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14

National Infrastructures as Complex Interactive Networks

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14.1 Introduction: Complex Interactive Networks[1]

The increasing complexity and interconnectedness of energy, telecommunications, transportation, and financial infrastructures pose new challenges for secure, reliable management and operation. No single entity has complete control of these multi-scale, distributed, highly interactive networks, or the ability to evaluate, monitor, and manage in real time. In addition, the conventional mathematical methodologies that underpin today's modeling, simulation, and control paradigm are unable to handle their complexity and interconnectedness. Complex interactive networks are omnipresent and critical to economic and social well-being. Many of our nation's critical infrastructures are complex networked systems, including:

- Electric power grid
- Oil and gas pipelines
- Telecommunication and satellite systems
- Computer networks such as the Internet
- Transportation networks
- Banking and finance
- State and local services: Water supply and emergency services.

Interactions between networks such as these increase the complexity of operations and control. The networks' interconnected nature makes them vulnerable to cascading failures with widespread consequences. Secure and reliable operation of these systems is fundamental to our economy, security and quality of life, as was noted in the "Critical Foundations- Protecting America's Infrastructures", by the President's Commission on Critical Infrastructure Protection Report published in October 1997 and the subsequent Presidential Directive 63 on Critical Infrastructure protection, issued on May 22, 1998.

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[1] This chapter is primarily based on a series of presentations given by the author at several universities and professional events to provide program framework for the EPRI/DoD's Complex Interactive Networks/Systems Initiative (CIN/SI). The presentation is available at: http://www.epri.com/srd/cinsi/.

Management of disturbances in all such networks, along with prevention of cascading effects throughout and between networks, requires a basic understanding of true system dynamics, as well as effective distributed control so that, after a disturbance, parts of the networks will remain operational and even automatically re-configure themselves. Interactive networked systems present unique challenges for robust control and reliable operation, such as:

- Multi-scale, multi-component, heterogeneous and distributed nature of these large-scale interconnected systems.
- Vulnerable to attacks and local disturbances which can lead to widespread failure almost instantaneously.
- Characterized by many points of interaction among a variety of participants – owners, operators, sellers, buyers, customers, data and information providers, data and information users.
- The number of possible interactions increases dramatically as the number of participants grows. As a result, the complex activity of these networks greatly exceeds the ability of a single centralized entity to evaluate, monitor, and manage them in real time.
- Too complex for conventional mathematical theories and control methodologies.

As an example, the U.S. electric power system developed over the last hundred years without a conscious awareness and analysis of the system-wide implications of its current evolution under the forces of deregulation and interaction with other infrastructures. The possibility of power delivery beyond neighboring areas was a distant secondary consideration. Today, the North American power network may realistically be considered to be the largest machine in the world since its transmission lines connect all the electric generation and distribution on the continent.

From a broader view, infrastructure networks with several functional, operational and management layers as well as many independent points of interaction between owners, operators, sellers, and buyers are considered complex because the number of possible interactions rises at a dramatically higher rate than the number of participants. Infrastructures that interact with their users and other networks (e.g., an automatic switching system for telephone calls), create additional complexity because the interaction of their elements further increases the number of possible outcomes.

The various areas of interactive infrastructure networks present numerous theoretical and practical challenges in modeling, prediction, simulation, cause and effect relationships, analysis, optimization and control of coupled systems comprised of a heterogeneous mixture of dynamic, interactive, and often nonlinear entities, unscheduled discontinuities, and numerous other significant effects. The science of complex adaptive systems is considered particularly relevant to interactive infrastructure dynamics and security. In many complex networks, for instance in the organization of a corporation, the human participants are both the most susceptible to failure and the most adaptable in the management of recovery. Modeling these networks, especially in the case of economic and financial market simulations will require modeling the bounded rationality of actual human thinking, unlike that of a hypothetical "expert" human as in most applications of artificial intelligence. Furthermore, a pertinent question is at what resolution should sensing, modeling, and control be started to achieve the overall objectives of efficiency, robustness and reliability?

In this chapter, many of these challenges are presented; we first present a brief overview of an initiative in this area followed by motivation and rationale for considering modeling, simulation and control methodologies for such large-scale network problems. To this end an overview of four infrastructures and their interactive vulnerabilities that we consider pertinent is included. This is followed by a discussion of self-healing for infrastructure networks; a more detailed discussion of the objectives and program content for the Complex Interactive Networks/Systems Initiative (CIN/SI) is followed by conclusion.

14.2 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 is working to develop new tools and techniques that enable large national infrastructures to function in ways that are self-stabilizing, self-optimizing, and self-healing.

The Complex Interactive Networks/Systems Initiative (CIN/SI) is a 5-year, $30 million program of Government Industry Collaborative University Research (GICUR), funded equally by DoD and EPRI. GICUR research focuses on breakthrough concepts to address major long-term challenges in complex interactive networks. Commonwealth

Edison Co. and Tennessee Valley Authority are also participating directly in the program, providing staff expertise, data and test sites.

CIN/SI was initiated in mid-1998, and work began in spring 1999. Major technical challenges are being addressed in modeling and simulation; measurement, sensing, and visualization; control systems; and operations and management. CIN/SI aims to develop modeling, simulation, analysis and synthesis tools for robust, adaptive and reconfigurable control of the electric power grid and infrastructures connected to it. Through this initiative, we are investigating new computation and control methods to enable critical infrastructures to adapt to a broad array of potential disturbances including attacks, natural disasters and inadvertent equipment failures.

There are clearly many opportunities for modeling, simulation, optimization and control in this area. Mathematical models of such interactive networked systems are typically vague (or may not even exist); moreover, existing and classical methods of solution are either unavailable, or are not sufficiently powerful. 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 that would enable parts of the networks to remain operational and automatically re-configure in the event of local failures or threats of failure. Detailed discussion of these issues as well as the CIN/SI program content is presented in section 14.18 of this chapter, after discussion of motivation for this effort, including societal context, examples of interactive networks, and nature of vulnerabilities in these large-scale systems.

14.3 Societal Context: Infrastructures and Population Pressure – a "Trilemma" of Sustainability

These infrastructures faced with increased density in today's urban population centers are becoming more and more congested. Human population centers have grown dramatically in the past century, creating a "trilemma" of sustainability issues: population, poverty, and pollution. In 1900, there were no cities with 10 million or more people. By 1950, London and New York had crossed this threshold; by 2020 there will be more than 30 of these "megacities," and by 2050 there will be nearly 60 cities of this size. The stress these megacities place on infrastructures will be immense.

What steps can be taken then to deal effectively with this trilemma? There are technology megatrends that may enable us to tackle such problems while managing resources more efficiently and improving the quality of life. These trends include:

- Information revolution: the ability to disseminate knowledge instantaneously around the globe via the Internet; information technology giving rise to virtual communities and an expanded international economy;
- Materials advances: designer alloys, ceramics, polymers, nanotechnology, and biomimetics offering new capabilities (computer memory and speed, sensors, superconductivity, and superstrength);
- The new genetics: Human Genome Project providing the information foundation for medical advances; agricultural biotechnology offering the potential for feeding the world's population using less land.

Such technologies may help us manage international economies more effectively and feed the world's population while using less land. However, application of these advances will require many new developments as well as re-thinking the operation of national infrastructures. As an example, complex interactive networks can be viewed as multi-layered, multi-resolutional intertwined grids; some of these networks have physics (or first principles) super-imposed on graphs, and each one of these infrastructures has many different levels. CIN/SI's goal is to develop methodologies, protocols, and controls that can self-heal and stabilize such systems.

14.4 Genesis: President's Critical Infrastructures Report

CIN/SI complements a federal study of national infrastructures and their vulnerability to cyberattack. Key conclusions of the study include the following:

- Our most critical infrastructures are not in jeopardy, but the danger and number of threats to them are increasing.

- Now is a good time to develop ways to protect our infrastructures, since many industries are in a period of transition due to adjustment to the new Information Age, deregulation, or both.
- Protecting infrastructures should be a cooperative effort among government agencies, infrastructure owner and operators, and the research community.

