform arrays of units with spatial symmetry (such as platoons of vehicles on a highway, formations of unmanned aircraft, or fluids within arrays of sensors and actuators for micro-electro-mechanical systems). Decentralized control is not imposed, but localized control solutions appear naturally in optimizing the results. Additional work extended these methods to systems that lack spatial symmetry, explored the conditions on communication parameters necessary to preserve dynamic stability and performance of the solutions, and provided a generalization that reduces decentralized control to an appropriate robust synthesis problem under certain conditions.

Other researchers explored hybrid control, in particular that using impulsive control systems. Hybrid (both continuous and discrete) behavior aspects are present in many modern physical systems and infrastructures; examples are found in interconnected power systems, air traffic control, robotic systems, chemical processes, and other systems. Impulsive control systems for such hybrid systems may be viewed as a generalization of switching control systems, i.e., systems whose dynamics change abruptly in response to a control command. Researchers developed an optimal control theory for nonlinear dynamic control systems with additive impulse effects, discussed solutions to optimal impulsive control problems in general, and considered stability analysis of switched linear systems.

Finally, the consortium addressed congestion control in complex networks such as communications systems and power grids. Congestion control mechanisms in today's Internet represent one of the largest artificial feedback systems and, until recently, analysis was beyond the reach of modeling and control theory. Researchers applied advances in understanding equilibrium properties of resource allocation to develop a theoretical approach and several theorems for controlling congestion based on pricing signals. These signals, which measure the amount of congestion, are used to model the feedback mechanism between network and sources and provide a means of regulation.

Communications research extended to the evaluation and design of TCP protocols, both existing and new, with the aim of performance in wireless applications. Today's TCPs were designed for hardwired systems where error rates are very low; they are not optimal for wireless and mixed wired/wireless systems where data packets may be lost as easily due to link errors as to router congestion. Researchers developed and analyzed three approaches to optimizing TCP for wireless systems. All are based on the use of available bandwidth to dynamically adapt window size to meet changing path conditions. Promising variations to the TCP Westwood approach, in particular, were analyzed extensively. In related work, researchers explored the Long-Range Dependence (LRD) properties of Internet communications traffic and analyzed their impact on traffic policing schemes and overall network performance.

# 4 APPLICATION TO EPRI "DIFFICULT CHALLENGES"

This chapter identifies applications of CIN/SI results to the 15 "Difficult Challenges" that hinder progress towards EPRI's *Electricity Technology Roadmap*. The discussion focuses on CIN/SI applications to Difficult Challenge #3: 'Increasing robustness, resilience and security of the energy infrastructure' (which is CIN/SI's charter), but it also describes roles for CIN/SI results in addressing other of the Difficult Challenges.

## 4.1 Overview of EPRI "Difficult Challenges"

In 1997-98, EPRI introduced the *Electricity Technology Roadmap*. The *Roadmap* is an exploration of the opportunities and threats for electricity-based innovation during the coming 25 years, summed up in a set of technology development destinations and R&D pathways to reach these destinations.

The *Roadmap* is being updated in 2002-03. Technology development destinations and R&D pathways are being revised to reflect progress and changes of the past five years. In addition, based on extensive review and synthesis of experience in using the *Roadmap* as a planning tool since 1998, 15 "Difficult Challenges" have been identified that hinder progress towards the *Roadmap* destinations. These Difficult Challenges focus on challenges in five areas—1) power system reliability, 2) revolution in services, 3) economic growth and productivity, 4) electricity supply, and 5) environmental protection. By addressing challenges as opposed to technology topics, the Difficult Challenges provide a means to define actions necessary to reach the *Roadmap* destinations. The challenges are inherently interdisciplinary and overlap to some degree. They are not intended as a comprehensive list of all the technology developments related to defining the power system of the future, but rather reflect only the highest value, highest priority issues.

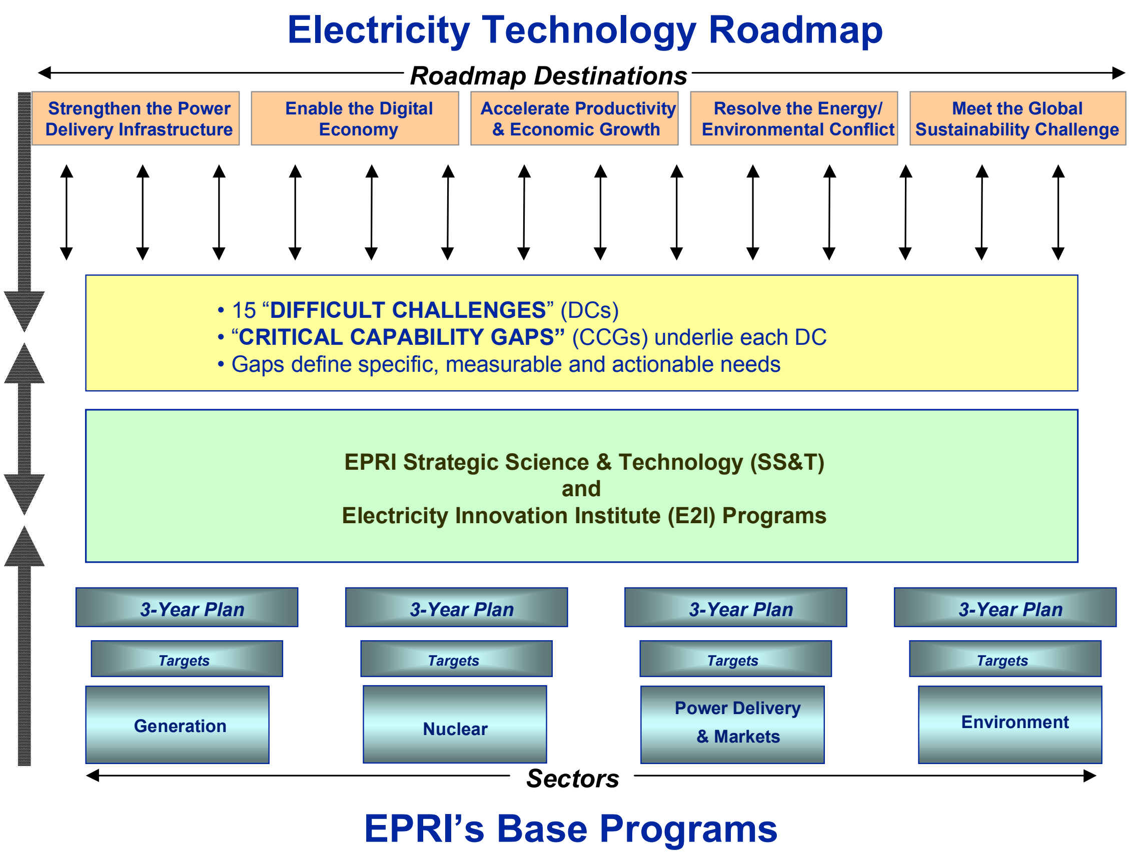



**Figure 4-1**
**Conceptual outline of EPRI *Electricity Technology Roadmap***
This diagram shows the relations of the "Difficult Challenges" to the *Roadmap* destinations and EPRI R&D program.

The 15 Difficult Challenges are as follow: (* indicates possible CIN/SI application)

<u>Power System Reliability</u>

1. Increasing transmission capacity, grid control and stability*
2. Improving power quality and reliability for precision electricity users*
3. Increasing robustness, resilience, and security of the energy infrastructure*
4. Exploiting the strategic value of bulk storage technologies

<u>Revolution in Services</u>

5. Transforming electricity markets*
6. Creating the infrastructure for a digital society*

7. Development of electricity-based transportation systems*

Productivity and Economic Growth

8. High efficiency end uses of energy
9. Advances in enabling technology platforms*

Electricity Supply

10. Maintain and strengthen portfolio of generation options*
11. Universal global electrification*
12. Accelerated development of carbon capture and storage technologies

Environmental Protection

13. Improved methods for effectively communicating and applying scientific research*
14. Ecological asset management
15. Sustaining and improving water availability and quality*

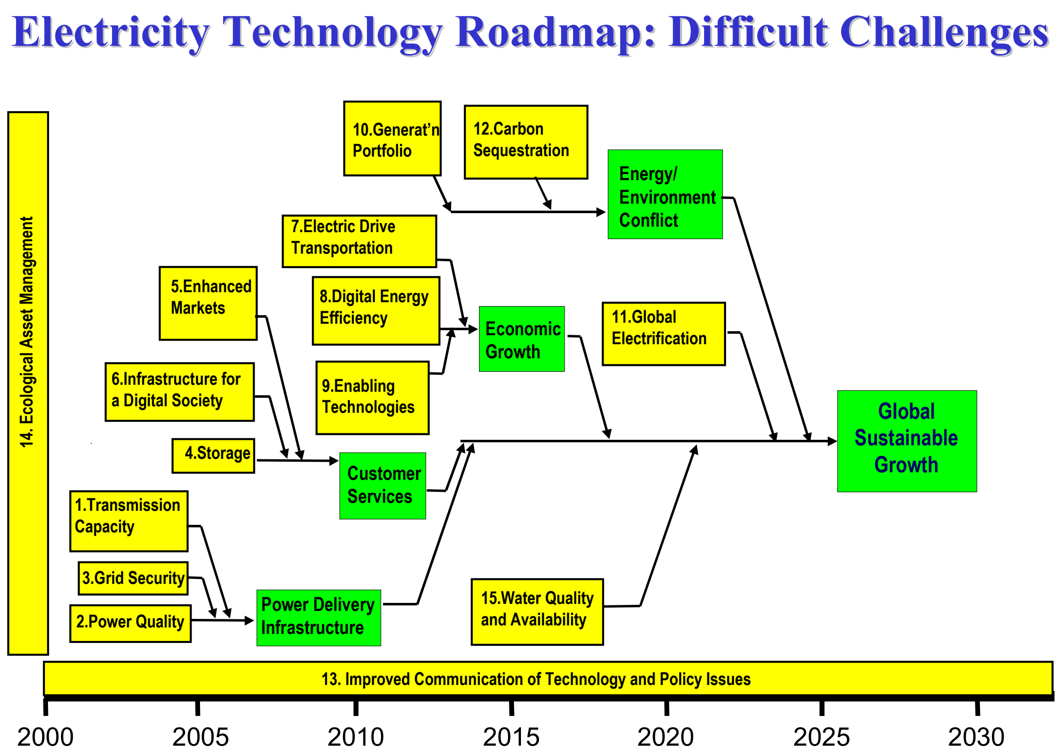



**Figure 4-2**
**Timeline showing major milestones for *Electricity Technology Roadmap* (shaded) and "Difficult Challenges" for 2000-2030.**

## 4.2 Application of CIN/SI Results to Difficult Challenge #3

Of all the Difficult Challenges, CIN/SI results are directly applicable to Difficult Challenge #3: 'Increasing robustness, resilience, and security of the energy infrastructure.' Particular considerations of this challenge are to reduce or eliminate vulnerabilities of the energy infrastructure to a broad spectrum of threats and support development of a long-term, comprehensive strategy to prepare for the diverse threats posed by terrorism. These are concerns that CIN/SI was launched specifically to address.

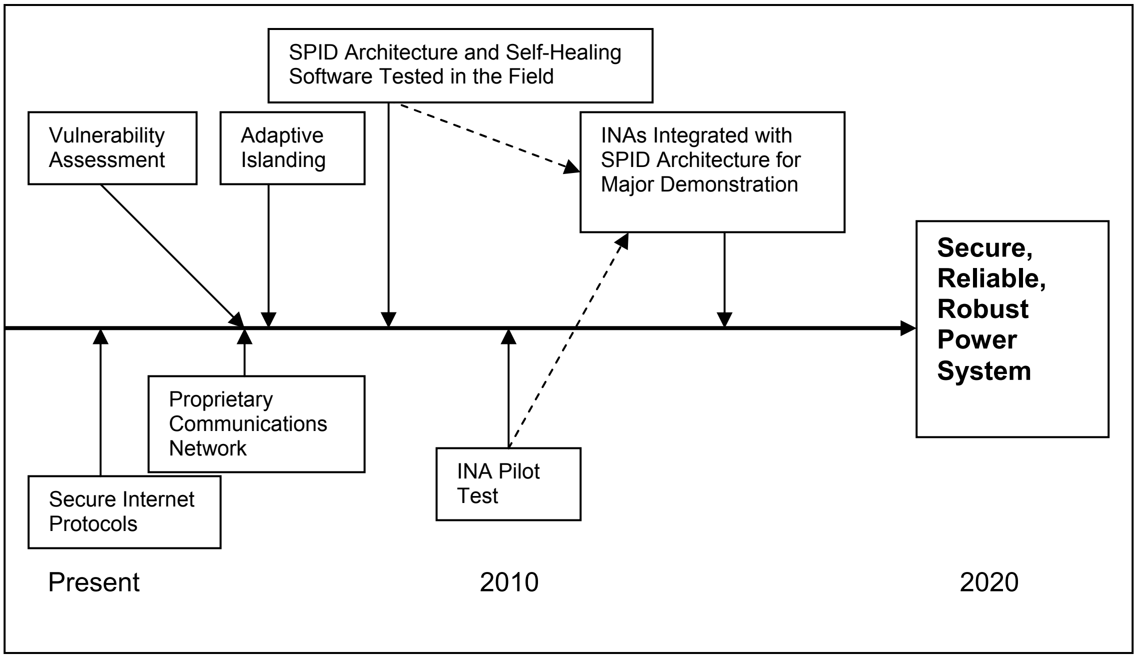



**Figure 4-3**
**Timeline of major milestones to achieve EPRI's Difficult Challenge #3, "Increasing robustness, resilience, and security of the energy infrastructure."**

### *4.2.1 Difficult Challenge #3: 'Increasing robustness, resilience, and security of the energy infrastructure'*

Both the importance and difficulty of protecting power systems has long been recognized. In 1990, the Office of Technology Assessment (OTA) of the U.S. Congress issued a detailed report, *Physical Vulnerability of the Electric System to Natural Disasters and Sabotage*, concluding: "Terrorists could emulate acts of sabotage in several other countries and destroy critical [power system] components, incapacitating large segments of a transmission network for months. Some of these components are vulnerable to saboteurs with explosives or just high-power rifles." The report also documented the potential cost of widespread outages, estimating them to be in the range of $1-5/kWh of disrupted service, depending on the length of outage, the types of customers affected, and a variety of other factors. In the New York City outage of 1977, for example, damage from looting and arson alone totaled about $155 million—roughly half of the total cost.

During the decade since the OTA report, the situation has become even more complex. In addition to physical vulnerability, the increased susceptibility of power systems to disruptions in computer networks and communications systems must now be considered as well. The number of documented cyber attacks increased some 25-fold between 1997 and 2001, and countless more attacks go undetected. Power system control has also become more centralized, in order to improve operating efficiency. Such centralization, however, might be exploited by terrorists to magnify the effects of a localized attack. In addition, many customers have also become more dependent on electronic systems that are sensitive to power disturbances. A 20-minute outage at an integrated circuit fabrication plant, for example, has cost $30 million.

Some of the complexities involved in protecting power systems and related infrastructures were identified by the *Electricity Infrastructure Security Assessment*, developed by EPRI in response to the September 11, 2001, terrorist attacks. In particular, this assessment identified three different kinds of threats that need to be considered:

- Attacks *upon* the power system. In this case, the electricity infrastructure itself is the primary target—with ripple effects, in terms of outages, extending into the customer base.
- Attacks *by* the power system**.** Here the ultimate target is the population, using parts of the electricity infrastructure as a weapon. Power plant cooling towers, for example, could be used to disperse chemical or biological agents.
- Attacks *through* the power system. Utility networks include multiple conduits for attacks on other infrastructures, including lines, underground cables and tunnels. An electromagnetic pulse, for example, could be coupled through the grid to damage both electricity and telecommunications networks.

This Difficult Challenge thus represents a potentially critical "showstopper" for realizing key *Roadmap* destinations, including particularly the goal of boosting economic productivity and prosperity through a digital economy, and enabling customer-managed service networks. Indeed, if infrastructure security is not assured, even maintaining current levels of productivity and service will be jeopardized. Conversely, as CIN/SI results suggest, deploying some of the advanced technologies needed to enhance security will also have a positive effect on efforts to improve grid reliability and coordinate power system operations with those of other infrastructures.

### 4.2.2 Critical Capability Gaps and CIN/SI Results

In order for Difficult Challenge #3 to be met, several Critical Capability Gaps (CCGs) need to be addressed. These CCGs are:

- Power System Vulnerability Assessment
- Power System Adaptive Islanding
- Secure Communications
- Strategic Power Infrastructure Defense System
- Self-Healing Grid
- Intelligent Network Agents
- Mathematical and Computational Foundations for Complex Interactive Networks

CIN/SI results directly address these seven gaps, as discussed below.

- CCG: Power System Vulnerability Assessment. The first priority among efforts to improve overall system security is to assess vulnerabilities to terrorism (or natural disturbances) and identify the most effective countermeasures.

  CIN/SI Results. Five of six CIN/SI consortia made significant progress in vulnerability assessment techniques for the power grid and other CIN.

  The Caltech consortium devised a means to analyze the structure of a network to understand network behavior and identify where cascading failures are likely.

  Harvard consortium researchers developed an alternative CIN analysis approach based on interacting Markov Chains, and applied it to identify vulnerable links in power system simulations and to explore the spread of malicious software on the Internet as well. Harvard researchers also extended ordinal optimization theory to address CIN data mining, laying the groundwork for a computationally effective approach to identify which of multitudinous parameters to monitor in order to predict or quickly detect imminent cascade collapse or other abnormal behaviors.

  At CMU, researchers identified a complementary data mining method that can determine the type of a disturbance on a power system in near-real time based on data about dynamic frequency deviation and rate of frequency change collected from dynamic recording devices.

  Practicable approaches for gathering the data for data mining (and monitoring the status of a power grid or other CIN) was advanced by the PSERC consortium led by Cornell, using robust Spinglass and gossip-based techniques. And to combat disturbances, PSERC researchers showed that nonlinear coupling elements (such as Flexible AC Transmission System, or FACTS, elements) can be designed into power networks to introduce passive energy "sinks" that arrest and confine propagating oscillations introduced by fault events, and they developed theory and designs for a simple class of mechanical oscillators.

  The UW-led APT consortium devised dynamic decision event tree techniques that enable fast system-wide vulnerability assessment with respect to various sources of threat. They also developed new techniques to quantify the vulnerability of communication systems, and to evaluate the impact of communication failures on the power grid.

- CCG: Power System Adaptive Islanding. Following a major terrorist attack or natural calamity, initial reaction will focus on creating self-sufficient islands in the power grid, adapted to make best use of the network resources still available.

  CIN/SI Results. Specific techniques for adaptive islanding were developed by two consortia.

  The UW/APT consortium established proof of concept for a powerful adaptive islanding scheme, based on real-time system contingencies, that reduces the probability of cascading failures and minimizes load lost.

CIMEG researchers developed quantitative criteria for defining self-sufficient islands (called by them 'local area grids') within a power network, based on forecasts of available load. To help local islands function on their own and adapt to changes, CIMEG also advanced a very promising hybrid neural network/fuzzy logic methodology for forecasting short-term local electricity demand at the customer level, and a new neural network/wavelet approach for short-to-mid-term forecasting.

- CCG: Secure Communications. A wide-area, secure communications system is needed to replace use of the Internet for critical monitoring and control functions, in order to reduce vulnerabilities and improve availability of critical information for system recovery.

  CIN/SI Results. Four consortia advanced means to ensure secure, effective communications for a power system or other critical infrastructure.

  The Harvard-led consortium developed an efficient new framework, based on fluid flow analysis methods, for modeling large-scale, high-speed communication networks as would be need for a power system or other CIN.

  Caltech researchers evaluated design of data-transfer protocols as well as how to measure performance in high-speed networks.

  PSERC identified Spinglass probabilistic communications techniques that can support real-time simulation, control, and decision-making in power systems. This consortium also developed a new Internet/Intranet technology for tracking of the state of a complex network that is robust against failures or disruptions or attack, is completely scalable to load (or size of network), and is rapidly convergent.

  UW/APT researchers devised an Internet-based information exchange structure for the power system and the electricity market and developed its application to wide-area state estimation in a market environment.

