INTERDEPENDENT RESPONSE OF TELECOMMUNICATON AND ELECTRIC POWER SYSTEMS TO SEISMIC HAZARD

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Kanoknart Leelardcharoen

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INTERDEPENDENT RESPONSE OF TELECOMMUNICATON AND ELECTRIC POWER SYSTEMS TO SEISMIC HAZARD

Approved by:

Dr. Barry J. Goodno, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. A. P. Meliopoulos
School of Electrical and Computer Engineering
Georgia Institute of Technology

Dr. James I. Craig
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Reginald DesRoches
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Leonardo Dueñas-Osorio
Department of Civil and Environmental Engineering
Rice University

Date Approved: August 15, 2011

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SUMMARY

Infrastructure systems are essential to the functioning of contemporary societies and economies. A major disruption to the built environment can lead to severe public safety issues and economic losses. Within the past few decades, modern control and information technologies have been rapidly developed in an attempt to improve the reliability of individual utility systems by exchanging technologies across them. One of the major ramifications is the emergence of interdependencies among these critical infrastructure systems, especially when facing major disruptions. Failure of an individual system becomes more likely to affect the functionality of other interconnected infrastructure systems. In order to mitigate such consequences, the mechanics of interdependencies and failure propagation among the systems must be understood.

This research focuses on the development of a framework for probabilistically quantifying interdependent responses of two essential infrastructure systems – telecommunication and electric power systems – subjected to seismic hazards, which are one of the most powerful and geographically extensive threats. The study explores the effects of seismic hazards beyond the obvious seismic-induced physical damage to utility system facilities. In particular, the seismic evaluation of telecommunication systems considers the degradation of system performance due to physical damage and the abnormally high usage demands in telecommunication systems expected after catastrophic earthquakes. Specifically, a newly developed seismic-induced congestion model is proposed, and the probabilistic formulations of the critical interdependencies across telecommunication and power systems are presented in a probabilistic framework.

The study illustrates the procedure for fragility analysis of interdependent systems and presents a practical application through a test bed implementation in Shelby County, TN.

From this study, telecommunication systems are found to be very vulnerable to seismic-induced congestion. The electric power interdependencies amplify the degradation in telecommunication systems up to 50% in their vulnerability while electric power operations are heavily dependent upon telecommunication infrastructures and the fragility median of electric power system observability can decrease by 30%. The study also indicates up to 100% overestimation of the independent fragility analysis and the results reveal the relationship between system topology and the sensitivity of system performance to the intensity of interdependencies. The proposed methodology is expected to be a valuable tool for decision making in evaluating seismic mitigation strategies and also to provide the foundation for future studies on interdependent responses of other critical infrastructures.

CHAPTER 1

INTRODUCTION

In the modern world, public safety, economic prosperity, and social activities heavily depend on the functionality of complex infrastructure systems. Electric power grids, water networks, oil and gas distribution systems, transportation infrastructure, and telecommunication systems are examples of these critical lifeline systems.

Over the last few decades, these infrastructure systems have greatly improved their efficiency to adequately meet growing demands. One result of this improved control and efficiency is that interdependencies among infrastructure systems have increased dramatically. The technology of each infrastructure system is built upon the advancements of the others. As an example, the banking and financial systems have benefited from the advancements in information and communications technologies. Instant trading in the stock market, world-wide automatic teller machines (ATMs), and instant approval of credit card transactions are all made possible by data transmission over telecommunication networks. Also, electrical systems have benefited from advancements in natural gas infrastructures: more gas turbines are used in electric power generation because of the improvement in reliability and efficiency of natural gas production and transmission (Amin 2000).

Although these systems are engineered to supply continuous services, rare incidents such as natural disasters and terrorist attacks can cause major disruptions. The terrorist attacks on September 11, 2001, the 2004 Great Sumatra earthquake and Indian Ocean tsunamis, 2010 Chile earthquake, 2011 Japan earthquake and tsunamis, and Hurricanes Katrina and Ike are but the most recent reminders that efforts to mitigate devastating consequences of lifeline disruptions require the understanding of not only the individual infrastructure system behavior, but also understanding of their interactions.

Interdependency is defined as a bidirectional relationship between infrastructure systems. There are four primary classes of interdependencies: physical, cyber, geographic, and logical. Physical interdependency describes the material input-output connections among infrastructure components. Geographical interdependency exists because of the co-location of infrastructure system components. An infrastructure is said to have cyber interdependency when its state relies on information transmitted through the information infrastructure. Other linkages that are not physical, cyber, or geographic connections are classified as logical interdependencies (Rinaldi et al. 2001, Rinaldi 2004). Among the four classes, cyber interdependency is considered the most important by the United States government. Presidential Decision Directive 63 (PDD-63) on Critical Infrastructure Protection recognizes that the information system is a key system that supports other critical infrastructures. Protecting telecommunication and information systems from disruptions is the focus of the directive because such disruption can lead to other critical infrastructure failures or large scale inefficient operation (Heller 2001).

Currently, telecommunication systems represent one of the fastest growing infrastructure sectors. As a result, most infrastructures have some form of cyber-interdependency. For example, the electric power system expands services and maintains stability using Supervisory Control and Data Acquisition (SCADA) Systems to continuously transmit voltage, current, and power information from facilities to power control centers using telecommunication networks. This information is used for real-time calculation of supply, demand, and status of the overall system. The electric power control center uses this information to send appropriate instructions to match supply and demand and maintain overall system stability (Meliopoulos 2005). This trend also enhances the development of smart electric power grids that are capable of self-healing.

Other infrastructures rely on telecommunication and information systems to function or recover functionality. Another example of a cyber-interdependent infrastructure is the transportation system. Traffic control systems collect information from automated sensors installed at intersections and highways, and transmit the information to traffic control centers. Traffic signals are then remotely controlled by the control center through cyber-technology, responding to any incidents on roadways efficiently.

Earthquakes have been recognized as serious threat to infrastructures around the world. Past earthquakes have demonstrated their destructive effects on infrastructure system functionality and post-disaster recovery. At a 6.7 magnitude, the 1994 Northridge earthquake caused widespread disruptions to transportation, water, power and communication systems. Los Angeles highways, which normally carry high traffic volume, were closed for several months due to extensive damage. Several communities were without water for up to two weeks. The Los Angeles Department of Water and Power (DWP) and Southern California Edison Company (SCE) suffered a direct loss totaling $183 million. Approximately 950,000 customers were without electricity after the initial shock. The call volume in the Public Switched Telephone Network (PSTN) jumped to almost four times the normal volume and caused significant congestion, thereby increasing wait time for 911. Most central telephone office outages were caused by power outages (Schiff 1995). One year later, the Hyogoken-Nanbu earthquake, also known as the Kobe earthquake, measuring 6.9 in magnitude, devastated Japanese infrastructure systems. The damages to highways alone were estimated at $5 billion and resulted in delayed rescue and recovery operations. A massive effort was required to restore telephone communication service, for which total damage was estimated at $3 billion. Water outages in Kobe lasted up to 60 days. Direct economic losses were estimated at $200 billion (Schiff 1999). However, indirect losses due to industrial and economic disruptions were even higher.

Understanding how infrastructure systems react to seismic hazards will help improve their joint performance during and after disasters. Previous studies focused on individual systems, with very few considering interdependencies. Not considering such interdependencies underestimates the magnitude of lifeline infrastructure disruption. Recently, some studies have considered physical and geographic interdependencies (Dueñas-Osorio 2005, Kim et al. 2007). However, not many studies include *cyber* interdependencies. As the overall built infrastructures becomes more and more dependent on information systems, understanding the interdependencies between them during seismic hazards will help to better prepare for reliable operation and effective mitigation should such events occur.

1.1 Research Objectives

The overall goal of this research is to develop methodologies for evaluating the interdependent response of telecommunication and electric power systems. The methods developed are used to estimate the performance and interdependency of both systems under seismic conditions. The research results provide guidelines for the improvement and design of existing and future systems. Moreover, they are expected to be useful in developing efficient post-earthquake recovery plans. In order to achieve this goal, four intermediate objectives are established.

First, this thesis develops the necessary methodologies and models for evaluating the seismic performance of telecommunication systems. Voice and data telecommunication systems selected for interdependent analysis in this study includes the public switched telephone network (PSTN), cellular telephone networks, and the SCADA system. Two common impacts of seismic hazards on infrastructure systems are considered. The first is the physical damage to system components that significantly affect infrastructure performance. The second impact is the high post-disaster communication demand. High call volume on the PSTN is commonly expected after an earthquake, and is a cause of network congestion, leading to delays in communication and overall system failure.

Second, this research defines, simulates and validates the interdependencies between telecommunication and electric power systems. The two interdependencies considered in this study are: (1) the dependency of telecommunication network operation on electric power and (2) the dependency of electric power system operation upon data communication.

Third, the study provides a comprehensive framework for interdependent performance assessment of infrastructure systems subjected to seismic hazards. The contributions of various network components to the seismic system-level performance are investigated. The seismic performance of the interdependent systems is probabilistically estimated from network topologies and performance matrices of network components.

Finally, this thesis demonstrates real-world applications of the proposed methodologies on seismic mitigation. Examples of the economic impacts and losses assessment after earthquake events, along with the planning of pre-earthquake mitigation actions and post-earthquake recovery actions are given. Moreover, the application on seismic performance evaluation of existing infrastructures is illustrated.

1.2 Thesis Organization

This dissertation is divided into seven chapters. Chapter 2 reviews existing research in the fields of lifeline earthquake engineering on telecommunication systems, electric power grids and interdependent infrastructures. Chapter 3 presents the effects of seismic hazard on telecommunication and electric power systems. Chapter 4 presents the fundamental topological, flow, and reliability characteristics of each system and introduces mathematical network models used for seismic performance evaluation. In Chapter 5, the interdependencies between telecommunication and electric power system are defined. Critical assumptions are also presented. The results from the proposed interdependent system analyses are presented in Chapter 6. In particular, seismic response of the test bed infrastructure systems to seismic hazards are discussed and the effects of interdependencies are demonstrated. This chapter also demonstrates the application of the proposed methodologies to minimizing seismic disruptions. Examples of seismic evaluation of existing systems are provided to illustrate an application to optimal mitigation actions and efficient recoveries strategies. Finally, Chapter 7 summarizes the research findings, concludes the study, and suggests future research directions in the area.

CHAPTER 2

TELECOMMUNICATION AND ELECTRIC POWER SYSTEMS IN LIFELINE EARTHQUAKE ENGINEERING

This chapter reviews the relevant literature on electric power and telecommunication systems, and provides a critical appraisal of previous studies regarding their seismic performance along with a discussion on emerging infrastructure interdependencies. The chapter is divided into three sections. The first section is a review of research in the lifeline earthquake engineering field related to individual systems. The review starts with the studies supported by national earthquake institutes and relevant organizations, and then continues with the contribution of individual researchers. In the second part, research in interdependent infrastructures is reviewed. Finally, a critical appraisal of the current state of the research and opportunities to further the knowledge base of the field are provided.

2.1 Review of Previous Work

The 1971 San Fernando, California, Earthquake was the first earthquake to cause significant damage to bridges, power, telecommunication, water, and gas systems in the continental U.S. since the 1933 Long Beach earthquake (Schiff 2004). Because these systems are vital to modern societies, the term “lifelines” was first used to refer to civil infrastructure systems shortly after the San Fernando earthquake to emphasize their importance.

Following the San Fernando earthquake, the American Society of Civil Engineers (ASCE) formed the Technical Council on Lifeline Earthquake Engineering (TCLEE) to address the earthquake engineering aspects of lifeline systems (Schiff 2004). TCLEE is comprised of several technical committees focusing on different sections of lifelines. The efforts to improve seismic performance of electric power and telecommunication lifeline systems are made through the Electrical Power and Communications Lifelines Committee. A number of design and installation guidelines for electric and communication equipment are provided based upon experiments and experience from past earthquakes. However, the performance evaluation of infrastructures at the system level is hardly addressed.

The Applied Technology Council (ATC) is another organization that conducts research in lifeline earthquake engineering. In 1982 the Federal Emergency Management Agency (FEMA) awarded ATC a contract to develop earthquake damage evaluation data for facilities in California, known as the ATC-13 project. Damage, loss, and restoration times were evaluated for a number of California infrastructures on the basis of expert opinions (Applied Technology Council 1985). In 1988, FEMA awarded ATC another contract known as the ATC-25 project to develop seismic vulnerability functions and study the impacts of lifeline disruption in the conterminous United States. Lifelines considered in the ATC-25 project included electric power, water, transportation, gas and liquid fuel supply systems, and emergency service facilities such as hospital, fire, and police stations. Other facilities, such as telecommunication, nuclear and fossil-fuel power plants, and other water, electric, and transportation facilities were excluded from consideration due to unavailability of inventory data or the need for more in-depth studies.

The goal of the ATC-25 project was to estimate direct damage and associated loss for nationwide scenario earthquakes. Seismic vulnerability functions for each lifeline component were developed by regression analysis of data from the ATC-13 project. The functions include direct damage and residual capacity functions. The direct damage function is a relationship between repair costs, as a fraction of facility value, and Modified Mercalli Intensity (MMI), a measure of seismic intensity effects at a particular site. The residual capacity function is a fraction of the initial capacity available after an earthquake as a function of elapsed time after the initial shock for given MMI levels.

For a scenario earthquake, the MMI for each facility within the affected areas was determined. The direct damage and residual capacity of each component were then calculated using vulnerability functions. Residual capacities of individual lifeline systems were then evaluated by integrating the component residual capacities. For site-specific lifeline systems, such as airports, police stations, and medical care centers, system residual capacity is the average of facility residual capacities. For networked lifeline systems, such as oil pipelines and highways, the minimum-cut-maximum-flow theorem was used to determine system residual capacity as the ratio of maximum flow of a damaged system to its corresponding undamaged system. Although electric power systems are obviously networked lifeline systems, power grids were considered site-specific lifelines for residual capacity analysis in the ATC study. Only residual capacities of transmission substations were considered. Transmission lines and network flow were ignored for electric power systems (Applied Technology Council 1991). These assumptions result in underestimated direct and indirect economic losses from power grid unavailability. For example, undamaged substations cannot contribute to system performance because they are disconnected by damaged transmission lines. Moreover, without considering connections among components, the effects of electric power system flow are missing.

The National Science Foundation (NSF) established three national earthquake engineering research centers to conduct research on various topics in earthquake engineering including lifeline engineering. The three centers are the Multidisciplinary Center for Earthquake Engineering Research (MCEER), the Pacific Earthquake Engineering Research Center (PEER), and the Mid-America Earthquake Center (MAEC) (National Science Foundation 1997). Originally NSF established the National Center for Earthquake Engineering Research (NCEER) in 1986; NCEER later became MCEER in

1998 at which time PEER and MAEC were also established. Research at MCEER has included a number of studies on lifeline engineering. Much of this is on water distribution, oil and gas transmission and electric power transmission systems (Chang et al. 1995, Shinozuka et al. 1998). Seismic performance of equipment and facilities has been studied intensively while limited studies have considered system-level performance, especially for electric power systems. One of the studies attempted to estimate the economic impact of electric power, gas, and water system disruption due to earthquakes in Shelby County, Tennessee. The study used modified results from the ATC-25 project to evaluate system restoration times. Functionalities of electric power transmission substations were used to represent the availability of electric power in a given area under the assumption that transmission substations are the most time-consuming to repair compared to other components, such as transmission lines and distribution substations (Chang et al. 1995). For economic impact estimation, this approach is reasonable; however, it gives no insight into the effects of system topology on response, and interactions among system components. Moreover, probabilistic estimation and interpretation of the results are still ambiguous.