The report by the Presidential Commission on Critical Infrastructures Protection was published on October 13, 1997. Subsequently, there were several studies and reports sponsored by other agencies; the Presidential Decision Directive 63 on Critical Infrastructure protection was issued on May 22, 1998 (www.info-sec.com/ciao/63factsheet.html and www.info-sec.com/ciao/paper598.html).

14.5 Examples: Complex Interactive Networks

In what follows we shall provide four examples of interactive networks and then discuss their vulnerabilities; beginning with the electric power grid.

The US electric power system evolved in the first half of the 20th century without a clear awareness and analysis of the system-wide implications of its evolution. This continental-scale electric power grid is a multi-scale, multi-level hybrid system. This infrastructure underlies every aspect of our economy and society. Possibly the largest machine in the world, its transmission lines connect all generation and distribution on the continent. A vertically integrated hierarchical networks consisting of the generation layer and the following three basic levels (Figure 14.1):

- *Transmission level* (a meshed network, combining extra high voltage, above 300 kV, & high voltage, 100-300 kV, connected to large generation units and very large customers; tie-lines to transmission networks, and to the sub-transmission level).
- *Sub-transmission level* (a radial or weakly coupled network including some high voltage, 100-300 kV, but typically only 5-15 kV, connected to large customers and medium sized generators), and
- *Distribution level* (typically a tree network including low voltage, 110-115 or 220-240 volts, and medium voltage, 1-100 kV, connected to small generators, medium- sized customers, and to local low-voltage networks for small customers).

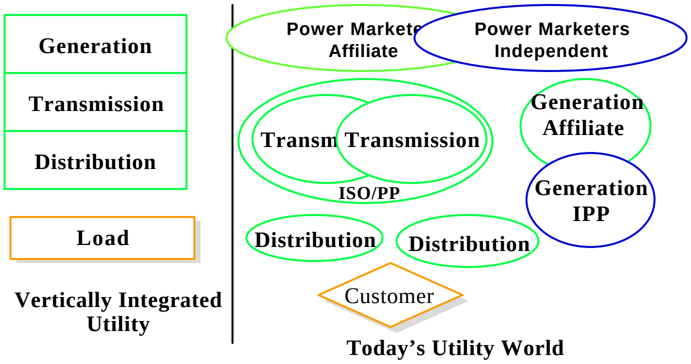


Figure 14.1 Vertically integrated hierarchical networks for traditional power systems and the structural changes now in progress

In its adaptation to disturbances, a power system can be characterized as having multiple states, or "modes," during which specific operational and control actions and reactions are taking place

- *Normal Mode:* Economic dispatch, load frequency control, maintenance, forecasting, etc.
- *Disturbance Mode:* Faults, instability, load shedding, etc.
- *Restorative Mode:* Re-scheduling, re-synchronization, load restoration, etc.

Some authors include an Alert Mode before the disturbance actually affects the system (DyLiaco 1967). Others add a System Failure Mode before restoration is attempted (Fink and Carlsen 1978). Besides these many operational, spatial and energy levels, power systems are also multi-scaled in the time domain, from nanoseconds to decades, as shown in Table 1:

Table 14.1 Multi-scale time hierarchy of power systems

Action/operation	Time frame
Wave effects (fast dynamics, lightning caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability Augmentation	Seconds
Electromechanical effects of oscillations in motors & generators	Milliseconds to minutes
Tie line load frequency control	1 to 10 seconds; ongoing
Economic load dispatch	10 seconds to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized & what is not)	Steady state; on-going
System state measurement and estimation	Steady state; on-going
System security monitoring	Steady state; on-going
Load Management, load forecasting, generation scheduling	1 hour to 1 day or longer; ongoing.
Maintenance scheduling	Months to 1 year; ongoing.
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact, etc.	10 years or longer

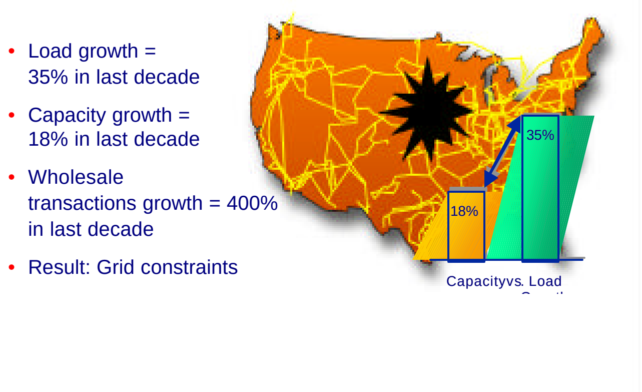
To make adaptive self-healing practical in agent-based, distributed control of an electric power system will require the development, implementation and widespread local installation of Intelligent Electronic Devices (IED) combining the functions of sensors, computers, telecommunication units, and actuators. Several current technological advances in power developments can provide these necessary capabilities when combined in an intelligent system design. Among them are:

- Flexible AC Transmission System (FACTS), high-voltage electronic controllers that increase power carrying capacity of transmission lines (already fielded by American Electric Power).
- Unified Power Flow Controller (UPFC), a third generation FACTS device, that uses solid-state electronics to direct the flow of power from one line to another to reduce overloads and improve reliability.
- Fault Current Limiters (FCL), that absorb the shock of short circuits for a few cycles to provide adequate time for a breaker to trip.
- Wide Area Measurement System (WAMS) based on satellite communication and time stamping using GPS, which can detect and report angle swings and other transmission system changes (in limited use within the Western Area Power Administration).
- Several innovations in the areas of materials science and high temperature superconductors, including the use of ceramic oxides instead of metals, oxide-power-in-tube (OPIT) wire technology, wide bandgap semiconductors, and superconducting cables.
- Distributed resources such as small combustion turbines, Solid-Oxide Fuel Cells (SOFC), photovoltaics, Superconducting Magnetic Energy Storage (SMES), Transportable Battery Energy Storage System (TBESS), etc.
- Information systems and on-line data processing tools such as: Open Access Same-time Information System (OASIS) and Transfer Capability Evaluation (TRACE). The latter software determines the total transfer capability for each transmission path posted on the OASIS network, while taking into account the thermal, voltage and interface limits. (OASIS, Phase 1, is now in operation over the Internet).

Increased use of electronic automation raises significant issues regarding the adequacy of operational security: (1) reduced personnel at remote sites makes them more vulnerable to hostile threats; (2) interconnection of automation and control systems with public data networks makes them accessible to individuals and organizations, from any world-wide location using an inexpensive computer and a modem; (3) use of networked electronic systems for metering, scheduling, trading or e-commerce imposes numerous financial risks implied by use of this technology.

Furthermore, competition and deregulation have created multiple energy producers who must share the same regulated energy distribution network --- such that this network now lacks the carrying capacity or safety margin to support anticipated demand. In the U.S. electrical grid, actual demand has increased some 35 percent, while capacity has increased only 18 percent (Figure 14.2). The complex systems used to relieve bottlenecks and clear disturbances during periods of peak demand are now at greater risk to serious disruption -- and technological improvements for these systems are needed.

The electric power grid's emerging issues include creating distributed management through using active-control high-voltage devices; developing new business strategies for a deregulated energy market; and ensuring system stability, system reliability, robustness, and efficiency in a competitive marketplace. Power systems are a rich area for research and development of tools, especially now because of increased competition and the use of technology to gain an advantage, as well as the challenge of providing the reliability and quality consumers are looking for.