- CCG: Strategic Power Infrastructure Defense (SPID) system. After an attack, SPID would analyze information about the status of the power system and secure communications system, and coordinate their use for adaptive islanding.

  CIN/SI Results. The SPID concept originally was proposed by the UW/APT consortium, and has been advanced considerably by this team during the CIN/SI. The consortium developed a conceptual design for the adaptive multi-agent SPID system applicable to a deregulated marketplace. The design is based on wide-area intelligent, adaptive protection and control systems. It has the abilities to 1) identify hidden failure modes and evaluate the impact of hidden failures on the power system; 2) perform system-wide vulnerability assessment incorporating the power system, protection system, and the communication system; 3) enables the power system to take self-healing actions through islanding and reconfiguration; 4) perform power system stabilization on a wide-area basis; and 5) monitor and control the power grid with a multi-agent system designed to reduce the power system vulnerability. A

SPID prototype has been developed, and the multi-agent software that integrates all the SPID agents has been demonstrated with the adaptive load shedding capabilities.

- CCG: Self-Healing Grid. Once a stable configuration of grid islands had been established after a terrorist attack, self-healing algorithms would gradually bring the power system back to its normal state as more resources became available. Application of these algorithms would also help optimize normal grid operations.

  CIN/SI Results. Specific techniques for grid self-healing were developed by two CIN/SI consortia.

  CIMEG researchers devised a power grid self-healing system, called TELOS (Transmission/Distribution Entities with On-Line Self-Healing), that manages islands within a grid and reintegrates them when appropriate. A TELOS prototype has been implemented in a commercial agent framework called “Grasshopper” and alpha-tested in off-line simulations. They also explored a support vector approach that may help reduce the complexity of developing good-neighborly relations among islanded parts of a grid.

  UW/APT researchers developed a scheme for grid self-healing that includes adaptive remedial action and islanding methods. This scheme includes multi-agent systems and temporal difference learning techniques.

- CCG: Intelligent Network Agents (INAs). Most sensing and control agents in a power system today simply respond to changing local conditions according to pre-programmed instructions. INAs would have decision-making capability, based on internal analysis of network-wide conditions. Once implemented, INA technology would facilitate adaptive islanding, SPID, and the self-healing grid.

  CIN/SI Results. Three consortia explored INA technology in depth and provided substantial new understanding of agent design, coordination, learning, and implementation.

  Investigations by the CMU consortia showed that distributed decision-making by INAs can produce globally optimal results, even if agents must make decisions with incomplete information about the state of the system. CMU identified heuristics that are available for agents to make decisions that are close to globally optimal decisions, which can lead to much more optimal systems than presently exist. To test and explore various INA concepts, they developed a unique real-time simulation environment for agent studies. CMU researchers also developed a new decentralized model predictive control scheme as a strategy for real-time INA control of power systems and other CIN, and successfully applied this control scheme to multi-area load-frequency control in model power systems. Finally, CMU developed new a new strategy for protective relaying in power system networks that exploits the ability of INAs to understand their environment. This approach makes protective relaying agents more aware of context (for better recognition of faults, disturbances, alert, and normal states) and is a promising way to greatly enhance robustness and agility for the entire system.

Researchers of the CIMEG consortium devised various anticipatory demand-side management and local dispatch strategies that INA would employ with their TELOS system, and validated these strategies on data from the Exelon and TVA power systems. CIMEG also developed new machine learning approaches and genetic algorithms for evolving INAs that can automatically learn the consumption patterns, track unexpected demand transients, and optimize power flow and generator/storage dispatch in a power grid island.

In the UW/APT consortia, researchers developed a number of software agents within the framework of the multi-agent SPID system, and validated all software algorithms using the same 179-bus system model.

- CCG: Mathematical and Computational Foundations for Complex Interactive Networks. Automated control of the (deregulated) power system will be needed during an attack or during a major failure in order to take actions to minimize the spread of damage and prepare the system for islanding and eventual reintegration. To provide real-time action, control decisions must be made independently by individual agents acting on local information, yet are integrated with the system as a whole to provide global optimum behavior.

  CIN/SI Results. All six CIN/SI consortia added to the mathematical and computational foundations for complex interactive systems, thereby leading towards integrated network control.

  Caltech consortium researchers developed the new concept of 'Highly Optimized Tolerance' to explain key characteristic behaviors of complex systems and identify weak links. They applied distributed control concepts to analysis and design of systems where dispersed agents interact dynamically with a coupled physical grid and coordinate their real-time actions through a communications substrate. They also devised three novel model reduction approaches that can speed the processing of data collected from sites throughout a complex distributed network, and explored the impact of uncertainty in distributed control of a CIN.

  Researchers of the CMU consortium developed a new transaction-based power flow analysis concept to adapt conventional AC power flow analysis tools to deregulated electricity systems where different (and dispersed) entities may be responsible for generation, transmission, and distribution functions.

  The PSERC consortium developed and tested new hybrid models for network control that combine both "top-down" command-and-control and "bottom-up" agent-type approaches. Researchers from both the PSERC and Harvard-led consortia demonstrated that relatively easy-to-solve fluid flow models can approximate and solve difficult control problems for CIN. Furthermore, Harvard researchers developed a new hierarchical modeling method to decompose and simplify the combinatorially complex stochastic optimization problems typical of complex networks. The Harvard consortium also devised a new control design theory for electric power systems and hybrid time-driven/event-driven systems, with application to the robust synchronization of generators within large electricity grids.

CIMEG researchers advanced basic anticipatory control theory as a tool for integrated control of complex networks, and applied the theory in developing an anticipatory control scheme for a small coal-fired generator.

The UW-led APT consortium developed and demonstrated multi-agent software to integrate numerous adaptive agents as part of the SPID scheme. Results suggest approaches for controlling failure propagation and performing adaptive islanding.

## 4.3 Application of CIN/SI Results to Other Difficult Challenges

Because many of the challenges facing the power system arise from its nature as a CIN, CIN/SI results apply to many of the other Difficult Challenges (DC) of the *Electricity Technology Roadmap* beyond that of grid security. These Challenges and their CCGs that are addressed by CIN/SI results (*in italics*) are discussed briefly below.

### *4.3.1 DC #1: Increasing Transmission Capacity, Grid Control and Stability*

This Difficult Challenge is to reduce or eliminate the vulnerability of the power delivery infrastructure to outages and poor power quality. The existing radial, electromechanically controlled grid must be transformed into an electronically controlled smart electricity network. This transformation will promote greater throughput of the transmission system, resolve loop-flow and other congestion management problems, and boost competitiveness.

CCGs addressed by CIN/SI Results:

- Wide area measurement/monitoring systems have not been implemented on a national basis. *CIN/SI consortia devised various approaches that make wide-area measurement/monitoring systems more practical and more effective for power networks (see Vulnerability Assessment, above).*

- Current implementations of hierarchical control technologies for flexible AC transmission systems (FACTS) do not meet the needs of large grid systems. *New methods for coordinating multiple FACTS controllers in a large power system were developed as part of CIN/SI work.*

- Technologies for complete automation of transmission and distribution grid and systems control functions are not currently available. *The CIN/SI advanced the mathematical foundations of control theory for automated measurement, monitoring, and management of CIN networks such as the power grid.*

- Distributed and intermittent renewable generation need to be integrated into grid operations and control. *Automatic control of any CIN by its nature will be distributed control (which is one of the challenges CIN/SI researchers worked to address), leading to easy accommodation of distributed and intermittent generation technologies.*

### 4.3.2 DC #2: Improving Power Quality and Reliability for Precision Electricity Users

The challenge is to improve the ability of the transmission and distribution systems to reduce the number and severity of power disturbances, with special emphasis on the need for "high nines" reliability for digital customers. This will require technologies such as distributed generation and storage systems, distribution automation, and interconnection standards for distribution systems.

<u>CCGs addressed by CIN/SI Results:</u>

- Distributed Resources (DR) interconnection standards and grid integration approaches are incomplete. *Distributed control of the power grid, pursued in the CIN/SI, inherently enables easy integration of DR technology.*

### 4.3.3 DC #5: Transforming Electricity Markets.

The interrelationship between electricity markets and infrastructure is undergoing a profound transformation. While this transformation is occurring, three major challenges need to be addressed simultaneously: 1) keeping incentives for investment in generation capacity sufficient to meet reliability expectations, 2) planning transmission system capacity, and 3) exploitation of efficiency gains from demand response.

<u>CCGs addressed by CIN/SI Results:</u>

- Shortcomings in supply and demand forecasting techniques lead to higher costs and volatility. *Improved approaches for forecasting electricity demand were developed and demonstrated by CIN/SI researchers, including hybrid neural network/fuzzy logic and neural net/wavelet techniques.*

- Markets, regulations, and technologies are needed to introduce demand responsive pricing. Open communication solutions for Distributed Resources to enable price, visibility, and integration with distribution system networks. *Robust wide-area communications systems explored in the CIN/SI are an essential technology for gathering electricity demand data and supplying system-wide pricing information in near-real time.*

### 4.3.4 DC #6: Creating the Infrastructure for a Digital Society

The demand for premium power (with reliability of six "nines" or better) is nearly 10 percent of U.S. load today, and will increase to as much as 70 percent by 2020. The supporting infrastructure will have to keep pace with the digitization of the economy. By 2020, essentially all industrial processes, manufacturing facilities, and commercial businesses will be interactively linked to employees and customers through the "energy web." The energy web will be a critical enabling technology for economic growth and productivity improvement over the next two decades.

CCGs addressed by CIN/SI Results:

- Automated distribution systems are not available. *The CIN/SI advanced the mathematical foundations of control theory for automated measurement, monitoring, and management of the power distribution system and other CIN.*

### 4.3.5 DC #7: Development of Electricity-Based Transportation Systems

Examples of electric transportation systems include battery-powered or fuel cell autos, and mag-lev trains. They use electricity in different ways. The different approaches to using and generating electricity imply widely differing impacts on the electricity infrastructure and electricity demand.

CCGs addressed by CIN/SI Results:

- Assessments of electricity demand impact and reliability requirements for all forms of electricity-based transportation are not available. *Methods for analyzing complex interacting infrastructures that were developed in the CIN/SI may provide a means for accurately assessing the grid impact of electricity-based transportation options.*

### 4.3.6 DC #9: Advances in Enabling Technology Platforms

The *Roadmap* identifies five limit-breaking “technology platforms” where acceleration of the underlying sciences will have a high impact on the capability of the infrastructure, and can improve productivity in a wide range of critical manufacturing and process industries. The platforms are: 1) Materials, 2) Sensors, 3) Microminiaturization, 4) Information Technology, and 5) Biotechnology.

CCGs addressed by CIN/SI Results:

- Information and communications technology advances are needed to meet the needs of a digital electricity system. CIN/SI research advanced understanding of fundamental methods to improve the robustness, design, and operation of communications systems.

- Methods are currently unavailable to design embedded nano-sensors for performance monitoring of all electricity-based equipment. *Embedded nano-sensors greatly expand the range of CIN (can make almost anything into a CIN) by providing points of data collection and control almost anywhere. CIN/SI’s distributed data collection, data mining, and agent technologies will be critical to their successful application.*

- Human performance requirements must change rapidly to keep up with changes in utility equipment, plant operations, and job definitions. *Humans can be defined as adaptive agents just as software or control systems can. As such, the various technologies advanced in the CIN/SI for understanding and optimally coordinating agents may be applied to assess and define human performance needs as well.*

### 4.3.7 DC #10: Universal Global Electrification

Today, half the world's population exists on a few hundred kilowatt-hours (kWh) per person per year, and 2 billion more lack any access to electricity. Achieving universal electrification by 2050 will require bringing electricity to at least 100 million more people every year, and establishing a minimum annual per capita electricity supply of at least 1000 kWh for the world's poorest. Accomplishing this will require 10 million megawatts of new electricity generating capacity worldwide by 2050.

<u>CCGs addressed by CIN/SI Results.</u>

- The use of risk management tools should be expanded as a basis for policy-making. *CIN/SI analysis techniques for CIN may provide efficient computing approaches that can revolutionize risk management, by allowing more comprehensive simulation of critical infrastructures.*

- Energy infrastructure to support distributed generation at larger scale. *Inherent in CIN/SI work to provide automatic control of a power system is distributed control that leads to easy accommodation of distributed generation technologies.*

### 4.3.8 DC #13: Improved Methods for Effectively Communicating and Applying Scientific Research

An improved scientific understanding of the environmental and health issues associated with current and potential future electric technologies is critical to their continued viability and growth. Technologies for mitigating possible effects need to be developed. Improved risk assessment and management tools are needed to assess the complex environmental and economic tradeoffs created by constantly evolving, interrelated environmental regulations. Regulatory designs need to be advanced to achieve environmental goals as efficiently and equitably as possible. The value of these advances to society will increase markedly as policy proposals with increasingly greater economic and technological consequences, such climate policies, are put forward and debated.

<u>CCGs addressed by CIN/SI Results:</u>

- Development of multi-stakeholder, science-based assessments of impacts for existing, emerging, and potentially critical future technologies. *Systemic analysis of CAS infrastructures and their interactions as is emerging in CIN/SI research may provide a defensible means of scientifically assessing the impact of technologies and systems.*

### 4.3.9 DC #15: Sustaining and Improving Water Availability and Quality

Sustainable water supplies for a growing world population presents a critical economic, environmental, and international political issue, and its importance will grow over the next half-century. Water problems impact the electricity industry from several standpoints, including power production, electricity use, and grid topology. For instance, more than 40 percent of all

U.S. stream flow passes through a power plant cooling or hydroelectric system, and new facilities must be sited with the availability of water in mind.

CCGs addressed by CIN/SI Results:

- Poorly understood impact of practices (e.g., eco-value trading and electricity impacts) and technology solutions for each deficit area, especially the compatibility of macro- and microscale impacts, including generation/power delivery planning model results. *CIN models developed in the CIN/SI tackle the challenge of connecting macro- and micro-scale disturbances—indeed, this issue is at the heart of CIN science—and thus may provide a tool for analyzing water practices and technology solutions.*

- Need software/models to guide to the final determination of the pilot sites, and to evaluate the projected macro-scale impacts of the pilots. *As above.*

# 5
# NEXT STEPS

This chapter 1) describes the present state of understanding about complex interactive networks (CIN) and systems as a result of the CIN/SI program, 2) introduces key technologies and follow-on research projects that grew out of CIN/SI technology transfer, and 3) discusses the next-step research needed to develop complete modeling, measurement, and management capabilities for complex infrastructures and defense systems in critical areas.

## 5.1 State of Understanding about Complex Interactive Networks and Systems

The CIN/SI represents one of the first and largest systems approach to complex interactive networks, based on advancing the mathematical and theoretical foundations. CIN/SI results have advanced understanding from incomplete theoretical concepts about complex networks to substantive theoretical and practical knowledge having many applications for resilient infrastructure (Table 5-1).

**Table 5-1**
**Understanding of Complex Networks in Key Challenge and Solution Component Areas before and after CIN/SI**

| | Solution Components | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Challenges** | **Measurement & Sensing (including visualization)** | | **Modeling & Theory** | | **Simulation** | | **Control System Design** | | **Operation & Management** | |
| | before | after | before | after | before | after | before | after | before | after |
| **Efficient Operation** | 3 | 4 | 3 | 4 | 3 | 3.5 | 3 | 3.5 | 3 | 3.5 |
| **Security and Robustness** | 2 | 3.5 | 3 | 4 | 3 | 4 | 2 | 4 | 2 | 3.5 |
| **Cascading Failure - single infrastructure** | 1 | 3.5 | 2 | 3 | 2 | 4 | 1 | 4 | 2 | 3.5 |
| **Cascading Failure - multiple infrastructures** | 1 | 3.5 | 1 | 3 | 1 | 4 | 1 | 4 | 2 | 3.5 |

**Key: 1—minimal understanding**
**2—some understanding but insufficient for practical applications**
**3—partial understanding with some useful practical applications**
**4—solid understanding with many practical applications**
**5—complete (or near-complete) understanding and applicability**
**Shading indicates the degree that understanding advanced by CINSI research.**

Overall, CIN/SI produced theoretical and applied findings that increase the dynamic reliability and efficiency of complex networks. Fundamental understanding was achieved of interdependencies, coupling, and cascading in these networks, which provides practical abilities to identify, characterize, and quantify failure mechanisms as to the danger they present. New models were developed that can predict behavior of complex systems, marking a significant advance over previous models in which systems and failures could only be analyzed after-the-fact or for a limited number of pre-set scenarios. Also developed were prescriptive procedures and control strategies that can mitigate and eliminate failures in these systems, as well as initial designs for self-healing and adaptive architectures. New CIN/SI understanding of the trade-offs between robustness and efficiency for complex networks ensure that the new designs will provide desired levels of performance and security.

Taken together, CIN/SI findings enable the practical realization of integrated sensing, modeling, simulation, optimization, and robust control of networks and systems of all kinds. Progress was made on several cross-cutting mathematical themes for large-scale networks, including the relations among complexity, structure, and computations, as well as how to model and manage uncertainty (which arises in many complex systems because they are so large all the data cannot be known by all the controllers—or by any single one—at once). Other cross-cutting themes include new approaches to geometrization as well as modeling and analysis at multiple scales and resolutions. Real advances were made in understanding very large and/or high dimensionality data sets and in real-time simulation and modeling. Data management and real-time simulation issues alike arise in design and modeling problems for many types of systems, not only complex networks.

These advances in knowledge unleash new opportunities. For example, the theoretical foundation laid by CIN/SI work opens a new horizon for lifting the "fog of war" through better simulation. Advances in the fidelity and cost-efficiency of modeling complex systems enable "*in silico"* simulation testing of plans, designs, and devices in the context of a whole system. Interdependencies, not just of single components and contingencies but of whole infrastructures and complexes, can be accounted for. Another new horizon from CIN/SI results is realization of concepts for integrated sensing, communications, and control of complex networks. CIN/SI results make possible the use of control software embedded throughout a system to assess dynamic data to counter disturbances, mange complex modes, and respond to changing capabilities for sensing and actuation in case of damage to the system. Similarly, distributed sensor software can leverage distributed computing paradigms and ensure database reliability and fault tolerance for survivability and security. Like many CIN/SI results, both *in silicio* and integrated sensing/control concepts can be applied to manage an electricity grid or other infrastructure system, or employed for defense applications (such as coordinating operations of a ship-based distributed power system in the face of damage or attack or creating a powerful, survivable network-centric objective force from distributed sensors, soldiers, weapons systems, defense analysts, and command elements).

Despite the many advances of CIN/SI, the theoretical foundation remains incomplete for full modeling, measurement, and management of the power system and other complex networks. Two pertinent issues for future investigations are 1) why and how to develop controllers for centralized versus decentralized control, and 2) issues involving adaptive operation and robustness to disturbances that include various types of failures.