For over a decade, PEER has made a number of contributions to the earthquake engineering community. PEER research is focused on the concept of performance-based engineering. For lifeline engineering research activities, the PEER lifelines program was also formed. The goal of the program is to improve seismic safety and reliability of lifeline systems. Most PEER lifeline research projects focus on electric power systems and transportation networks, because PEER research is mainly funded by the California Department of Transportation, California Energy Commission, and Pacific Gas & Electric Company. In order to develop unified lifeline risk and reliability models for lifeline research projects, modeling platforms are also studied. Evaluation of system performance is included in one of the six steps of the modeling platforms (initialization, inventory of facilities, evaluate component performance, evaluate system performance, and summary of results). Use of simple performance algorithms or the expert opinion of system operators is recommended as a minimum for the electric power system in this step. The algorithms evaluate connectivity and load-flow of the system (Werner et al. 2002). Although the study establishes the platform for seismic risk and reliability analysis of a lifeline network, further research and results on system evaluation are not available.

The MAE Center has studied a variety of topics including the characteristics of intraplate earthquakes. Earthquakes in mid-America are less frequent than those along the Pacific coast of the United States but their consequences tend to be higher. As a result, MAEC research is focused on topics related to consequence-based risk management (CRM). MAEC's core research is separated into four thrust areas: concepts of consequence-based risk management, core engineering technologies (also called "engineering engines"), social and economic science, and applied information technology. Studies of lifelines are included in the core engineering technologies thrust area which also includes transportation systems and interdependent lifeline networks.

In addition to these three earthquake engineering centers, the Institute of Electric and Electronics Engineers (IEEE) is another organization interested in the reduction of earthquake impacts on electric power systems. Because an earthquake is a potential cause of substation loss and cascading failure of power grids, the IEEE focuses on improving seismic performance of substations. It provides recommendations for the seismic design of electric substations focusing on substation buildings and equipment. Installation, design considerations, qualification methods, and seismic performance criteria of equipment are included (Institute of Electrical and Electronics Engineers 2005). However, interactions among substations and power grid system performance after earthquakes are not considered. Although telecommunication systems are included in the IEEE scope of studies, earthquake impacts to telecommunication networks have not been addressed by the organization.

In order to ensure reliable electric power systems after earthquakes, overall system performance must be properly considered. To date, studies of the seismic performance of electric power systems in lifeline earthquake engineering have focused on equipment and facilities performance, not overall system-level performance. While system performance of networked systems is highly dependent upon system connectivity and topology, not many studies of system performance under seismic conditions have been conducted. A lack of insight into seismic response of overall systems can prevent improvement of power grid reliability. Since the power grid is spatially distributed, detailed analysis of network flow is needed to reveal responses of critical areas and key components whose individual performance contribute significantly to overall system performance. This information on network flows facilitates optimal improvement of system functionality when resources are limited. Until recently, there has been a lack of understanding of electric power system performance under seismic conditions.

The seismic performance of electric power systems is of more concern to the earthquake community than that of telecommunication systems. This is because past California earthquakes resulted in little damage to telecommunication networks compared to power grids. However, this may not be true for other parts of the U.S. where there are no seismic provisions in place (Schiff 2004). Moreover, new technologies for telecommunication systems, such as modern digital telephone switches and optical fiber transmission lines, tend to increase equipment capacity. These modern telecommunication systems are widely used by utility companies loosely to catch up with the increase in demands without considering the effects on system reliability. This raises the question of flow concentration issues. The loss of a few high capacity components can significantly degrade system performance when the system is under stress (Wong 1998).

Besides seismic-induced physical damage, congestion in telecommunication networks is another reason why seismic performance of telecommunication systems should not be neglected. Past earthquakes such as the Northridge and Kobe earthquakes showed that the communication demand increases significantly after earthquake events. Most calls are initiated outside of the affected area because of safety concerns of disaster victims (Tang 1998). The most recent 2011 Japan earthquake also indicates increase of 8 to 10 times beyond normal demand (ASCE 2011). This can cause substantial communication delays within the affected areas.

Since communication is critical to the efficiency of emergency response and recovery actions, its reliability needs to be assured. However, there is still a lack of understanding of the response of telecommunication systems to earthquakes, and this can lead to poor seismic performance of the system and delay of overall recovery activities.

2.2 Interdependent Infrastructures

In the past, critical infrastructures were physically and logically developed as separate systems with minimal interconnection. However, advances in information technology and the necessity of more efficient operation of these systems has increased their interdependencies. Although efficiencies maybe increased by integration of systems, coupled infrastructures are also vulnerable to disruptions and failure propagation within and across systems. In order to ensure general public health and safety, a better understanding of infrastructure interdependencies is required to reduce their vulnerabilities (President's Commission on Critical Infrastructure Protection 1998). Although seismic performance of lifelines has been studied by the earthquake engineering community since the 1971 San Fernando Earthquake, the interdependency or interaction of lifeline systems was not considered until the mid-1980s (Yao et al. 2004). TCLEE formed the Lifeline System Interdependencies Committee (LSIC) to address interdependency issues in lifeline systems only shortly after the 2010 Chile earthquake. Some significant studies are summarized in this section.

Interdependent responses of infrastructures are usually observed and recorded from post-earthquake investigations. There are many impacts of system interdependencies that cause significant disruptions to lifelines. These interdependencies are summarized and classified into four categories as follows (Nojima and Kameda 1991):

Category A: Functional disaster propagation - Interactions are listed in this category when failures of lifeline components affect functionality of other system components. For example, failure of an electric power substation reduces the serviceability of water pumping stations and telephone switches in the service area.

Category B: Physical disaster propagation - This category describes interactions that cause physical damage to other systems. For instance, an explosion of underground gas transmission lines causes breaks in adjacent telephone lines and water pipes that run in parallel.

Category C: Hindrance in the recovery stage - This category represents interactions that cause delays and/or difficulties to recovery activities of other lifelines. For example, damage to transportation networks may result in the delay of electric power substation repair, as service teams are prevented from reaching damaged substations in a timely manner. Damage to telecommunications systems may also delay notification of lifeline managers informing them of damage to other systems.

Category D: Influences on alternative systems - Interactions in this category are those whose failures affect other lifelines that can be used as alternatives for the same purpose. For example, disruptions to telephone systems increase the use of two-way radio communication network among emergency response agencies.

In the study by Nojima and Kameda (1991), Category A was considered a major issue. Cross Impact Analysis, a systematic method to evaluate the probability of occurrence of various events in an interaction relationship, was used to quantify functional disaster propagation. To demonstrate this method, two lifeline systems, electric power and water networks were considered. Commonly, the event that a water pumping station is not functional (event E_n) is caused by: (1) water network failure resulting in no water supplied to the station (event E_1), and (2) electric power system failure to supply power to the station (event E_2). However, water pumping stations are usually equipped with backup generators. Therefore event E_2 does not necessarily lead to event E_n. From probability theory, the probability of event E_n is written as:

$$P(E_n) = P(E_1) + \big(1 - P(E_1)\big) \times P(E_2) \times a_{2n} \qquad (2\text{-}1)$$

Where $P(\bullet)$ denotes probability and a_{2n} is a cross impact factor representing the degree of probabilistic contribution of event E_2 to event E_n. This factor is calculated by fault tree analysis of event E_n. The probability that event E_n occurs due to interdependencies is distinguished and determined as $P(B)$. Since E_1 is the event that E_n occurs due to water system alone, not interdependency, events E_1 and B are mutually exclusive. From probability theory and Equation 2-1, both $P(B)$ and $P(E_2) \times a_{2n}$, therefore, represent the probability that event E_n occurs due to interdependencies. The cross impact factor is then obtained as:

$$a_{2n} = P(B)/P(E_2) \qquad (2\text{-}2)$$

In this case, the cross impact factor represents the degree of interdependency between the electric power system and the pumping station. It also indicates the effectiveness of the backup generator.

This study introduced fundamental concepts of probabilistic analysis of lifeline interdependency. It should be noted that only component-level analysis of functional interdependency was considered by Nojima and Kameda (1991). However, there are many situations for which failures of a lifeline system affect overall functionality of other lifeline systems, not just specific components. For example, failure of the SCADA system that controls the electric power grid may not affect the operation state of specific electric substations, but performance of the entire system may be adversely affected. Without real-time information from SCADA systems, the electric power control center may have difficulties maintaining system stability.

Infrastructure interdependencies do not attract the interest of earthquake engineers alone. Since continuous operation of these systems is critical, their vulnerability and reliability are of interest to researchers in broader fields.

From the system science perspective, infrastructure interdependencies can be classified into four categories. Unlike the four categories defined by Nojima and Kameda (1991) that are based upon propagation effects onto other systems, system scientists (Rinaldi et al. 2001) classify infrastructure interdependencies based upon their types of relationship. The four classes of the interdependencies are defined as follows:

Class 1: Physical interdependency - Two infrastructures are physically interdependent if the state of each depends upon the material outputs of the other. For example, transportation and electric power systems are physically interdependent because power systems need transportation networks to transport coal from sources to coal-fired electric generator plants while transportation systems need power to illuminate and operate traffic signals.

Class 2: Geographic interdependency - Infrastructures are geographically interdependent if a local environmental event can create state changes in them. An example of this interdependency is a common right-of-way of collocated elements of different infrastructures.

Class 3: Cyber interdependency - Infrastructures exhibit cyber interdependency if their states depend on information transmitted through the information infrastructure. For example, the electric power system has a cyber interdependency because its operation is highly dependent on the state of the system, whose information is transmitted through SCADA systems.

Class 4: Logical interdependency - Two infrastructures are logically interdependent if the state of each depends upon the state of the other via some mechanism that is not a physical, geographic, or cyber connection. Policy, legal, or regulatory regimes are common factors that affect logical linkages among infrastructures.

In comparing the two sets of classifications, the latter is based upon types of the linkages among infrastructures, while the former considers the effects of interdependence. When detailed causes and effects of interdependencies are identified and modeled, the latter system science classification becomes more meaningful because it is based on the causes of the interdependencies.

Since highly destructive earthquakes are considered rare events, historic records may be too scarce to be useful. Models and simulations may provide the only guidance for strategy or policy development (Rinaldi 2004). Models and simulations, such as dynamic simulations, agent-based modeling, and physics-based modeling, are recommended to address the complexity of these interdependencies. However, to develop accurate and reasonable models and simulations, each infrastructure system needs to be understood in depth. For example, electric power operation, as well as the fundamental of SCADA system, needs to be understood in detail before models and simulations are created; otherwise insights are too general and of limited application. For this reason, the task is not easy and multidisciplinary efforts are essential.

Recently, models representing the interdependent responses of infrastructures to potential threats such as natural disasters and terrorist attacks have been developed in order to better understand their interactions since the records of the real responses are insufficient. Graph theory and statistical methods are widely employed to characterize and measure the performance of networked infrastructures. An important study by Dueñas-Osorio (Dueñas-Osorio 2005) uses fundamental topological properties including mean distance, vertex degree, cluster coefficient, and redundancy ratio to describe infrastructure networks. Dueñas-Osorio also proposed generic network performance measures such as efficiency, connectivity loss, and service flow reduction to evaluate infrastructure network functionality after disruptions. Interdependencies between two infrastructures are represented by conditional probabilities. These methodologies are applied to electric power and water networks to demonstrate their applications (Dueñas-Osorio 2005). Although this approach sheds light on the issues of interdependent network modeling in earthquake engineering, certain details, such as directions of flows and fragility function of the links or edges, yielded further refinements. A MAE Center research team later addressed some modeling issues, such as improving the algorithm and implemented them in the development of MAEViz, a seismic loss estimation tool (Kim et al. 2007).

Although the approach proposed by Dueñas-Osorio (2005) and Kim et al. (2007) is developed for general networked infrastructures, some network properties and performance measurements, such as network flow reduction, are still limited to transmission and distribution networks: i.e., networked systems that transmit and distribute goods such as electric power, water, oil and gas networks. For other infrastructures such as information and telecommunication systems as well as personal transportation, these properties and measurements are not adequate to capture critical issues such as travel time and communication delays and congestion. In order to include telecommunication infrastructures in interdependent analysis, a new modeling approach is needed.

Although, the interdependent telecommunication systems are not widely studied, there is growing public concern about reliability of telecommunication infrastructure. Due to a number of large telecommunication disruptions in the late 1980’s and early 1990’s, the Federal Communication Commission (FCC) required landline communication carriers to report service disruptions of at least 30 minutes in duration and 30,000 customers affected since 1991 (Snow et al. 2006). From the FCC's record, Snow et al. (2006) analyze the frequency of telecommunication outages due to power loss. The research focuses on the reliability of the interdependent electric power and telecommunication systems before and after the terrorist attack on September 11th, 2001. The study utilizes probabilistic models, such as the power law model and the piecewise linear model, to determine interdependent reliability. The observed bilinear trend in the piecewise linear model concludes that the reliability improved after the attack. However, the study still shows strong correlation between electric power and telecommunication systems, especially in large-scale disruptions, such as the large blackout in August 2003.

Besides this reliability study, the interdependency of electric power and telecommunication has also been studied in more detail. Rosato et al. (2008) investigated the consequence of electric power failure on an internet network. They simulated failure of power grids by eliminating power transmission lines and evaluated power reduction levels due to re-dispatching by using a DC power flow method. The functionality of the internet nodes was geographically related to neighboring electric power nodes. This study used a coupling coefficient, α, to model the strength of the interdependencies. The coupling coefficient ranged between 0 and 1, with $\alpha = 0$ representing that internet nodes independent from power nodes, and $\alpha = 1$ meaning that the functionality of internet nodes totally depends upon the power level from power nodes. The study also investigated Quality of Service (QoS) of the internet network at different data traffic levels, where QoS of the internet network is defined as the average delivery time of the data packet sending from origin nodes to destination nodes. The amount of traffic was represented by variable λ, a fraction of the number of origin nodes that originate data packet to the network at each time step of the simulation.

Although this study (Rosato et al. 2008) represents a first attempt among few studies which try to define methodologies to characterize the dependencies between electric power and telecommunication systems, the results show some key insights into the coupling systems. The reduction in power level reduces the number of functioning internet nodes and degrades the QoS of the internet network. The results show that for intermediate coupling coefficient ($\alpha = 0.75$), the average delivery time of the internet network increases dramatically when the number of simultaneously removed transmission lines increases, especially at low amounts of traffic.

2.3 Limitations of Existing Studies

Previous research fails to adequately address specific modeling issues in order to achieve an understanding of the interdependent response of electrical power and telecommunication infrastructures to seismic hazards.

First, although lifeline earthquake engineering has been studied for decades, there is limited research in the area of system performance of telecommunication networks. Most past studies have only focused on seismic performance of equipment and individual facilities. In addition, there are no reasonable network performance measures for characterizing the performance of telecommunication systems.

Second, congestion and flow concentration issues in telecommunication systems are insufficiently addressed or omitted in previous studies of telecommunication lifelines. Effects of delays in communication need to be explored so that the efficiency of mitigation and recovery activities can be improved.

Third, there is a lack of understanding of the interdependencies between electric power and telecommunication infrastructures. Although the physical dependencies (Class 1 above) of telecommunication systems on electric power grids can be reasonably simulated by the procedure proposed by Dueñas-Osorio (2005) and Kim et al. (2007), new approaches are required to model cyber dependencies (Class 3) of power grids on telecommunication systems.

Fourth, there is still inadequacy of the understanding the interdependent responses of the two infrastructures under seismic conditions. Even though Snow et al. (2006) and Rosato et al. (2008) have already investigated the interdependencies between electric power and telecommunication systems under normal conditions, the interdependent responses under seismic condition, which involves congestion issues due to abnormally high demand have not been addressed.

Finally, inadequate treatment of the interaction between telecommunication and electric power systems results in overestimation of their seismic performance. Efficient mitigation and consequence minimization actions are not possible without considering these interdependencies.

CHAPTER 3

EFFECTS OF SEISMIC HAZARD ON TELECOMMUNICATION AND ELECTRICAL POWER SYSTEMS

Earthquakes have brought devastation to critical infrastructure systems in many regions of the world. Electric power, telecommunication, and transportation systems are among the set of critical infrastructures that when disrupted by seismic hazard can greatly affect post-disaster recovery. Although seismic-induced physical damage is known to contribute to degradation of system performance of lifeline systems, data traffic congestion in telecommunication systems due to abnormally high demand is another effect from earthquakes which degrades system performance even further.