- Load growth = 35% in last decade
- Capacity growth = 18% in last decade
- Wholesale transactions growth = 400% in last decade
- Result: Grid constraints

Figure 14.2 Increased transactions and impact of deregulation on demands for access to the U.S. electricity grid (EPRI)

14.6 Example: Telecommunications Networks

Emerging issues are similar to those found in the energy grid. Parallel algorithms are sought with distributed intelligence that can handle network disruptions and delays, as well as investigations into the telecommunication system's interconnection to the power grid (Figure 14.3). These include determination of true dynamics of interactive nature of this interaction as well as insights into what are the interactive vulnerabilities and when they potentially may lead to cascading failures. This will require developments in reliability theory, risk assessment, modeling, and mathematical analysis of the underpinnings involved in cascading and development of control and management tools for prevention and mitigation of such events. In addition, the following are desirable:

- Parallel algorithms with distributed intelligence to handle network delays and disruptions
- Smart onboard orbit management of telecommunications satellites

Telecommunications networks offer fixed or mobile services, including:

- Fixed network services: public switched telephone networks, public switched data networks
- Wireless network services: cellular, PCS, wireless ATM
- Computer networks: the Internet

Increasing interactions take place between this infrastructure and the electric power grid; size and complexity continues to increase at a rapid rate. For example, 13 geo-stationary communications satellites were launched in the 1960s, 35 in the 1970s, 69 in the1980s, 130 between 1990-1996, and an additional 120 are expected before the end of this decade while the number of satellite operators has risen from two in the 1960s to 50 in 1996 and is expected to reach 60 by 2000. These numbers exclude most Russian and Chinese-built satellites (source: Via Satellite). The figures indicated correspond to various layers of satellite networks that are utilized for diverse applications, these include: Low Earth Orbit (LEO, below 2000 km, as low as 200 km), Geo-stationary Earth Orbit (GEO), Medium Earth Orbit (MEO-2000-20000 km), and Global Positioning System (GPS). Applications include: transponders (cellular telephone, transcontinental telephone, video, data and other Internet services), global positioning, video, and military. Their main capabilities include:

- Transponder (repeater, frequency changed, code format may change, for communication applications)
- Generate pseudo-random code on prescribed frequencies (GPS)
- Generate precisely spaced timing signals (GPS)

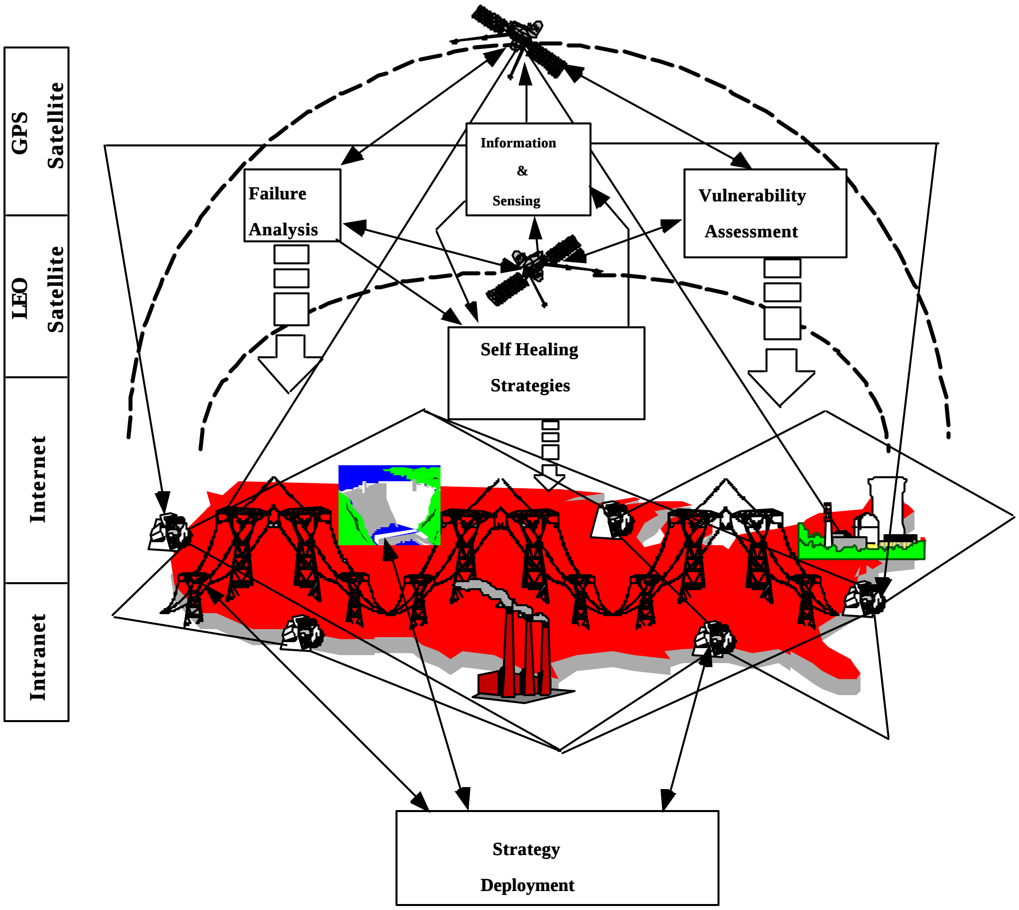


Figure 14.3 An example of complex interactive networks: Telecommunication and the electric power grid (courtesy of Prof. C-C Liu, U. of Washington)

Currently in service are: 172 non-military satellites, 3625 transponders, 81 spacecraft (on order). It is expected that there will be 2251 new transponders in the next five years with 15-to-25-year lifetimes. Present applications include: telephone, video, internet/data, military, GPS and transponder. Current and future applications to Electric power systems applications include (Heydt1999):

- Surveying overhead transmission circuits, and determination of rights of way.
- Transmission of system data / SCADA systems (usually via telephone circuits)
- Overhead conductor sag measurement
- Phasor measurement units (a precise timing signal derived from the GPS to time-tag measurements of AC signals)
- Fit sine wave to signals, and determine magnitude and phase of v(t), i(t) in remote locations
- Generate real time picture of system states, and real time power flow.
- Fast response control data from LEOS can be more than 100 times less delay than high Earth orbit satellites--faster control. Existing parallel data stream facilities exist-- effectively a high speed global RS-232 channel

14.7 Example: Banking and Finance Networks

In the realm of banking and finance networks, two primary concerns are banking and commodity transactions over electronic media. How do we perform data mining and knowledge discovery in multiple, mixed structure financial databases? How do we create secure networks for real-time financial transactions? What new business strategies are needed for internal reorganization, external partnerships, and market penetration? And how can multiple intelligent agent modeling and simulation of corporate entities help?

14.8 Example: Transportation and Distribution Networks

From a broader historical perspective, rapid lines of transportation and communication constitute the foundation of all prospering societies; they are fundamental to national economies and quality of life. The evolution of the United States into a world power is closely related to the development of the railway system which opened up a vast continent with all its natural resources. Today, the backbone of the U.S. transportation system and economy is an interstate highway system that has continually evolved since the 1930s (Figure 14.3).

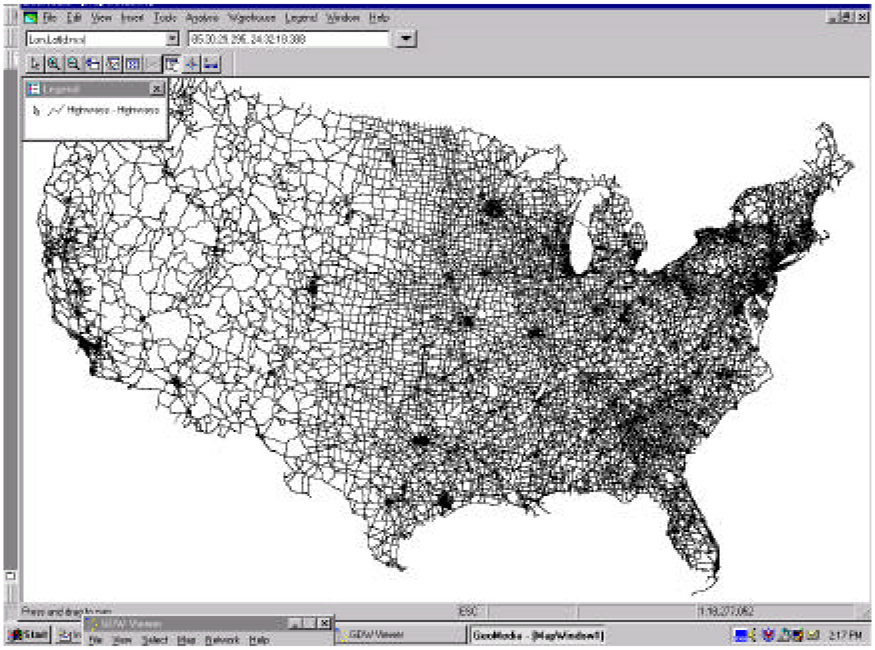


Figure 14.3 U.S. interstate highway system (courtesy of Dr. Joseph Knickmeyer, MTMC)

However, this infrastructure, faced with increased density in today's urban population centers, is becoming more and more congested. The U.S., along with many other nations, is seeking a solution to this worsening traffic congestion problem. Such solutions have to be viewed in terms of the economic, social and political environments together with the technological capability of the nation. Furthermore, the costs associated with generating and maintaining the road infrastructure are rising; the impact of inefficiencies can be measured in quantifiable terms of loss of labor-hours in the workplace and loss of fuel, as well as intangibly in terms of pollution and the generally increased stress level of a work force using these transportation channels.