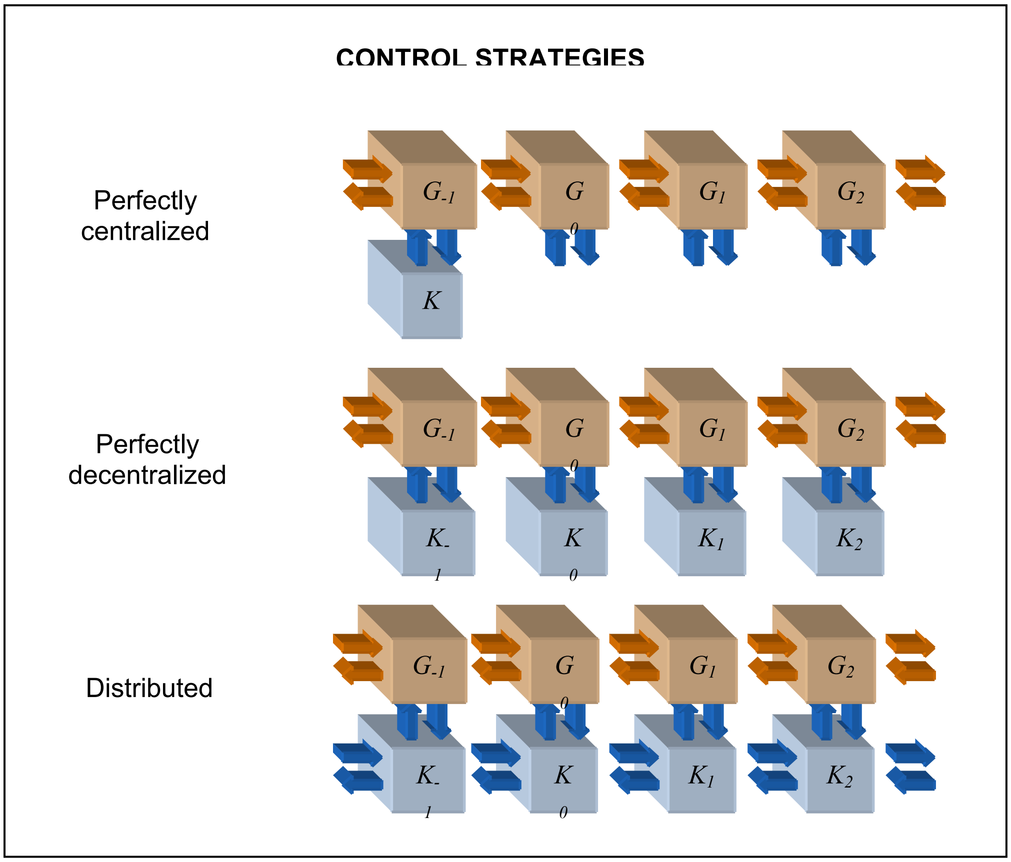



**Figure 5-1**
**Control Strategies for a Complex Interactive System.**
A key unresolved issue for complex interactive systems is understanding what control strategy (centralized, decentralized, or hybrid distributed) provides optimum performance, robustness, and security, and for what types of systems and under what circumstances (in the figure "K" indicates controller and "G" indicates sensor or actuator).

## 5.2 Technology Transfer from the CIN/SI

The fundamental theoretical advances resulting from CIN/SI findings have been captured in several hundred technical papers and presentations over the years of the Initiative. In addition, many new technologies and practical applications have been identified and are now under (or planned for) further development. EPRI, for example, extracted 19 promising technologies for commercial development. DOD identified another group of technologies for potential military applications. These and other technologies resulting from the CIN/SI hold promise for application in other infrastructure areas as well, such as

- Internet communications and security
- Manufacturing process control
- Command and control networks

- Traffic flow over road and highway nets
- Long-term design for critical infrastructures such as freeways and pipelines

### *5.2.1 Technical Papers and Presentations*

During the three years of CIN/SI research, more than 360 technical papers have been published or submitted for publication. Results have also been presented and discussed at more than a dozen technical workshops and scientific meetings held by EPRI, the U.S. Army Research Office, the National Science Foundation, and IEEE, among others. Appendix D provides a complete list of CIN/SI papers and presentations to date.

### *5.2.2 EPRI Technologies Extracted from CIN/SI Results*

Some 19 technologies identified by EPRI for commercial power system applications are drawn from the research results of all six CIN/SI consortia. Several of these technologies were selected for further development in base-funded core research projects planned to begin in 2003, and other technologies are being planned for development in Initiatives and special programs.

Wide area protection (sensing & measurement) and control. Dispersed sensors and techniques to fully exploit them were developed as part of APT consortia research. Technologies include GPS synchronization of widely-placed sensors, effective communications that account for time delays between sensors, and robust control schemes that exploit wide area measurement data.

Possible next steps for 2003 and beyond include further development of two derivative technologies. One is a wide-area sensing scheme to improve dynamic rating capabilities for transmission lines by tracking actual conductor sag and local wind speed in real-time. The other is a controller design concept that can employ wide area signals to provide additional damping for system oscillations that can occur at high levels of power transfer.

Intelligent islanding. APT researchers made a first step towards adaptive islanding of power systems with an initial concept for on-line islanding in response to contingencies and quickly developing conditions. In addition, the CIMEG consortium developed technology for pre-defining self-sufficient local area grids or islands within existing power networks. These concepts incorporate the new considerations of deregulated power systems in islanding strategy and apply adaptive load forecasting techniques to ensure secure operation of grid islands that may have limited generation resources.

In the near term, intelligent islanding technologies from CIN/SI can be developed as a part of the Self-Healing Electricity Infrastructure Initiative within EPRI's CEIDS (Consortium for Electric Infrastructure to Support a Digital Society) program. In addition, methodologies for adaptive intelligent islanding are of special interest for improving grid security from terrorist attack and are being moved into power industry programs such as the EPRI Infrastructure Security Initiative (ISI).

Adaptive self-healing control—Strategic Power Infrastructure Defense (SPID) System. Prototype SPID technology that automatically defends a wide-area power system from failures and reconfigures the system after disruptions was developed by CINSI's APT consortium. Prototype software was successfully tested on a 179-bus system model, demonstrating the feasibility of SPID architecture and multi-agent implementation. Specific technologies devised as part of SPID include adaptive relaying technology, adaptive remedial action and islanding technology, and multi-agent technology for adaptation in dynamic environments.

Three coordinated research thrusts will begin as early as 2003 to develop SPID technology. A project, called "Adaptive Self Healing Techniques," has been proposed as part of EPRI's base program to support additional SPID integration and testing. A focus of this program will be assessment of threats and system vulnerability, as well as decision-making about when and where to island. SPID development is also a key component of the CEIDS Self-Healing Electricity Infrastructure Initiative. And SPID technology for improving grid security from terrorist attack is being planned for development within the ISI and other industry programs.

System vulnerability assessment. CIN/SI research into system vulnerability resulted in several assessment technologies. One is a tool based on new vulnerability indices for power system dynamics and control, as well as protection and for communication systems. Another is a tool that provides real-time determination of regions of vulnerability and analyses of hidden failures for a system. These tools employ new technologies for efficient data mining and analysis of complex interactive networks.

Development of system vulnerability technology is continuing in 2003-04 as part of the ISI.

Genetic algorithm-based optimal power flow and energy storage. CIMEG researchers developed a machine-learning technology that manages optimum power flow for a power system, including dispatch of generators and use of energy storage units such as capacitor banks and advanced devices. Genetic algorithms are used for efficient performance.

Neuro-fuzzy load forecasting. A very effective technology was developed by the CIMEG consortium for predictive modeling of electricity load. The technology combines neuro-fuzzy forecasting with a multi-scale wavelet-based signature extraction technique that provides quick identification of mode changes. Tests proved the technology to dramatically improve prediction accuracy, especially for unexpected events such as sports finals or sudden storms.

Further development of neuro-fuzzy load forecasting technology is being considered for core EPRI research that would combine this technology with anticipatory dispatch strategy (see below). Development would aim at forecasting and dispatch for small pre-defined power system islands called Local Area Grids (LAGs).

Anticipatory dispatch. Anticipatory dispatch technology for small generators was developed and tested by CIMEG researchers. This technology is designed to ensure secure operation of grid islands that may have limited generation resources, by anticipating power consumption and allocating dispatch based on load forecast data (such as is generated by neuro-fuzzy forecaster technology). Testing showed the CIMEG anticipatory dispatch technology to require only $1/25^{th}$

of the control effort required by conventional reactive dispatch schemes, thereby providing substantial maintenance and reliability benefits to power system equipment.

Further development of this technology combined with neuro-fuzzy load forecasting is being considered (see above).

TELOS (Transmission/Distribution Entities with On-Line Self-Healing) system. The TELOS technology prototype created by CIMEG is designed to avert power failures by integrating generation, storage, and demand management resources within local grid areas and anticipatory dispatch that automatically adapts to daily fluctuations. Distributed computing is employed, and the prototype includes full JAVA implementation of all agents.

Development planned for 2003 focuses on implementation of the basic components of TELOS, including deployment in intelligent, adaptive controls for localized areas of the Exelon and TVA power systems. Also planned are improvements to the TELOS GUI.

Transmission resource allocation. Researchers of the Carnegie-Mellon consortium developed a Pareto point-based resource allocation technology that adapts conventional power flow tools to the reality of today's deregulated transmission markets. This technology incorporates transmission line congestion constraints within the dispatch sensitivity analysis to provide optimum power flow under real-world conditions. It also lays a foundation for fairly distributing the losses created by transmission transactions among the selling generators.

EPRI can begin further technology development as soon as 2003. This work may include extensions to multi-region scenarios and capacity optimization, as well as addressing seams between transmission control regions. Another possibility is development of value-based transmission allocation under market and system uncertainties.

System protection reliability. CIN/SI research development technology for understanding the reliability of protection for critical infrastructures. The technology is based on probabilistic methods and models, and focuses in particular on vulnerabilities of information systems that underpin energy infrastructure and power markets.

System protection reliability technology may be developed in 2003 as part of ISI work.

Distributed computing and scalability issues. PSERC researchers devised and demonstrated a fully scalable distributed computing technology that reliably tracks the state of a complex system in real time. This technology provides a qualitative estimation of system state and is useful for applications in which absolute accuracy and consistency among dispersed locations is less important the maintaining a flow of fresh data.

Context dependent network agents (CDNA) for auction designs and testing. A new agent-based technology for automated simulation testing of preliminary designs for electricity markets and auctions was developed in CIN/SI research by building on the improved decision-making ability of agents that are informed about the context in which they function. This technology can be used to gain a greater understanding of how policies, economic designs and technology might fit into infrastructure, as well as guidance for their effective deployment and operation. It could be used, for example, for studying proposed schemes for electricity deregulation to avoid the mistakes made by California in its 1996 deregulation effort.

Generation companies as independent agents ("coloring electrons"). Carnegie-Mellon consortium researchers developed exact simulation technology that can determine the root causes and entities responsible for losses in a power system for both steady state and dynamic analyses. In effect, this technology tracks individual electrons from the different generators on a system. It has important applications in understanding how to allocate responsibility in and develop fair rules for deregulated markets.

Possible follow-on work for "coloring electrons" technology may include incorporation with vulnerability assessment and protection technique. This combination of technologies could provide detailed simulation of significant events and sample paths on a power grid, identify mitigation schemes that address regions of vulnerability and hidden failures, and support grid monitoring and operations under new Quality of Service constraints that reward or penalize an energy company based on performance characteristics.

CDNA for real-time system monitoring and control. A variety of focused CDNA-type technologies were developed for system monitoring and control. Key technologies include a neural network algorithm for agent-based fault detection and classification, a synchronized sampling algorithm for fault location, and strategies that coordinate the two algorithm with each other as well as with external controllers. These technologies were designed to enhance the usefulness and real-time capabilities of Dynamic Recording Devices (DRDs) now used on power systems to collect data primarily for after-the-fact analysis.

Development of these technologies for enhanced DRD applications is possible in 2003 or beyond. The objective is to prepare power systems for Quality of Service constraints by giving system operators the fault and system state information they need to act with efficiency and confidence when faced with unclear, unexpected, and/or conflicting situations. A particular desire is for quicker restoration of service following an outage. The ultimate objective is to develop technology that enables use of DRDs for fault analysis, integration of data from multiple devises, identification of oscillation modes and other activities to enhance real-time reliability and security of system operations, i.e., provide robustness against power system destabilizers.

CDNA for system security and control. CDNA researchers devised technology that helps identify appropriate parameter setting and structures for controller-agents in a multi-agent system. Proper settings and structures are critical to realizing the possibilities offered by multi-agent control. For example in a simple system of two agents, neither can stabilize the overall system using its local signal alone, but with coordination the two agents, each using its local signal, can.

Beginning in 2003, CDNA coordination technology could be developed by investigating structures for both explicit and implicit information. Adaptive coherency and tuning, signal selection, and context-dependent control of specific power system control devices will be explored. Also a catalog could be developed listing control design strategies for systems with many controllers.

Mathematical and computational foundations (MCF) for Complex Interactive Networks (CIN)—Highly Optimized Tolerance (HOT). Researchers of the Caltech-led consortium explored the theoretical foundations for complex interactive networks and developed the HOT technology concept to analyze and understand them. Among other things, the HOT concept explains the distribution of failure event sizes in complex systems and the trade-offs between system efficiency and system robustness. It provides insights into the design, behavior, and protection of all manner of complex networks, from power grids to ecologies to the Internet.

MCF for CIN—Distributed systems and control. A variety of distributed control systems were developed in the CIN/SI consortia. For example, fundamentals were devised in the CIN/SI of a decentralized control technology for distributed systems of agents that are dynamically coupled to a physical medium, such as a power grid or the Internet, and coordinate through a communications substrate that may experience delays. Researchers devised promising new methods for designing local/global controls for systems having arrays of agents with spatial symmetry; these control designs are computable even for very large-scale networks. Understanding was also extended of hybrid impulsive control for the Internet and other distributed complex networks.

MCF for CIN—Graphs, networks, and grid applications. Researchers of the Purdue consortium employed a newly introduced learning paradigm to identify informative patterns of loads/demands in power grids (e.g., for the city of Dekalb and portions of Chicago, Illinois) and other high dimensional spaces through a novel neural network technique and graphical analysis. In addition, Harvard/MIT researchers applied a graph-based small-world computational technique a 1200 bus model (e.g., for the Western U.S. grid as well as one for the PG&E network) to find "vulnerability paths" in interconnected grids of a particular topology and developed fortification techniques. Extension of the CIN/SI HOT technology yielded a novel graph-based approach for examining phase transitions and critical phenomena in complex networks. This approach has been applied to reveal key effects played by the structure of power system on its overall behavior and its robustness to cascade events. Another application of graph-based analysis to coupled map models of population dynamics identified how particular non-optimal system states arise in order to allow for recovery from rare but catastrophic events.

MCF for CIN—Uncertainty analysis. Another extension of HOT technology by the Caltech consortium explored the critical impact of uncertainty and risk on design and control for complex systems such as power markets and trading systems, by examining markets as an interaction of heterogeneous agents. Researchers developed "dynamic hedging" techniques that can minimize and control market risk, and also began construction of a mathematically correct and accurate theory of trading to minimize risk.

### 5.2.3 Other EPRI Programs Related to CIN/SI Results

In addition to the base-funded research projects planned for 2003 and beyond, CIN/SI technologies form the basis for several additional EPRI research programs, projects, and Initiatives (Figure 5-2).

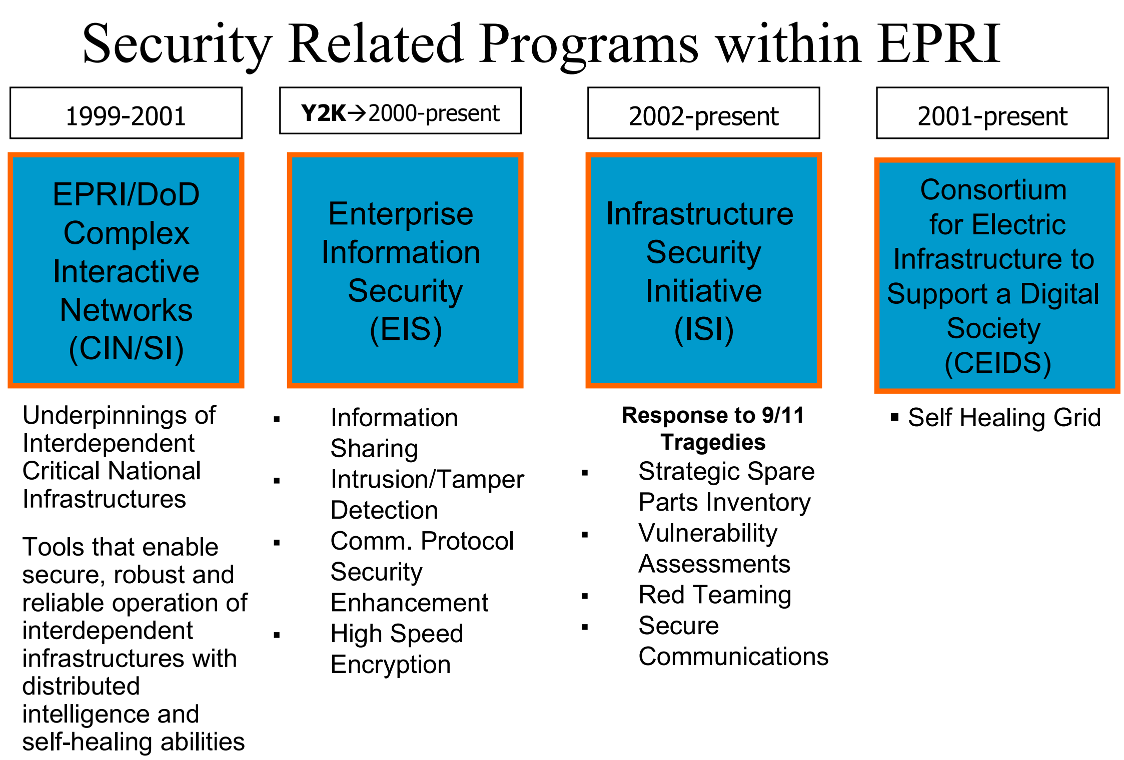



**Figure 5-2**
**Other EPRI Programs that build on CIN/SI Results**

<u>CEIDS Initiative.</u> CEIDS is a wide-ranging, long-term effort to develop advanced power systems for a digital society (Figure 5-3). CIN/SI results are being applied in two major CEIDS programs: Self-Healing Electricity Infrastructure and Rapid Simulation and Modeling.

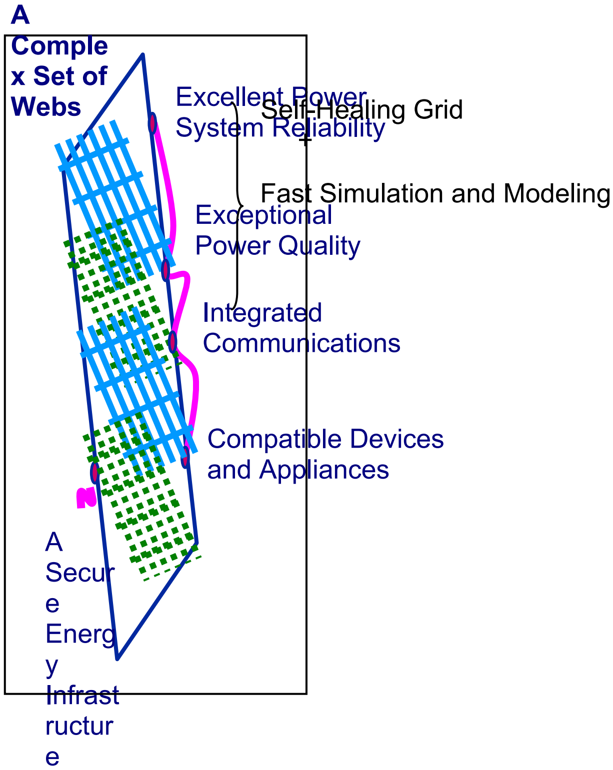



**Figure 5-3**
**CEIDS Infrastructure for a Digital Society.**
This complex set of webs is based on technologies for grid self-healing and fast simulation and modeling first developed in CIN/SI research.

- Self-Healing Electricity Infrastructure. The CIN/SI technology concept of self-healing electricity infrastructure is presently the largest of the four Initiatives in EPRI's CEIDS program. This Initiative builds on CIN/SI technologies for self-healing, adaptive islanding, and SPID system. Research is coordinated with the base-funded work noted above.

- Rapid Simulation and Modeling. Another CIN/SI-derived CEIDS program that will be launched in late 2002/early 2003 is the rapid simulation and modeling project. This project is designed to provide the mathematical underpinning and look-ahead capability need for a self-healing grid. The objective is fast, look-ahead simulation, contingency planning and rapid restoration, as well as integration of real-time dynamic information to update simulation-based prescriptive and predictive models. As such, this project extends CIN/SI research and results for simulation of vulnerability assessment. The technical approach combines simulation and analytical tools to accomplish four tasks:

  1. Simulation modeling of complex electric networks

  2. Analysis methodology for abnormal behavior

3. Control, management, and optimization of complex electricity networks

4. Data mining and early prediction of abnormal behaviors

Electricity Innovation Institute Infrastructure Security Initiative (ISI). The ISI is a two-year, fast-track effort launched in 2002 in response to the tragedies of 9/11. ISI activities fall into three major areas:

1. pinpoint vulnerabilities in the electric power infrastructure

2. develop strategies to strengthen and protect the grid

3. outline plans for repaid recovery from any attacks that might occur.

