An Overview of Energy and Telecommunications Interdependencies Modeling at NISAC

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Abstract. The National Infrastructure Simulation and Analysis Center (NISAC) is responsible for providing fundamentally new modeling and simulation capabilities for the analysis of critical infrastructures. We believe that by developing and exercising a variety of modeling approaches, over time we can build up a mosaic of collected insights and intuition and understanding about how complex, interdependent infrastructure systems will respond to disruptive events. This article describes some of our modeling efforts to date as related to energy and telecommunications and their interactions. We consider highly-abstracted models that allow experimentation about the interplay between network topology and tolerance for evaluating system robustness against cascading failures. And at the opposite end of the spectrum, we also consider high-fidelity models that include a sufficiently realistic representation of infrastructure elements to allow simulation of infrastructure responses to a variety of disruption scenarios. We conclude this article by showing how systems knowledge accumulated from this range of modeling efforts was used to forecast the infrastructure impacts from Hurricane Katrina.

Keywords. Energy, Telecommunications, Infrastructure, Interdependencies, Modeling

Introduction

The mission of the National Infrastructure Information and Analysis Center (NISAC) is to provide new modeling and simulation capabilities for the analysis of critical infrastructures, their interdependencies, vulnerabilities, and complexities. Use of these simulation capabilities can help improve the robustness of our Nation's critical infrastructures by aiding decision makers in the areas of policy assessment, mitigation planning, education, training, and near real-time assistance to crisis response organizations. The size and complexity and interdependent nature of modern infrastructure networks require that we use simulation techniques as a supplement to the expert opinions of infrastructure specialists. The value in employing computer models derives especially from the differences that are identified between them and mental constructs of the infrastructure professionals. When conflicting results of a mental and a computer model are analyzed and the underlying causes of those differences are identified, new insights are gained and both of the models can be improved. In this way, the modeling studies can support policy analysis and crisis response operations directly by providing timely simulation results. And perhaps more importantly, simulation of infrastructure disruptions can support emergency preparedness planning and disaster response by broadening the responders' understanding of the complex interactions between adjacent infrastructures.

By developing and exercising a variety of modeling approaches, over time we have been able to accumulate understanding about how interdependent infrastructure systems will respond to disruptive events. This article describes some of our modeling efforts to date as related to energy and telecommunications and their interactions. We begin by considering a highly-abstracted network model of the electricity grid in the western US. We show that examining the interplay between network topology and tolerance provides a mechanism for evaluating system robustness against cascading failures. Next, we briefly present the use of systems models of aggregate supply and demand dynamics to consider the downstream implications of disruptions to SCADA (supervisory control and data acquisition) systems. Then, the bulk of this paper presents a high-fidelity model of a metropolitan telecom voice network that allows simulation of infrastructure responses to a variety of disruption

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scenarios. We conclude by showing how expertise developed in part from conducting this range of model development and simulation exercises, supported the forecasting of infrastructure impacts from Hurricane Katrina.

1. Network Modeling of Electric Grid Robustness

In this work, a series of networks representative of electrical power transmission networks were generated having a variety of topological properties [1]. One notable feature of comparison between these various networks was the relative abundance of highly connected nodes as is indicated in Figure 1. As a model of an attack, each network had exactly one of its most highly connected nodes removed, with the result that in some cases, one or more remaining nodes became congested with the reassignment of the load. The congested nodes were then removed, and the "cascade failure" process continued until all nodes were uncongested. The ratio of the number of nodes of the largest remaining cluster to the number of nodes in the original network was taken to be a measure of the network's resiliency to highest-degree node removal. It was found that network resiliency was sensitive to the relative abundance of the most highly connected nodes. In general, the greater the overall network connectivity, the greater the robustness of the network. A higher degree of connectivity made the network less susceptible to cascading failure as a greater number of routes were available to shoulder the reassignment of the load.

In related work, the western North American regional electric power transmission network was analyzed based on its topological characteristics. This electricity transmission region is the largest geographically of the eight US transmission regions with a footprint of 1.8 million square miles and a service territory including all or portions of the 14 western US states, Alberta and British Columbia in Canada, and the northern portion of Baja California, Mexico. In this case attacks directed against the most connected node were compared against to attacks against the node conducting the highest load. As shown in Figure 2, for systems having sufficient tolerance to load variation, the transmission network is much more resilient to targeted attacks against the most connected node in comparison to attacks against the highest load node. Simulation results indicate this particular network is not very resilient to attacks against the highest load node. Loss of the largest load conducting node led to significant cascading as the adjacent nodes proved to have insufficient capacity to shoulder reassignment of the shed load. Fortunately, the nodes carrying the largest loads are difficult to identify without conducting detailed analyses.