Within the U.S., the Department of Transportation (USDOT) estimates that the annual cost of congestion to the U.S. in lost productivity alone is over $100 billion. In addition, more than 40,000 persons are killed and another five million injured each year in traffic accidents. Where feasible, increasing the number of lanes will expand the present system capacity, but such measures are recognized to be expensive and disruptive. The ITS program in the U.S. was launched as part of public law passed by Congress, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, Public Law 102-240. The goals are to improve the safety, capacity and operational efficiency of the surface transportation system, while at the same time reducing the environmental footprint and energy impacts. Along these lines the U.S. Department of Transportation has identified six generic ITS thrusts, shown in Table 14.2.

Table 14.2 ITS thrusts in the United States.

Advanced Traffic Management Systems	Commercial Vehicle Operations
Advanced Traveler Information Systems	Advanced Public Transportation Systems
Advanced Vehicle Control Systems	Advanced Rural Transportation Systems

We believe that it is the area of Advanced Traffic Management Systems (ATMS), because of its broad geographical coverage and direct impact to regional economies, which perhaps offers the greatest analytical challenge and the most substantial payoff. In the case of ATMS, recent travel demand and capacity projections indicate that it will no longer be possible to meet the growing demand for travel through the addition of roads. Hence, the ATMS challenge is to improve travel capacity through management of the existing road infrastructure (Amin et al. 1995, Garcia-Ortiz et al. 1998, and Amin 1999).

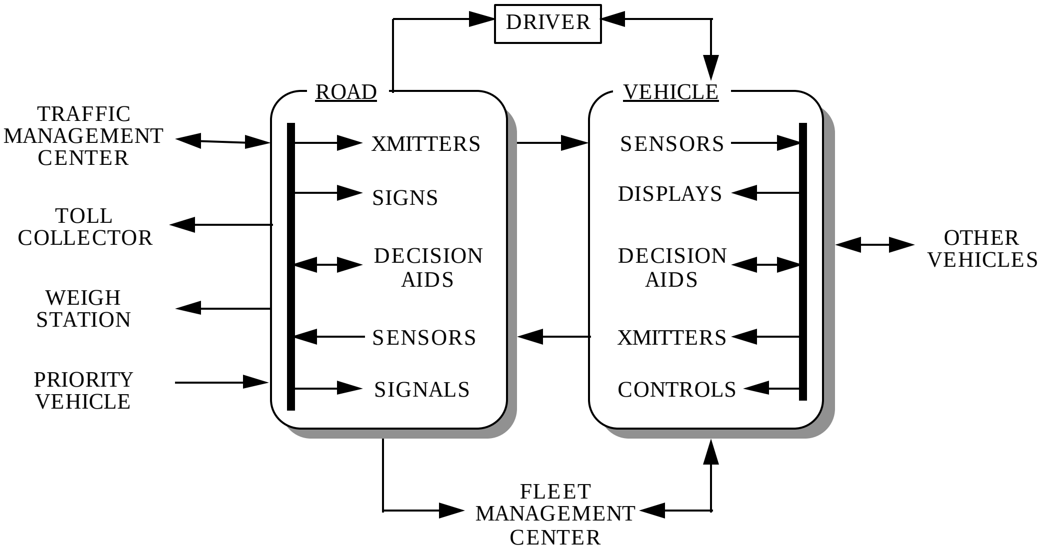


Figure 14.4 Sensors and communication devices allow the road and the vehicle to exchange data that is used to plan, implement, and manage daily activities.

ITS will rely on the consolidation of information technology combined with automotive and highway technology to achieve its objective. This will be accomplished by placing sensors and communication devices alongside the road, as well as in the vehicle (Figure 14.4). These will allow the road to “know” its operational status, which will then be “communicated” to the vehicle, which will in turn help to make informed decisions about which routes to take and daily activity planning. The road data collected will also be used by public and private concerns to plan, implement, and manage their daily operations, i.e., traveller information, traffic management, public and rural transportation management, priority vehicle management, and freight and fleet management.

In the area of transportation and distribution networks (air, land, and sea), emerging issues include: electrification of transportation; links with sensors, telecommunications and satellites; traffic modeling, prediction, and management; multi-resolutional simulations; real-time optimization with provable performance bounds; and how to use the intersection of mathematics, control and system science, economics, computer science, artificial intelligence, biology and so on to tackle these problems.

The realization of all of this will not come from one megasystem but rather from the development of a wide range of small, complementary systems ranging from electronic route guidance, to pre-emptive signal control and to automated highways.

14.9 Vulnerabilities

Any of these infrastructures can be vulnerable to both deliberate and accidental disturbances. The interconnected nature of these infrastructures means that single, isolated disturbances can cascade through and between networks with potentially disastrous consequences. Large-scale failures (i.e., failures in areas geographically remote from the original problem) and failures in seemingly unrelated businesses can occur. Because these networks support critical services and supply critical goods, disturbances can have serious economic, health, and security impacts. Therefore, there is a need to develop an ability for these infrastructures to self-heal and self-organize at the local level, in order to mitigate the effects of such disturbances.

The occurrence of several cascading failures in the past has helped focus attention on the need to understand the complex phenomena associated with these interconnected systems. In November 1965, a blackout in the Northeastern US created a power system collapse in 10 states; a blackout in the tri-state area of Pennsylvania, New Jersey, and Maryland occurred in 1967; New York City experienced a blackout in July 1977; and a voltage collapse in France triggered a blackout in December 1978. More recently, the Western US grid experienced outages in July and August of 1996 affecting 11 U.S. States and two Canadian provinces. Most recently, on December 8, 1998 blackout in the San Francisco Bay Area, cascaded from San Mateo and affected 2 million people for up to seven hours.

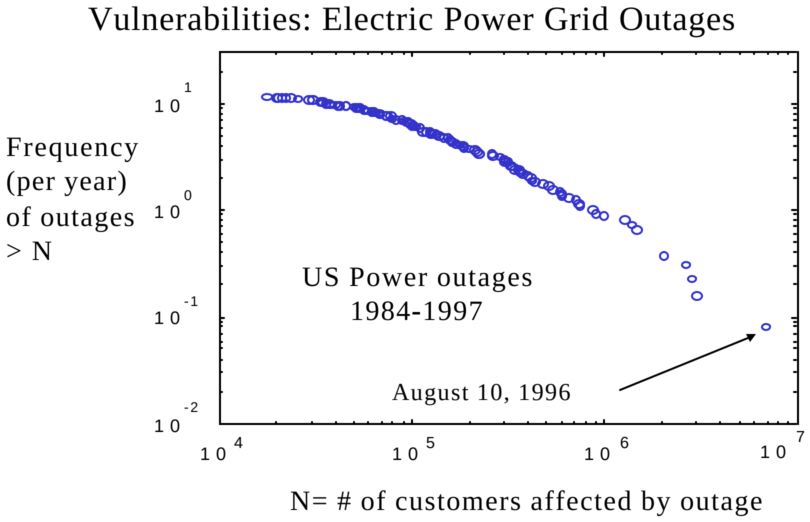


Figure 14.5 Major electric power outages in the U.S., affecting nearly 700,000 customers once a year and 7 million customers once every decade (data from NERC http://www.nerc.com/dawg; log-log plot courtesy of Prof. John Doyle, California Inst. of Technology)

The failure in the Northwest U.S. in August 1996 has several import effects and noteworthy lessons; it shows how cascading can lead to widespread network consequences:

- Faults in Oregon at the Keeler-Allston 500kV line and the Ross-Lexington 230kV line resulted in excess load . . .
- Which led to the tripping of generators at McNary Dam, causing 500 MW oscillations . . .
- Which led to the separation of the North-South Pacific Inter-tie near the California-Oregon border . . .
- Which led to islanding and blackouts in 11 U.S. states and two Canadian provinces.