Key aspects of the Initiative build upon CIN/SI results, in particular the vulnerability and secure communications program areas.

Enterprise Information Security (EIS). EPRI's EIS program grew out of Y2K (Year 2000) preparedness programs. The present focus is on four major task areas:

1. information sharing

2. intrusion/tamper detection

3. communication protocol security enhancement

4. high-speed encryption

CIN/SI results are being applied in each of these areas.

### 5.2.4 Defense Applications of CIN/SI Results

The theoretical foundation created by CIN/SI for designing, controlling, and protecting complex interactive systems provides the essential framework for the dispersed network-centric objective force envisioned for the future military. Efficient and fast modeling, robust design and control, and effective protection strategies all are necessary for this force, and all were addressed through CIN/SI research and development (Figure 5-4).

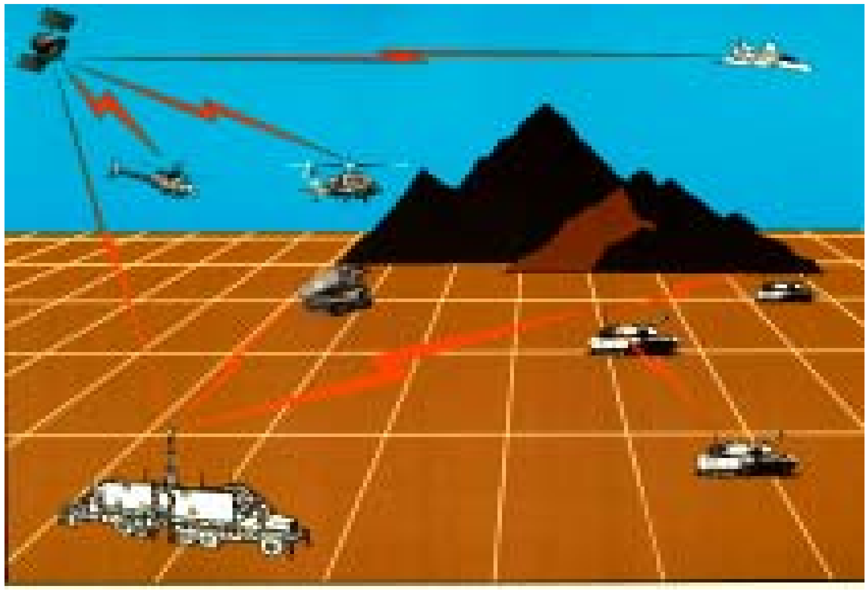


**Figure 5-4**
**Military Force of the Future.**
The future military force will employ integrated network control to coordinate all major functions on a regional basis, enabling more flexible system operations to meet changing conditions. Data will be gathered from all parts of the battlefield and combat theater, real-time analysis will provide instantaneous assessment of threats and opportunities, and resources will be dispatched on a regional basis to meet the challenge. Finally, soldiers on the ground will be integrated fully into command and sensor nets with two-way communications.

These new capabilities raise new opportunities for truly effective "*in silico*" simulation testing (analogous to high-fidelity flight simulators) for new devices and policies in the context of a whole battlefield, combat theater, or global framework. As is the case with the electric power system, full-scale *in vivo* testing for defense applications generally takes place only at full power in the heat of battle. Improved capability for predicting unintended consequences of designs and policies beforehand can identify failings that may be costly, even of human life.

For specific applications, many of the CIN/SI technologies developed for the electricity industry are appropriate for advanced military applications as well, both for their electric power systems (modern defense systems such as ships, aircraft, temporary bases and even vehicles require considerable power infrastructure), logistics functions ("an army travels on its stomach"), and for command and control functions. Key similarities exist between electric power networks and military command and control systems, as shown in Figure 5-5.

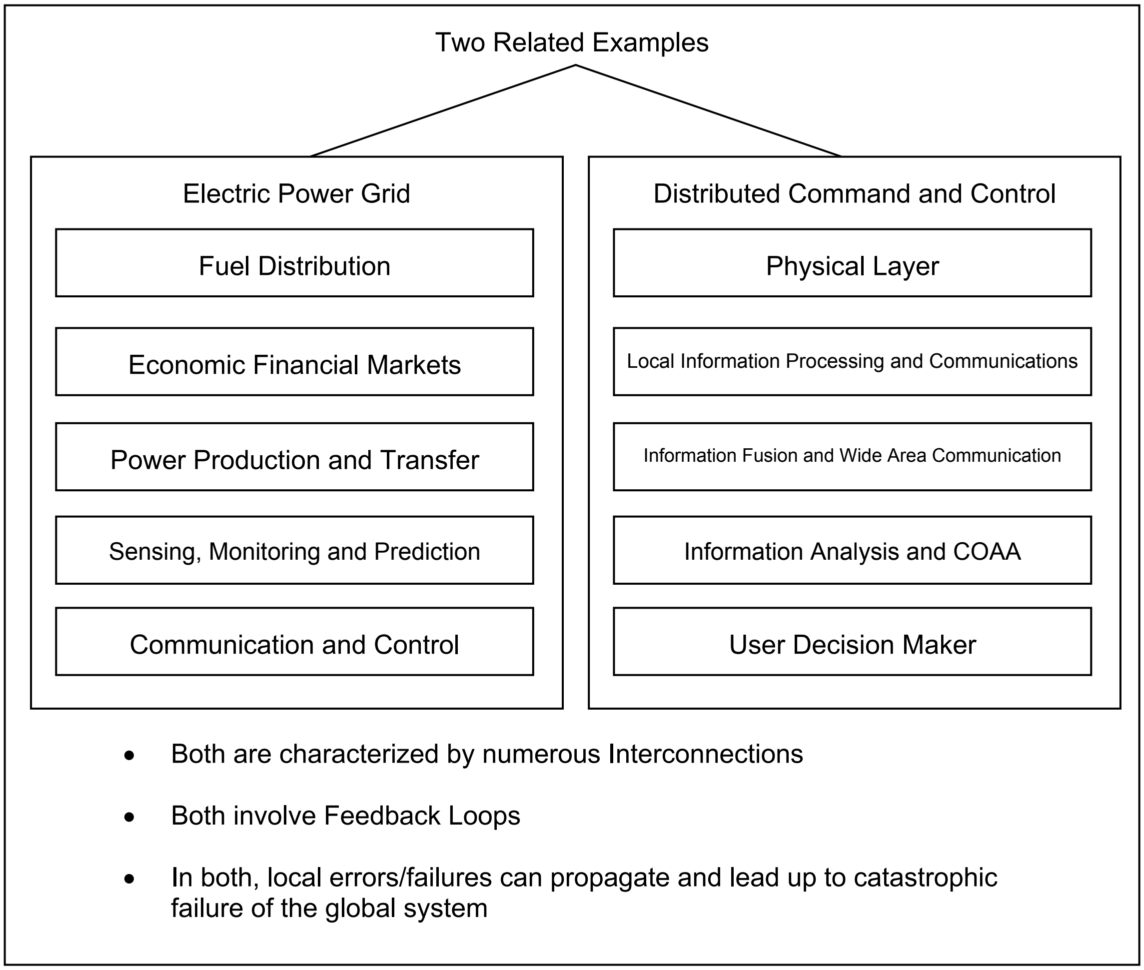



**Figure 5-5**
**Similarities between an Electric Power Network and a Military Command and Control System.**
Electricity grids and many military command systems exhibit links-and-layers structures, numerous interconnections among dispersed components, feedback loops, and the potential for local failures or errors to propagate and cascade, causing catastrophic failure of the larger system. For comparison, a typical electric utility incorporates the communications and control capabilities approximately equal to a U.S. Army division.

For example, self-healing technology can be employed in a ship, aircraft, vehicle, sensor system, communications net, command structure, or other defense system to automate recovery and maintain maximum performance after taking damage, just as it can help a power grid function during a storm that knocks out key components. Likewise, adaptive islanding technology will help dispersed defense systems keep functioning when damaged in combat or terror situations, by breaking a system in smaller components that can do their job on their own. SPID technology can guard defense communications and computer systems, among others, against attack in the first place. Another application envisioned for multi-agent SPID technology is coordination and control of small land-mine clearing robots. For this application, the robots themselves are considered to be the reactive layer, nearby soldiers or formations serve as the coordination layer, and the local or regional battle command center makes the high-level decisions of the deliberative layer.

In fact CIN/SI results can potentially be applied by the DOD to improve its ability to control and acquire data from the unmanned aerial vehicles through bandwidth optimization and congestion control protocols explored in CIN/SI.

For the future, the U.S. DOD has identified a number of specific CIN/SI research results and technologies for further development in a variety of defense programs. These program include:

Network-Centric Warfare. Superior information about enemy location and strength, properly applied, can multiply the effectiveness of a friendly force many times over. DOD is working to realize information-based force multipliers by networking sensors, decision-makers, and fighting forces on the battlefield and around the globe. The result of this networking is a highly interconnected, highly complex system. As such, CIN/SI work advances network-centric warfare capabilities in the fields of fast situation awareness (state estimation), filtering to find important information and anomalies in massive datasets (data mining), scaleable algorithms for analysis of complex systems, and robust control structures, among other areas.

Battle Command Systems. The DOD is exploring the potential of moving towards model-based command concepts, as opposed to the traditional message-based command approach. With model-based command, units and formations are guided by an organic real-time model of the battle or theater situation. Command messages need only be sent by exception or in extraordinary circumstances. This approach offers the significant advantage of minimum need for communications. In addition, it is readily coordinated with network-centric warfare systems both for deliberate strategic planning and for crisis action planning. To be effective, however, extremely sophisticated fast models linked to distributed databases will be required. CIN/SI results support DOD study of model-based battle command by providing insight into and solutions for such topics as distributed computing in complex systems, management and mining of dispersed data, state estimation using distributed sensors, and efficient communications.

Warrior Extended Battlespace Sensors (WEBS). Network-centric warfare and model-based command rely on information superiority. To help provide information superiority, DOD is exploiting advances in microtechnology and low-power processors and communications to pursue massive application of small, robust, and inexpensive sensors, called WEBS (Figure 5-6). Sensor types to be developed include acoustic, seismic, magnetic, infrared, visible, radar, passive RF/ELF, and others, in both mobile robot and unattended stationary applications. WEBS are envisioned for data collection in diverse roles, among them targeting, security, situation awareness, and damage assessment. Many advances are needed to make WEBS practical, such as visualization technology that allow a user to understand the situation and interact with WEBS to infuse command intent into the sensors. Several important advances stem from CIN/SI work, including robust communications with a high level of interference, intelligent agent technology, distributed computing and networking, and decentralized command and control.

# Warrior Extended Battlefield Sensors (WEBS)

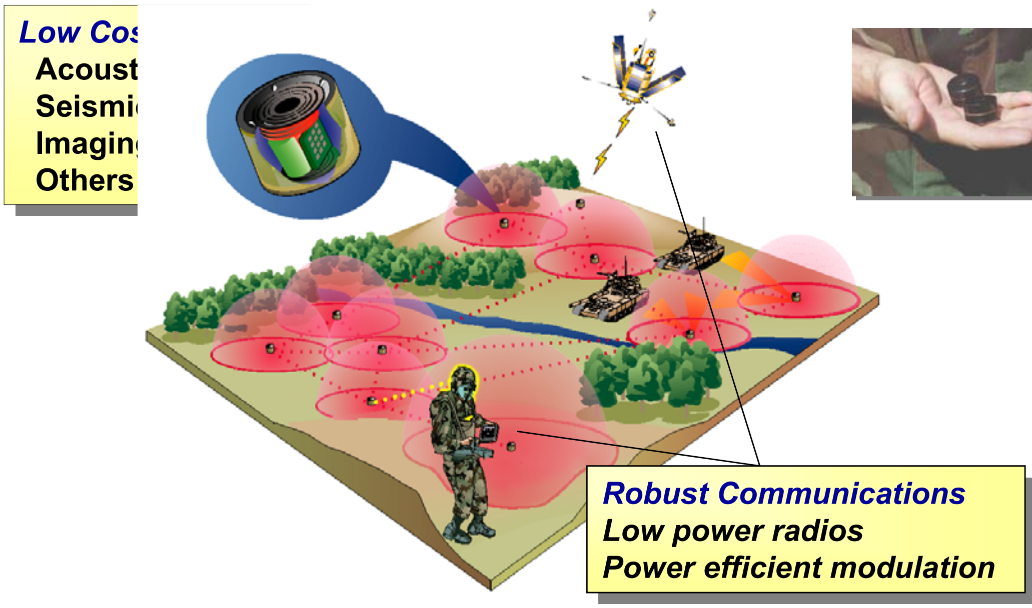



**Figure 5-6**
**Warrior Extended Battlespace Sensors (WEBS)**
Massive application of small, robust, and inexpensive sensors called WEBS is being pursued as a means of acquiring information superiority for effective network-centric warfare.

Distributed Intelligent Agent for Logistics (DIAL). Building on the deployment and supply lessons of 1991's Desert Storm and more recent deployments, DOD is upgrading its strategic logistical ability to better meet the global challenge of modern warfare. The objective is to change from traditional "just in case" logistical deployment to "just in time" logistics. One advanced tool under development to provide such capability is DIAL. DIAL addresses force generation, force movement, port operations, and strategic deployment within and from the continental United States (Figure 5-7). The heart of DIAL is a standardized, model-independent database of force status that can be dynamically coupled with any other DOD system or model. This "time-phased force and deployment database" includes information on force sequencing, routing of forces to be deployed, movement data associated with the forces, estimates of non-unit related cargo, and estimates of support requirements. CIN/SI results support the development of DIAL with extensive modeling and simulation tools for complex networks, efficient status and situation reporting algorithms, a variety of agent-based technologies, and approaches for parallel computing, flow analysis, and congestion control. Additional needs for DIAL include algorithms for "path planning," contingency analysis, optimal routing, load-ability, and available transfer capability.

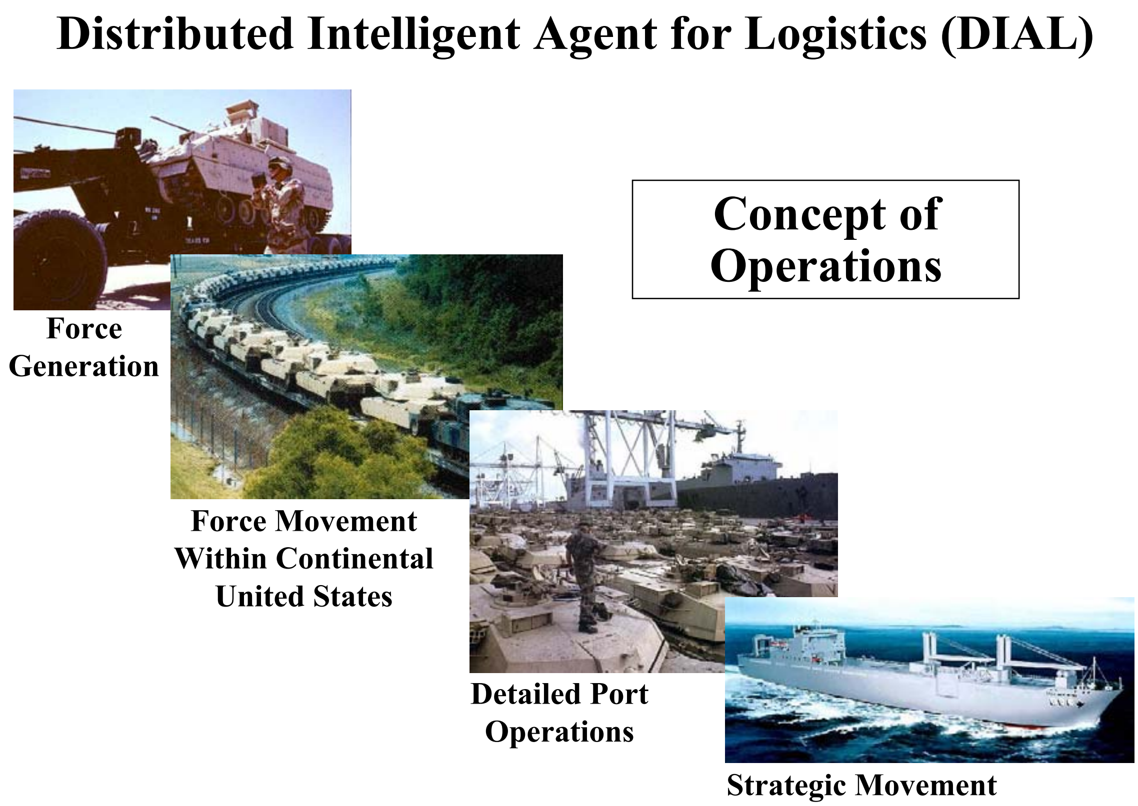



**Figure 5-7**
**Distributed Intelligent Agent for Logistics (DIAL)**
DIAL coordinates force generation, force movement, port operations, and strategic deployment within and from the continental United States, with the aim of "just in time" logistics.

Comprehensive Logistics and Warfighting Simulation (CLAWS). CLAWS bridges the gap between rear-area logistics management of DIAL and battle-area command-and-control activities. As such, it extends DIAL to create an intelligent, end-to-end logistics system dynamically coupled with a warfighting (or other operational) simulation for inter-theater applications. Applications of CIN/SI work to CLAWS are similar to those for DIAL.

## 5.3 Next-Step Research Program

CIN/SI results lay a solid foundation in the new field of analysis and control for complex interactive systems, but many system issues remain for future investigation. The following sections identify areas of research and specific issues needing to be addressed in order to fully realize the CIN/SI vision of robust, self-optimizing, self-healing control for power networks, other critical infrastructures, and defense applications for the future (Figure 5-8).


**Figure 5-8**
**Electric power system of the future.**
The future power system will employ integrated network control to coordinate all major power system functions on a regional basis, enabling more flexible system operations to meet changing customer needs.

Data will be gathered from all parts of the system and analyzed in real time, resources will be dispatched on a regional basis to keep up with load changes, and power electronic devices will provide instantaneous control of power flow. Finally, consumers will be integrated fully into electricity markets by electronic meters with two-way communications.

### *5.3.1 Next Steps for a Self-Healing Grid*

CIN/SI's prototype TELOS system has some capabilities for power grid self-healing, and some concepts will be deployed in intelligent, adaptive controls on real-world power systems in 2003. However, the ultimate goal of the self-healing grid is to provide automated capabilities that can anticipate many potential problems, reduce recovery time when unexpected disturbances actually occur, and enhance performance of normal operations. To reach this goal, three primary objectives still need to be achieved: 1) dynamically optimize the performance and robustness of the system, 2) quickly react to disturbances in such a way as to minimize impact, and 3) effectively restore the system to a stable operating region after a disturbance. For the full self-healing grid concept to be implemented, technology development must be supported in several areas:

- Development of fast algorithms to propose alternative reconfigurations of the system
- Look-ahead simulations to verify the feasibility and reliability of each configuration.
- Develop modeling and analysis capabilities to understand the true dynamics of a CAS network
- Development of new modeling techniques that can be used to analyze the dynamics of transmission and distribution networks
- New modeling techniques to halt disturbances quickly (in the order of milliseconds or faster)
- Improved optimization and control theory leading to implementable algorithms for grid optimization
- Decision analysis able to model hybrid (discrete/continuous) systems
- Stability simulation capabilities
- Automation of recovery operations to carry out actual reconnections for grid reconfiguration quickly and effectively.
- Tools to make human intervention on both transmission and distribution systems more efficient.
- Incorporate self-healing into the software of intelligent network agents for integration into SPID control architecture
- Develop anticipatory control theory: combining predictions with scheduling and optimal control
- Enhance TELOS with contingency analysis capabilities, quantify performance and prepare for on-line mode of operation (verification and validation)

### *5.3.2 Next Steps for Adaptive Islanding*

As a first step towards adaptive islanding, CIN/SI researchers developed initial concepts for on-line islanding in response to contingencies, as well as quantitative criteria for pre-defining small islands within existing power systems. Full implementation of adaptive islanding will provide a flexible technique to minimize the overall impact of a disturbance (including terrorist attack), taking into account the location and severity of damage, load status, and available generation. Adaptive islanding could be applied either as a precautionary measure to terrorism threats detected by intelligence agencies or storm threats predicted by weather forecasters, or as an automatic or operator-triggered response to sudden, unexpected disturbances. Implementation of such adaptive islanding will require considerable additional advances. Areas of research include:

- Development of fast pattern-recognition and diagnostic systems to rapidly determine the locations and nature of disturbance events, distinguish between natural and terrorist events, and estimate the amount of damage

- Analytical capabilities to separate the grid optimally into self-sustaining electric islands
- Wide-area security monitoring
- Network topology estimation
- Use of wide-area measurement sensors in island settings
- Extend adaptive load-forecasting methods for use to dispatch distributed resources (DR) to help stabilize the power system in each island (and to prepare for eventual reconnection of the islands).