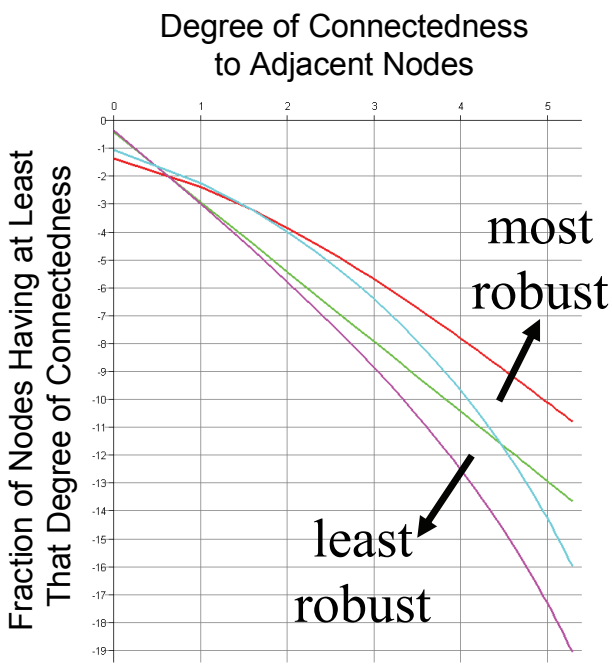

Figure 1. Electric grid robustness against cascading failure is enhanced in proportion to the number of highly connected nodes.

2. Dynamical Modeling of SCADA

Supervisory Control and Data Acquisition (SCADA) systems allow remote, real-time monitoring and management of infrastructure networks such as pipeline systems. Sandia Labs is a participant in the Institute for Information Infrastructure Protection (I3P), a US Department of Homeland Security consortium to identify and help mitigate threats to US information infrastructure. As part of our participation in this program, NISAC is studying the relationships between SCADA systems and oil and gas operations [2]. This work uses system dynamics modeling to understand the operational impacts of a SCADA disruption on the pipeline transportation of crude oil, refined products, and natural gas at a national level. Characterization data such as pipeline capacities, regional storage, and production are used together with a representation of how control signals that are passed between supply and demand side entities to understanding what policies may be effective in reducing both the immediate and lasting consequences of a disruption.

Figure 3 provides a schematic summary of the disruptive impacts of an interruption in SCADA. Typically, a disruption to either telecom or electric power will lead to a concomitant disruption to

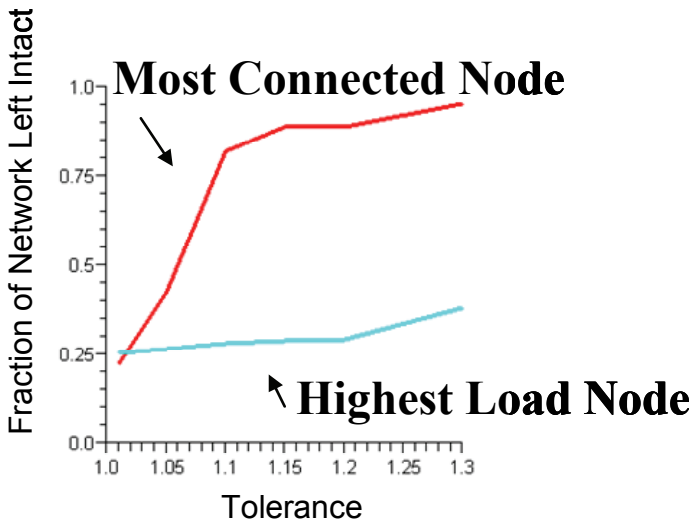

Figure 2. Electric grid robustness against cascading failure for the western North American transmission region is compared between targeted attack against the most highly connected node versus targeted attack against the node carrying the largest load. Assuming the network has sufficient capacity to tolerate load variation, the transmission network is much more resilient to targeted attacks against the most connected node in comparison to attacks against the highest load node.