This chapter first introduces the fundamentals of seismic hazards and describes mathematical models used to determine local seismic intensities and demands, such as peak ground acceleration (PGA) and peak ground velocity (PGV). Next, typical physical damage to electric power and telecommunication facilities due to seismic hazard are summarized along with the probabilistic models used to assess the seismic response and performance of such facilities. Finally, this chapter presents the background of traffic theory for telecommunication systems and proposes methods to estimate the effect of abnormally high user demand and retrial behavior of subscribers on telecommunication networks stressed by earthquake events.

3.1 Seismic Hazard

3.1.1 Seismic Hazard Characteristics

Each earthquake has unique characteristics. Three components—earthquake sources, ground motion attenuation, and local soil amplification—are necessary to determine seismic intensities at a given site when individual structures are analyzed for earthquake responses. However, infrastructure systems whose facilities are spatially distributed over a broad area also require that the spatial correlation of seismic intensities be considered (Adachi and Ellingwood 2009a, Jayaram and Baker 2009).

Earthquake Source

The earthquake source can succinctly be characterized by its epicenter and magnitude. Historical records and geographical information are normally used to identify earthquake sources in a target area. The location of earthquake epicenters is determined by earthquake records and locations of faults, while the frequency of earthquakes with a particular magnitude is estimated using earthquake records and the Gutenberg-Richter recurrence law.

Gutenberg and Richter (1949) proposed the recurrence law to first model the frequency of earthquakes in California. The law expresses the relationship between earthquake magnitude and frequency of the events. The Gutenberg-Richter recurrence law for earthquakes whose magnitude is not less than m in any given area is given by:

$$logN = a - b \cdot m \tag{3-1}$$

where N is the number of earthquakes in any given period. Parameters a and b are the recurrence parameters which are determined from earthquake records in that area. These parameters are different for different geographic regions.

Ground Motion Attenuation

Ground motion attenuation represents the propagation of seismic waves from the earthquake source to any given site. Attenuation depends greatly on the geological environment and path between earthquake and target sites. The construction of attenuation relationship is based on the records of earthquakes in an area with similar geology and on the concepts of random vibrations. A number of attenuation relationships are available for different regions. Some attenuation relationships for Western North America have been proposed by Abrahamson and Silva (1993), Archuleta et al. (1979), and Campbell and Bozorgnia (1994). Campbell (2003), Atkinson and Boore (2006), and Hwang and Huo (1997) provide attenuation relationships for Eastern and Central North America.

Normally, attenuation relationships provide mean or median values of local seismic intensities, such as PGA and PGV, as functions of earthquake magnitude and distance from the sites to earthquake epicenter. Due to its complexity and focus on point estimates, ground motion attenuation is one of the major sources of uncertainty in seismic risk assessment of spatially distributed infrastructure systems (Adachi and Ellingwood 2009a).

Local Soil Amplification

Local seismic intensities are dependent on local soil conditions. The seismic waves propagating from earthquake sources can either be amplified or damped due to geotechnical properties of the soil at the evaluated site. In engineering practice, the effects of local soil conditions are represented by local soil amplification factors. The seismic intensity obtained from attenuation relationships are multiplied directly by these factors to determine the surface seismic intensity at a site of interest.

FEMA (2004) categorizes the local soil amplification factor for six classes of soil condition—hard rock, rock, dense soil, stiff soil, soft clay, and soil requiring site-specific evaluation—in the 2003 National Earthquake Hazards Reduction Program (NEHRP) provisions. FEMA proposed these factors mostly based on the studies from earthquake records in the Western United States (Hwang et al. 1997). However, there is still a lack of study of the local soil amplification effects in other regions.

Similar to the ground motion attenuation, the soil amplification factor is another source of uncertainty in seismic risk assessment. The inherent uncertainty of the representation of local soil effects should be recognized. Sensitivity of the soil amplification factors to seismic performance assessment of infrastructural systems has been studied by (Adachi and Ellingwood 2009b).

Spatial Correlation of Seismic Intensities

The functionality of infrastructure systems depends on the individual functionalities of their facilities which are spatially distributed over a geographical area. Seismic intensities at the sites of these facilities are stochastically dependent on location and their covariance should be considered when assessing seismic performance of infrastructure systems (Adachi and Ellingwood 2009a, Jayaram and Baker 2009). The covariance of seismic intensities between two sites is typically presented as an exponential function of the distances between the sites, as in the studies by Shimomura and Takada (2004), Takada and Shimomura (2004), Wang and Takada (2005), and Adachi and Ellingwood (2009a), and Jayaram and Baker (2009) .

Hence, when studying geographically distributed systems, four components emerge—earthquake source, ground motion attenuation, local soil amplification, and spatial correlation of seismic intensities—as necessary to specify seismic hazard at any given infrastructure site. Two procedures commonly used for seismic hazard analysis are presented in the following section, and their adequacy for utility systems is discussed.

3.1.2 Seismic Hazard Analyses

Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis (PSHA) is a commonly used method to determine local seismic intensity at any given sites for design, analysis for retrofit, or seismic risk management. PSHA determines local seismic intensities by aggregating all possible earthquake sources which are likely to affect the sites of interest. Local seismic intensities due to each seismic source are evaluated using the first three seismic hazard characteristics—earthquake source, ground motion attenuation, and local soil amplification. At a site, these intensities are weighted by their probability of occurrence. The annual recurrence rates of earthquakes with any specific magnitude are calculated from the Gutenberg-Richter recurrence law. From the annual recurrence rates and the assumption that earthquake recurrence is a Poisson process, probabilistic seismic hazard maps showing seismic intensities (PGA, PGV, spectral velocity, or spectral acceleration) can be created for a specified probability of exceedance in a certain return period (McGuire 1995). The probabilistic seismic hazard maps used in engineering practice are consistently available in regulatory provisions (Adachi 2007).

Although probabilistic seismic hazard maps are used for design, analysis, retrofit, and seismic risk assessment of individual facilities, they are not suitable for seismic risk assessment of infrastructure systems whose functionalities are dependent upon spatially distributed facilities, since the spatial correlation of seismic intensities is lost in the aggregation process of the PSHA process (Adachi 2007).

Scenario Earthquake based Seismic Hazard Analysis

In contrast to PSHA, a scenario earthquake based seismic hazard analysis (SESHA) is a conditional seismic hazard analysis based on a specific earthquake event. Local seismic intensities are determined from a specific earthquake source (deterministic magnitude and epicentral location) using ground motion attenuation, local soil amplification, and spatial correlation of seismic intensities. One significant advantage of the SESHA over the PSHA is that SESHA can reveal specific details of earthquake risk for distributed facility sites. Therefore, SESHA is often used to investigate effects of a specific earthquake in the past. This application is useful for highly seismic active regions. However, SESHA is not so useful in the regions where the seismic occurrence rate is moderate and low (McGuire 2001).

One of the difficulties of applying SESHA for seismic risk assessment is to justify earthquake scenarios to be used in the analysis. Normally, major historical earthquakes are used as scenario earthquakes in high seismic regions; however, this is not the case for moderate and low seismic regions. In such regions, a specific earthquake scenario is selected from the deaggregation analysis of the potential earthquakes surrounding the areas. The United State Geological Survey, USGS (2009), provides interactive deaggregation tools for selecting events for SESHA.

3.1.3 Modified Mercalli Intensity Scale

The Modified Mercalli Intensity (MMI) is preferred over other seismic intensity indexes when seismic-induced communication demands are concerned because it is a scale measuring local seismic intensities based on the effects of earthquakes on human and man-made structures. The scale quantifies seismic intensity on a scale from I through XII. The MMI scale is subdivided into two ranges. The intensity levels of I through VII are based on human perception of ground shaking, while the higher intensity levels are based on the observed damage to man-made structure due to earthquakes. Although the MMI scale was not developed from any scientific background, it depicts well the severities of ground shaking at sites. The MMI scale is also meaningful to nonscientific audiences for this reason.

This research relates the MMI scale to the behavior of telephone subscribers reacting to earthquakes and quantifies communication demand on telecommunication infrastructures due to seismic hazard. Detailed discussions of seismic communication demand and corresponding seismic intensities are presented later in this chapter.

Since PGA and PGV are used extensively when seismic-induced physical damage is referred to, it is logical to map the MMI scale to equivalent PGA or PGV at typical sites. The MMI scale and corresponding PGA and PGV provided by Bolt (1993) are reproduced and presented in Table 3-1.

Table 3-1: Modified Mercalli Intensity (MMI) Scale and Correlated PGA and PGV

MMI Scale	Description	PGA (g)	PGV (cm/s)
I	Not felt except by a very few under especially favorable circumstances.		
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.		
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated.		
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.	0.015-0.02	1-2
V	Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.	0.03-0.04	2-5
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight.	0.06-0.07	5-8
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.	0.10-0.15	8-12
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stack, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed.	0.25-0.30	20-30
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.	0.50-0.55	45-55
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed, slopped over banks.	> 0.60	> 60
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.		
XII	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into the air.		

Source: Bolt, Bruce A. Abridged Modified Mercalli Intensity Scale, Earthquakes - Newly Revised and Expanded, Appendix C, W.H. Freeman and Co. 1993, 331 pp

3.2 Damage to Network Components Due to Earthquake

Experience from past earthquakes indicates that the most obvious effect of an earthquake on infrastructure facilities is physical damage to building structures and their contents which directly influences their functionality. Also, researchers have shown damage to infrastructure components from records of past earthquakes, where electric power systems and telecommunication systems are of particular interest (Schiff 1995, Tang and Schiff 1996, Tang 1998, Schiff 2004). A probabilistic model for risk assessment of network components is also discussed in this section.

3.2.1 Damage to Electric Power System components

For the purpose of earthquake investigations, electric power transmission network components are classified into 4 categories—control centers, generation facilities, substations, and transmission lines. Each component contains different equipment and performs specific functions. Earthquake-induced damage to each of these components is also different. Some common effects of earthquake to each of them are presented next.

Control Center

A control center is a central facility that provides overall system control of electric power grids in a geographical area. The control center provides crucial functions for reliable power grid operation even though it doesn't directly generate or transmit any electric power. The control center receives measurement data monitored and transmitted from local facilities which are spatially distributed, estimates the status of the entire system, and transmits appropriate commands back to the local facilities in order to maintain reliability and stability of system operation. Unlike water or gas distribution systems, power grids have no capability of storage exceeding generated power. Therefore the critical goal of the control center is to maintain an instantaneous balance of generated power and load (power demand) at all times.

Typically, a control center is a room located in a building classified as an important facility. Although the host building is specially designed to withstand earthquakes or any other threats, the functionality of the control center is dependent upon its critical equipments. Normally, a control center is equipped with control consoles, display equipments, computers, communication equipments, and other support systems, such as heat, ventilation, and air conditioning (HVAC), lighting, and emergency power systems. Each of the contents in a control center is vital to its functionality.

In practice, the floor of the control room is an access floor or a raised floor to accommodate wiring of the systems. This type of flooring does not perform well in earthquake environments. One of the common failures of a control center due to earthquakes is the collapse of the floor which results in damage to the equipment resting on it. The failure of other non-structural components, such as suspended ceilings, backup generators, or HVAC systems, also affects the efficiency of control centers. This creates unsafe environments for operators to occupy the control center and operate the power grid.

Power Generation Facilities

Generation facilities are the facilities where other forms of energy are converted to electric power. There are several types of generation facilities, such as fossil power plants, nuclear power plants, hydropower plants, and solar power plants. However, the majority of power consumed in the US as of 2010 comes from fossil power plants. Therefore, this section will address fossil power plants only (USEIA 2009).

Fossil power plants generate electric power by burning fossil fuel, such as coal, oil, and gas, either to boil water and generate high pressure steam to drive turbines, or to drive turbines directly with combustion gas from burning fuel, or by a combination of the two. A fossil power plant consists of main components, including fuel and chemical storage tasks, water boilers, combustion or stream turbines, piping, and duct work. These components are essential to the operation of the facility and are also vulnerable to strong ground motion. Damage to these components, such as liquid storage tanks leaking, water boilers leaking, damage to turbine thrust bearings, and rupture of high pressure piping or duct work breaking, can disrupt facility operation. Beside these components, most power plants also include control rooms which function similar to control centers except they are used to control only the plant and not entire grid systems. Since control rooms in a power plant are also vulnerable to seismic hazard, the same failure modes for control centers apply to them, as seen in past earthquakes.

Electric Substations

Substations serve vital functions in electric power systems. Besides transforming voltage between transmission and distribution networks, they also provide protection to transmission lines, equipment, and the entire system. Substations are equipped with sensing devices for monitoring the condition of the system. During an abnormal event, substations are informed by these devices and control centers to isolate transmission lines or equipment from the system and prevent them and the system from large disruptions.

The key equipment normally found in substations are circuit breakers, disconnect switches, and transformers. Each of these equipments is vulnerable to strong ground motion. There are three main failure modes of these equipments commonly found after earthquakes: failure of porcelain insulating components, failure of cast-aluminum components, and failure of equipment anchorage. Since porcelain and cast-aluminum have preferable electrical properties, they are widely used in equipment found in typical substations. However, they do not perform well in cyclic loading condition caused by earthquakes due to their brittle mechanical properties. Failure of equipment anchorage is another common cause of equipment failure. Most equipment in substations has small footprints and high centers of gravity. High moments exerting on their anchorage at the base are therefore expected when they are subjected to earthquake forces. The failure of equipment anchorage may also result in damage to the equipment due to rocking or tipping over.

Transmission Lines

In transmission power systems, high voltage transmission lines connect and deliver electric power to network components. They are normally supported by steel frame transmission towers. From past earthquake experience, transmission towers perform well. Only limited damage is found, and most is due to foundation failures, large ground displacement, and liquefaction (Schiff 1997).

3.2.2 Damage to Telecommunication System Components

From past earthquakes, telecommunication network components perform relatively well under seismic conditions. Nonetheless, failures of some components are still found following earthquake events. Common failures found in telecommunication network components are failures of electronic equipment, such as computers, server cabinets, switch boards, circuit boards, and battery racks. This equipment is vulnerable due to the various configurations, which are predominantly tall and slender. Without proper anchorage, they are likely to rock or overturn during an earthquake. This equipment is delicate and sensitive to motion. Accidental contact of dislodged circuit boards inside rocking equipments can result in severe damage of the equipments (Tang and Schiff 1996, Schiff 1997).

3.2.3 Network Component Functionality Assessment

Functionalities of infrastructural networks are dependent upon functionalities of their components. In order to assess infrastructure network performance, the functionality of individual network components is evaluated first. In real situations, a facility has multiple states of functionality—fully, partially, or non-functional. However, the non-functional state is the one of most concern. A network component can become non-functional due to a series of events, such as damage to the facility building resulting in limited access to the facility, dislodged circuit boards, or disconnected cables. The concept of system reliability and fault tree analysis are frequently used to assess probabilistic functionality of infrastructure facilities and systems (FEMA 2004, Leelardcharoen 2005, Adachi 2007).

A fault tree diagram is a representation of a failure event which consists of combined effects of several sub-events (Melchers 1999). A fault tree diagram typically consists of event blocks and operation gates. Two examples of fault tree diagrams are shown in Figure 3-1 and Figure 3-2.