The estimated total cost to the people affected reaches $1.5 billion and some experts believe that such cascade effects could have been prevented by shedding, or dropping, approximately 0.4 percent of total load on the network for 30 minutes. If we can gain such insights afterwards, can one develop predictive capabilities that understand the true dynamics of the system and can predict *apriori* what kinds of problems may arise? If not, is there a way to at least mitigate and localize the effects *in situ*? (It is important to note that load shedding is not typically a first option).

As an example of interdependencies between the markets and the electric grid, in summer 1998 price spikes showed energy infrastructure's inadequacy affecting markets (cf. June 22-26, 1998 price spikes, http://www.ferc.fed.us/electric/mastback.pdf). As an example of interdependencies between the electric grid and telecommunication network, an industry-wide Y2K readiness program identified telecommunications failure as the biggest source of risk of the lights going out on rollover to 2000.

Another well-known failure occurred in May of 1998. This failure, dubbed "The Day the Beepers Died" by *Newsweek*, was triggered when the Galaxy-IV satellite was disabled. Because the Galaxy-IV was equipped with the latest technology, causing almost all paging companies to use it, and it became a critical node in the graph. When it failed, 40 million pagers were affected, National Public Radio went off the air, airline flights were delayed, and data networks had to be manually switched to older satellites. PageNet, the largest pager provider in the US, has about 3,000 satellite dishes. When Galaxy-IV was disabled, each of those 3,000 dishes had to be manually realigned – a task that required one to two hours per satellite dish.

As another example of network vulnerabilities and interdependencies, it was reported on June 25, 1999 that the mobile-phone satellites could lead to their own downfall-- a large part of the network of satellites could self-destruct if just one of the satellites is hit by space debris according to computer simulations by scientists at the CNUCE Institute in Pisa, Italy (cf. Nature 399 743). Most space debris gradually drifts into the atmosphere and burns up on re-entry. According to the CNUCE researchers, there is a 10% chance that one of the Iridium satellites will be destroyed by debris within a decade, but the probability will increase to 10% within five years if one of the satellites is destroyed. If such a chain reaction starts it could make the entire low-Earth orbit unsuitable for satellites within one hundred years -five times faster than current estimates. Space agencies have become increasingly concerned about space debris after both the Russian Mir Space Station and the US Space Shuttle were damaged by flecks of paint traveling at over 13 kilometers per second. And last year a French spy satellite became the first satellite to be completely knocked out of operation by space debris. There are already 10 million pieces of debris larger than 1 millimeter surrounding the Earth. The danger of collisions is particular acute for satellites orbiting at an altitude between 800 and 1400 kilometers. Mobile phone companies are expected to launch hundreds of small satellites into this orbit in the next few years.

14.10 Vulnerabilities: Challenges

Avoiding failures in our critical infrastructures is a challenge because of their large-scale, nonlinear, and time-dependent behavior; furthermore: Mathematical models of such systems are typically vague or non-existent. In many cases, there are no methodologies for understanding the behavior of these complex systems. Control of these systems is a major challenge, since the number of components and types of possible interactions surpass what a central system could hope to manage.

14.11 R&D Objectives

CIN/SI aims to develop tools/techniques that enable large-scale and interconnected national infrastructures to: self-stabilize, self-optimize, and self-heal. In order to achieve this goal, the following objectives were defined:

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

14.12 Objectives: Modeling

Qualitative and quantitative models of complex interactive systems including

- Formal methods for modeling of true dynamics and for real-time computation to cope with system uncertainties; computation of provable performance bounds;
- Multi-resolutional 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;
- Optimization and control theory along with decision analysis to model hybrid (mixed discrete/continuous) systems;
- Techniques for online mathematical modeling and decision support with partial inputs and in the presence of errors.

Currently, there are no mathematical models that can create useful top-down models for these systems – that is, models that start from large-scale graphs, systematically map them into de-coupled sub-systems, and investigate the interactions between them. Because there are so many components and potential interactions, deriving all-encompassing rules for complex infrastructures is impractical. Therefore, top-down models offer some insight but can't adequately reflect real-world situations for complex infrastructures. Traditional top-down models use algebraic/differential equations to simulate aggregate populations within a complex system. Specific internal mechanisms such as adaptation and learning are ignored, as is variation that might exist among individuals.

An alternative would be developing a bottom-up model (e.g., Wildberger 1999) for example for power industry applications. In this work, EPRI has found that the bottom-up approach allows implementation for the individual parts of a system. By concentrating on smaller parts of the system, deriving rules becomes more practical. Bottom-up models use agents to simulate the greater processes responsible for global patterns within the system and agent-based models let us evaluate the local mechanisms that produce emergent patterns.

Emerging "bottom-up" models focus on the individual parts of a system rather than the whole; focusing on smaller parts of the system makes deriving rules more practical. Finally, real-world complexity is modeled by letting the individual "agents" interact independently – which can provide a better understanding of the local mechanisms that produce emergent behavior, as opposed to the centralized control inherent in top-down models.

Through agent-based models, we can use simulation to better understand the large-scale, nonlinear behavior of our complex infrastructures in the hope of better amelioration of disturbances and prevent disastrous cascading effects. These complex interactive networks have also had parallels and applications to natural systems:

- the behavior of social insects (bees, ants)
- ecologies (predator-prey relationships)
- cellular interaction (immune and nervous systems)

The overall behavior of such systems emerges through the simpler independent behavior of many individual components – a phenomenon known as self-organized complexity. Economic and political movements, albeit quite different than engineered systems, can also exhibit these characteristics.

For engineered systems, such simulations can be used as a tool for helping build agent-like characteristics into infrastructure components so they can actively respond to their real-world environment automatically, independently, and cooperatively with other components, and developing complex infrastructures that are self-optimizing and self-healing through distributed management and control.

14.13 Objectives: Measurement

Analytical and computational tools for measuring large-scale complex networks including

- Real-time survey and status monitoring of systems;
- Real-time processing of large data sets; pattern extraction (data mining and cluster analysis);
- Techniques for correlating information from separate data sources/sensors;
- Intelligent sensors and actuators;
- Tools and techniques for system verification and validation;

- Adaptive strategies that help components discern their interactions with the environment;
- Methods for providing feedback about key environmental variables; ways to generate appropriate commands using local computational devices.

14.14 Objectives: Management

A comprehensive framework for distributed network management including:

- Real-time system state analysis;
- Open architectures, intelligent devices, and distributed multi-level controllers;
- Methods for reasoning, planning, negotiation, and optimization; methods for rule generation and modification;
- 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;
- 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;
- Overall control techniques in environments where intelligent response devices may be acting against each other;
- Methods for accommodating structural uncertainty and limiting impacts of system disturbances;
- Methods for predicting impending failures: root-cause modeling for real-time diagnosis; early warning and failure forecasting;
- Methods for recovering from emergencies.