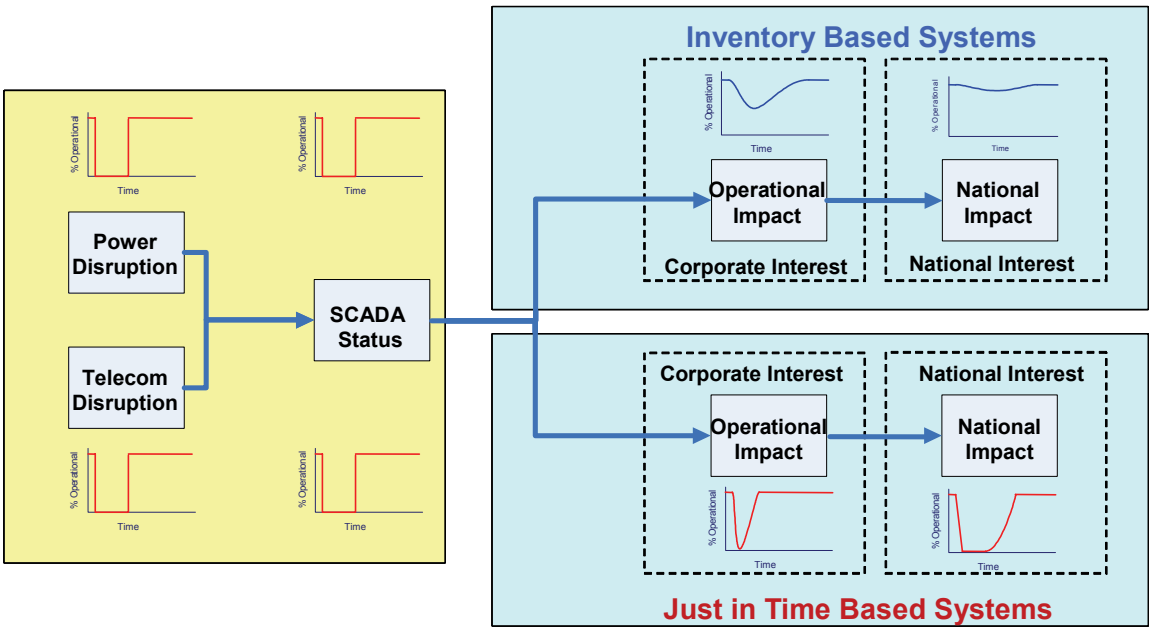

Figure 3. Summary schematic contrasting the response of inventory-based systems such as oil and gas pipeline transmission networks to those of just-in-time based systems such as electric power transmission networks.

SCADA operability. Our modeling work has shown that inventory-based systems – those systems having significant storage throughout their transmission network – fair comparatively well through SCADA disruptions because the storage in the network provides a buffering capacity to (at least partially) offset the loss of SCADA control. By resorting to manual operations, the network can continue to operate, albeit at reduced capacity. While the operational impact to individual commercial oil and gas entities may be significant, the overall national impact will usually be relatively small. We note that these findings are in contrast to what is typically experienced by just-in-time based transmission networks such as electric power and telecommunications where the lack of available storage within the system exacerbates the operational impact of SCADA disruptions making them much more vulnerable to a cascading response.

3. Discrete Event Modeling to Simulate Telecom Disruptions

The Network-Simulation Modeling and Analysis Research Tool (N-SMART) has been developed by Bell Labs for NISAC to support detailed wireline and wireless network simulations [3, 4]. N-SMART is a discrete event model which simulates a complete metropolitan area on a call-by-call basis. The model takes as input the telecom network architecture of a metropolitan area along with a statistical representation of call traffic loads to simulate normal operation. We can then add in a network failure scenario (such as an equipment outage or an overload in the call traffic) to evaluate network performance under adverse conditions. To model any particular metropolitan area, we use publicly-available information specifying the location and types of call processing switches as the basis for designing a realistic representation of the region's voice telephony networks using Bell Labs' circuit switch design tools. The network design provides (1) the call routing information, (2) the hierarchical switching network topology, and (3) the sizes for the switches and trunks.

The simulation engine consists of a call generation (and re-attempt) model, a call routing model, and a model of switch processing resources. The call generation model simulates the steps to be followed for the handling of all calls. First call attempts arrive at a particular switch for a specified destination switch as described by the traffic load and the traffic profile. The call is accepted and routed through the network if there are sufficient trunk and processing resources in the switch and the network. If a call is successfully set up, it uses a certain amount of network resources until it is completed. The call may also be blocked if the called line is busy or if the network is busy, due to either trunk blocking along the route of the call or switch blocking because of processor congestion. Blocked calls are reattempted later. The algorithm for handling calls and reattempts is summarized in Figure 4.