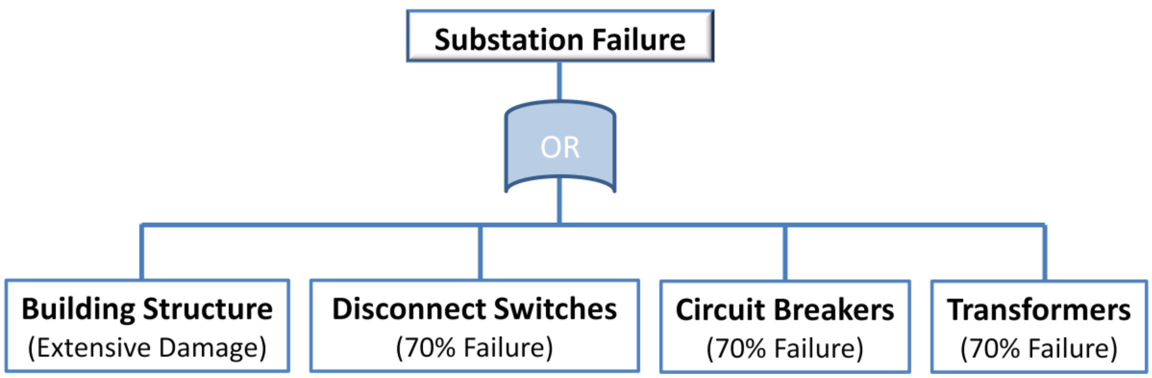


Figure 3-1: Fault Tree Diagram of the Electrical Substation Failure

Figure 3-1 shows the fault tree of the electric substation failure as described in FEMA (2004). This diagram suggests that the failure of an electric substation results from extensive damage to the substation building, 70% failure of disconnect switches, 70% failure of circuit breakers, or 70% failure of transformers. Accordingly, the failure probability of a substation, $P(E_{Substation})$ is calculated as follows:

$$P(E_{Substation}) = P\left(E_{Structure} \cup E_{Switch} \cup E_{Breaker} \cup E_{Transformer}\right) \qquad (3\text{-}2)$$

where $E_{Structure}$, E_{Switch}, $E_{Breaker}$, and $E_{Transformer}$ represent the events of extensive damage to the substation building, 70% failure of disconnect switches, 70% failure of circuit breakers, and 70% failure of transformers, respectively.

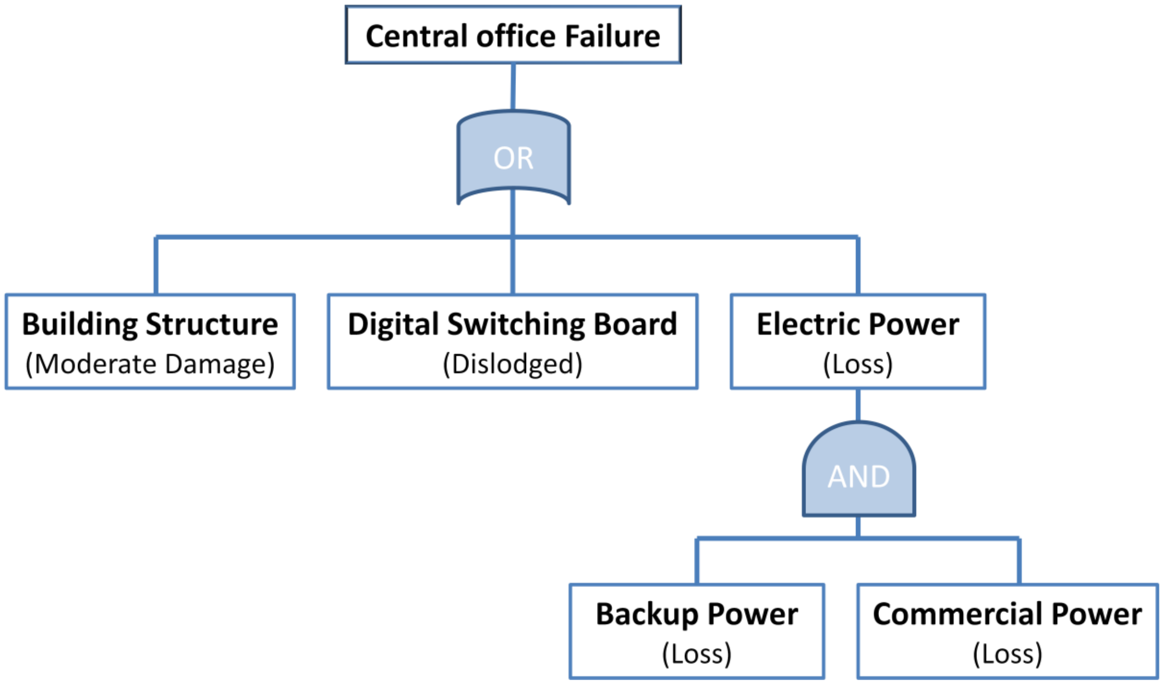


Figure 3-2: Fault Tree Diagram of Telephone Central Office Failure

Figure 3-2 presents the fault tree diagram of the failure of a telephone central office as described in (FEMA 2004). The failure results from moderate damage to the central office structure, a dislodged digital switching board, or loss of electric power, where the loss of electric power results from the loss of backup power and commercial power at the same time. The following equation presents the mathematical representation of Figure 3-2.

$$P(E_{CO}) = P\left(E_{Structure} \cup E_{Switching\_Board} \cup \left(E_{Backup} \cap E_{Commercial}\right)\right) \quad (3\text{-}3)$$

where $P(E_{CO})$ is the failure probability of a central office. $E_{Structure}$, $E_{Switching\_Board}$, E_{Backup}, and $E_{Commercial}$ are the events of moderate damage to the central office structure, dislodged digital switching board, lost of backup power, and commercial power, respectively.

From fault tree analyses and the damage functions of sub-components, damage functions or fragility functions of network components are constructed. The functions are customarily fitted to a log normal distribution, so that they are represented by the two lognormal parameters—median and dispersion. The fragility function parameters of telecommunication and electric power network components as functions of PGA used in this research are listed in Table 3-2.

Table 3-2: PGA Related Network Component Fragility Function Parameters for Nonfunctional Limit State

	Median (g)	**Dispersion**
Electric Power Network Components		
Gate Station (High Voltage Substation)	0.20	0.35
23 kV Substation	0.35	0.40
12 kV Substation	0.45	0.45
Telecommunication Network Components		
Point of Presence	0.40	0.60
Tandem Office	0.32	0.60
End Office	0.26	0.50

The parameters presented in Table 3-2 are based on the parameters proposed by FEMA (2004) with modifications to reflect a failure damage state and to include consideration of different structures for different types of central offices. For example, the structure of an end office is likely to be a small wood frame building while point of presence and tandem offices are 2-5 story concrete or steel frame buildings. The fragility functions are derived by included fragility function of these structures into the fault tree analyses for telecommunication network components. The plots of these fragility functions are show in Figure 3-3.

Experience from past earthquakes suggests that failures of transmission towers, lines, and telephone trunks are rare compared to other components (Schiff 1997). Therefore, it is reasonable to assume invulnerable power transmission towers and lines, and telephone trunks in this study.

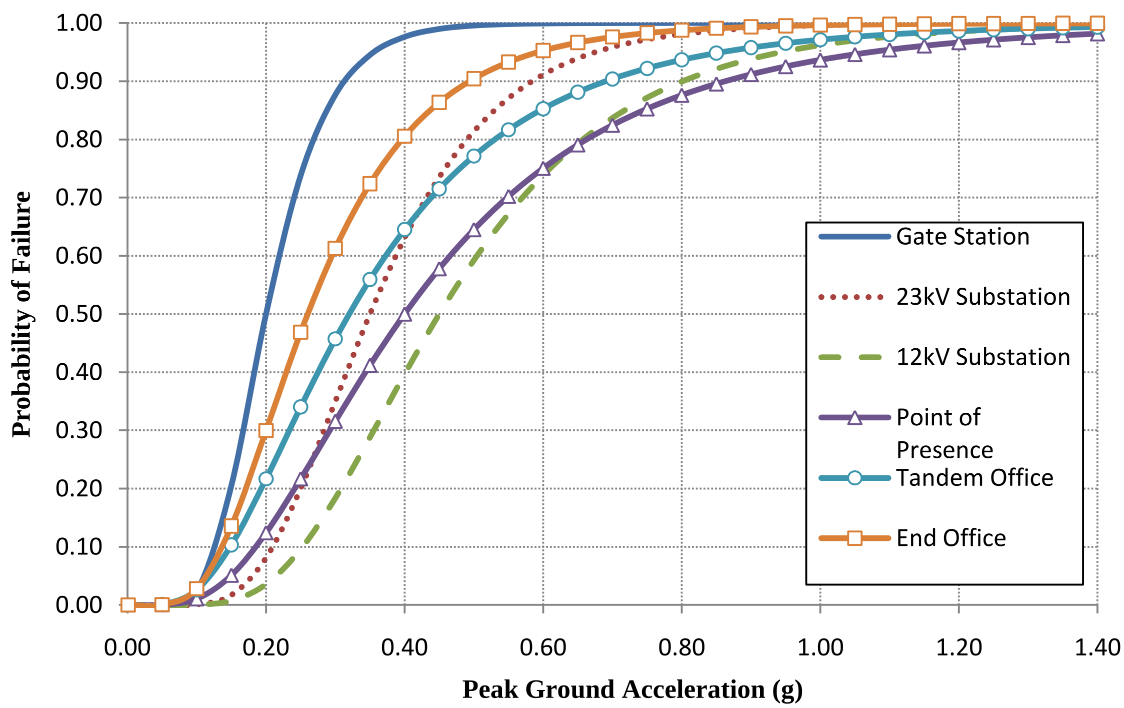


Figure 3-3: Failure Fragility Curves of Telecommunication and Electric Power Network Components

3.3 Congestion in Telecommunication Systems Due to Earthquakes

In telecommunication systems, it is uneconomical for physical resources such as switching and transmission facilities to be dedicated to each customer. There is only a small percentage of total customers who actually use the network or a portion of it at any given time. Therefore, telecommunication networks are designed such that common resources are shared among customers, recognizing that situations can arise where one or more customers are rejected or have to wait for connections, especially when communication demand becomes substantially higher than the design criteria.

After earthquakes events, there is evidence of abnormally high demand for communication. Some data have been collected from the 1994 Northridge and 1995 Kobe earthquakes (Tang 1998). The data shows that one central office in the affected area of the Northridge earthquake had a 3-fold increase from normal in call attempts in the first day after the earthquake. Moreover, the call attempts were over 10 times normal day attempts during peak periods. For the Kobe earthquake, the data was collected for the entire affected area. On the first day of the earthquake, there were approximately 50 times more call attempts from around Japan to the Kobe area than during a normal period. The call volume in the area was six times the normal volume three days after the earthquake and remained high several days after.

It is clear that increase in communication demand following an earthquake can be substantial. Since the telecommunication systems are not normally designed for this extremely high demand, severe congestion in the systems is very likely. Some studies (O'Reilly et al. 2004, Jrad et al. 2005, O'Reilly et al. 2005, Jrad et al. 2007, O'Reilly et al. 2007) have demonstrated the significance of telecommunication system degradation in cases of emergency and disaster due to high demand and congestion. Therefore, congestion is another major effect besides direct physical damage from earthquakes on telecommunication systems which cannot be ignored.

One major contributions of this research thesis is the development of a mathematical model to simulate calling profiles during abnormally high demand in communication systems due to earthquakes. The profiles are meant to be used for the study of seismic performance of telecommunication networks. The model utilizes and modifies teletraffic theory because it captures the problem of congestion, which is normally expected after catastrophic events such as earthquakes. Some relevant concepts in traffic theory are presented next. Prior to the detailed discussion of the model, the background of the traditional traffic theory for telecommunication systems is presented.

3.3.1 Introduction to Traffic Theory

Traffic theory, also referred to as teletraffic theory, was developed by A. K. Erlang, a Danish mathematician, at the beginning of the 20th century. It utilizes a branch of applied probabilistic theory since the demands of communication have stochastic characteristics. In the area of telecommunications, traffic is the flow of information through the telecommunication network. Although, concepts and techniques of traffic theory were developed for *Public Switch Telephone Network* (PSTN), they can also apply to general traffic networks.

<u>Traffic Demand</u>

In traffic theory, traffic demand or *offered load* is defined by two parameters, the *average arrival rate*, λ, and the average *holding time*, τ. The average arrival rate, λ, is the average rate at which customers request services or pick up the telephone to make phone calls. The average holding time, τ, is the average time that one customer requires service or remains on a call. The offered load, a, is defined by the product of these two parameters and it is a dimensionless quantity whose numerical values are expressed in *erlangs*.

$$a = \lambda\tau \tag{3-4}$$

For example, if 5 customers per minute want to use telephones and the average duration of each telephone call is 3 minutes, λ = 5 calls per minute and τ = 3 minutes per call, and the offered load, a, at the end office is then equal to 5×3=15 erlangs. This implies that the telephone switching equipment at the end office should have the capacity to serve at least

15 customers at the same time to ensure immediate service. In other words, offered load represents the average number of resources used by customers if there are enough resources available for all customers.

In a PSTN, offered loads do not remain constant throughout the day and instead peak during certain times. Hence, PSTNs are usually engineered to meet a specific quality of service, or *grade of servic*e (GOS), at certain periods of the year. These periods are called busy season busy hours (BSBHs), which are the busiest clock hours of the busiest weeks of the year. For example, a GOS criterion for switching offices or trunks may state that, over the twenty BSBHs, no more than 1 percent of service requests should be rejected due to unavailable communication channels. Normally, PSTN service philosophy is to provide high-quality, economical service during normal, daily use of the network. However, providing enough equipment to handle infrequent peaks, such as during periods after earthquakes is generally considered to be far too costly.

Blocking Probability

During holiday seasons and natural disasters, it is possible that a large number of customers or subscribers request telephone service simultaneously. As noted above, the PSTN is not designed for these infrequent local peaks. It is likely that all resources or capacities are in use and some requests are denied or blocked. Subscribers are informed that their requests were blocked by the busy signal sent from end offices. In traffic theory, requests for telephone and, to use another example, banking services are considered in the same manner. For example, the analog to a busy signal in banking is when a bank customer finds all tellers busy. The customer has two choices: wait in line for service or leave and come back later – for the telephone service, the subscribers must hang up (i.e., leave) and try again later. This situation is sometimes called *blocked-calls-cleared or lost-calls-cleared*, meaning calls leave the system immediately when they are blocked.

If a random load, *a*, is submitted to a system of capacity, *c*, such that blocked calls leave the system, fundamental assumptions of traffic theory state that the arrival distribution of calls follows a *Poisson distribution* and the holding time distribution follows a *negative exponential distribution*. As a result, the probability that an arriving call is blocked due to unavailable capacity can be expressed as

$$P_b = B(c,a) = \frac{\frac{a^c}{c!}}{\sum_{k=0}^{c} \frac{a^k}{k!}} \tag{3-5}$$

Equation 3-5 is *Erlang's loss formula*, also referred to as the *Erlang-B formula*, and P_b is the *blocking probability*. It should be noted that this formula is developed under the critical assumption that the offered load, *a*, is from an infinite or very large source and blocked calls never return to the system. For a finite source, the arrival rate, λ, tends to decrease after requests are served and leave the system, while Equation 3-5 is derived on the basis of a stationary arrival rate. However, blocked calls tend to return to the system, especially in emergency situations such as after earthquakes. Therefore, more general arrival rate should be higher than the one used to derive Equation 3-5. This study proposes an improvement of this model to assess system performance using a renewal process with Weibull distributions. A detailed discussion of the model is presented in the following sections.

The blocking probability concept is useful for system design and performance evaluation. It was first developed to determine optimum numbers of servers in queuing system such as the number of cashiers in supermarkets, the number of tellers in banks, and the number of switches in a PSTN. Values of blocking probability corresponding to offered loads are set as a GOS to determine capacity of systems. Besides application in system design, blocking probability is also used as performance measurement for queuing systems, especially for telecommunication systems. In this research study, the latter application is extensively used to quantify performance of telecommunication systems.

3.3.2 Sources of Communication Demand after Earthquake

Normally, communication demands in different areas are distinct depending upon the behavior and demographics of subscribers and their activities. In order to include this variation into the models of communication demands, a demographic signature of the target area is used. Total population, proportions of population subscribing to landline and mobile telephone services, and portions of migration population are used to justify different kinds of communication demands.