### 5.3.3 Next Steps for SPID System

Prototype SPID software was developed and tested by CINSI's APT consortium. Implementation of a full-scale SPID-based control system for a power network will require developing a portfolio of new technologies and support systems. A wide-area measurement system (WAMS), for example, will be needed to provide synchronized phasor measurements (voltage and phase angle) from widely separated points in a network. A new generation of other sensors will need to be developed and deployed in order to provide accurate information on a variety of system conditions. Protecting such information from tampering or sabotage will require development of a secure communications system. Finally, the completed SPID software—incorporating self-healing algorithms—will have to be built into the microprocessors that form the physical basis of intelligent network agents. In particular, future work will be needed in the following areas in order to achieve a mature technology for full deployment in the power industry:

- Real time on-line implementation of adaptive islanding techniques
- Real time implementation with topology processing and on-line update of islands
- Feasibility demonstration of the SPID with off-line studies in an Energy Management System (EMS) environment
- Strategic power infrastructure defense (SPID) system prototype with wide area measurements
- Islanding criteria for wide area measurements
- Advanced communication system designs/robust designs incorporating time delays
- Implementation of GPS synchronization for the robust control
- Advanced sensor development and sensor placement
- Collection of data on communication delays in various media and simulate the delays in designing robust control and remedial actions
- Risk management methodologies for complex systems
- Use of wide area control in complex systems

### 5.3.4 Next Steps for Vulnerability Assessment

Various approaches and techniques for evaluating vulnerability in complex networks have been devised in CIN/SI research, and additional research is being driven now by concerns about terrorist threats to critical infrastructure that have arise since the 9/11 attacks. Analytical and computational tools needed for measuring and modeling vulnerability in large-scale complex networks include:

- Formal methods for modeling true dynamics and for real-time computation to cope with system uncertainties and establish provable performance bounds
- Multi-resolution simulations, with the ability to go from the macro-to the micro-level, and vice versa
- "Artificial life" (cellular automata and multi-agent models) for modeling and solving otherwise intractable problems in networked systems
- Real-time survey and status monitoring of systems
- Techniques for correlating information from separate data sources/sensors
- Intelligent sensors and actuators
- Methods for providing feedback about key environmental variables
- Accelerated agent testing for discovering dangerous patterns
- Vulnerability assessment methodology for wide area communication and information networks
- Damage assessment and control to prevent catastrophic failures

### 5.3.5 Next Steps for Secure Communications for Dispersed Systems

CIN/SI results identify various technologies for robust yet efficient communications among dispersed agents and continental-scale systems, but additional research is required, including:

- Develop a realistic treatment of variable communication delays in controlled network environments
- Explore possibilities of using price-based incentives provided to individual users to control congestion via flow adjustments
- Completely develop a distributed communications protocol for power networks based on Spinglass and gossip techniques
- Study uniqueness of and asynchronous stability of Nash equilibria for routing in complex (random) CAS topologies
- Prediction for routing in communication systems (switching architecture)
- Network switching to support multiple types of network traffic with different performance requirements

### 5.3.6 Next Steps for Mathematical Computational Foundations for Integrated Network Control

Many schemes were devised and demonstrated by CIN/SI researchers for efficient computing and control of complex interactive systems. To enable full design and control capabilities for these systems, a comprehensive mathematical framework is needed, including

- Optimization and control theory along with the decision analysis to model hybrid (mixed discrete/continuous) systems
- Techniques for on-line mathematical modeling and decision support with practical inputs and in the presence of errors
- Automatic verification of real-time adaptive systems using formal proofs from specifications
- Task coordination of multiple intelligent agents (both artificial and human) in uncertain dynamic systems
- Overall control techniques in environments where intelligent response devices may be acting against each other
- Fluid simulation scheme for high speed communication networks with quantifiable accuracy and ability to model packet-based routing and congestion control
- Control of large networks, involving multiple players with, perhaps, conflicting goals
- Characterization of interdependencies, cascading failures, and other mechanisms of network failure
- Disturbance detection and threshold-based security monitoring
- Distributed computation and control
- Quantum networks: fundamental physical limits to information and computation
- Unified theory of control, communications, computing for complex systems
- Statistical physics and theoretical foundation for robustness of designed systems
- Characterize the physical limits of information and networks
- Extend complexity theory criteria for model selection/validation with particular emphasis on theoretical foundations using minimum description length principle and stochastic complexity

### 5.3.7 Next Steps for Intelligent Network Agents

Through CIN/SI research, considerable progress has been made in developing realistic test cases for simulated agents, introducing new techniques for coordination and on-line context interpretation, and identifying ways to use the agents to help integrate physical network operations with real-time market functions. Extending CIN/SI results to create a new generation of context-dependent INAs is one of the most complex tasks facing developers of the power system of the future. Specific tasks include:

- Development and integration of agents that are semi-autonomous yet collaborative
- Agents that are both modular and fully integrated
- Agents able to function in multiple modes
- Strategies for agents to self-improve based on experience
- Adaptive strategies that help components discern their interactions with the environment
- Methods for agent reasoning, planning, negotiation, and optimization
- Methods for rule generation and modification
- Tools for automated negotiation and risk management among self-interested agents (e.g., game theory with computational and resource bounds)
- Algorithms for "optimal" performance by independent agents with independent objectives
- Large-scale CDNA application demonstrations
- CDNA validation and formal analysis

# 6
# CONCLUSION

This chapter describes CIN/SI links to future research challenges and research programs, some perspectives about the Initiative and its results, and lessons learned.

## 6.1 "Grand Challenges" for the Electricity Enterprise

During a six-month period in late 2001 and early 2002, the U.S. National Science Foundation (NSF) and EPRI hosted a series of three workshops to focus attention on the latest concerns facing the electricity enterprise. One workshop addressed the need for transmission system enhancement; one looked at the intersection of economic, electric power and adaptive systems; and one explored global dynamic optimization of the electric power grid. Each was organized around several "grand challenges" that identified the critical issues for each topic. The workshops and challenges were:

### *6.1.1 Workshop 1: Urgent Opportunities for Transmission System Enhancement (October 2001)*

- Lack of transmission capability: transmission load is projected to grow in the next ten years by 25 percent and the grid by only 4 percent
- Grid operation in a competitive market environment: open access created new and heavy, long distance power transfers for which the grid was not designed
- Growing power infrastructure vulnerability: heavier loading is making the grid even more vulnerable

### *6.1.2 Workshop 2: Economics, Electric Power, and Adaptive Systems (March 2002)*

- Economics: how to design competitive electric power markets
- Electric power engineering: redefining power system planning and operation in the competitive era
- Adaptive systems: problems with adaptive control technologies

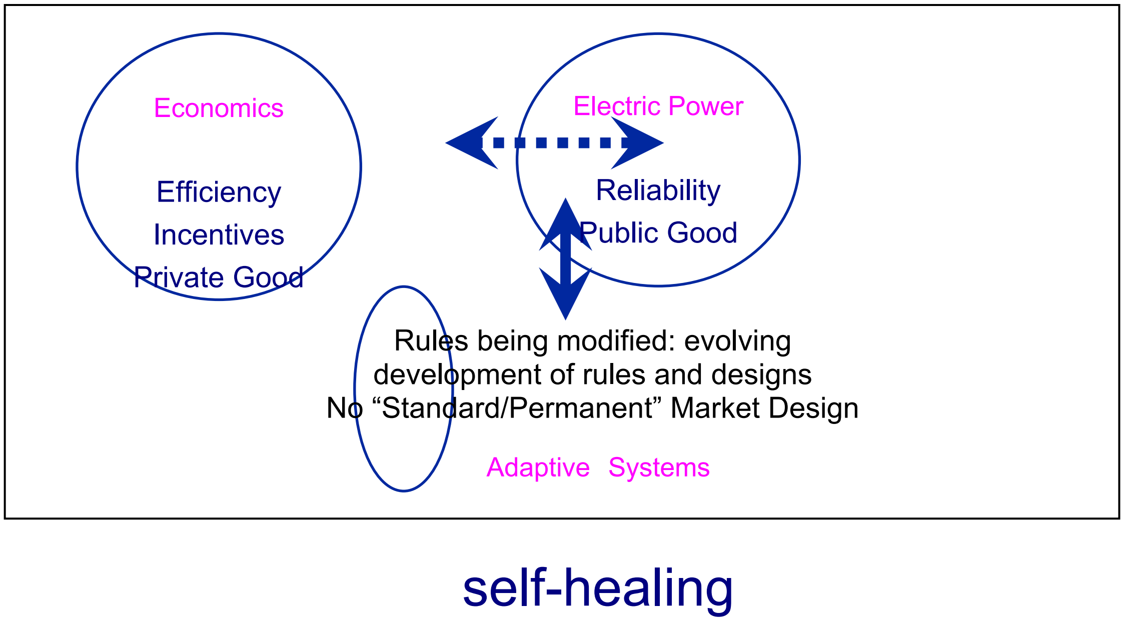



**Figure 6-1**
**Links among Economics, Electric Power, and Adaptive Systems.**
Grand challenges in each of these three areas were the subject of the second of three EPRI/NSF power industry workshops held in 2001-2002.

### *6.1.3 Workshop 3: Global Dynamic Optimization of the Electric Power Grid (April 2002)*

- What is the "optimum" type, mix, and placement of control hardware
- How to achieve integrated network control
- How to coordinate centralized and decentralized control
- What infrastructure hardware will be required by various strategies
- Needs for benchmark network to test theories
- Need pilot schemes to prove validity of concepts after simulation

These challenges are real and significant, despite the advances made in the coordinated program of CIN/SI research to answer them. Major technical challenges were addressed through this Initiative in the areas of modeling and simulation for complex interactive systems; measurement, sensing, and visualization; control systems; and system operations and management. These advances better position us to take on the grand challenges of the 21st century, for critical infrastructures (as well as national defense alike), but considerable additional research advances will be required.

## 6.2 CIN/SI Perspectives

The CIN/SI, a jointly funded $22 million GICUR program between the Deputy Under Secretary of Defense (Science and Technology), through the ARO, and EPRI, ran for three years, from 1999 to early 2002.

During the course of this program, new tools and techniques were developed that enable large national infrastructures to self-healing. CIN/SI-designed tools and techniques that will help ensure the reliability and robustness of the country's interdependent infrastructures for energy, communications, finance, and transportation. The emphasis has been on the "hard engineered" national infrastructures along with economics modeling. Two particular areas in which important advances were made are 1) identifying and controlling cascading failures in electric power systems and other complex networks, and 2) implementing data exchange and control systems for dispersed sensors and agents.

The new tools and techniques of CIN/SI also advance DOD capabilities for futuristic network-centric warfare, where important force multipliers will be provided by superior information. CIN/SI advances in the areas of 1) coordinating multiple intelligent agents and 2) managing massive dispersed data sets are proving particularly important.

Extensive material is available about the specific results of the program, including more than 360 technical papers published or in press. Some 19 technologies have been extracted to date and are being moved into industry-funded programs at EPRI, and at least five ongoing DOD programs draw significantly upon CIN/SI results.

From a broader impact, CIN/SI created tremendous visibility for the value and application of applied mathematics and complex systems theory and stimulated other significant research activities. The Initiative received high praise from members of the Governing and Oversight Council (see Appendix B), the electric power industry, and government agencies including the White House Office of Science and Technology Policy, National Science Foundation, Department of Energy, the National Laboratories, and several organizations involved in the Critical Infrastructure Protection effort. Indeed, the White House Office of Science and Technology Policy identified the CIN/SI as the lead and only federal R&D initiative on infrastructure interdependencies, as well as a significant initiative for critical infrastructure protection. The spirit of private-public partnerships that result in substantial achievements for both the public interest and the private sector were well met.

## 6.3 Lessons Learned about Team Formation and Continued Innovation

During its three years of activity, the CIN/SI program involved more than 200 researchers, advisors, and managers representing more than 40 separate organizations from academia, private industry, and both civilian and military government agencies. This large size and diversity were necessary to address the challenge of self-healing for complex interactive systems, which would be far beyond the scope any single university research department or private contractor.

All accounts agree that the Initiative was highly successful despite its size and diversity of members. Important research results were achieved, program objectives were met, and the work was professionally and personally rewarding for participants.

### 6.3.1 CIN/SI Success Factors

The success of the CIN/SI was no accident, but instead represented the hard work of many people. Factors relevant to the Initiative's success include the following (also see Appendix C):

- Strong technical and organizational infrastructure
- Clear purpose, language, and communication at all levels. The theme and vision were set very early on, before work began, and revisited on an on-going basis.
- Multiple channels available for knowledge transfer
- Support from senior management and stakeholders

As a result, the CIN/SI fostered true innovation in an emerging field of science and technology. Innovation is well thought of a team sport: it is most often achieved when ideas and objects/tools are brought together in novels ways as never before. Continued innovation such as was achieved through this Initiative will help us overcome the global challenges of today and tomorrow.

### 6.3.2 CIN/SI as a Model for Other Initiatives

The success of the EPRI/DOD CIN/SI program has resulted in the subsequent formation of related research programs by other organizations. The largest of these programs and the organizations overseeing them are:

<u>DOE and the National Laboratories.</u>

- Infrastructure Interdependencies (including the National Infrastructure Simulation & Analysis Center, NISAC, at Sandia National Lab)
- Critical Path Infrastructure Program

<u>DOD and DARPA.</u>

- Intrusion Tolerant Systems Program (on the cyber dimensions of the CIN/SI)
- Networks in the Skies and Fault Tolerant Networks
- Advances in Enterprise Control Program (on the application of control theories to military command and control)
- Effects-based, Nonlinear Analysis and State Estimation (Endstate)

- HACQSIT Hierarchical Adaptive Control for Quality of Service Intrusion Tolerance (on self-healing approaches for computer system back-up and recovery)

National Science Foundation.

- Exploratory Research on Engineering the Transport Industries (ETI) Initiative
- 1998 Knowledge and Distributed Intelligence Initiative (KDI)
- NSF/ONR Partnership in Electric Power Networks Efficiency and Security (EPNES).

Europe.

- European Union: Infrastructure Security and Interdependencies Initiative
- European Commission: Infrastructure Interdependency Roadmap
- Research teams from CESI, Pirelli, EDF, and several universities including Polytechnic Institute of Grenoble (INPG), ETH in Zurich, and Lusanne.

# A
# ORGANIZATIONS AND ADVISORS INVOLVED WITH THE CIN/SI

The Complex Interactive Networks/Systems Initiative was a joint project of the

- Deputy Under Secretary of Defense for Science and Technology, acting through the Army Research Office (ARO)
- EPRI Strategic Science and Technology (SS&T) program

As a wide-reaching GICUR, the Initiative attracted widespread interest and participation far beyond the initial funding organizations and academia. Diverse government agencies, private industry, universities, and international organizations were involved throughout the research and oversight process, as follows:

## A.1 Universities

- Arizona State University
- Boston University
- Caltech (lead)
- Carnegie-Mellon University (lead)
- Cornell University (lead)
- Fisk University
- George Washington University
- Harvard University
- Iowa State University
- MIT
- Purdue University (lead)
- RPI
- Stanford University
- Texas A&M University
- University of California, Berkeley
- University of California, Los Angeles

- University of California, Santa Barbara
- University of Illinois, Urbana-Champaign
- University of Massachusetts
- University of Minnesota
- University of Tennessee
- University of Washington (lead)
- University of Wisconsin, Madison
- Virginia Polytechnic Institute
- Washington State University
- Washington University, St. Louis

## A.2 U.S. Government

- Department of Commerce
- Department of Defense
- Department of Energy
  - National Laboratories
  - Offices of Critical Infrastructure Protection and Energy Assurance
- Department of State
- Department of Transportation
- Federal Aviation Administration
- National Science Foundation
- Tennessee Valley Authority
- Western Area Power Administration.
- White House Office of Science and Technology Policy

## A.3 State and Local Governments

- California Energy Commission
- National Governors Association

## A.4 International Governments

- Asia
- European Union

## A.5 Private Sector

- ABB
- CESI
- Commonwealth Edison/Exelon Corp
- IBM
- Intel
- Pirelli
- Powertech
- Raytheon

## A.6 EPRI SS&T Interest Group (Review and Advice)

- American Electric Power (AEP)
- Bonneville Power Administration (BPA)
- California Energy Commission (CEC)
- California Independent System Operator (CA-ISO)
- Consolidated Edison of New York
- CPS-SATX
- Duke
- Electricité de France
- ESKOM
- Fortum
- GPU Nuclear
- Idaho Power
- Illinois Power
- Independent System Operator of New England (ISO-NE)
- Keyspan Energy
- Manitoba Hydro
- New York Power Authority (NYPA)
- Orange & Rockland Utilities
- Southern Company
- TXU and ONCOR

- VTT Energy
- Wisconsin Energy
- Western Area Power Administration (WAPA)

# B
# CIN/SI PROCESSES, GOVERNANCE, AND OVERSIGHT

A key pertinent dimension in the success of a large Initiative involves processes, governance, and oversight of the overall work. Processes were successfully implemented for the EPRI/DOD CIN/SI program, by jointly creating and actively participating in a Governing and Oversight (G&O) Council. The G&O Council consisted of ten voting "statesman/director" members, appointed by funding participants (five appointed by DOD and five by EPRI).

## B.1 Governing and Oversight Council

The objectives of the G&O Council as defined in the research announcement and in the agreement between DOD and EPRI were:

> *"The Government and EPRI will create and actively participate in a Governing and Oversight Council (the "Council") to*
>
> 1. *review, evaluate, select, fund and track the progress of university research efforts in the Initiative;*
> 2. *develop a plan of theoretical and applied research to guide the research;*
> 3. *promote collaboration and integration of results among participating consortia;*
> 4. *review, extend or terminate research support as conditions dictate.*
>
> *The Council, under its direction, will utilize EPRI in concert with Army Research Office (ARO) to manage the joint projects under the Initiative. Its membership shall be no greater than ten voting members who shall be drawn from funding participants, including DoD.*
>
> *In order to integrate the results from all participating consortia to meet the overall objectives of the Initiative, the Council will manage the Initiative in a larger consortium environment. Each participating consortium will be expected to share information, ideas and results with other participating consortia."*

To supplement the G&O Council, EPRI provided overall program coordination, jointly issued requests for proposals, organized source selection processes, negotiated and issued contracts, managed project expenditures and milestones, and coordinated the deliverables to meet EPRI-DOD objectives.