Thus far, we have built combined wireline/wireless telephony network models for the cities of Chicago, Houston, and Seattle. We have used these three models to simulate a wide variety of disruption scenarios.

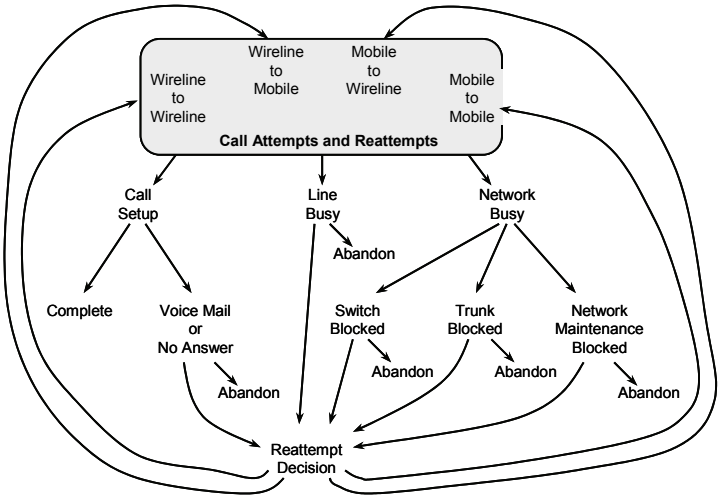

Figure 4. Schematic showing the possible outcomes for generated calls and reattempts. Notice that the model allows the call originator to reattempt using different network options (wireline versus wireless as specified by probabilities for switching). This can occur either at the point of call origination or at the call's destination. For example, a caller that was unsuccessful in their first attempt originating their call from their mobile phone may reattempt their call later using their wireline phone; or, an unsuccessful attempt to a wireline phone may prompt a reattempt to the recipient's mobile phone.

3.1. Houston/Galveston Rita Simulation Scenario

As Hurricane Rita formed and began tracking towards the Texas Gulf Coast in September 2005, we used the N-SMART model for the Houston metro area to help gauge the potential range of telecom outages to be expected should Houston receive a direct hit. The worst case scenario we considered during that analysis is presented here, consisting of a wide-scale electric power outage and extensive flooding in the southeast region of the metro area. We hypothesized that the power outage would lead to the loss of 12 of the region's 22 wireless switches as the cell towers homed to those switches drained their backup battery power within the first several hours. Further, we hypothesized that 18 of the region's 78 local wireline switches would become inoperable due to flooding. Fortunately, the storm passed east of Houston and our predictions of significant loss of operability did not come to fruition. Still, these simulation results are instructive because they show the magnitude of disruption to telephone service that is possible, given a large natural disaster such as a hurricane.

Wireless handles 36% of the call volume in the Houston area[2]. We expected extensive disruption to the wireless network in the event of a wide scale power outage (due to short backup battery life). In contrast, the wireline network handles power outages much better because their switching offices typically have diesel generators as backup power. Much of the call volume that is unable to connect calls on the wireless network will attempt to compensate by switching over to the wireline network. So wireline will be affected by increased call volume due to the switchover from wireless. Previous network modeling [4] has shown that, in general, wireline and wireless networks in a metropolitan area support each other in times of disruption (to either network). The presence of multiple networks enhances resiliency of overall network communications – even though they weren't specifically designed to provide such redundancy. This resiliency is caused by customer behavior in switching networks when one is failed. But, the downside to the switchover in demand onto the non-disrupted network is that it may cause significant congestion in the destination network. In fact, in this simulated case, significant degradation of the wireless network caused inundation of the wireline network and degradation of service as users switch over to wireline, the remaining operational network.

Typical call volume for the Houston metro area during the peak calling period is about 700 thousand new calls generated every 10 minutes. Figure 5 shows that during the simulated disruption, the number of generated calls skyrockets. The vast majority of first attempt calls are blocked by the failure of many network switches. These unsuccessful calls generate a growing number of reattempts which cause significant congestion on the remaining portion of the operable network. In this way, the number of calls generated can become significantly greater than the first attempts, resulting in switch processor overloads. In addition, as these processors become overloaded, their processing capacity becomes reduced, leading to further decreases in network throughput during the overload.