In order to simulate call profiles after earthquakes, the reasons which trigger communication demand should be understood and characterized. The proposed model considers three major sources of communication demand after an earthquake.

<u>Source 1: Communication among Subscribers within Earthquake Affected Areas</u>

These communication demands represent the calls that originate from the subscribers in the earthquake affected areas, who are aware of the earthquake event and worry about other subscribers they know within the affected areas. Therefore, these demands are estimated from the number of subscribers in the affected areas. This type of demand tends to cause congestion to the entire PSTN and mobile telephone network in the affected areas. This demand registers to telecommunication system when the ground shaking level is strong enough so that some people in the affected area can feel it. This demand is assumed to increase with shaking intensity level and reaches the possibly maximum demand when the shake can be felt by all in the affected area. On the Modified Mercalli Intensity (MMI) scale, the ground shaking levels which some people can feel are approximated at the intensities of III and the level at which all people can feel them is about VI.

Source 2: Communication between Emergency Service Agencies and Subscribers in Earthquake Affected Areas

Earthquakes are destructive and always threaten public safety. Hence, one of the important sources of the communication demand is from people in the affected areas who need emergency attention. Generally, emergency calls are designed to be handled by a central location so that the request can be forwarded to proper dispatch units. Therefore, this kind of demand concentrates and causes congestion to the emergency response call center. This communication demand strongly depends on the severity of the earthquake. Emergency attention is critically important during severe earthquakes. It is logical to assume that the needs of the earthquake victims for emergency attention are directly dependent upon the level of destruction level of building structures and equipment. The proposed relationship between earthquake intensity and this communication demand is based on the assumption that the demand is triggered when some structures are damaged and reaches the maximum possible demand when the majority of the earthquake victims lives are threatened due to severe damage to structures. According to the MMI scale, an intensity of IV indicates that some damage starts to occur to poorly constructed building structures and the intensity level of VIII indicates that all people in the earthquake affected area will face a life threatening situation.

Source 3: Communication Attempts from Subscribers outside the Earthquake Affected Area

This kind of demand is normally expected following catastrophic events. The demand originates from subscribers who are not directly affected by the events but they are concerned about the safety of the victims. In order to quantify this demand, the migration population in earthquake affected areas is used under the assumption that migration population is likely to relate to the population outside the area. This type of demand is significant in the area with a large number of migration populations. Similar to the demand for emergency attention and response, this demand causes congestion to a specific location that connects to long distance telephone networks or toll networks because local telephone networks generally connect to a toll network at a facility, so-called the point of presence. Without feeling ground shaking, subscribers outside earthquake affected area learn about the earthquake event from national news and other media. Once earthquake events are reported on national news, the subscribers outside the area start to worry about their family, friends and acquaintances and make phone calls to check up on them. Since the subscribers outside the area have no detailed insight of the events, this kind of demand depends on their knowledge of earthquake consequences. It is assumed that the demand immediately reaches the maximum once the outside subscribers are informed about earthquake events from national media. From observation of past earthquakes reported on national media, strong ground motions are more likely to be reported than weak ones, and the smallest magnitude earthquakes reported on nation news have had magnitudes of 2.5 to 3.5 depending on the areas of the events. For example, within the New Madrid Seismic Zone, an earthquake of magnitude 2.8 has been the weakest earthquake reported on national media. The shake was centered about 40 miles north of Memphis, TN on January 16, 2009 (The Associated Press 2009).

In general, intensities of earthquake events reported in the media are referred to using Richter or moment magnitudes. However, it is logical to convert the Richter scale values to corresponding seismic demands, such as PGA and PGV and then MMI, to be consistent with the other two demand sources and physical damage to structures. Seismic intensities corresponding to this source strongly depends on local earthquake characteristics, so the intensity level cannot be specifically pre-assigned as with the other demand sources. The corresponding seismic demands can be calculated using attenuation relationships and local soil amplification factors of the target area as described earlier in this chapter.

3.3.3 Probabilistic Model for Earthquake Communication Demand

In traffic theory, arrival rate and holding time of the call are two main ingredients of the communication demand. During normal days, offered loads tends to be random and normally modeled using a Poisson process and negative exponential distribution for arrival process and holding time distributions, respectively. However, after earthquakes, it is possible that a large number of subscribers request communication service simultaneously. In such a situation, a Poisson process and negative exponential distribution are not valid (AT&T Bell Laboratories 1983). Poisson processes have constant rate of time between events (memoryless property) which contradicts with heterogeneous arrival process. The time between each call arriving to the system tends to be much shorter than normal during catastrophic events. The holding time also becomes shorter and more predictable. The probability of finding long call conversation is less. Thus, to better describe such an abnormal communication pattern after earthquakes, a renewal process and the Weibull distribution are used to simulate earthquake call profiles, given their ability to handle more general cases and relax typical teletraffic arrival rate and holding time assumptions.

Another important characteristic of communication demand in emergency situations is retrial attempts. After earthquakes, a higher blocking probability is commonly expected in telecommunication systems. The call attempts which are blocked have higher probability of returning to the system, especially in emergency situation. The retrial attempts increase the arrival rate of the communication demand and cause more severe congestion.

In order to simulate the effects of abnormally high demand after earthquakes, all three components, arrival rate, holding time, and retrial, need to be simultaneously modeled and justified. The discussions of communication demand of each individual component are thus presented with numerical examples.

Arrival Rate and Interarrival Time for Seismic Communication Demand

Although arrival rate is meaningful for the traditional traffic theory, its inverse provides better probabilistic interpretation when a renewal process is used instead of the Poison process. Therefore, *interarrival time*—the time between the occurrences of call attempts—is discussed, instead of arrival rate, in this section.

A Poisson process is a renewal process whose interarrival time is described by the exponential probability distribution function, whereas a renewal process is a generalization of the Poisson process with arbitrary interarrival time distribution input. Due to its constant *rate* parameter, the exponential distribution is not a good probabilistic model to represent the interarrival time of call attempts after earthquake events.

The term, *rate*, sometimes referred to as *hazard rate* or *failure rate*, is an important characteristic function of a positive continuous random variable which represents the lifetime of an event. In this case, the event is referred to as the event that no call attempt arrives to the system after the arrival of the last call. The rate function, $h(t)$, of a cumulative distribution function (CDF), $F(t)$, is defined by

$$h(t) = \frac{f(t)}{1-F(t)} \tag{3-6}$$

where $f(t)$ represents the probability density function (PDF) corresponding to $F(t)$. From equation 3-6, $h(t)$ is also interpreted as the conditional probability density function that the event of age t will end in the next moment.

After an earthquake, the interarrival time tends to decrease dramatically and the chance of finding long interarrival time ending in the next moment is more than the shorter one ending in the next moment. This means not only that the interarrival time becomes much less after an earthquake but also that the rate of longer interarrival times ending in the next moment should be higher. Therefore, the probabilistic distribution representing the seismic interarrival time of call should demonstrate this characteristic, which departs from the traditional constant rate models.

The Weibull distribution is commonly used to model lifetime of an event due to its flexibility of adjusting the rate of the distribution. Its PDF, CDF and rate function are given by

$$f(t;\beta,\alpha) = \frac{\beta}{\alpha}\left[\frac{t}{\alpha}\right]^{\beta-1} e^{-[t/\alpha]^{\beta}}, t > 0 \tag{3-7}$$

$$F(t;\beta,\alpha) = 1 - e^{-[t/\alpha]^{\beta}}, t > 0 \tag{3-8}$$

and

$$h(t;\beta,\alpha) = \frac{\beta}{\alpha}\left[\frac{t}{\alpha}\right]^{\beta-1}, t > 0 \tag{3-9}$$

in which β and α are the parameters of the distribution. β is referred to as the *shape parameter* and α is referred to as the *scale parameter*. Both parameters are positive real numbers. It can be seen that $h(t)$ increases over t when $\beta > 1$, decreases over t when $\beta < 1$, and it is constant over t when $\beta = 1$. It should be also noted that a exponential distribution with mean α is a special case Weibull distribution with parameters α and $\beta = 1$.

The proposed model utilizes the Weibull distribution to simulate the interarrival time distribution of the call attempts after earthquakes by varying the distribution parameters for different seismic intensities and sources of communication demands. A numerical example illustrates the application of the Weibull distribution on the interarrival time distribution of call attempts after earthquake. The example demonstrates the calculation of the interarrival time Weibull distribution of a central office in the metropolitan area of Shelby County, Tennessee.

In July of 2008, the Shelby County population was estimated to be about 907,000 (Population Division 2009). About 26.7% of the total population is a migration population. In the United States, there are about 142 telephone subscribers (both fixed and wireless telephones) per 100 people (International Telecommunication Union 2009). Therefore, the total number of both fixed and wireless telephone subscribers is estimated to be about $907{,}000 \times 142/100 = 1{,}284{,}000$ in the Shelby County area. According to *Central Office Lookup Tools* (Marigold Technologies 2007), there are 34 telephone central offices serving in the area (37,760 subscribers per central office). During normal busy hours, it is assumed that the offered load is 0.083 erlangs per subscriber (Jrad et al. 2005) or about 0.0166 calls per minute for the average holding time of 5 minutes. For one central office, the offered load is $37{,}760 \times 0.083 = 3{,}134$ erlangs or about 627 calls per minute for 5minutes average holding time. To satisfy the typical standard GOS of maximum 1 percent blocking probability for any given route of a telephone call during a busy hour, a central office in Shelby County is designed to serve 3,320 subscribers at the same time according to Equation 3-5.

From the demographic signature of Shelby County area and the assumptions of the seismic communication sources, the maximum numbers of possible call attempts from the three sources at different seismic intensity levels are estimated as follows:

Source 1: Communication among Subscribers within Earthquake Affected Areas

At the seismic intensity from III to VI in the MMI scale (equivalent to a PGA of up to 0.05g), all people in the earthquake affected area feel the ground motion and produce the maximum possible call demands. It is an easy task to estimate the amount of the demands, while the accuracy of the estimation depends on availability of information, such as telephone usage records or surveys on telephone subscriber behavior. However, due to the absence of such information, some assumptions are made in this study, so that the application of the proposed method can be numerically demonstrated. In this example, it is assumed that each subscriber has a close relationship to three other subscribers on average. This assumption is based on the average estimated family size of

3.19 (U.S. Census Bureau 2009) which is rounded up to 4 members per family. Each subscriber is assumed to make a phone call to each family member after an earthquake occurring during work hours when the family members are not together. This implies that each subscriber makes three phone calls within a certain period right after feeling ground shaking (within the first hour after the major shock, in this case). The average number of call attempts becomes $3 \times 37{,}760/60 = 1{,}888$ calls per minute per central office (about 3 times the design load) or 0.00053 minute average interarrival time. A linear increase of arrival rates is assumed from the design arrival rate at the seismic intensity III (equivalent to PGA of 0.010g) to the arrival rate of 1,888 calls per minute. The linearity assumption should be refined when more information becomes available in the future. The scale parameter of this source (equivalent to exponential mean of interarrival time) is defined by

$$\alpha_{i1}(PGA) = \begin{cases} 0.0017 & PGA < 0.01g \\ (32{,}625PGA + 256.75)^{-1} & 0.01g \leq PGA \leq 0.05g \\ 0.00053 & PGA > 0.05g \end{cases} \quad (3\text{-}10)$$

To simulate the increasing rate of the interarrival time distribution the shape parameter is defined by

$$\beta_{i1}(PGA) = \begin{cases} 1.0 & PGA < 0.01g \\ 12.5PGA + 0.875 & 0.01g \leq PGA \leq 0.05g \\ 1.5 & PGA > 0.05g \end{cases} \quad (3\text{-}11)$$

where α_{ij} and β_{ij} represent scale and shape parameter of interarrival time of source j respectively.

Source 2: Communication between Emergency Service Agencies and Subscribers in Earthquake Affected Areas

The maximum possible arrival rate for this type of demand occurs at the seismic intensity of VIII (equivalent to a PGA of 0.25g). The magnitude of the demand is calculated according to the assumption that a subscriber in the area requires one emergency call within the first 15 minutes right after the major shock or $37{,}760/15 = 2{,}517$ calls per minutes per central office. This assumption is based on the fact that requests for several emergency services can be done in one call since emergency call centers are interconnected to several emergency service providers. The relatively shorter period for this source of demand is assumed to reflect the emergency situation. For the emergency call rate at the seismic intensity IV (equivalent to PGA of 0.015g) and lower which is not yet triggered by ground shaking is assumed to be the normal day emergency call rate which is about 2.09 calls per subscriber per year (O'Reilly et al. 2005) or about 0.15 calls per minute per central office. By assuming a linear increasing of the arrival rate over seismic intensity levels beyond normal operation, the scale parameter, α_{i2}, can be defined by

$$\alpha_{i2}(PGA) = \begin{cases} 6.66 & PGA < 0.015g \\ (10{,}710PGA - 160.5)^{-1} & 0.015g \le PGA \le 0.250g \\ 0.00040 & PGA > 0.250g \end{cases} \qquad (3\text{-}12)$$

For emergency call in the catastrophic events, the rate of interarrival time is assumed to be 2.0 for the maximum possible load and 1.0 (exponential distribution) for the normal day emergency calls. This assumption can be updated when more information becomes available. Thus β_{i2} is defined by

$$\beta_{i2}(PGA) = \begin{cases} 1.0 & PGA < 0.015g \\ 4.260PGA + 0.9361 & 0.015g \leq PGA \leq 0.250g \\ 2.0 & PGA > 0.250g \end{cases} \qquad (3\text{-}13)$$

Source 3: Communication Attempts from Subscribers outside the Earthquake Affected Area

The nature of this demand is similar to the first demand except the magnitude of the load depends on the number of migration population, not the total population. By assuming 3 calls per migration subscribers within 60 minutes, the maximum possible arrival rate is 504 calls per minute per central office or 0.00198 minute interarrival time. For the normal day toll offered load which is not triggered by earthquake news, the load is about 7% of the local call (Liu 1980) which is about 44 calls per minute per central office. Hence, for this example α_{i3} and β_{i3} are defined by

$$\alpha_{i3}(PGA) = \begin{cases} 0.0227 & PGA < 0.02g \\ 0.00198 & PGA \geq 0.02g \end{cases} \qquad (3\text{-}14)$$

and

$$\beta_{i3}(PGA) = \begin{cases} 1.0 & PGA < 0.02g \\ 1.5 & PGA \geq 0.02g \end{cases} \qquad (3\text{-}15)$$

It can be seen that a seismic demand of 0.02g is the level corresponding to a moment magnitude of 3.5 in the Shelby County area which triggers some level of national news coverage.

It should be noted that this numerical example is created from the best available records of the usage of a typical PSTN and the demographic signature of the affected area from the literature. By adjusting parameters of the Weibull distributions, a more accurate model can be obtained from fitting a more detailed usage record of the targeted network to the input probability distributions.

Holding Time for Seismic Communication Demand

Similar to interarrival times, holding times after earthquakes tend to become shorter than those on the normal day due to the nature and the purpose of the call. A majority of telephone calls during emergencies have a specific objective, such as to report the emergency situation or to inquire about the status of family members. Normal daily calls have a wider variety of purposes such as conference calls which can be more than an hour long to normal business calls which may be only 3-5 minutes long. The use of the Weibull distribution over the exponential distribution repeats for the holding time. The longer calls tend to have higher probability of ending. Since the rate of the holding time distribution is expected to increase over time, the Weibull distribution with increasing rate is more suitable than an exponential distribution with constant rate.