## B.2 Members of the CIN/SI Governing and Oversight Council

The CIN/SI could not have been as successful as it was without the dedicated service and support of the G&O Council members. Individual serving on the Council during 1999-2001 were:

- Dr. Chester Carroll, Chief Engineer, U.S. Army Aviation and Missile Command
- Dr. Jim Chang, Director of the U.S. Army Research Office and Army Research Labs
- Dr. Marc Jacobs, Program Director at the U.S. Air Force Office of Scientific Research
- Dr. Gail Kendall, Director of Strategic Science and Technology at EPRI (now Managing Director at the China Light and Power Research Institute in Hong Kong)
- Dr. Wendy Martinez, Program Director at the Office of Naval Research
- Mr. Bruce Renz, Vice President-American Electric Power (AEP)
- Mr. Thomas Tanton, Executive Office-California Energy Commission (CEC)
- Mr. Stephen Whitley, Chief Operating Officer, New England Independent Systems Operator (formerly, at the initial appointment, General Manager of Tennessee Valley Authority)
- Dr. Dan Willard, U.S. Army HQ, Pentagon
- Ms. Vickie VanZandt, Vice President and Chief Engineer-Bonneville Power Administration (BPA)

# C
# DEVELOPMENT AND LEADERSHIP OF RESEARCH CONSORTIA

## Development and Leadership of Research Consortia: Lessons learned and possible road ahead for continued innovation

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The objective of this presentation is to discuss issues involved in the formation, and successful operation of research consortia. As an example, the Complex Interactive Network and Systems Initiative, CINSI, is a program that aims to develop tools and techniques that will enable national infrastructures to self-heal. EPRI and DOD are jointly funding the project for about $30 million over five years. From the very start, the funding partners appreciated that the research challenges were beyond the scope of any single contractor or university department; thus CINSI was organized on a consortia basis. The kick-off for the program was held in May 1999. There are six consortia, each comprising about three to six universities and, in a few of the consortia, an industrial partner. I shall provide an analysis of the funded consortia and discuss issues involved based on models of (i) creativity and innovation and (ii) successful knowledge management projects. Pertinent issues and some thoughts on successful team formation and continued innovation include:

- Why form consortia? Is collaboration and teaming worthwhile? Does it lead to elitist “us vs. them” attitudes instead of open communication leading to creative work? How to identify and prevent such tendencies? Identify potentially divisive issues including allocation of resources among consortia members.
- Setting the theme very early on and up front, before the actual work begins, in a clear examination of assumptions, re-visiting groups' vision and re-examining their responsibilities after their selection and at an on-going basis.
- Communication: How would the consortia participants share their progress reports inter-/ intra-consortium? How would the consortia participants share their progress reports with funders? How often, in what form? Also… satisfying the associated milestones and time-lines.
- Avoid “micro managing”; encourage researchers’ own feeling of excitement for their innovative work and of their control over their activities and contributions. A good

opportunity to enhance this, for example, by asking each team to develop its own methods of effectively communicating between the various members of the team. Culture and chief researchers' attitudes could play a key role in success or failure of graduate student interactions both within a university and between them. Charging the members to develop their own communication processes, make it their responsibility/goal to be successful rather than "micro-managing" this process ourselves. They may come up with exciting and effective ways of communicating. There may be other areas where management can enhance their performance by charging them to develop solutions, rather than giving them directives.

- Face-to-face meetings with follow-up regular interfacing and creating inter-dependence: Workshops, formal sets of meetings as well as opportunistic forms of interaction among them.
- Facilitate mechanisms (and allocate budgets and rewards) for collaboration at "lower levels" including graduate students and faculty working together; developing as much familiarity with each other as possible. E.g. graduate student symposia: Request each consortium to provide a few (say 2) challenging problems before the meeting and then have them work on it for three days and present the results; follow-up efforts and results (funding for their travel).
- Identify and set clear go/no-go points. Also be aware of the ever-present conflict between managing a project to enhance creativity and managing a project to optimize the chances of success and go/no go is part of this, as is regular reporting of progress.
- Clearly and explicitly address/discuss the role of the overall consortium manager: Many of the points indicated depend on a strong and consistent unifying presence provided by the overall consortium management team. In particular, one of the challenges faced is managing the program to its overall goals while balancing varying (or even conflicting) interests of stakeholders that include other commitments and sources of funding. Assembling and managing the consortium has to recognize and plan for these somewhat competing agendas. Also, this issue underscores the points made about communication, and how to optimize handling this issue effectively, since it is present in almost all consortia. Another aspect of the communications that has proven absolutely essential to effective management of this "competing agenda" issue is consistent and frequent external communication to the various stakeholders of the purpose, progress, and characteristics of the consortium. This not only builds consensus, but to some degree it supersedes the competition between the various agenda because the external expectations and image take precedence.

These observations can be analyzed using models of (i) creativity and innovation and (ii) knowledge management (KM). These two are linked themes, as they are potential synergies in creating knowledge, then leveraging it and developing a potentially positive feedback loop.

“Creativity” drives the step in which knowledge is created and built: the discovery of research results and development of innovations are creative processes. Although each result and innovation is useful in its own right, the discipline of knowledge management enables them to be leveraged. KM does this by revealing the synergies in the results and innovations; by cross-fertilizing the outputs of that first creative step and enabling researchers to combine the existing knowledge in new ways, thus prompting fresh innovation and discovery. In summary, KM provides a feedback mechanism for the creation of further knowledge.

Before we focus on the macro organization of multi-university consortia, it is pertinent to consider a “smaller” example let us view a school or even a department as a “learning consortium”. As we know the core competency of a research university is not transferring knowledge but creating it—a shared responsibility of faculty and students. This requires inversion of the top-down faculty-centered view to a learning community where students are coupled to other students, faculty, other professionals and research communities, employers, and funding agencies. In addition, students naturally cross-departmental lines and create novel connections. Student feedback on teaching, direction of research and internal structure of the school can be valuable.

Since faculty are the key to making any university design work, a new approach to faculty selection is also called for. Thus the criteria for faculty selection in a school that plans to focus the energy of its students and faculty on challenges posed by nature, society, and technology must go beyond the usual criteria. Traditional criteria of research and teaching excellence within a single disciplinary context will need to take into account potential larger impact and trans-disciplinary interests and experiences. These may include demonstrated record of being innovative, interactive, integrative, and willingness to be involved. Creation of new curricula and courses need to be considered involving courses that mix "bottom-up" learning (which builds up a broad base of general competency and work toward tackling topics at the frontier) with "top-down" learning (starts with a frontier problem and works its way down, working at picking up knowledge required to understand a frontier problem or solution). Also mix single discipline courses taught by one professor, with trans-disciplinary courses, taught by a team of professors representing different departments. Remain adaptive and avoid predetermined rigid curricula and encourage students’ feedback and their learning activities from each other. Encourage teams of students to work on key questions and develop ways for them to share their results with other teams and even other schools—e.g. through the Internet.

Establish problem-oriented entities, Centers, which cut across departmental boundaries and create bridges between departments and disciplines (historically departments of material science, bio-medical engineering and even earth and planetary sciences were created in this way). Such centers can be an inspiration for new courses, seminars to address challenges posed by nature and society. In addition, these centers can be devoted to nurturing "pre-centers" with the responsibility of exploratory and strategic research on a wide range of trans-disciplinary problems. This may even be a Center of Centers and as it matures, the university can consider spinning it off into a new and more specialized Center (which may over time become a Department). But to keep this as a living and thriving system, it is important to keep this Center of Centers small, adaptive, flexible and innovative, rather than becoming a school or college.

## Creativity

Over the last 15 years, studies of creativity have paid increasing attention to the issue of *climate*. This can be discriminated from culture in that it refers to the more accessible and observable behaviors and attitudes – culture usually refers to deep-rooted beliefs and values. A widely cited study is that of Ekvall (1991). He considered climate as a moderating force on communications, problem solving, decision-making, learning and motivations. He studied 35 Swedish and US organizations and classified them into two groups: innovative and stagnated. He showed that 10 factors (in his nomenclature, dimensions) discriminated them, as shown in Table C-1.

**Table C-1**
**Creative climate dimensions**

| *Dimension* | *Creative climate* | *Uncreative climate* |
|---|---|---|
| Challenge | Enjoyable and energetic | Alienated and indifferent |
| Dynamism | Excitedly busy | Boringly slow |
| Idea time | Off task play | Little off task play |
| Playfulness | Happy, humorous | Dull, serious |
| Conflict | Debated with insight | Warfare |
| Openness | Trusting, failure accepted | Suspicious, failure punished |
| Support | People listen | Critical, negative comments |
| Freedom | Independent initiatives | Passive, rule bound |
| Debates | Contentious ideas voiced | Little questioning |
| Risk taking | Act on new ideas | Detail and committee bound |

**(source: Ekvall, 1991)**

Looking at Ekvall's dimensions it is clear that there is a tension between the freedom required for creativity and the control needed for properly administering a large project. This paradox is recognized but can be resolved:

> "bureaucracy and formalism are enemies of creativity and innovation, but nevertheless we do need formal procedures and routines to be able to utilize the creative potential existing in the organization" (Ekvall, 1991).

Indeed we have found that it pays to have both a disciplined, structured environment with long breaks that allow time for creativity (innovation requires blocks of discretionary time[1]).

## Knowledge Management (KM)

Definitions of knowledge abound. In the knowledge management (KM) literature, a typical one is "information combined with experience, context, interpretation and reflection" (Davenport, de Long and Beers, 1998). Similarly, there are many definitions of knowledge management, but they all seem to come down to the same question: how can organizations use knowledge more effectively?

KM is a key step in realizing additional value from the initiative. By establishing methods of easily sharing and accessing each others data, information and knowledge, the consortia will be able to exploit synergies that would not otherwise have been apparent. In my opinion, this would greatly enhance the prospect of uncovering truly radical innovations. Knowledge management

[1] One of my colleagues pointed out that while the above ideas are great, throughout history, some of the best creativity has come right after warfare, dark ages or other tragic events.

was an explicit part of the CINSI Request for Proposal. I think it is therefore reasonable to evaluate the consortia against the criteria that are indicators of successful KM projects. Just as there are many definitions of KM, there are many lists of criteria by which to establish quality. A typical list is that provided by Davenport *et al. (ibid.*). Although their paper focuses on large KM projects, many of their factors are transferable to a situation such as CINSI, where there is a relatively small budget available for such issues. Relevant success factors are:

- Technical and organizational infrastructure.
- Clear purpose and language.
- Multiple channels for knowledge transfer.
- Senior management and stake-holder support.

Does any of this actually matter? The consortia are producing knowledge, so does it matter if they only interact and actively share this knowledge once a year or more? I believe it does, in the sense that the consortia are missing a major opportunity. Referring to Nonaka's work on knowledge management (1991), we see that one of the crucial elements is already in place: redundancy. For Nonaka, the process of creating new knowledge depends on "tapping the tacit and often highly subjective insights, intuitions and hunches of individual employees and making those insights available for testing and use by the company as a whole." And this requires redundancy:

> "Redundancy is important because it encourages frequent dialogue and communication. This helps create a 'common cognitive ground' among employees and thus facilitates the transfer of tacit knowledge. Since members of the organisation share overlapping information, they can sense what others are trying to articulate" (Nonaka, 1991).

The EPRI/DoD CINS program has plenty of redundancy, as is clear from the (type of challenge *vs.* type of solution) matrix that has been used to analyze the CINSI portfolio. However without open and effective communication channels between these overlapping parts, all the benefits of redundancy will be lost. Effective collaboration and other related areas will be discussed during the panel session.

## Bigger picture

"The empires of the future," said Winston Churchill, "are the empires of the mind". Echoing this in his 1981 book, *Investing in people: The Economics of Population Quality*, Economist and Nobel Laureate, Theodore Schultz, argued that the wealth of nations is not limited by land or minerals, it comes predominantly from "the acquired abilities of people, their education, experience, skills and health." What are we doing about this?

Nations have been slow to heed this wisdom, and what is needed is not done. Children's education, particularly for girls, is not a high priority for many governments. In many industrialized countries educational systems remain troubled, teachers don't enjoy the respect they once enjoyed and investments on development of "human capital" are minimal (Nichols 1999).

In the U.S. scientist and engineers working in R&D make up about 75 out of every 10,000 people employed, about 80/10,000 in Japan, 50/10,000 in UK, 30 in Italy and fewer than a handful in most developing countries. US spending in R&D accounts for 2.5% of the GDP, yet the results rippling outward from the investments in technology—and its related educational base—accounts for "perhaps 50% of the past growth of the American economy. I don't mean to overstate the roles of science and technology. But nations that invest in those fields of human capital do better economically than those nations that do not."

In more developed countries, competition for funds and jobs is often fierce, and the need to account for every penny on shortening deadlines saps the energy out of every R&D team; hence the young investigators see the future as both tempting and frustrating. Even worse, many scientists feel the "chill of attitudes" noted 20 years ago by an English immunologist Sir Peter Medawar, in his book Advice to a Young Scientist. "One of the worst forms of snobbism in science is that which draws a class distinction between pure and applied science." How much time and energy is squandered simply because investigators find it necessary to defend the rationale for, the existence of, excellence in,... activities that are economically motivated?

While being conscious of such hurdles, there is a synergy when researchers, their ideas and teams work together; innovation is most often achieved when ideas and objects/tools are brought together in novel ways as never before. The prevailing paradigm for the analysis and optimization of system operations, as well as for engineering design itself, uses a “top down” approach through mathematical programming. It is based philosophically on the prevailing scientific methodology of “reductionism.” Although this scientific method has been remarkably successful in, for instance, reducing chemistry to physics, it has not been able to completely reduce biology to chemistry or sociology to biology.

Indeed, throughout most of our civilization, scientific explanation by reduction have given rise a subdivision of the natural and engineered systems into smaller and smaller bits and areas of specialization. While specialized innovation has given us and our societies many comforts of modern life, but a new mode of interaction and collaboration has risen in the last few decades by the use of information technology including the earlier ARPA Net and the WWW. To quote from the special section of the December 4$^{th}$, 2000 issue of the TIME on Innovators and Inventions of the Year:

> “… One consequence might be that we finally recognize history’s Great Innovators for what they were: the products of a culture of scarcity that taught us to regards them and their talents as rare. That they were (and are) especially talented is in no doubt here. But semi-intelligent information technology and the transition of a culture from one of information scarcity to one of abundance may for the first time allow all of us into the invention game. Then technology will provide the nuts-and-bolts backup to give shape to whatever any imaginative brain can conceive. And there are more than 6 billion imaginative brains out there across the planet waiting for opportunity…”

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Past exchanges with my colleagues at EPRI, including Frank Goodman, Richard Lordan, Robin Jones, Revis James, and Peter Hirsh, as well as with Robert Holmes (EPRI loan-in from PowerGen 1998-2000), who assisted me on "soft" issues of communication and KM in EPRI/DoD CIN/S program.

# D
# EPRI/DOD GICUR PROGRAM: CIN/SI EVENTS AND PUBLICATIONS

## D.1 CIN/SI Events

The kickoff meeting for the initiative was held on May 5, 1999 in the Virginia Campus of George Washington University. Proceedings were issued to participants on CD-ROM. An all-day workshop was held at the IEEE Conference on Decision & Control, Dec. 5, 1999, Phoenix, Arizona. First Annual Review Meeting of the funded consortia was held on June 7, 2000 in Palo Alto, followed by a meeting of the 10-member Governing and Oversight Council on June 8, 2000. For highlights of the June 8th Governing and Oversight Council meeting, please see: http://www.epri.com/targethigh.asp?program=207896&value=&objid=242145

Several additional workshops were held, including:

- ARO-sponsored workshops in GWU and in UC-Berkeley
- Two workshops were held during the IEEE PES Summer meeting (July 2000) and PES Winter meeting (January 2001),
- A joint NSF/DOE/EPRI workshop on Future Directions for CIN/S (November 2000).
- The 2nd annual review & Governing Council meeting was held on April 19-20, 2001
- A series of three EPRI/NSF conferences in 2001-2002on “grand challenges” facing the electricity industry
    - Urgent Opportunities for Transmission System Enhancement (October 2001)
    - Economics, Electric Power, and Adaptive Systems (March 2002)
    - Global Dynamic Optimization of the Electric Power Grid (April 2002)

CIN/SI Publications and Technical Reports: Monthly and quarterly reports as well as several background publications were made available from Massoud Amin or Robert Launer.

The list of publications that follow are the majority but not all of the output of the CIN/SI. At the time of this writing, additional publications are in preparation and will be expected to appear in 2002 and 2003-2004; approximately a total of 450-470 publications ultimately are expected.

## D.2 CIN/SI Publications from WO 8333-01

Participants: University of Washington (lead), Arizona State University, Iowa State University, Virginia Polytechnic Institute.

Investigators: *Washington*—Chen-Ching Liu (PI), M. J. Damborg, M. L. El-Sharkawi, J. N. Hwang, M. T. Sun, S. Tanimoto; *Arizona State*—Gerald Heydt, G. Karady, R. Gorur, K. Holbert, F. C. Hoppensteadt, J. Si , D. Tylavsky; *Iowa State*—Vijay Vittal, V. Ajjarapu, M. H. Kammash, W. Kleinman, J. McCalley, G. Sheble, L. Tesfatsian, S. S. Venkata; *Virginia Tech*—Arun Phadke, J. De La Ree, Y. Liu, L. Mili

### *D.2.1 WO 8333-01: Submitted for publication (to appear in 2002)*

R. S. Gorur, R.G. Farmer, et al., *The Application of Analytical Hierarchy Process to Analyze the Impact of Hidden Failures in Special Protection Schemes*, (under review for publication with JEPSR, Elsevier press).

G. Karady, A. Daoud, and M. Mohamed: "On-Line Transient Stability Enhancement Using Multi-Agent Technique," To be presented in *Proceeding IEEE, PES*, WM02, 2002.

J. Bower, and D. Bunn, "Experimental Analysis of the Efficiency of Uniform-Price Versus Discriminatory Price Auctions in the England and Wales Electricity Market," *Journal of Economic Dynamics and Control*, to appear.

H. Wu, H. Ni, G. T. Heydt, "The Impact of Time Delay on Robust control Design in Power System," submitted to *IEEE Power Winter Meeting*, 2002.

H. Wu, "SPID Quarter Report," University of Washington, Seattle, WA, May 2001

### *D.2.2 WO 8333-01: 2001 (or submitted for publication to appear in 2001)*

L. Tesfatsion, "Structure, Behavior, and Market Power in an Evolutionary Labor Market with Adaptive Search," Journal of Economic Dynamics and Control, to appear.

K. E. Holbert and G. T. Heydt, "Prospects For Dynamic Transmission Circuit Ratings," International Conference on Circuits and Systems, Sydney, Australia, May 2001.

A-R Khatib, L. Mili, A/ Phadke, J. De La Ree, Y. Liu "Internet Based Wide Area Information Sharing and Its Roles in Power System State Estimation" Proceedings of the 2001 IEEE-PES Winter Meeting, Columbus, OH, 28 January-1 February, 2001.

Q. Qiu, L. Mili, A.G. Phadke, "Risk Assessment of Cascading Outages Due to Relay Hidden Failures" North America Power Symposium, 2001.

V. Vishwanathan, J. McCalley, V. Honavar, "Design and Implementation of a Multi-agent System Infrastructure and Negotiation Framework for Electric Power Systems," IEEE Power Tech Conference, Porto, Portugal.

Q. Chen, K. Zhu, and J. McCalley, "Dynamic Decision-Event Trees for Rapid Response to Unfolding Events in Bulk Transmission Systems," IEEE Power Tech Conference, Porto, Portugal.

G. T. Heydt, C. C. Liu, A. G. Phadke and V. Vittal, "Crisis in the Electricity Energy Supply - Solutions for the future," submitted to IEEE PES Computer Applications in Power, 2001.

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### *D.2.3 WO 8333-01: Publications in 2000*

B. Reeves and Y. Liu, "Development of a Virtual Museum - Experience Learned in the Process," 2000 ASEE Southeastern Section Annual Meeting.

A. Khatib, X. Dong, B. Qiu, and Y. Liu, "Thoughts on Future Internet Based Power System Information Network Architecture," IEEE PES Summer Power Meeting, Seattle, July 2000.

H. Ni, G. T. Heydt, and R. G. Farmer, "Autonomous Damping Controller Design for Power System Oscillations," IEEE PES Summer Meeting, Seattle, July 2000.

M. Djukanovic, M. Khammash, and V. Vittal, "Sensitivity Based Structured Singular Value Approach to Stability Robustness of Power Systems," IEEE Trans. Power Systems, Vol. 15, No. 2, May 2000, pp. 825-830.

C. Liu, J. Jung, G. T. Heydt, V. Vittal, and A. Phadke, "Conceptual Design of the Strategic Power Infrastructure Defense (SPID) System," IEEE Control System Magazine, August 2000, pp. 0-52.

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V. Petrov and G. B. Sheble, "Power Auctions Bid Generation with Adaptive Agents Using Genetic Programming," Proc. 2000 North America Power Symposium, Oct. 2000.

### *D.2.4 WO 8333-01: Publications in 1999*

G. B. Sheblé, Computational Auction Mechanisms for Restructured Power Industry Operation, Kluwer Academic Publishers, ISBN 0-7923-8475-X, (1999).