Figure 6 shows the ratio of admitted calls to the first attempts, providing some measure of the proportion of calls that get through eventually (albeit often after many reattempts). This 40% success rate is indicative of a significantly degraded network.

Figure 7, gives a spatial representation of the extent of network degradation in the Houston metro

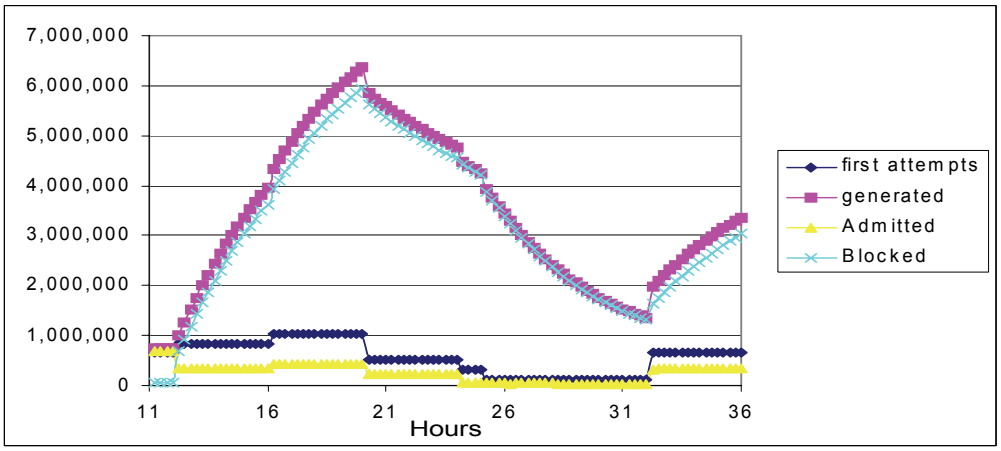

Figure 5. Simulated call volume (in 10 minute increments) for Houston during a hurricane disruption scenario in which power outages and flooding cause significant damage to switches.

[2] This consists of all calls that are either: (1) mobile to mobile calls (4% of all calls), (2) calls between mobile and local wireline phones (24%), and (3) long-distance calls to or from local mobile phones (8%). The remainder of all calls is completed entirely within the wireline network.

area, showing very high levels of switch blocking and trunk blocking in the local telephone network.

We believe simulation studies such as these are useful for a variety of potential purposes, such as emergency response planning, or network design evaluation[3].

4. Hurricane Katrina Fast Analysis for Telecom

NISAC support to the US Department of Homeland Security includes performing "fast analysis" exercises to support emergency response during natural disasters other unexpected disruptive events. During Hurricane Katrina, we provided 2 pre-event information reports that analyzed the potential infrastructure impacts and estimates of projected economic damage. For example, FEMA uses this type of information to help direct the pre-positioning of resources. These analyses were briefed to the Homeland Security Operations Center, the DHS Secretary, and the White House. A series of 10 post-event evaluations were also provided for Hurricane Katrina in response to continuing information

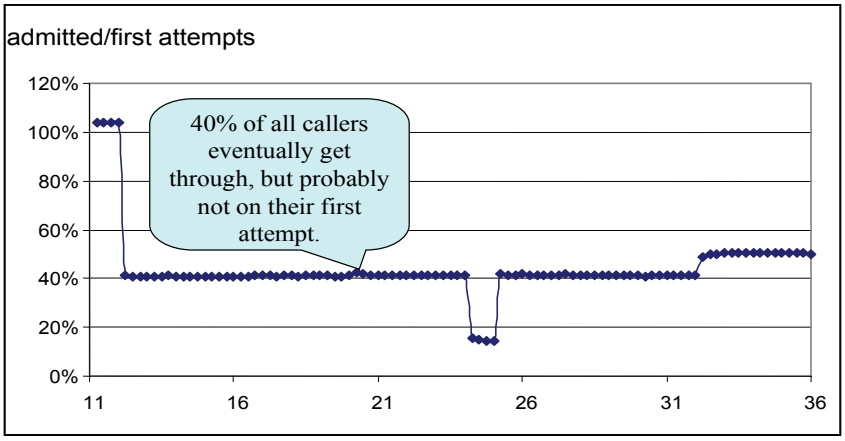

Figure 6. The ratio of admitted calls to first attempts provides a practical estimate of the proportion of call attempts that eventually successful.