There is not so much variation in the holding time distribution relative to the interarrival times across demand sources, although the nature of the communication differs from the regular phone calls on normal days. Holding time for a call must be long enough to exchange necessary information. Therefore, in this model, the scale parameters of the holding time distribution, α_h, for all three communication sources are assumed constant while minor variation is applied to shape parameters, β_h, to adjust the rates of the distributions. The Weibull distribution parameters for the holding time of the three sources corresponding to the interarrival rate for the numerical example are defined as follows:

Source 1: Communication among Subscribers within Earthquake Affected Areas

$$\alpha_{h1} = 5.0 \tag{3-16}$$

$$\beta_{h1}(PGA) = \begin{cases} 1.0 & PGA < 0.01g \\ 12.5PGA + 0.875 & 0.01g \leq PGA \leq 0.05g \\ 1.5 & PGA > 0.05g \end{cases} \tag{3-17}$$

Source 2: Communication between Emergency Service Agencies and Subscribers in Earthquake Affected Areas

$$\alpha_{h2} = 3.0 \tag{3-18}$$

$$\beta_{h2} = 1.5 \tag{3-19}$$

Source 3: Communication Attempts from Subscribers outside the Earthquake Affected Area

$$\alpha_{h3} = 4.0 \tag{3-20}$$

$$\beta_{h3}(PGA) = \begin{cases} 1.0 & PGA < 0.02 \\ 1.1 & PGA \geq 0.02 \end{cases} \tag{3-21}$$

These parameters are extrapolated from normal day communication demand parameters. They will be used to simulate the effects of high demand on a central office. The effects of all demand variability are presented and discussed in the following section. It should be stressed that the presented parameters can be adjusted when pertinent records and additional data of system performance under distress conditions become available in the future.

Retrial Attempts of Seismic Communication Demand

In the event of an earthquake when telecommunication systems are overloaded, it is likely that several call attempts are blocked due to unavailable servers. These blocked calls tend to come back to the system as retrial attempts. Jrad et al. (2007) demonstrate that retrial attempts are likely in the case of emergencies and significantly affect the performance of telecommunication systems.

There are two components of the retrial attempt model, probability of retrial and interarrival time of retrial attempts. Liu (1980) distinguishes retrial attempt probability for different reasons of blocking during the normal day operation from available records (e.g., no answer, busy, equipment blockage and failure, among others). Jrad et al. (2007) suggest an 80% probability of retrial attempt for calls in emergency situation. In this model, the 80% probability makes sense only for the communication within the earthquake area and the communication from outside. However, 100% probability retrial attempt is more appropriate for the communication between subscribers and emergency response centers due to the necessity and urgency of the calls.

The interarrival time of retrial attempts is defined as the time between the unsuccessful attempt and the following attempt. From the available records of retrial in a normal day (Liu 1980), the shape parameter of the Weibull distribution for retrial attempt interarrival time, β_r, is 0.470. Due to the limitation of the records, it is assumed that the retrial behavior of each source has similar characteristic, so β_r is assumed the same for all sources. In order to simulate the retrial after earthquakes, scale parameters are assigned for each of the communication sources as follows

Source 1: Communication among Subscribers within Earthquake Affected Areas

$$\alpha_{r1} = 6.65 \tag{3-22}$$

Source 2: Communication between Emergency Service Agencies and Subscribers in Earthquake Affected Areas

$$\alpha_{r2} = 2.22 \tag{3-23}$$

Source 3: Communication Attempts from Subscribers outside the Earthquake Affected Area

$$\alpha_{r3} = 6.65 \tag{3-24}$$

The presented scale parameters are selected on the basis of median interarrival retrial time assumptions. For the first and the third sources, the mean of 15 minutes interarrival retrial time is assumed while the mean of 5 minutes is for the second sources. These assumptions are based on the work of (Liu 1980).

Effects of Seismic Communication Demand on Network Components

From the proposed probabilistic model of the communication attempts, the effect of abnormally high communication demand due to earthquakes can be studied. Since the communication demands from each source respond to earthquake intensity differently, and they are introduced to telecommunication systems simultaneously, numerical simulation becomes a preferable method to estimate the effects of the high demand on telecommunication systems. The numerical simulation methods also allow modeling of details, such as the delay of the third source of communication due to the national news distributions, and retrial attempts, to be included in the study. More insights on how each communication source contributes to the performance of the systems and the effects of retrial attempt can be observed from numerical experiments.

The examples of the interarrival time, holding time and retrial attempts presented earlier are simulated and input into a typical central office designed for the Shelby County area with the capacity of serving 3,320 calls simultaneously. Some of the results are presented and discussed below.

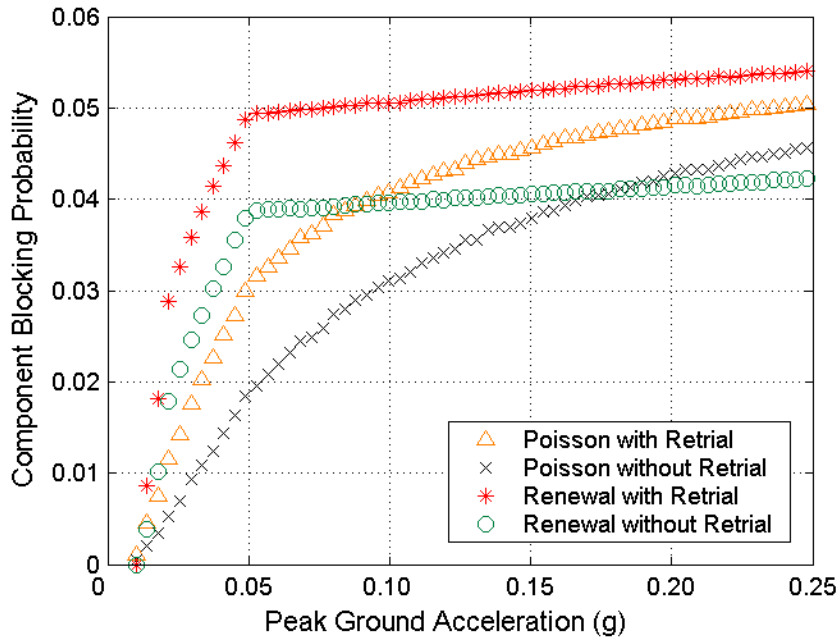


Figure 3-4: Component Blocking Probability due to Renewal and Poisson Seismic Communication Demand Models with and without Retrial Attempts

Figure 3-4 shows the plot between seismic demand in term of PGA and blocking probability of a central office subjected to four different communication demands—the traditional traffic theory demand (Poisson process demand model) with and without retrial attempts, and the proposed renewal demands with heterogeneous times with and without retrial attempts. While the renewal demands as defined in the previous section have distinct rates of variability, the traditional traffic theory demand is assumed to increase linearly from the designed load of the central office (3,134 erlangs) to 4 times the load between 0.01g and 0.25g PGA (Houck et al. 2004). The linearity implies that the number of subscribers participating in the demand varies linearly over the intensity of ground shaking. The traditional Poisson load is quantified using the traffic overloading scenario in the study of Houck et al. (2004). This scenario was defined to simulate the effects of a disaster situation on telecommunication systems which is considered to be the maximum possible demand on the system in this example. The retrial attempt model for the traditional load is based on Liu (1980) which is identical to retrial in sources 1 and 3 of the renewal model as defined earlier.

Each curve in Figure 3-4 is plotted from the result of the numerical simulation process starting from a given seismic intensity level (PGA). Then, the parameters of the Weibull distributions (renewal process model) or exponential distributions (Poisson process model) for interarrival time, holding time, and retrial interarrival time are determined from Equation 3-10 to Equation 3-24. From the appropriate distributions and the parameters corresponding to the selected PGA, a call profile (including the time when each call arrives at a central office and the length of each call) is generated randomly following the probability distributions and inserted into a central office. If lines or channels are available when a call arrives, the call enters the central office and it is counted as a successful call. The number of available lines is reduced by one. Then, the call exits the system after it stays in the system for the length of the call and the line or channel becomes available. If there is no line available when a call arrives, the arriving call is counted as a blocked call and reenters the queue in the profile. The time that the blocked call returns to the system is randomly generated following the retrial interarrival time distribution (Equation 3-22 through Equation 3-24). At the end of each call profile, the blocking probability of the component is calculated. These steps are repeated several times to obtain probability distribution of blocking probability for each PGA level. Finally, a mean blocking probability is plotted for each PGA to create the curves in Figure 3-4

From the plot, it can be seen that the Poisson process curves are fairly smooth as a result from the linear increase in offered load; however, the renewal process curves show some shape transitions. There are three noticeable transitions in each renewal process curve. These transitions are caused by the recognition of different sources of seismic-induced communication demand.

The first transition observed at PGA = 0.05g (intensity III in the MMI scale) indicates that demand source 1 reaches its maximum possible amount because all subscribers have participated in this source of communication demand. For PGA = 0.05g and greater, the parameters of the renewal process of source 1 stay constant. Therefore, the increase in blocking probability beyond such PGA level is caused solely by the demand source 2 because the number of subscribers who need emergency attention still increases with seismic intensity as a result of increase in structural damage.

Another transition in the renewal process curves occur at PGA = 0.25g (intensity VIII in the MMI scale) where the demand source 2 reaches its maximum possible amount. This is because all subscribers have tried to access telecommunication system according to the assumption that all subscribers need emergency attention after subjected to a PGA = 0.25 or greater. The blocking probability does not increase further since all sources have reached their maximum possible amount of demand. The renewal process model parameters do not change even if the seismic intensity increases.

The last transition is expected at PGA = 0.02g where the demand source 3 is triggered by news report. This sudden exertion of the demand results in the increase in blocking probability by about 1%. This increase may vary depending on the demographic and seismic signature of the target area.

The plot also shows significantly greater significant effects of retrial attempts on the renewal demand than the traditional demand. Retrial attempts increase blocking probabilities of the renewal demand by up to 15% while the traditional demand shows only 10% difference. Although the retrial characteristic of the traditional demand and majority of the renewal demand are the same, the higher retrial rate and higher retrial probability of emergency communication demand source well amplifies the effect of retrial on the renewal demand.

In cases when the majority of blocked calls reenter a system as retrial attempts, other statistics, such as the number of retrial attempts and time required for blocked calls to connect successfully to the system, also provide meaningful indicators of system performance.

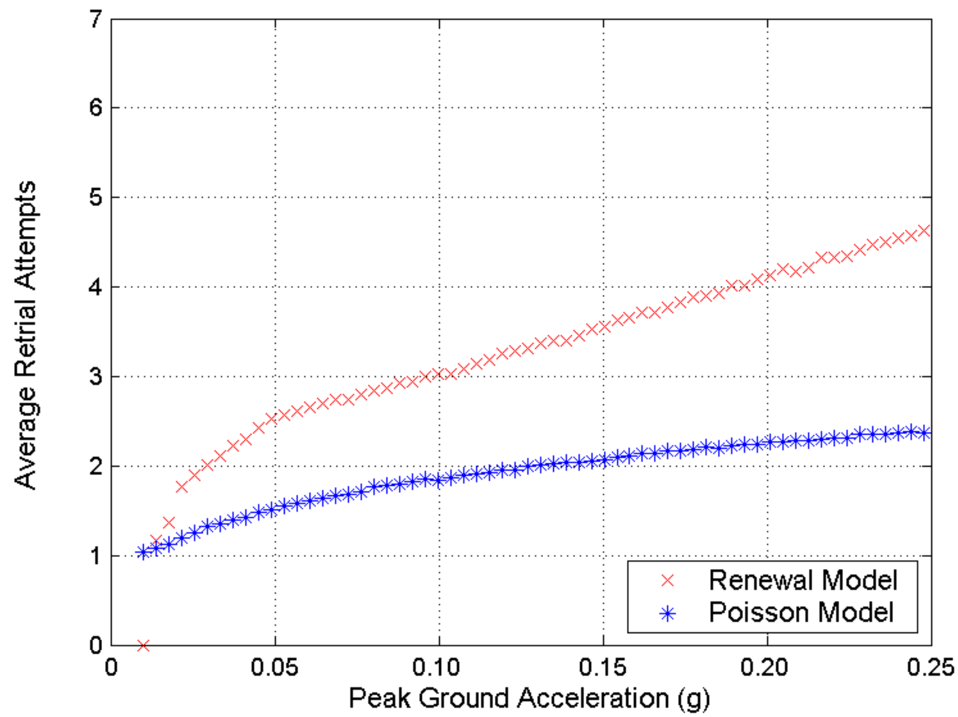


Figure 3-5: Average Retrial Attempts of Blocked Calls due to Renewal and Poisson Seismic Communication Demand models

Figure 3-5 presents the plot of average retrial attempts of blocked calls for a typical Shelby County central office which is subjected to renewal communication demand and traditional Poisson process demand against seismic intensity. The plot shows the increase of the retrial attempts due to the increase in the original demand in PGA. The higher original demand in terms of PGA in the Poisson and renewal processes results in higher blocking probabilities for both first attempts and retrial attempts. This causes a blocked call to require more than one reattempt to successfully connect to the central office and also results in longer delays per call, as shown later in Figure 3-7 and Figure 3-8, even though the retrial characteristics are independent of PGA.

Figure 3-5 also shows significant differences in average retrial attempts at the central office subjected to renewal demand and traditional Poisson demand. More retrial attempts in the renewal demand are expected because the blocking probabilities of the renewal demand are higher, as shown in Figure 3-4. The plot shows the numbers of retrial attempts of the renewal demand are much greater than those of the traditional Poisson demand at high PGA, even though the differences between blocking probabilities of the two demand models are less at high PGA, especially higher than 0.05g. This is a result of the higher retrial probability and shorter interarrival retrial time of demand source 2. The average retrial attempts of the renewal demand can become almost twice the average retrial attempts of the Poisson demand. This suggests a high sensitivity of the central office performance to retrial behavior which agrees with the conclusion from the study of Jrad et al. (2007).

For the renewal demand, the plot of average retrial attempts clearly shows the different responses of the central office in the ground shaking perception range and the physical damage range. The rate of increase in the number of retrials over PGA is the highest in the overlap range (between 0.015g and 0.05g), while the high rate is still present at higher PGA due to the retrial behavior of the demand source 2. To better understand the effects of retrial behavior, the plot of average retrial attempts of each demand source is presented in Figure 3-6.

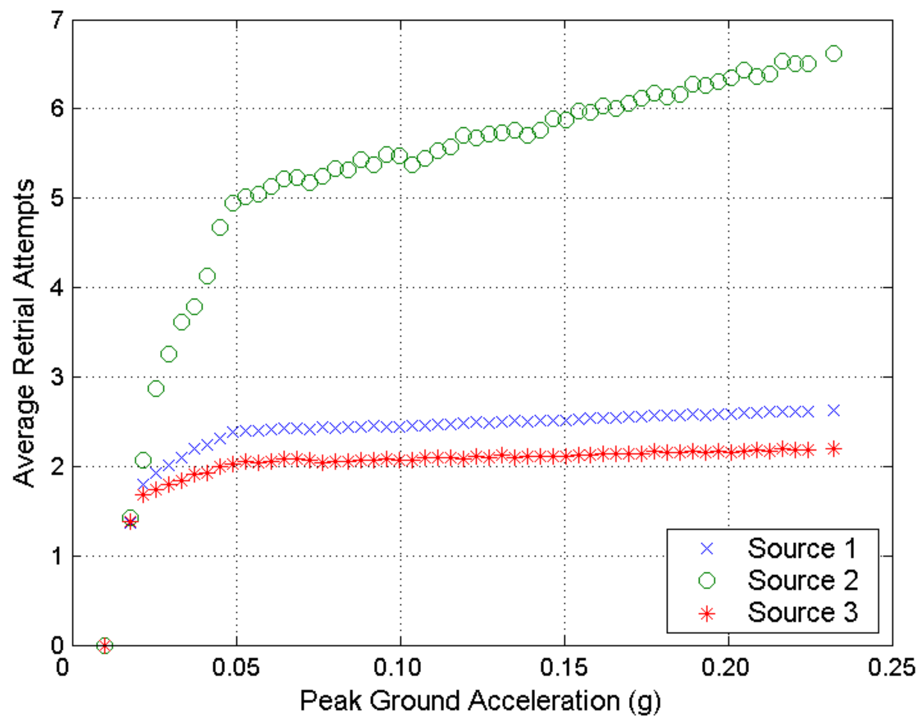


Figure 3-6: Average Retrial Attempts of Blocked Calls due to Renewal Seismic Communication Demand Displayed by Source Type

Figure 3-6 reveals that retrial behavior affects the average retrial attempts per call. While the average retrial attempts of demand source 1 and 3 are close since their retrial behaviors are identical, the average retrial attempts of demand source 2 are significantly higher due to shorter interarrival retrial times. It can also be seen that the average of retrial attempts of demand sources 1 and 3 are close to those of the Poisson demand (Figure 3-5) which shares the same retrial behavior. This suggests that the characteristic of the first attempts of sources 1 and 3 have only slight effects on average retrial attempts per call. The higher first attempt demand magnitude results in slightly more average retrial attempt per call. From the plot of average retrial attempt by renewal demand sources, it is quite clear that the retrial behavior of the demand source 2 causes the significant difference between the renewal and Poisson demands.