V. Petrov, C. W. Richter, and G. B. Sheblé, "Economically Destabilizing Electric Power Markets for Profit," Department of Electrical and Computer Engineering, Iowa State University, Ames, Iowa 50011, 1999.

G. Phadke, S. H. Horowitz, and J. S. Thorp, "Aspects of Power System Protection in the Post-Restructuring Era," Conference Paper, Proceedings of the 32nd Hawaii International Conference on System Sciences, Los Alamitos CA, 1999.

## D.3 CIN/SI Publications from WO 8333-02

Participants: Purdue University (lead), University of Tennessee, Fisk University, Commonwealth Edison Co. (ComEd), Tennessee Valley Authority (TVA)

Investigators: Purdue—Lefteri H. Tsoukalas (PI), A. L. Bement, A. K. Elmagarmid, T. J. Downar, E. N. Houstis, O. Uluyol; Tennessee—Robert Uhrig, A. Gribok, J. Lawlor; Fisk—H. J. Caulfield; TVA—D. T. Bradshaw, K. Morris; ComEd—D. C. Schooley, J. P. Crane

### *D.3.1 WO 8333-02: Submitted for publication, partial list (to appear in 2002)*

Caulfield, H. J., “Operation of Large, Distributed Complex Systems,” submitted to The International Journal of Smart System Design.

H. J. Caulfield, J. L. Johnson, M. P. Schamschula, and R. Inguva, “A General Model of Primitive Consciousness,” Revision into Cognitive Systems Research

### *D.3.2 WO 8333-02: 2001 (or submitted for publication to appear in 2001)*

Gribok, A.V., Ibrahim K. Attieh, J. Wesley Hines, Robert E. Uhrig, Stochastic Regularization of Feedwater Flow Rate Evaluation for Venturi Meter Fouling Problem, Inverse Problems in Engineering (submitted).

Krishnan, V., Viswanathan, S., Houstis, L.H., Elmagarmid, A., Tsoukalas, L.H., An Agent-Based Architecture for Autonomous Control of the Electric Power Grid, IEEE Power Letters, (submitted in 2000)

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### D.3.3 WO 8333-02: Publications in 2000

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Uluyol, O, Ragheb, M., Tsoukalas, L.H., “Neural Network with Local Memory for Nuclear Reactor Power Level Control,” Journal of Nuclear Technology, Vol. 133, Feb., 2001.

Uhrig, R.E., “Reviewing Various Types of Intelligence Systems for Applications to Nuclear Power Plants,” Proceedings of the ANS International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies, (NPIC & HMIT 2000), Washington DC, November 2000.

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Dasseni, E., V. Verykios, A. Elmagarmid, and E. Bertino, "Hiding Association Rules by Using Support and Confidence," Proceedings of the International Conference on Information and Knowledge Management, (Proceedings of CIKM).

Fieno, T., Tsoukalas, L.H., “Anticipatory Regulation of Complex Power Systems,” Proc. of Chaos and Anticipatory Systems, CASYS'2001, Liege, Belgium, August 2001.

Tsoukalas, L.H., Wang., X., Gao., R. "The Electric Power System as a Customer-Driven System Endowed with Self-Healing Capabilities: A Report on CIMEG," Proc. of IREP 2001: Bulk Power Systems Dynamics and Control V - Security and Reliability in a changing Environment, Onomichi, Japan, Aug. 26-31, 2001.

Tsoukalas, L.H., Gao, R., Bougaev, A., " Self-Healing Power Systems: A Report on CIMEG Activities," Symposium on Intelligent Forecasting, Diagnostics and Control, Santorini, Greece June 26-29, 2001.

## D.4 CIN/SI Publications from WO 8333-03

Participants: Harvard University (lead), Boston University, Massachusetts Institute of Technology, University of Massachusetts-Amherst, Washington University-St. Louis

Investigators: Harvard—Yu-Chi Ho (PI), D. Pepyne: BU—C. G. Cassandras; MIT—M. Ilic: UMASS-Amherst—T. Djaferis, W. B. Gong; Washington University-St. Louis— M. V. Hegde, P. S. Min, J. Zaborsky

### *D.4.1 WO 8333-03: Submitted for publication (to appear in 2002):*

Akl, B., M. Hegde, P. Min, and M. Naraghi-Pour, “Power Compensation for Flexible Allocation of Capacity in CDMA Networks,” submitted to IEEE Transactions on Vehicular Technology.

Akl, B., M. Hegde, M. Naraghi-Pour, and P. Min, “Multi-Cell CDMA Network Design,” to appear IEEE Transactions on Vehicular Technology.

Akl, B.G., Hegde, M.V., Min, P.S., and Naraghi-Pour, M., “Power Compensation for Flexible Allocation of Capacity in CDMA Networks.” Submitted to IEEE Transactions on Vehicular Technology.

Cassandras, C.G., Wardi, Y., Melamed, B., Sun, G., and Panayiotou, C.G., “Perturbation Analysis for On-Line Control and Optimization of Stochastic Fluid Models,” to appear in IEEE Trans. on Automatic Control, 2002.

Dai, L., “Perturbation Analysis via Coupling,” to appear IEEE Transactions on Automatic Control.

Dai, L., C.-H. Chen, and J. Birge, “Convergence Properties of Two-Stage Stochastic Programming,” submitted to Journal of Optimization Theory and Applications.

Djaferis, T.E., “Stability Preserving Maps and Robust Design,” submitted, International Journal of Control.

Djaferis, T. E. and D. M. Cushing, “Robust Control Design Using Stable Polynomial Parameterizations,” submitted, 2002 American Control Conference, Anchorage, Alaska, May 2002.

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Gokbayrak, K., and Cassandras, C.G., “Adaptive Call Admission Control in Circuit-Switched Networks,” to appear in IEEE Trans. on Automatic Control, 2002.

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### *D.4.2 WO 8333-03: Publications from 2001*

Cassandras, C.G., Sun, G., and Panayiotou, C.G., "Stochastic Fluid Models for Control and Optimization of Systems with Quality of Service Requirements," Proc. of 40th IEEE Conf. Decision and Control, pp. 1917-1922, December 2001.

Cassandras, C.G., Sun, G., Panayiotou, C.G., and Wardi, Y., "Perturbation Analysis of Multiclass Stochastic Fluid Models," subm. to 15th IFAC World Congress, 2001.

Cassandras, C.G., Pepyne D.L., and Wardi, Y., "Optimal Control of a Class of Hybrid Systems," IEEE Trans. on Automatic Control, Vol. 46, No. 3, pp. 398-415, March 2001.

Chen, Z and Y.-C. Ho, "Feature Selection as a Stochastic Combinatorial Optimization Problem," submitted IEEE Transactions on Knowledge and Data Engineering, 2001.

Chen, Z., Machine Learning Approaches towards Automatic Target Recognition, Ph.D. dissertation, Harvard University, 2001. (Advisor Y.-C. Ho)

Cho, Y.C., Cassandras, C.G., and Kwon, Y.H., "Optimal Control for Steel Annealing Processes as Hybrid Systems," subm. to IEEE Trans. on Control Systems Tech., 2001.

Cho, Y.C., C.G. Cassandras, and D.L. Pepyne, "Forward Decomposition Algorithms for Optimal Control of a Class of Hybrid Systems," International Journal of Robust and Nonlinear Control, Vol. 11, No 5, pp. 497-513, April 2001.

Cushing, D., An Ordinal Optimization Technique for Robust Control Design, Masters Thesis, Dept. of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA, 2001. (Advisor T.E. Djaferis)

Djaferis, T.E., D.L. Pepyne, and D.M. Cushing, "An Ordinal Optimization Framework for Robust Design," Proceedings 40th IEEE Conference on Decision and Control, pp. 4388-4393, Orlando, Florida, December, 2001.

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Guan, X.-H., Y.-C. Ho, and D.L. Pepyne, "Gaming and Price Spikes in Electric Power Markets," IEEE Transactions on Power Systems, Vol. 16, No. 3, pp. 402-408, August 2001.

Ho, Y.-C. and D.L. Pepyne, "Simple Explanation of the No Free Lunch Theorem of Optimization," Proceedings of the 40th IEEE Conf. Decision and Control, Orlando, Florida, December 2001.

Ilic, M., "T&D Technologies: Systems Integration Opportunities and Challenges," presented at MA Roundtable discussion on Energy, November 2001.

Ilic, M., "T&D Technologies: Systems Integration Opportunities and Challenges," presented at Workshop on Electricity Security and Survivability, Carnegie Mellon Electricity Industry Center, (CEIC), CMU, November 2001.

Lee. J.T., E.T.W. Lau, and Y.-C. Ho, "The Witsenhausen Counterexample: A Hierarchical Search Approach for Non-Convex Optimization Problems," IEEE Transactions on Automatic Control, Vol. 46, No. 3, pp. 398-415, March 2001.

Panayiotou, C.G. Cassandras, C.G., and Zhang, P., "On-Line Inventory Cost Minimization for Make-to-Stock Manufacturing Systems," subm. to American Control Conf., 2001.

Panayiotou, C.G., and Cassandras, C.G., "On-Line Predictive Techniques for "Differentiated Services" Networks," Proc. of 40th IEEE Conf. Decision and Control, pp. 4529-4534, December 2001.

Paschalidis, I.C., Liu, Y., Cassandras, C.G., and Zhang, P., "Threshold-based Control for Make-to-Stock Models: A Synergy Between Large Deviations and Perturbation Analysis," Proc. of 40th IEEE Conf. Decision and Control, pp. 4523-4528, December 2001.

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Pepyne, D.L., W.-B. Gong, and Y.-C. Ho, "Modeling and Simulation for Network Vulnerability Assessment," presented at the 40th U.S. Army Operations Research Symposium (AORS XL), Fort Lee, VA, October 9-11, 2001.

Wardi, Y., Melamed, B., Cassandras, C.G., and Panayiotou, C.G., "IPA Gradient Estimators in Single-Node Stochastic Fluid Models," to appear J. of Optimization Theory and Applic., 2001.

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Yoon, Y.T., "Electric Power Network Economics; Designing Principles for a for-profit Independent Transmission Company and Underlying Architectures for Reliability," Ph.D. dissertation, MIT, 2001. (Advisor M.D. Ilic)

Yoon, Y.T. and M.D. Ilic, "Independent Transmission Company (ITC) for Profit and Markets for Transmission," MIT Energy Lab Publication, MIT EL 01-002 WP, January 2001.

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Cho, Y.C., and C.G. Cassandras, “Optimal Control of Steel Annealing Processes for Hybrid Systems,” Proceedings of the 39th IEEE Conference on Decision and Control, pp. 540-545, December 2000.

Cho, Y.C., C.G. Cassandras, and D.L. Pepyne, “Forward Algorithms for Optimal Control of a Class of Hybrid System,” Proceedings of the 39th IEEE Conference on Decision and Control, pp. 975-980, December 2000.

Gokbayrak, K., and C.G. Cassandras, C.G., “Hybrid Controllers for Hierarchically Decomposed Systems,” Proceedings of 2000 Hybrid System Control Conference, pp. 117-129, March 2000.

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Pepyne D.L., and C.G. Cassandras, “Optimal Control of Hybrid Systems in Manufacturing,” Proceedings of the IEEE, Vol. 88, No. 7, pp. 588-591, July 2000.

Cassandras, C.G., C.G. Panayiotou, G. Diehl, W.-B. Gong, Z. Liu, and C. Zou, “Clustering Methods for Multi-Resolution Simulation Modeling,” Proceedings of SPIE's 14th Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Control, April 2000.

Chen, Z., “Why Does Naive Bayesian Learning Algorithm Work?,” submitted to Data Mining and Knowledge Discovery, December 2000.

Chen, Z., and Y.-C. Ho, “Feature Selection as a Stochastic Combinatorial Optimization Problem,” submitted to the International Joint Conference on Artificial Intelligence, December 2000.

Ho, Y.-C., “At the Gates of the Millenium: Are We in Control?,” panel discussion report, IEEE Control systems Magazine, Vol. 20, No. 1, February 2000.

Ho, Y.-C., "Integrating Optimization and Simulation," panel paper at the Winter Simulation Conference, 2000.

Ho, Y.-C., C.G. Cassandras, C.-H. Chen, and L. Dai, "Ordinal optimization and Simulation," Journal of the Operations Research Society, Vol. 21, pp. 490-500, 2000.

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Ilic, M.D., and P. Skantze, "Electric Power System Operation by Decision and Control", IEEE Control Systems Magazine, Vol. 20, No. 4, August 2000.

Yoon, Y.T., "A Practical Mean-Variance Hedging Strategy in the Electricity Markets," May 2000.

Yoon, Y., J. Arce, K. Collison, M. Ilic, "Implementation of Cluster-based Congestion Management Systems," Proceedings of the 4th International Conference on Power System Operation and Planning (ICPSOP'2000), August 2000.

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Yoon, Y., K. Collison, J. Arce and M. Ilic, "Practical Implementation of Congestion Cluster Pricing Method," August 2000.

Yoon, Y., E. Fumagalli, J. Arce, and M. Ilic, "Assessing reliability as the Electric Power Industry Restructures," August 2000.

Guo, Y., W.-B. Gong, and D. Towsley, "Time-Stepped Hybrid Simulation for Large-Scale Networks," Proceedings of INFOCOM'2000.

Misra, V., W.-B. Gong, and D. Towsley, "Fluid based analysis of AQM routers supporting TCP flows with an application to RED," Proceedings of ACM/SIGCOMM, 2000.

Akl, R., M. Hegde, M. Naraghi-Pour, and P. Min, "Multi-Cell CDMA Network Design," Proceedings of the IEEE International Conference on Communications, June 2000.

Akl, R., M. Hegde, M. Naraghi-Pour, and P. Min, "CDMA Network Design to Meet Non-uniform User Demand," Proceedings of the International Teletraffic Congress, March 2000.

Yoon, U., S. Park, and P. Min, "Performance Analysis of Multiple Rejects ARQ at RLC (Radio Link Control) for Packet Data Service in W-CDMA System," Proceedings of IEEE Globecom, November 2000.

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Yoon, U., S. Park, and P. Min, "Performance Analysis of Multiple Rejects ARQ for RLC (Radio Link Control) in the Third Generation Wireless Communication," Proceedings of WCNC, September 2000.

Lin, X.-C., "Optimization under Uncertainty: A New Framework and its Applications," Ph.D. dissertation, Harvard University, November 2000.

Gokbayrak, K., "Surrogate Optimization Methods for Discrete and Hybrid Systems," Ph.D. dissertation, Boston University, November 2000.

Lee, L., F. Abernathy, and Y.-C. Ho, "Production Scheduling for Apparel Manufacturing Systems," Production Planning and Control, Vol. 11, No. 3, 2000.

### *D.4.4 WO 8333-03: Publications in 1999*

Gokbayrak, K., and C.G. Cassandras, "Stochastic Optimal Control of a Hybrid Manufacturing System Model," Proceedings of the 38th IEEE Conference on Decision and Control, pp. 919-924, December 1999.

Cassandras, C.G., Q. Liu, D.L. Pepyne, and K. Gokbayrak, "Optimal Control of a Two-Stage Hybrid Manufacturing System Model," Proceedings of the 38th IEEE Conference on Decision and Control, pp. 450-455, December 1999.

Cassandras, C.G., and D.L. Pepyne, "Hybrid System Models for Integrated Manufacturing," Proceedings of the Hong Kong Symposium on Robotics and Control, Vol. II, pp. 615-620, July 1999.

Li, D., L. Lee, and Y.-C. Ho, "Vector Ordinal Optimization—A New Heuristic Approach and its Application to Computer Network Routing Design Problems," International Journal of Operations and Quantitative Management, Vol. 5, No. 5, pp. 211-230, December 1999.

Yu, C., J. Leotard, and M. Ilic, "Dynamics of Transmission Provisioning in a Competitive Power Industry," Journal of Discrete Event Dynamic Systems, Vol. 9, No. 4, November 1999.

Zaborszky, J. and M. Ilic, "General Structure of the Regulated, Deregulated, and Other Generation Dispatch Systems," IEEE PowerTech'99.

## D.5 CIN/SI Publications from WO 8333-04

Participants: Cornell University (lead), George Washington University, University of California-Berkeley, University of Illinois, Washington State University, University of Wisconsin

Investigators: Cornell—Robert Thomas (PI), K. P. Birman, H-D. Chiang, J. Guckenheimer, A. Nerode, F. B. Schneider, S. Strogatz, J. S. Thorp; George Washington—Nozer D. Singpurwalla, H.G. Abeledo, J. Chandra, A.Eskandarian, T.A. Mazzuchi, R. M. Soland, R. Soyer, D. Ullman, Jarayam Sethuraman (consultant from Florida State); UC-Berkeley—Pravin Varaiya, Venkat Anantharam, Shmuel Oren, Shankar Sastry; Illinois—Peter Sauer, T. M. Basar, J. Bentsman, G. Gross, I. Hiskens, P. R. Kumar, S.P. Meyn, T. J. Overbye, M. A. Pai, A. Vakakis; Washington State—A. Bose, A. Saberi, K. Tomsovic, M. Venkatasubramanian; Wisconsin—R. Agrawal, F. Alvarado, J. Bucklew, C. DeMarco, R. Lasseter

### *D.5.1 WO 8333-04: 2001 (or submitted for publication to appear in 2001)*

Altman,E., Basar,T., Jimenez, T., and Shimkin, N., “ Routing into two parallel links: Game-theoretic distributed algorithms”, Jour. Parallel and Distributed Computing, Special issue on Routing in Computer and Communication Systems, 2001 (to appear)

Altman, E., Basar,T., Jimenez,T., and Shimkin, N., “ Competitive routing in networks with polynomial costs”, IEEE Trans. Automatic Control, 2001 (to appear)

Alvarado, F. L.., Meng, J., DeMarco, C.L., and Mota, W.S., “ Stability analysis of interconnected power systems coupled with market dynamics”, IEEE Trans. Power Systems (submitted)

Bentsman, J., “ Biorthogonal wavelet based identification of fast linear time-varying system: Part I- system representations, and Part II- identification algorithms and performance", ASME Journal of Dynamic Systems, Measurement and Control (submitted)

Bredin, J., Kotz, D., Rus, D., Maheswaran, R.t., Imer, T., and Basar, T., “ A market-based model for resource allocation in agent systems”, Franco Zambonelli,Editor, Coordination of Internet Agents, Kluwer, 2001 (to appear)

Bredin, J., Maheswara, R.T., Imer, T., Basar, T., Kotz, D., and Rus, D., “ A computational market to regulate mobile-agent systems”, (submitted)

Bucklew, J.A., “ The blind Monte-Carlo simulation problem”, Signal Processing, (to appear)

Callaway, D., Newman, M., Strogatz, S., and Watts, D., “ Exact solution of percolation on random graphs with arbitrary degree distribution”, ( in preparation )

Chen, J., Thorp, J.S., and Parashar, M., " Analysis of electric power system blackout time series", Proc. 34th Annual Hawaii International Conference on System sciences,(to appear)

Chen, C., Petty, K., Skabardonis, A., Varaiya, P., and Jia, Z., " Freeway Performance Measurement System: Mining loop detector data", Proc. 80th Annual Meeting of Transportation Research Board, Jan. 2001, (to appear)

Chuang, A., Wu, F., and Varaiya, P., " An application of Cournot theory to generation expansion planning in a competitive electricity industry, J. Regulatory Economics (submitted)

Chuang, A., Wu, F., and Varaiya, P., " A game-theoretic model for generation expansion planning: problem formulation and numerical comparisons, IEEE Power Systems, (submitted)

Coury, D.V., Thorp, J.S., Hopkinson, K.M., and Birman, K.P., " An agent based current differential relay for use with a utility internet", ( in preparation )

Deng, S., and Oren, S.S., " Priority network access pricing for electric power", (submitted)

Falk,J.E., Singpurwalla, N.D., and Vladimirsky, Y.Y., " Optimal reliability allocations", (submitted)

Grijalva, S. and Hiskens, I.A.," Hybrid system modeling of frequency control and load shedding", Proc. 32nd North American Power Symposium, Oct.2000 ( to appear )