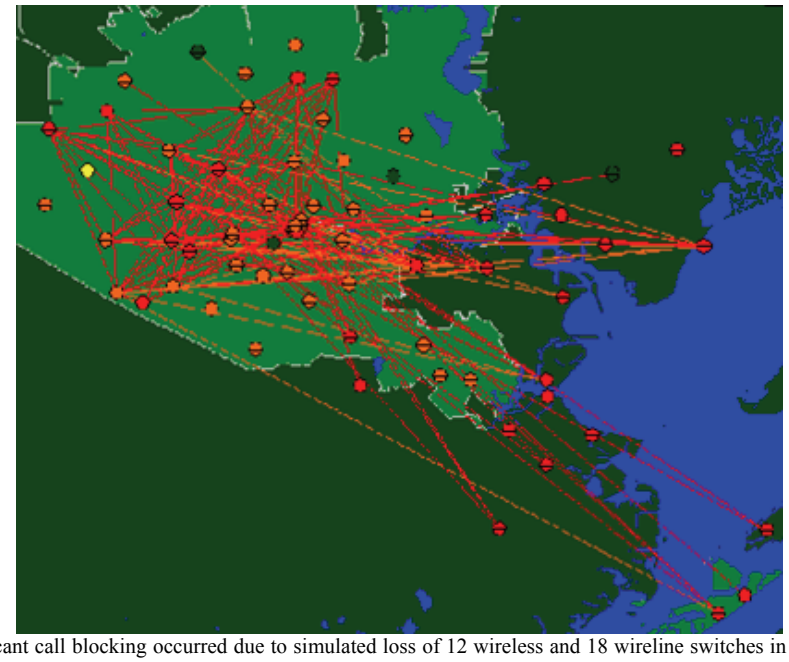

Figure 7. Significant call blocking occurred due to simulated loss of 12 wireless and 18 wireline switches in the Houston metro area. Nodes represent switches and lines represent trunks connecting the switches. Red = greater than 75% blocking; Orange = between 50% and 75% blocking; Yellow = between 35% and 50% blocking; Blue = between 20% and 35% blocking; Green = between 10% and 20% blocking; Grey = between 1% and 10% blocking.

[3] Currently, telephony networks are designed to handle the highest traffic busy interval of the day under normal operating conditions without undue call blocking. Network performance during disruptive events is not a design criterion – aside from one major exception. Telephone companies do protect their service against power blackouts.

needs. These reports provided assessments of economic impacts and the impacts of infrastructure damage. A compendium report [5] provides a summary of the entire effort.

Specifically regarding the telecommunications sector analyses, we found that some of the insight derived from our previous modeling exercises helped inform the content of fast analyses for Katrina [6]. In these reports, we did well at predicting that damages would be:

- Confined to localities directly along storm paths. We correctly anticipated that national long distance and data networks would remain almost entirely operational.
- More extensive in the wireless networks as compared to the wireline network.
- For the wireless networks, predominantly due to wind damage and loss of electric power to cell towers.
- For the wireline network, predominantly due to flooding of switches and the downing of telephone poles disabling the "last-mile" communication link to homes and small businesses.

We also foresaw that:

- Telephone switches could run out of reserve power if the outage to the electrical system lasted for several days, and repair crews are unable to refuel the backup generators.
- The speed of network repair would be limited by lack of access due to flooding.

However, we did less well at predicting some aspects:

- While we predicted that sufficient availability of both labor and replacement switching equipment, it was reported that both labor and equipment resources were stretched to the limit.
- We failed to comment entirely about the likelihood of survivability of emergency communications.

And finally, it has been generally recognized that the Hurricane Katrina exposed shortcomings in governmental emergency response to natural disasters. In particular to telecommunications, two areas have been identified which improvements would assist the emergency response effort:

Emergency Telecommunications – improvements are needed to increase the survivability and interoperability of emergency communications networks – especially so that they are able to remain functional during extended power outages and/or significant degradation of the public telephony networks.

Development of a Common Operating Picture – FEMA recognizes the need for development of a real-time means to collect, share, and integrate disparate information gathered during the course of a disaster event. Better access to this information would help improve response effectiveness while facilitating the coordination between the decentralized network of government agencies, charitable relief organizations, and infrastructure service providers.

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