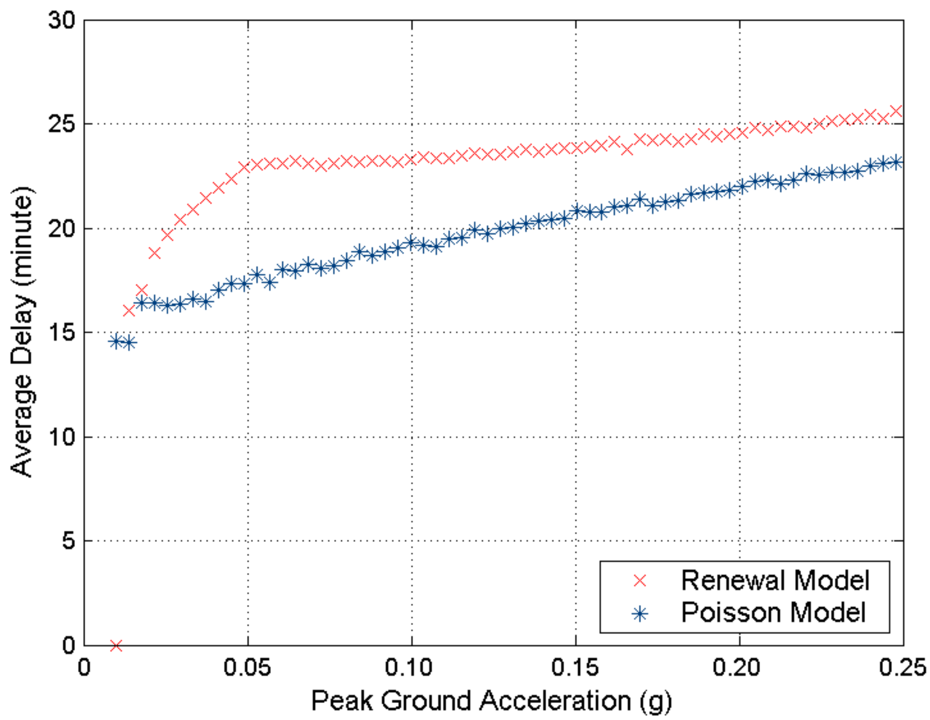


Figure 3-7: Average Delay per Blocked Call due to Seismic Communication Demand

Figure 3-7 presents the plot of average delay per blocked call of the renewal and the Poisson demand. Note that the delays are defined as time lags between the first blocked attempts and the successful attempts of the same calls. For time-sensitive communication, such as emergency calls or data transfer in SCADA systems used in electric power operation, this statistic is very critical. Long delay could result in instability and unreliable operation of power grids or even death in life-threatening emergencies.

The delay only occurs when the central office experiences such high volume of calls that some calls are blocked and returned to the system as a retrial. Since the retrial behavior has a mean interarrival retrial time of 15 minutes, it can be seen from the plot that the average delay is approximately 15 minutes when the average number of retrials is approximately one (PGA between 0.01g and 0.015g). Although the mean interarrival retrial time is independent of seismic intensities, the plot shows positive correlation with PGA because the high blocking probability of the central office results in the situation where retrial calls are also blocked. Several retrial attempts are needed for a call to go through the system. This is consistent with Figure 3-5, where longer delays are expected when more retrial attempts are required.

Figure 3-7 shows a lower rate of increase in delay versus PGA than the rate of increase in the number of average retrial attempts shown in Figure 3-5. This is a result of the shorter interarrival retrial of demand source 2 (5 minutes). Even though more retrial attempts are required, they come back to the system with much higher rate. Hence, demand source 2 a has better chance to successfully connect to the system in a shorter time. This conclusion is supported by the plot of average delay of each demand source in Figure 3-8. It can be seen that the delay of demand source 2 is comparably shorter than those of demand source 1 and even of demand source 3 at low seismic intensities. Moreover, Figure 3-8 also shows the rates of increase in average delay of each demand source correspond to the rates of increasing in average retrial attempts shown in Figure 3-6.

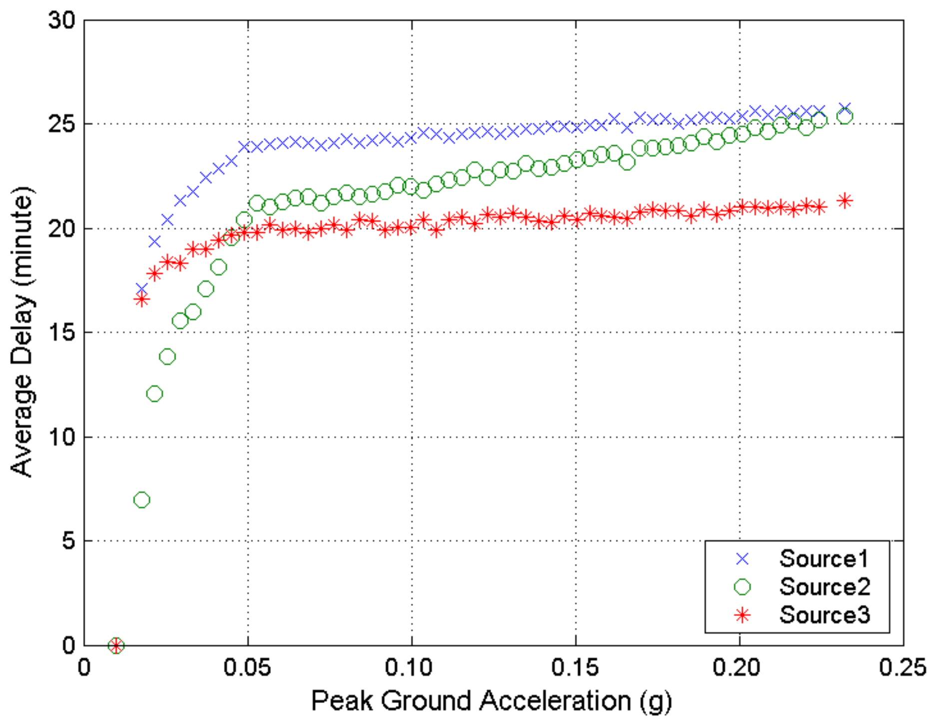
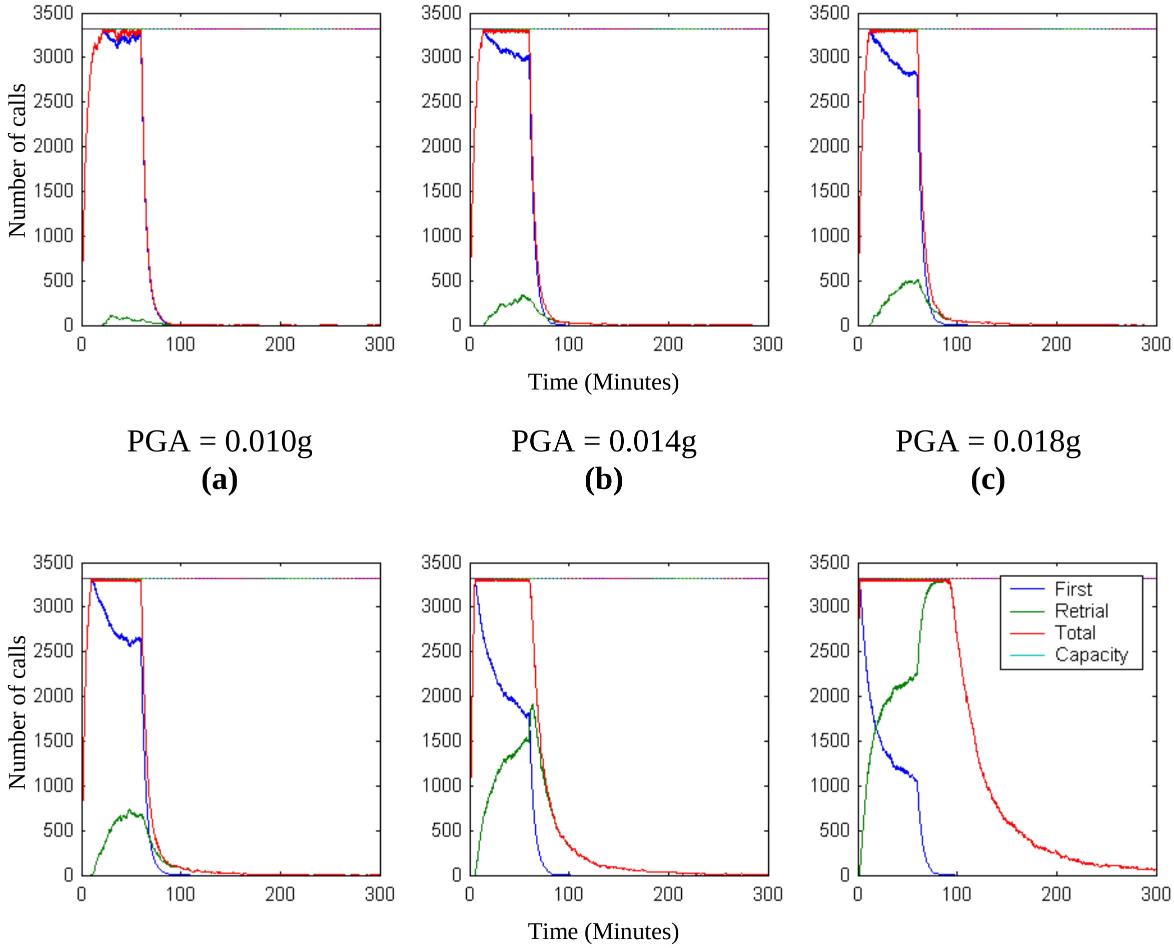


Figure 3-8: Average Delay per Blocked Call due to Renewal Seismic Communication Demand Displayed by Sources

The plot in Figure 3-8 is also useful in explaining the degradation of the system in delay for dial tone. Demand source 2 is the communication demand due to the needs of emergency service and it is considered more critical and more time-sensitive than demand sources 1 and 3. The consequence of the same delay in source 2 is definitely worse than in source 1 or 3. For example, at PGA of 0.05g, the average delay for source 1 is approximate 24 minutes while the delay is approximate 20 minutes for source 2. Although the delay for source 2 is shorter, a 20-minute delay in requesting emergency service is not acceptable and could result in fatalities while a 24-minute delay in source 1 might just raise more concern by the subscribers who make phone calls. Therefore, it is critical to obtain the information shown in Figure 3-8 by source type in order to assess the consequence of the degradation of the telecommunication system.

As also seen on the previous plots, the noticeable transition in the response due to the distinguishing of communication sources also appears in Figure 3-7 and Figure 3-8. The expected delay of central office is the most sensitive to seismic intensity in the overlap range between the ground shaking perception and seismic-induced physical damage ranges (Sources 1 and 2). The average delay of the renewal demand is also longer than the Poisson demand. The overall performance of this central office subjected to the renewal demand is worse than the same central office subjected to the traditional Poisson demand.

Besides the blocking probability, the number of retrial attempts, and the delay of blocked calls, server status is another statistic that can provide insight into the behavior of a central office. The server status of a central office is the variation in the number of calls in the telephone switch or server in time. Normally, a server status is shown as a plot of the number of calls in the server versus time of day. In a normal day situation, a server status varies throughout the day due to activities of subscribers. However, the server status developed in this study focuses on the transient state excited by seismic events. Therefore, the time scale of server status in this study represents time lags after the initial shock of an earthquake. The variation in the server status before the earthquake is assumed to be very small compared to the abnormally high load from the earthquake. Hence, the effects of small variation in the status of the servers during the normal operation period are beyond the scope and concern of this study.



PGA = 0.010g
(a)

PGA = 0.014g
(b)

PGA = 0.018g
(c)

PGA = 0.022g
(d)

PGA = 0.053g
(e)

PGA = 0.260g
(f)

Figure 3-9: Server Status of a Central Office Subjected to Poisson Demand by Attempts

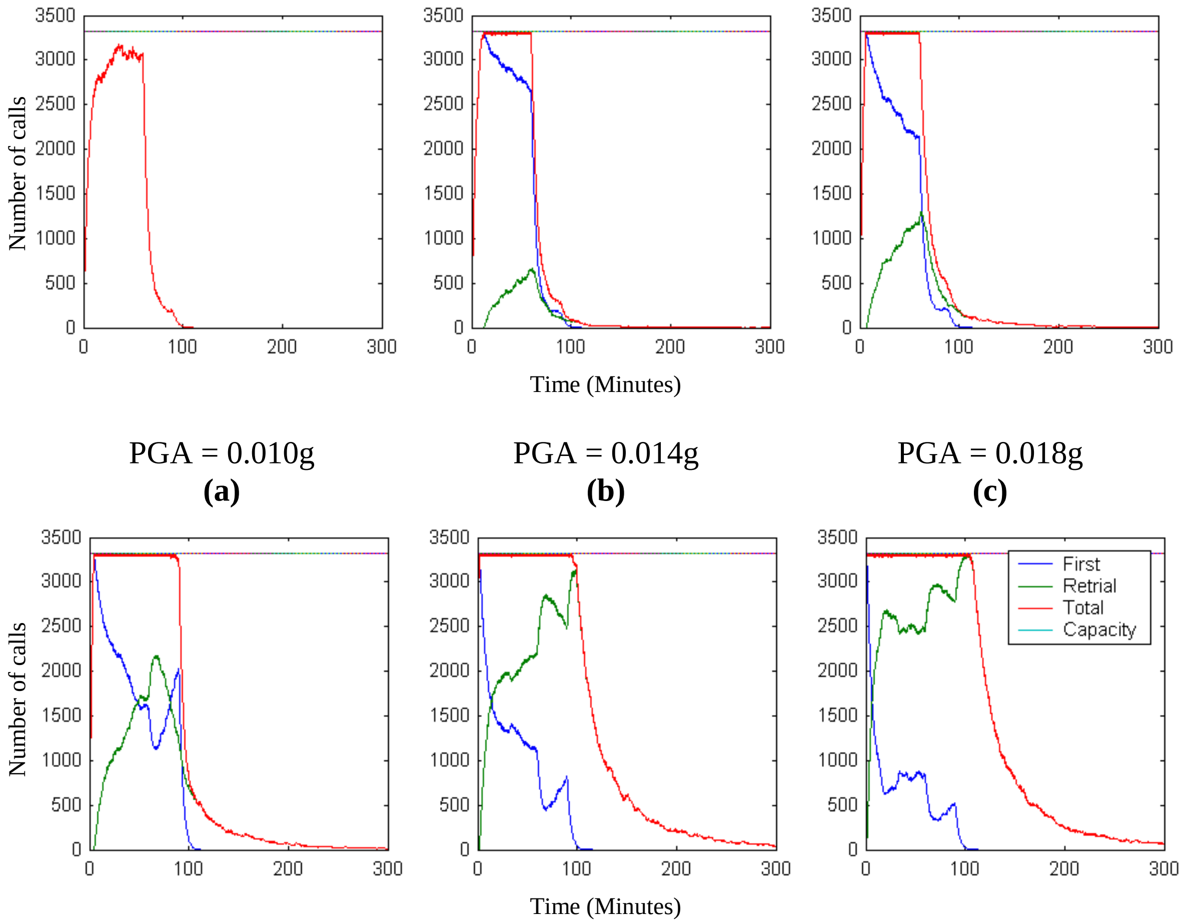
Figure 3-9(a) through (f) show the traffic profiles of a central office subjected to the traditional Poisson demand corresponding to PGA levels of 0.010g, 0.014g, 0.018g, 0.022g, 0.053g, and 0.260g, respectively. These PGA levels are the seismic intensities in which the renewal demand significantly changes. These server statuses are compared to the statuses of the central office subjected to the renewal demands.