14.15 Distributed, Multi-Level Control

Although past work in agent-based models of the electric power industry emphasize the solution of economic questions, they are intended as a major step toward multi-level, distributed control of the grid by the agents themselves (Wildberger 1997a-1999, Amin 1998a-b). As these simulations become more detailed and physically realistic, intelligent agents will represent all the individual components of the grid. Advanced sensors, actuators, and microprocessors, associated with the generators, transformers, buses, etc., will convert those grid components into intelligent robots, fixed in location, that both cooperate to ensure successful overall operation and act independently to ensure adequate individual performance. These agents will evolve, gradually adapting to their changing environment and improving their performance even as conditions change. For instance, a single bus will strive to stay within its voltage and power flow limits while still operating in the context of the voltages and flows imposed on it the overall goals of the power system management and by the actions of other agents representing generators, loads, transformers, etc. All lines, and most other components, have safety and capacity restrictions which are relatively "soft" since they are based chiefly on the estimated life reduction resulting from operation outside their specifications. High and low voltage limits, for instance, may not be exceeded by specified percentages for more than specified time periods. Maximum thermal limits, expressed in megavolt-amperes (MVA), are also set in percentage-time, but ultimately, most components would fail catastrophically and, for instance, overhead lines would sag until they caused a short circuit to the earth.

More complex components, such as a generating plant or a substation, will be analyzed using object-oriented methods to model them as class and object hierarchies of simpler components, thus creating a hierarchy of adaptive agents (EPRI 1996, Wildberger 1997a, Amin 1998a-b). These agents and sub-agents, represented as autonomous "active objects," can be made to evolve by using a combination of genetic algorithms and genetic programming. In this context, classes are treated as an analogy of biological genotypes and objects instantiated from them as an analogy of their phenotypes. When instantiating objects to form individual agents, their class attributes, which define all the potential characteristics, capabilities, limitations or strategies that these agents might possess, can be selected and recombined by the operations typical of genetic algorithms, such as crossover and mutation. The physics specific to each component will determine the allowable strategies and behaviors of the object-agent representing that component. Existing instrumentation and control capabilities can be augmented and computer experiments run with hypothetical, optional capabilities in order to evaluate their benefit and the actual way in which their use might evolve. The operational parts of each class, its services or methods, may also be evolved through genetic programming using similar techniques. Their evolution will be governed by a “fitness” function embodying a combination of ensuring their own survival and meeting the global security and efficiency goals.

Modeling the electric power industry in a control theory context is especially pertinent since the current movement toward deregulation and competition will ultimately be limited only by the physics of electricity and the topology of the grid. The CAS simulation 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 operation for the mutual benefit of all.

14.16 Self-Healing the Electric Power Infrastructure

Like telecommunications, transportation, or computer networks, the electric power grid is geographically dispersed, nonlinear and interactive. Without immediate, local intervention, disturbances propagate almost instantaneously throughout the network. Both for rapid recovery from damage and for faster response to routine demand, it is preferable to delegate to the local level, as much of the control as is practical (Wildberger 1997b, Amin 1998a-b). A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to just that information necessary to achieve global optimization and to facilitate recovery after failure.

If this were to be accomplished by detailed programming on the part of the designer, it would require evaluating and accounting for an enormous number of possible situations with no guarantee that the designer actually included them all. A revolutionary new approach, that comes from the computer experiments of CAS research, is to let the agents evolve -- each one changing in a way that adapts to its environment as that environment is modified by external forces and by the evolutionary changes in the other agents. This research has found that, given the capability for merely rudimentary intelligent behavior, the agents will self-organize in a way that benefits the CAS even as it benefits them individually. Such adaptation may be defined as the *capacity for modification of goal-oriented individual or collective behavior in response to changes in the environment*. There are several aspects of adaptation that are important for the study and use of CAS. First, a distinction should be made between learning as an experience-based response (for example: sorting through a set of pre-determined patterns to find the optimal response in the set), and innovation, which requires the development of new patterns not previously known to that agent. It is also useful to distinguish between active and passive adaptation. *A passive adaptive agent responds to changes in its environment without trying to modify that environment. An active adaptive agent exerts some control or influence on its environment in order to improve its adaptive power*. In effect, it conducts experiments, and learns from them. Lastly, in modeling CAS, it is necessary to distinguish between individual and population learning. Individual agents must exhibit enough plasticity to respond to environmental conditions and to other agents in a way that enhances their survival or meets other goals. In order to learn a strategy that increases its “fitness,” the agent has to gather and store enough information to adequately forecast and deal with changes that occur within a single generation. The population then adapts through the diversity of its individuals. This implies that some individuals always survive and their individual actions benefit the population goals, so that the population evolves over many generations, surviving as a recognizable organization.

The agent community is allowed to evolve by causing innovative changes in the parameters of individual agents to be generated randomly and/or systematically. These parameter changes, in turn, produce changes in the agents’ actions and decisions, so that the agents “tinker” with the rules and the structure of the system. Agents subjected to increased stress (resource shortages, environmental pressures, and financial losses) increase their level of tinkering until some develop strategies able to relieve that stress. Some individual agents succeed (grow, reproduce, increase their profits) while others fail (shrink, die, are replaced, bought out). This implies that failure, at some level, will be permitted, but that additional copies or combinations of the most successful individuals will take the place of the less successful. (Holland 1975, Wildberger 1996)

In any situation subject to rapid changes, *completely centralized control requires multiple, high-data-rate, two-way, communication links, a powerful central computing facility, and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed,* i.e., when the system is stressed by natural disasters, purposeful attack, or unusually high demands. Management of disturbances in all such networks, and prevention of cascading effects throughout and between networks, require a basic understanding of the true system dynamics, as well as effective distributed control functions to enable parts of the networks to remain operational or even to automatically re-configure themselves in the event of a threat or other potentially destabilizing disturbance.

When failures occur at various locations in such a network, the whole system breaks into isolated "islands," each of which must then fend for itself. With the intelligence distributed, and the components acting as independent agents, those in each island have the ability to re-organize themselves and make efficient use of whatever local resources remain to them in ways consonant with the established global goals to minimize impact on the overall network. Local controllers will guide the isolated areas to operate independently, while preparing them to rejoin the network without creating unacceptable local conditions either during or after the transition.

14.17 CAS as a Unifying Paradigm

A CAS model is particularly appropriate for any industry made up of many, geographically dispersed components that can exhibit rapid global change as a result of local actions. This is characteristic of the industries which make up a national or international "infrastructure," including telecommunications, transportation, gas, water and oil pipelines, the electric power grid, and even the collection of satellites in earth orbit. The whole combined infrastructure is, itself, a CAS consisting of many individual, and often autonomous, components.

All the infrastructure industries in the United States, and to a significant extent in many other nations, have multiple ownership and management, and they operate with only a minimum of regulation by the national government. The international infrastructure is operated by a combination of national governments, national corporate entities, and, increasingly, by international corporations. It is regulated only by treaties whose enforcement depends heavily on the goodwill and cooperation of all parties. *A useful approach to analyzing these national and international infrastructures is to model their components as independent adaptive "agents"* -- partly cooperating and partly competing with each other in their local operations while pursuing global goals set by a minimal supervisory function. Computer simulations can be used to test the feasibility of distributed management and control of these infrastructure industries, their viability under stress, and their potential for self-healing after disturbances.

However, this approach is not applicable only to infrastructure industries. The CAS concept has the potential to provide a new paradigm for the design, control, operation and maintenance of any complex, interconnected system, especially one that possesses significant technological content.

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, these problems with scientific explanation by reduction have given rise to much of the research in CAS. (Cowan *et al*. 1994) Scientists working in this field are trying to develop and test theories by working "bottom-up" rather than "top-down." They start with the known behavior of component parts, 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.

Top-down modeling of a technological system 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 top-down models are often over-simplified to the point where they do not adequately reflect any actual situation. Although considerable theoretical work has been done with the more general forms of mathematical programming and multi-objective optimization, the practical analyst and designer most often falls back on a single-objective model and approximates its solution with linear programming.

The most common approach to the mathematical modeling of continuous complex systems uses differential and algebraic-differential equations. The parameters of these equations approximate phenomenological attributes of the aggregate population that makes up the system under consideration. They do not identify specific internal mechanisms nor consider variation among individuals. Agent-based modeling simulates the underlying processes believed responsible for the global pattern, and allows us to evaluate which mechanisms are most influential in producing that emergent pattern. Bottom-up modeling with agents focuses on the behavior of less complex individuals that make up the larger system. These relatively simple agents can be modeled in detail. The autonomous interaction among them is the source of all the complex structure that would otherwise have to be programmed.