Grijalva, S. and Sauer, P. W., " Complex-flow network limits and static system collapse" , Proc. 32nd North American Power Symposium, Oct. 2000 ( to appear )

Guo, S.M., Shieh, L.S. and Chandra, J., " Adaptive control for nonlinear stochastic hybrid systems with input saturation", Proc. 34th Hawaii International Conference on System Sciences, Jan. 2001 ( to appear )

Gupta, P., and Kumar, P.R., " Internet in the sky: The capacity of three dimensional wireless networks", (submitted)

Hiskens, I. A., " Stability of limit cycles in hybrid systems", Proc. 34th Hawaii International Conference on System Sciences, Jan. 2001 ( to appear )

Hiskens, I. A. and Davy, R.J., " Exploring the power flow solution space boundary", IEEE Transaction on Power Systems ( submitted )

Hiskens, I.A., " Nonlinear dynamic model evaluation from disturbance measurements", IEEE Trans. Power Systems (submitted)

Hopkinson, K.M., Birman, K.P., and Jenkins, K., " Simulation of Gravitational Gossip in an electric power grid management system", ( in preparation )

Imer, O., Compans, S., Basar, T., and Srikant, R., " ABR congestion control in ATM networks", IEEE Control System Magazine, 21, 2001 (to appear)

Jenkins, K., Birman, K.P., and Hopkinson, K.M., " Analysis of Gravitational Gossip protocol", ( in preparation )

Jia, Z., Varaiya, P, Chen, C., and Skabardonis, A., " Congestion, excess demand, and revealed capacity in California freeways", (submitted)

Kong, C. W., and Eskandarian, A.," Assessing network reliability using neural networks", ( in preparation)

Lee, J. and Chiang, H.D., " Constructive homotopy methods for finding all multiple DC operation points of nonlinear circuits and systems", IEEE Transaction on Circuits and Systems, (to appear )

Lindley, D. V., and Singpurwalla, N. D., " Exchangeable, causal and cascading failures", (manuscript completed )

Meyn, S.P., " Sequencing and routing in multiclass queuing networks: Part I Feedback regulation", SIAM J. Control and Optimization,(to appear)

Meyn, S.P., " Sequencing and routing in multiclass queuing networks: Part II Workload relaxation", (submitted)

Newman, M., Strogatz, S., and Watts, D., ' Random graphs with arbitrary degree distribution and their applications", (in preparation )

Oliva, R. and Guckenheimer, J. " Computational tools for the analysis of large complex, hybrid dynamical systems", (in progress)

Ozekici, S., and Soyer, R., " Network reliability assessment in a random environment", (in preparation )

Pakzad, P. and Anantharam, V. " A new look at the distributive law: A family of examples", (in preparation)

Saberi, A., Stoorvogel, A, Sannuti, P., and Niemann, H., " Fundamental problems in fault detection and identification", International Journal of Robust and Nonlinear Control, (to appear)

Sauer, P. W., Reinhard, K., and Overbye, T. J., " Extended factors for linear contingency analysis", Proc. 34$^{th}$ Hawaii International Conference on System Sciences, Jan. 2001 (to appear)

Sethuraman, J., " Transmission loss in a network with large number of nodes", (in preparation)

Sethuraman, J., " Flows, capacities of channels and utilization of networks", (in preparation)

Shen, M. and Venkatasubramanian, V., “ Algorithms for on-line generator dynamic parameter estimation”, IEEE Trans. Power Systems ( submitted )

Shen, M, Venkatasubramanian, V. Mittlestadt, W. and Goddard, R., “ Load parameter estimation in pacific northwest”, IEEE Trans. Power systems ( submitted )

Shen, M. and Venkatasubramanian, V., “ Estimation of excitation system parameters for two WSCC generating units”, IEEE Trans. Power Systems ( submitted )

Singpurwalla, N., and Swift, A., “ A paradox in network reliability”, (submitted)

Singpurwalla, N., “ the hazard potential of items and individuals”, (submitted)

Ullman, D., “ Measuring Reliability of Networks”, (submitted)

Vakakis, A. F., “ Inducing passive nonlinear energy sinks in vibrating systems”, Journal of Vibration and Acoustics, (submitted)

Venkatasubramanian, V., “ Stability boundary analysis of large nonlinear systems subject to state limits”, Proc. 34th Hawaii International Conference on System Sciences, Jan. 2001 ( to appear )

Viswanath, P., Tse, D., and Ananthram, V., “ Asymptotically optimal waterfilling in vector multiple access channels”, IEEE Trans. Information Theory, (submitted)

Wagner, A. and Anantharam, V., “ Control of interacting systems”, (under preparation)

Wang, H., and Thorp, J.S., “ Enhancing reliability of power protection systems economically in the post-restructuring era”, 32nd Annual North America Power Symposium, (submitted)

Zhao, H. and Bentsman, J., “ Block diagram reduction of interconnected linear time-varying systems in time-frequency domain”, Journal of Multidimensional Systems and Signal Processing ( to appear)

Zhao, H., Li, W. and Bentsman, J., “ H-infinity prediction and unconstrained H-infinity predictive control: multi-input-multi-output case”, Internal. J. of Robust and Nonlinear Control, 11, 59-86, 2001

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Alpcan, T., and Basar, T., “ A variable rate model with Qos guarantee for real-time Internet traffic”, Proc. SPIE Internal. Symp. on Information Technologies 2000

Alpcan, T., and Basar, T., " Communication network games and real-time algorithms for Nash equilibria", 9th International Symposium on Dynamic Games and Applications, Adelaide, Australia, December 2000

Bentsman, J., " Wavelet –based identification of fast linear time varying systems using function space methods", Proc. ACC, June 2000

Bredin, J., Maheswaran, R.T., Imer, T., Basar, T., Kotz, D., and Rus, D., " A game-theoretic formulation of multi-agent resource allocation", Proc. 4th Internal. Conf. Autonomous Agents, 349-356, Barcelona, Spain, 2000

Chandra, J, " Planning and operation in a de-regulated power system: A tutorial", IRRA, Tech Rep., 2000

Chaniotis, D. and Pai, M. A., " Iterative solver techniques in dynamic simulation of power systems", Proc. IEEE Power Engineering Society, July 2000

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Coury, D. V., Thorp. J.S., Hopkinson, K.M., and Birman, K. P., " Agent technology applied to adaptive relay setting for multi-terminal lines", IEEE Power Engineering Symposium, July 2000

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Gupta,P and Kumar, P.R. "The capacity of wireless networks", IEEE Transactions on Information Theory, vol.46, 388-404, (2000)

Gupta, I, Birman, K.P., and van Renesee, R., " A probabilistically correct election protocol for large groups", DISC 2000, Toledo, Spain, Oct. 2000

Hisken, I.A., Pai, M.A., and Nguyen, T.B., " Bounding uncertainty in power system dynamic simulations", Proc. IEEE PES 2000 Winter Meeting, Singapore, Jan. 2000

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Meng, J., DeMarco, C.L., and Alvarado, F. L., " Stability of time delay power markets", Proc North American Power Symposium, Oct. 2000

Nguyen,T. B., Pai, M. A. and Hiskens, I.A., " Direct computations of critical clearing time using trajectory sensitivities", Proc. IEEE Power Engineering Society, July 2000

Oren, S.S., " Capacity payments and supply adequacy in competitive electricity markets", VII Symposium of Specialists in Electric Operational and Expansion Planning, May 2000

Pellegrinetti, G., Zhao, H. and Bentsman, J., " Unconstrained H-infinity predictive control with H-infinity prediction: single-input-single-output case", Internal. J. of Robust and Nonlinear Control, 10, 1279-1316, 2000

Saberi, A., Stoorvogel, A., and Sannuti, P. " Exact, almost , and optimal input decoupled (delayed) observers", International Journal of control. 73, 552-581,2000

Shen, M., " A new framework for parameter estimation of power system dynamic models", Doctoral dissertation, School of Electrical Engineering and Computer Science, Washington State University, Pullman.

Singpurwalla, N. D., " Warranty contracts and equilibrium probabilities", Statistical Science in Courtroom ( edited by J.L. Gastwirth ), Springer Verlag, 2000

Singpurwalla, N. D., Booker, J, and Bennet, T., " Uncertainties and their assessment", Proc. Third International Symposium on soft Computing for Industry, 2000

van Renesse, R., " Scalable and secure resource location", Proc 33rd Hawaii International Conference on System Sciences, Jan. 2000

Venkatasubramanian, V. and Shen, M., " Decentralized estimation of power system dynamics models", Proc. IEEE CDC, December 2000

Zhang, J. and Alvarado, F. L., " Cascading contingency analysis", Proc. North American Power Symposium, Oct. 2000

### *D.5.3 WO 8333-04: Publications in 1999*

Altman,E., Basar, T., and Srikant, R., " Congestion control as a stochastic control problem with active delays", Automatica, 35, 1937-1950, 1999

Birman, K.P., Hayden, M., Ozkasap, O., Xiao, Z., Budio, M., and Minsky, Y., " Bimodal multicast", ACM Trans. On Computer Systems, May 1999

Birman, K.P., " A review of experiences with reliable multi-cast", Software, Practices and Experience (John Wiley & Sons), 29(9), 741-774, 1999

Meng, J., and DeMarco, C. L., " Application of optimal multiplier method in weighted least-square state estimation Part I: Theory", Proc North American Power Symposium, Oct. 1999

Meng, J. and DeMarco, C.L., " Application of optimal multiplier method on weighted least-square state estimation Part II: Simulation", Proc. North American Power Symposium, Oct. 1999Shen,

M., Venkatasubramanian, V, Abi-Samara, N. and Sobajic, D., " A new framework for estimation of generator dynamic parameters", PE-097-PRS (08-99).

## D.6 CIN/SI Publications from WO 8333-05

Participants: Carnegie Mellon University (lead), Rensselaer Polytechnic Institute, Texas A&M University, University of Minnesota, University of Illinois

Investigators: Carnegie Mellon—Bruce Krogh (PI), P. Khosla, E. Subrahmanian, S.Talukdar; RPI—Joe Chow; Texas A&M—Garng Huang, Mladen Kezunovic; Minnesota—Bruce Wollenberg; Illinois—Lui Sha

### *D.6.1 WO 8333-05: Submitted for publication (to appear in 2002)*

Bykhovsky and J. H. Chow, “Power System Disturbance Identification from Recorded Dynamic Data at the Northfield Substation,” submitted for publication.

E. Camponogara and S.N. Talukdar, “Matching Agents to Tasks in Networks,” submitted to INFORMS Journal on Computing.

Fradi, S. Brignone, and B. Wollenberg, “Calculation of Energy Transaction Allocation,” to appear in IEEE Transactions on Power Systems.

D. Jia and B.H. Krogh, “Minimax feedback model predictive control for distributed control with communication,” submitted to 2002 American Control Conference.

Lim, S., Lee, K., and Sha, L., "Ensuring Integrity and Service Availability in a Web Based Control Laboratory", Journal of Parallel and Distributed System, Special Issue on Security in Mission Critical Real-time Systems, Accepted for publication.

S. Vasilic and M. Kezunovic, "An Improved Neural Network Algorithm for Classifying the Transmission Line Faults", IEEE PES Power Winter Meeting, New York, U.S.A., Jan. 2002.

X. Wei, J. H. Chow, and J. J. Sanchez-Gasca, “On the Sensitivities of Network Variables for FACTS Device Damping Control,” submitted to the IEEE Winter Power Meeting, 2002.

### *D.6.2 WO 8333-05: Publications from 2001*

G.M. Huang and T. Zhu, “TCSC as a Transient Voltage Stability Controller,” in Proc. IEEE/PES Winter Meeting, Columbus, OH, 2001.

D. Jia and B.H. Krogh, “Distributed Model Predictive Control,” in Proc. American Control Conference, June 2001.

M. Kezunovic and S. Vasilic, "Design and Evaluation of Context-Dependent Protective Relaying Approach", IEEE Porto Power Tech' Conference, Porto, Portugal, Sep. 2001.

M. Kezunovic and S. Vasilic, "Advanced Software Environment for Evaluating Protection Performance During Power System Disturbances Using Relay Models", CIGRE SC 34 Colloquium, Sibiu, Romania, Sep. 2001.

Z. Ren and Bruce H. Krogh, "Mode-Matching Control Policies for Multi-Mode Markov Decision Processes," in 2001 American Control Conference.

Z. Ren and Bruce H. Krogh, "Adaptive Control of Markov Chains with Average Cost," IEEE Trans. on Automatic Control, vol. 46, no. 4, pp. 613-617, April 2001.

D. Ristanovic, S. Vasilic, M. Kezunovic, "Design and Implementation of Scenarios for Evaluating and Testing Distance Relays", North American Power Symposium, College Station, Oct. 2001.

Sha, L., " Using Simplicity to Control Complexity", IEEE Software, July/August, 2001.

S. Talukdar, "Agents," Lecture notes, talk given at Cornell, Nov. 7, 2001

S. Talukdar, "CDNA for Auction Testing," Grid Operation and Planning Meeting sponsored by EPRI, Washington, DC, June 2001.

S.N. Talukdar and E. Camponogara, "Network Control as a Distributed, Dynamic Game," in Proc. 34$^{th}$ Hawaii International Conference on System Sciences, January 2001. (Best paper award in the Complex Systems Track.)

S. Wang and J.H. Chow, "Regional Pole Placement via Low-Order Controllers with Extension to Simultaneous Stabilization," Proc 2001 American Control Conference, pp. 1163-1168.

S. Vasilic and M. Kezunovic, "New Design of a Neural Network Algorithm for Detecting and Classifying Transmission Line Faults", IEEE Transmission and Distribution Conference, Atlanta, U.S.A., Oct. 2001.

### *D.6.3 WO 8333-05: Publications in 2000*

G.E. Boukarim, S. Wang, J.H. Chow, G.N. Taranto, and N. Martins, "A Comparison of Classical, Robust, and Decentralized Control Designs for Multiple Power Systems Stabilizers," in Proc. IEEE Summer Power Meeting, 2000. (To appear in IEEE Transactions on Power Systems.)

A. Bykhovsky and J.H. Chow, "Dynamic Data Recording in the New England Power System and an Event Analyzer for the Northfield Monitor," in Proc. VII SEPOPE, Curitiba, Brazil, May 2000.

E. Camponogara, Controlling Networks with Collaborative Nets, Ph.D. Dissertation, Electrical and Computer Engineering Department, Carnegie Mellon University, Pittsburgh, PA, August 2000.

J.H. Chow, J.J. Sanchez-Gasca, H. Ren, and S. Wang, "Power System Damping Controller Design using Multiple Input Signals," IEEE Control Systems Magazine, vol. 20, no. 4, pp. 82-90, 2000.

A. Fradi, S. Brignone, and B. Wollenberg, "Calculation of Energy Transaction Allocation," to appear in IEEE Transactions on Power Systems.

G.M. Huang and H. Zhang, "Coordinating Bilateral Transactions with the Centralized Economic Dispatching as an Extended OPF Function," in Proc. IEEE/PES Winter Meeting, Singapore, 2000.

G.M. Huang and Q. Zhao, "Multi-Objective Solutions for the Coordinating Auctions of Different Commodities in Power Markets," in Proc. IEEE/PES Summer Meeting, Seattle, WA, 2000.

G.M. Huang and Q. Zhao, "An Auction-Based Dispatch Algorithm for Deregulated Power Systems," in Proc. IEEE/PES Winter Meeting, Singapore, 2000.

M. Kezunovic, "Advanced Modeling Approaches and Simulation Tools for Power Engineering Research and Development," in Proc. Multiconf. on Systemics, Cybernetics and Informatics SCI 2000 / Conf. on Information Systems, Analysis and Synthesis ISAS 2000, vol. 9, July 2000.

H. Ren, J.H. Chow, S. Wang, G.N. Taranto, and N. Martins, "Controller Structure Design using PSS in a Multimachine Power System," in Proc. VII SEPOPE, Curitiba, Brazil, May 2000.

D. Seto, J.P. Lehoczky, L. Sha, and K.G. Shin, "Trade-off Analysis of Real-Time Control Performance and Schedulability," Journal of Real Time systems, 2000.

L. Sha, X. Liu, M. Caccamo, and G. Buttazzo, "Online Control Optimization Using Load Driven Scheduling," in Proc. IEEE Conference on Decision and Control, December 2000.

L. Sha, L. Xue, and R. Chandra, "On the Schedulability of Flexible and Reliable Real Time Control Systems," to appear in Journal of Real-Time Systems, 2000.

S.N. Talukdar and E. Camponogara, "Collaborative Nets," in Proc. 33rd Hawaii International Conference on System Sciences, January 2000.

S.N. Talukdar, E. Camponogara, and H. Zhou, "A Design Space for Enterprises," in Proc. 2nd DARPA-JFACC Symposium on Advances in Enterprise Control, Minneapolis, MN, July 2000.

S. Wang and J. H. Chow, "Low-order Controller Design for SISO Systems using Coprime Factors and LMI," IEEE Transactions on Automatic Control, vol. 45, pp. 1166-1169, 2000.

## D.7 CIN/SI Publications from WO 8333-06

Participants: California Institute of Technology (lead), Massachusetts Institute of Technology, University of California-Los Angeles, University of California-Santa Barbara, Stanford University, University of Illinois

Investigators: Cal Tech—John Doyle (PI), K. M. Chandy, M. C. Cross, J. E. Marsden; MIT—G. C. Verghese, B. C. Lesieutre; UCLA—Fernando Paganini, R. Bagrodia, M. Gerla; UCSB—J. Carlson, L. Petzold; Stanford U.— S. Lall, Illinois—C. Beck

### *D.7.1 WO 8333-06 Submitted for publication (to appear in 2002):*

Ayazifar, B., "Graph Spectra and Modal Dynamics of Oscillatory Networks," Ph.D. thesis, EECS Department, MIT (expected July 2002).

Ayres de Castro, G., and F. Paganini, “Convex Synthesis of Localized Controllers for Spatially Invariant Systems,” Automatica, vol.38, (no.3), pp. 445-56, March 2002.

Ayres de Castro, G., Paganini F., ``An IQC Characterization of Decentralized Lyapunov Functions in Spatially Invariant Systems", submitted to the 2002 Conference on Decision and Control.

Ball, J.A, J. Chudoung and M.V. Day, “Robust Optimal Switching Control for Nonlinear Systems”, in review, SIAM J. Control and Optimization.

Bamieh, B., F. Paganini, M. Dahleh ``Distributed Control of Spatially Invariant Systems" to appear in IEEE Transactions on Automatic Control, July 2002.

Beck C.L., and R. D'Andrea, “Noncommuting Multi-Dimensional Systems Realization Theory: Minimality, Reachability and Observability”, in review, IEEE Trans. on Automatic Control.

Beck, C.L., and R. D'Andrea, “Model Reduction Methods and Error Bounds for Spatially Distributed Control Systems,” in preparation.

Beck, C.L., “Coprime Factors Reduction for Multi-Dimensional Systems,” in preparation.

Beck C.L., and R. D'Andrea, “Minimality, Controllability and Observability for a Class of Multi-Dimensional Systems”, in review, Automatica.

Beck, C.L., and R. D'Andrea, “Model Reduction Methods and Error Bounds for Spatially Distributed Control Systems,” in preparation.

Beck, C.L., and P. Bendotti, "Balanced Model Reduction for Unstable Uncertain Systems," in preparation.

Cao, Y., S. Li, L.R. Petzold, and R. Serban, "Adjoint Sensitivity Analysis for Differential-Algebraic Equations: The Adjoint DAE System and its numerical solution," submitted to the SIAM J. Scientific Computing.

Cao, Y., S. Li, and L.R. Petzold, "Adjoint Sensitivity Analysis for Differential-Algebraic Equations: Algorithms and software," to appear in the Journal of Comp. Appl. Math.

Cao, Y. and L.R. Petzold, "A Subspace Error Estimate for Linear Systems," submitted to SIAM Journal on Matrix Analysis and Applications.

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## D.8 Other CIN/SI Publications

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TP-114666: From Power Laws to Power Grids: A Mathematical and Computational Foundation for Complex Interactive Networks, May 2000 (Authors: PI and Co-PIs at CalTech, MIT, UCLA, UC-Santa Barbara, U. of Illinois)

### D.8.4 Other CIN/SI Publications:

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