Figure 14.6 shows one possible abstract design for an intelligent agent. Six of the interior blocks suggest models or functions that might be possessed by the agent, although not all agents would need all of these. Each of these blocks could be realized by algorithms and heuristic rules embodying some of the many methods of artificial and computational intelligence in common use today, such as: neural networks, fuzzy logic, genetic algorithms, symbolic expert systems, etc. By combining these in the structure of an agent, the CAS model can serve as a unifier for intelligent control, subsuming all the techniques of modern control theory (including robust, adaptive, nonlinear, stochastic and optimal control) to produce a complete system that is self-organizing, self-reconfigurable, and self-repairing.

The CAS paradigm is especially appropriate for the design and analysis of interactive systems in which humans directly participate. In a simulation of the system, adaptive agents may be used to model the humans as well as those parts that are completely automated. Computer experiments can suggest the appropriate tasks and specific goals for both the humans and the robotic parts of the system, as well as the information required by the humans and its most efficient sources. This approach may even be applied to the actual operation of interactive systems or of organizations composed mainly of humans. A recent article (Cebrowski and Garstka 1998) suggests that a CAS model of military operations may lead to a revolution in military affairs not seen since the Napoleanic era, since only an approach based on bottom-up organization, continuous play, co-evolution and self-synchronization can produce the speed of command required in a complex, fast-changing, and information-rich environment.

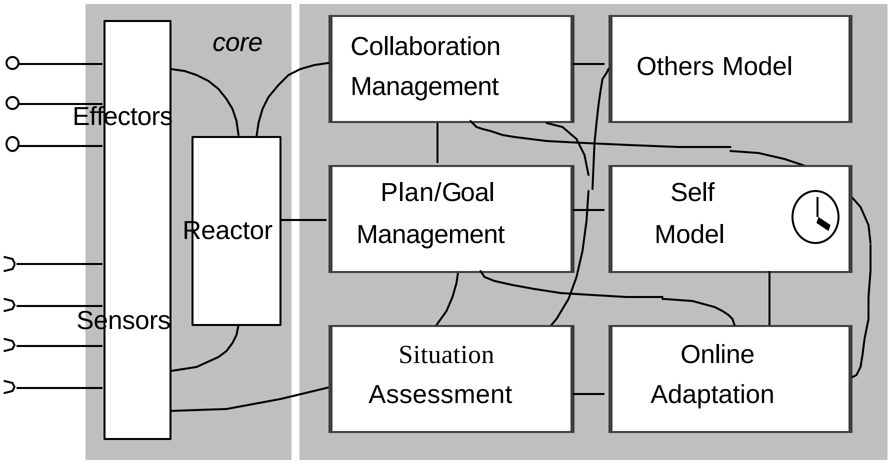


Figure 14.6 Abstract Agent Design

14.18 CIN/SI Program Content

The EPRI/DoD Complex Interactive Networks/Systems Initiative (CIN/SI) goal is 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/ameliorate cascading effects through and between networks.
- Tools/techniques that enable large-scale and interconnected infrastructures to: self-stabilize, self-optimize, and self-heal.

It is planned that many of these new capabilities will be developed in the next decade to effectively model, analyze and operate geographically dispersed but operationally interconnected industries, including energy, telecommunications, transportation and distribution, banking and finance. All of these are themselves complex networks, non-linear, and interacting both among themselves and with their human owners, operators, and users. As the complexity of these intertwined operations has increased, they have become responsible for much of “the good life” that we, at least in the more developed countries, lead today. However, with those increasing benefits come increasing risks. A common characteristic of all these networks is that local actions have the potential to create global effects by cascading throughout the network and even into other networks. The challenge of developing self-regulating systems includes these areas:

- Measurement, sensing, and visualization

- Modeling and simulation
- Control systems
- Operations and management.

Through a very highly competitive source selection process, the EPRI/DoD Complex Interactive Networks/Systems Initiative (CIN/SI) has funded six consortia, consisting of 28 universities, to address these challenges. Funded research include:

1. Power Laws and the Power Grid: A Mathematical Foundation for Complex Interactive Networks (Consortium: CalTech, MIT, UCLA, UC-Santa Barbara, U of Illinois). Technical areas include: Basic theory of complex interactive systems with application to power and communication networks; short-term objectives:
   - Power laws and the power grid: Analysis of optimization-induced power-law behavior in idealized networks (thousands of nodes).
   - Development of nonlinear model reduction capability to study dynamic models of the power grid of moderate scale (up to a hundred generators).

2. Context-Dependent Network Agents (Consortium: Carnegie Mellon U, RPI, Texas A&M U, U of Minnesota, U of Illinois). Technical areas include: Development of context-dependent network (CDN) agents; agent templates and components and development of models for restructured power system models; short-term objectives:
   - Power system modeling framework that maps global conditions into a distributed decision making architecture.
   - Real-time infrastructure for the agent modules and robust operating system for data communication: Development and demonstration of a context-dependent agent module architecture and preliminary agent coordination rules on two test scenarios.

3. Minimizing Failures While Maintaining Efficiency of Complex Interactive Networked Systems (Consortium: Cornell U, George Washington U,UC-Berkeley, U of Illinois, Washington State U, U of Wisconsin). Technical areas include: Implications of a wide distribution of independent entities actively interacting through and with complex interactive infrastructure networks. Potential for local actions to create effects that cascade throughout the network and/or into other networks. Stochastic analysis and reliable performance of complex networks; short-term objectives:
   - Definition and formulation of the layered network and their attributes. Coordinated approach to the several communication systems needed for the emergent power system.

4. Modeling and Diagnosis Methods for Large-Scale Complex Networks (Consortium: Harvard U, Boston U, MIT, UMASS-Amherst, Washington U.-St. Louis). Technical areas include: Discrete Event Dynamical Systems (DEDS); Simulation modeling of complex networks; Modeling and diagnosis methods for large-scale networks; short-term objectives:
   - Development advanced simulation tools (perturbation analysis and ordinal optimization) to improve robust stability and quick detection of faults in complex systems.

5. Intel. Management of the Electric Power Grid: Anticipatory Multi-Agent, High Performance Computing Approach (Consortium: Purdue U, U of Tennessee, Fisk U, Commonwealth Edison Co., Tennessee Valley Authority). Technical areas include: Energy Infrastructure management and anticipatory multi-agent, high performance computing; short-term objectives:
   - Modeling of part of the grid (ComEd/TVA) for use in the development and testing of an anticipatory approach.

6. Innovative Tech. for Defense Against Catastrophic Failures of Complex, Interactive Power Networks (Consortium: U of Washington, Arizona State U, Iowa State U, Virginia Tech). Technical areas include: Self-healing strategies for competitive environments: Interactive power networks; Wide-Area Measurement Systems (WAMS) for infrastructures; short-term objectives:
   - Conceptual design of the Strategic Power Infrastructure Defense (SPID) system: Model of the electricity markets; control and protection strategies against catastrophic failures; sensing, information, computing and control strategies.

Areas of research being investigated by each consortium are depicted in Figures 14.7-14.8 as a canvas of research and development:

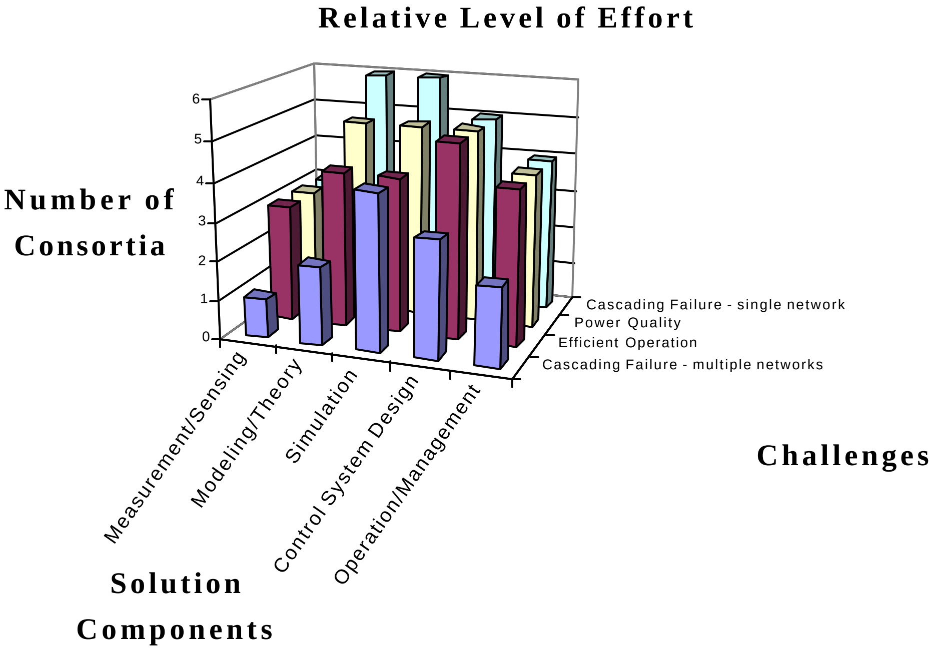


Figure 14.7 Relative Level of Effort vs. Challenges and Solution Components

	Measurement and Sensing (incl. Visualization)	Modeling/ Theory	Simulation	Control Systems Design	Operation and Management
Efficient Operation	Harvard Purdue U WA	Caltech Cornell Harvard Purdue	CMU Harvard Purdue U WA	Caltech CMU Cornell Harvard U WA	CMU Harvard Purdue U WA
Power Quality	Harvard Purdue U WA-	Caltech CMU Cornell Harvard Purdue	Caltech CMU Harvard Purdue U WA	Caltech CMU Cornell Harvard U WA	CMU Harvard Purdue U WA
Cascading Failure (single network)	Harvard Purdue U WA	Caltech CMU Cornell Harvard Purdue U WA	Caltech CMU Cornell Harvard Purdue U WA	Caltech CMU Cornell Harvard U WA	CMU Cornell Purdue U WA
Cascading Failure (multiple networks)	Harvard	Caltech Cornell	Caltech- Cornell Harvard U WA	Cornell Harvard U WA	Cornell U WA

Solution Component

Challenges of Reliable and Robust Operation vs. Solution Compents.
Consortia Lead Universities: Caltech; Carnegie Mellon U; Cornell U; Harvard U; Purdue U; U of Washington

Figure 14.8 A canvas of research and development for reliable and robust operation vs. solution Components

In order to address the challenges indicated earlier in this chapter, we envisage development of the following capabilities in order to realize the creation of smart systems capable of reliable operation:

- Measurement and sensing
  - — Improvement of sensor and communication technologies and real-time processing of large data sets, flag rare events, extract patterns and correlate information from separate data sources/sensors.

- Filter massive data, communicate, coordinate and display information in a timely manner.
- Develop of real-time tools for enhanced "system observability" that provide a visual depiction of reliability indicators to the system operators as well as tools for contingency planning and assessing "what if" situations.
- Fault diagnosis and correction: Develop models for mapping faults to alarms. Algorithms for identifying faults that cause the observed alarms.
- Establishment of critical monitoring requirements which would permit timely detection of the precursors of potentially harmful disturbances; both at the local and global network levels.
- Knowledge tools for integration of information from various sources.
- Real-time survey and status monitoring of systems. Decipher, analyze and integrate knowledge contained in data. Generate, gather, and represent complex data and information.

- Modeling and simulation:
  - Further research to enhance the understanding and security of interconnected networks.
  - Basic understanding of the true system dynamics and robust distributed control to enable networks to remain operational.
  - Simulation, analysis and modeling methods and tools for large-scale systems. On-line mathematical modeling and decision support with partial inputs and in the presence of errors.
  - Modeling and analysis of interdependencies between infrastructures to enhance our understanding of their behavior.
  - Use look-ahead simulation to predict failure events in power system networks.
  - Development of multi-resolutional simulations to handle multi-scale nature of power systems in real time, capable of going from macro to micro level.
  - Tools for automated negotiation and risk management among self-interested agents (game theory with computational and resource bounds).

- Control systems:
  - Development of open architectures, intelligent devices, coupled with distributed multi-level controllers for large-scale hybrid systems.
  - Address implementation issues as well as system-theoretic concerns including stability, controllability and observability; merging of information and control.
  - Identification of key network attributes for flow control.
  - Formulation of power system protection strategy that incorporates stronger adaptive links between real-time simulation and the control of devices: Development of models of impedance relays, remedial action schemes and other devices that use local information.
  - Development of target parameters for general topologies to judge the security of power system network.
  - Basis issues in real-time integrated failure analysis and event propagation for distributed control and failure containment.
  - Tools for anticipatory local grid control systems.
  - Faster and more accurate physical control systems. Overall coordinated control since the intelligent fast response devices may be acting against each other.

- Operation and management:
  - Management of disturbances in all such interconnected networks and prevention of cascading effects throughout and in between them.
  - Secure and manage distributed resources, represent, control, and optimize processes in real-time (e.g., electric power grid and tele-communication networks).
  - The need to optimize the energy network architecture for maximum power transfer.
  - Integration of the above technologies into an operational system.

14.19 Conclusion

Many of our nation’s critical infrastructures are complex interdependent networked systems; prime examples are the highly interconnected and interactive industries, which make up a national or international infrastructure, including telecommunications, transportation, gas, water and oil pipelines, the electric power grid, and the collection of satellites in earth orbit.

Interactions between network such as these increase the complexity of operations and control. Secure and reliable operation of these systems is fundamental to our economy, security and quality of life. These large-scale networks are characterized by many points of interaction among a variety of participants—owners, operators, sellers, and buyers. The networks' interconnected nature makes them vulnerable to cascading failures with widespread consequences.

The EPRI/DoD Complex Interactive Networks/Systems Initiative, which began in mid 1999, is leading toward a concept of controls that are “self-healing” in the sense that they make the system automatically reconfigurable in the event of material failures, threats or other destabilizing disturbances. In light of this work, the question is raised as to whether there is a unifying paradigm for modeling the simulation and optimization of time-critical operations (both financial transactions and actual physical control) in any multi-scale, multi-component and distributed system. These are the characteristics of any industry made up of many, geographically dispersed components that can exhibit rapid global change as a result of local actions.

With the advent of deregulation, unbundling, and competition in the electric power industry, new ways are being sought to improve the efficiency of that network without seriously diminishing its reliability. Complexity of the electric power grid combined with deregulation and ever-increasing interaction between interconnected infrastructures offer new and exciting scientific and technological challenges.

From a viewpoint of strategic research and development, there are many scientific and technological challenges posed by the lack of a unified mathematical framework with robust tools for modeling, simulation, control and optimization of time-critical operations in hybrid, complex, distributed and interactive networks with multi-scale and multiple components. The EPRI/DoD Initiative on Complex Interactive Networks/Systems emphasizes the mathematical foundations and robustness of complex, networked systems; it aims to develop:

- methodologies for robust distributed control of heterogeneous, widely dispersed, yet interconnected systems;
- techniques for exploring interactive networked systems at the micro (individual component) and macro (emergent property) levels;
- tools to prevent/ameliorate cascading effects through and between networks;
- tools/techniques that enable large-scale and interconnected national infrastructures to: self-stabilize, self-optimize, and self-heal;
- ways to enable these infrastructures to help address the trilemma of population, poverty, and pollution.

14.20 Acknowledgments

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14.21 References

14.21.1 Web sites with downloadable material and software

A presentation package for the EPRI/DoD University Research Initiative on Complex Interactive Networks/Systems is available on EPRI’s web site at: http://www.epri.com/srd/cinsi/. The CIN/SI research announcement DAAG55-98-R-RA08, is at: http://www.aro.army.mil/research/complex.htm.

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