The server status in Figure 3-9 shows variation of total, first, and retrial call attempts which successfully connect to the server and occupy server capacity in time. All plots share similar characteristic. Each of them can be distinguished in three main periods of time.

The first period is the period when the calls start entering the server and reach the capacity of the server. This period involves only first call attempt since no calls are blocked yet, so there are no retrial attempts register to the system. The profiles show that this period become shorter when arrival rates of calls become higher at higher PGA levels.

The second period is when the server is congested due to overloading. The server starts rejecting the request for service because the capacity has been reached. Some of the blocked calls start coming back to the server as retrial attempts shortly after and amplify the overloading. The plots show the rise in the number of retrial attempts entering the server, while the amount of first attempts drop. At low arrival rate and seismic intensity, this congestion period ends once first attempts stop. In this example, the first attempts are made to the server for 60 minutes after the initial shock. Thus, this period ends at 60 minutes in Figure 3-9(a) through (d). However, this is not true at higher arrival rate and PGA when more first attempts are blocked and even more retrial attempts try to come back to the server. This results in the extension of the congestion period because the server is still stressed by large amount of retrial attempts even if first attempts stop entering the server. Figure 3-9(e) and (f) show the sudden drop of first attempts in the server and the sudden rise of retrial attempts at 60 minute when the first attempts stop entering the server. It can be seen that retrial attempts successfully connect to the server at much higher rate once first attempts stop entering the server. Figure 3-9(f) shows the congestion period can be extended up to almost 100 minutes after the initial shock.

Finally, the last period represents the relaxation of the server. This period shows the gradual decrease in the number of calls to the server as they leave the server after the termination of the call. In this period, the server recovers from congestion and it is available to accept more calls.



PGA = 0.010g
(a)

PGA = 0.014g
(b)

PGA = 0.018g
(c)

PGA = 0.022g
(d)

PGA = 0.053g
(e)

PGA = 0.260g
(f)

Figure 3-10: Server Status of a Central Office Subjected to Renewal Demand by Attempts

Figure 3-10 shows the server status plots for the renewal demand. The three characteristic periods shown in the plots of the Poisson demand in Figure 3-9 also appear in the plots of the renewal demand. However, the variation of first and retrial attempts between the two demand models is clearly different since the renewal demand model consists of three sources which are introduced to the central office at different times—Source 1 is active in the first 60 minutes after the initial shock, Source 2 is active in the first 15 minutes after the initial shock, and Source 3 is active 30 minutes after the first shock for 60 minutes.

The server statuses in Figure 3-10 are presented only to illustrate the different variations in time between the Poisson (Figure 3-9) and the renewal demands. To provide additional insights, the server status of the renewal demand displayed by sources is shown in Figure 3-11.

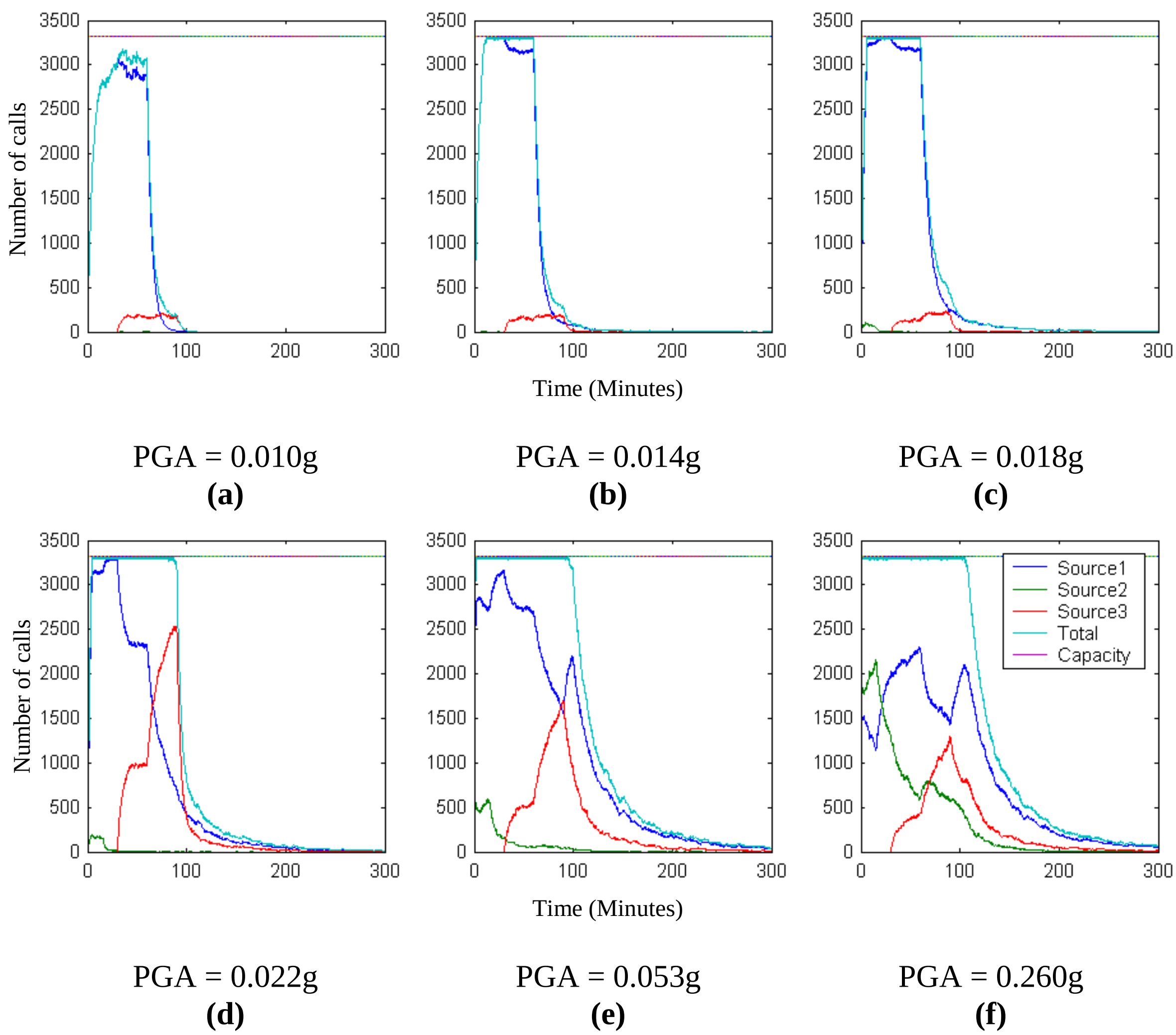


Figure 3-11: Server Status of a Central Office Subjected to Renewal Demand by Sources

Figure 3-11(a) is the server status of the central office subjected to renewal seismic communication demand of 0.010g PGA. At this seismic intensity, only a few subscribers in the area feel ground shaking. The offered load is close to the design load of the central office. The peak in the profile is just less than the capacity. Only demand source 1 and 3 register to the central office as defined earlier in this chapter. Demand source 1 dominates the central office while the magnitude of the demand source 3 is the normal day operation of long distant calls.

Figure 3-11(b) is the status of the server when the PGA level is 0.014g. The offered load of demand source 1 is about 1.2 times the load a a 0.010g PGA, while there are no changes to the offered load of demand source 3. Some calls are blocked and return to the system as retrial attempts as shown in Figure 3-10(b). However, the blocking probability of this profile is still low (1.8% blocking, shown in Figure 3-4).

In Figure 3-11(c) (PGA = 0.018g), the demand source 2 appear in the profile with small magnitude since only few damages to structural are presented and few emergency services are required. It should be noted that the demand source 1 and 2 enter the central office at the same time, but the demand source 2 ends earlier. At this seismic intensity, demand source 1 still dominates the system since the magnitude of the offered load of demand source 2 and 3 are very small compared to demand source 1.

At a PGA = 0.022g, the magnitude of the demand source 3 increases dramatically due to the recognition of the earthquake event by subscribers outside the affected area from national media. The profile in Figure 3-11(d) shows a significant drop of the demand source 1 when the demand source 3 arrives to the system (30 minutes after the initial shock). Shortly after, the system adjusts itself to a stable state (the state where the profile of each source becomes constant) before the demand source 1 ends at 60 minute and more demand source 3 continues connecting to the central office. Also note that the amount of retrial attempts becomes more significant, as previously shown in Figure

3-10(d). The congestion period of the server is extended due to demand source 3 which stops registering to the server after 90 minutes.

At a PGA = 0.053g, the magnitude of the demand source 1 has reached its maximum possible load while the magnitude of the demand source 3 remains constant. Because arrival rate of demand source 1 increases, Figure 3-11(e) shows the dominance of demand source 1 over the period of time. More retrial attempts of demand source 1 are collected and come back to the server with higher rate after demand source 3 is cleared from the system at 90 minutes after the initial shock. Figure 3-11(e) also shows more calls from demand source 2 entering the server due to more physical damage to structures and more life threatening emergency situations as expected at a higher PGA.

Figure 3-11(f) is the server status of the central office subjected to renewal seismic communication demand at a PGA of 0.260g. At this seismic intensity, the calls from all three demand sources reach their maximum possible magnitudes. Each demand source generates calls to the server differently in time. Source 2 dominates the server right after the initial shock while demand source 1 starts to occupy most of the system after demand source 2 drops from the system after 15 minute. Only retrial attempts of demand source 2 come back to the server afterward. Demand source 3 enters the server with the lowest rate 30 minutes after the first shock. When first attempts of demand sources 1 drop off from the server at 60 minutes after the shock, the calls from demand source 3 enter the server at a higher rates as the capacity of the starts to clear up. After 90 minutes, retrial attempts from each demand sources start to come back with higher rate due to the end of first attempts of all demand. It can be seen that the retrial attempts from demand source 1 are much more significant because the magnitude of the offered load of demand source 1 is the largest. Figure 3-11(f) also shows long congestion period of the server and almost instant congestion after the first shock.

Some critical conclusions can be drawn from the results presented. First, recognizing and distinguishing communication sources reveals more clearly the vulnerability of the central office, especially at low seismic intensities, which could result in even more vulnerability of an entire system with a low degree of redundancy. Second, retrial attempts play a crucial role in performance of the central office and should not be neglected in the performance analysis of telecommunication systems. Third, high arrival rate of retrial attempts from blocked calls reduces the delay of the calls and increase the chance of successfully connecting to the server; however, high arrival rate of retrial attempts significantly degrade the performance of the system and affects delays of calls from other demand sources. Fourth, a numerical method is necessary to capture the combined effects of distinct communication demand sources. Finally, communication sources with high magnitude of offered load occupied most of the server capacity and influence overall performance of the central office.

3.4 Summary

Understanding the effects of seismic hazards on the systems is essential. This chapter introduces seismic hazards and the determination of seismic intensity for geographically distributed network components at a local site. Earthquake source, ground motion attenuation, local soil amplification, and spatial correlation of seismic intensities are necessary ingredients for seismic hazard characterization. The two seismic hazard analyses—probabilistic seismic hazard analysis and scenario earthquake based seismic hazard analysis—are also presented. Common seismic-induced damage to various electric power and telecommunication network components are listed, along with the probabilistic assessment of their functionality. The failure fragility functions of the networks components used to demonstrate the application of the methodology developed in this research are also given.

Besides traditional physical damage due to earthquakes, this chapter introduces the concept of traffic theory and proposes the use of renewal process and Weibull distribution to model the abnormally high communication demand on telecommunication systems after earthquake events. Recognition and distinction of the communication sources of communication demands are important. The results from congestion simulation on a network component are presented at the end of the chapter. The comparison between the proposed congestion model and the traditional traffic theory suggests the underestimation of the traditional Poisson process modeling for low seismic hazard level. The contents of this chapter are used again in Chapter 6 as input for the functionality assessment of telecommunication, electric power, and the interdependent systems.

CHAPTER 4

NETWORK MODELS FOR SEISMIC PERFORMANCE EVALUATION

Individual infrastructure systems are designed to provide goods and services to satisfy public demands. Basic performance assessment of these infrastructures addresses the question whether they satisfy the demands. Performance measurement is necessary to answer this question. Although modern infrastructures perform well during normal daily operation, they occasionally fail to fulfill their tasks during catastrophic events. Understanding the causes of failure of these systems is critical to improve their reliability and ensure continuous services. Without proper performance evaluation, this goal cannot be achieved.

Since individual infrastructure systems are created for specific purpose, different performance measures are used for individual systems. For example, electric power systems are designed to distribute electric power from a limited number of generation facilities to customers in wide areas, so the amount of power received by customers or the number of customers remaining in service is frequently referred to as their performance indicator. Unlike power grids, telecommunication infrastructures are designed to provide connections over distance for communication. Instead of the amount of information transmitted through the networks and the timely delivery of the information are the major concerns, especially in the aftermath of disasters.

While the previous chapter provides the performance evaluation of network components, this chapter focuses on system-level performance. Backgrounds and fundamentals of telecommunication and electric power systems are presented, along with the introduction of mathematical models which are suitable for seismic performance evaluation of individual systems and their interdependent performance.

4.1 Telecommunication System

4.1.1 Fundamentals of Telecommunication Network

This study considers three types of telecommunication systems—public switched telephone network (PSTN), mobile telephone network, and data transmission network. The fundamental of the individual systems are discussed as follows.

Public Switched Telephone Network (PSTN)

In 1876, the first practical telephone was invented by Alexander Graham Bell. It was first used to communicate between two fixed points. However, it was of little use without some means of changing connections to other points on an "as-needed" basis. As a result, switching offices, called *central offices*, were established to provide switched connections to telephone subscribers within local areas. The central offices directly connected to end users via telephone lines or *loops*, are called *end offices*. To satisfy demands of longer distance connections, end offices were interconnected.

As networks grew, hierarchical connected networks were preferred to mesh-connected networks for economic reasons. Figure 4-1 and Figure 4-2 illustrate a hierarchical and a mesh-connected network, respectively. As shown, higher-level switching offices are needed to connect end offices in hierarchical networks. These offices do not connect directly to subscribers. Instead, they provide connections among end offices. These connections are referred to as *trunks*. Although, a hierarchical network needs a smaller number of trunks, a mesh-connected network is more reliable due to redundancy. Therefore, a practical PSTN is a combination of the two.

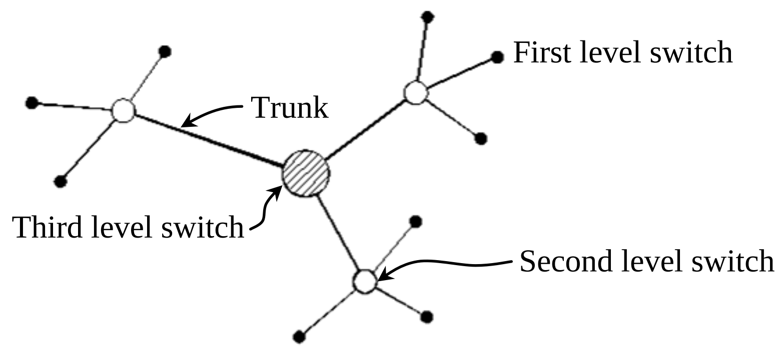


Figure 4-1: Hierarchical Network

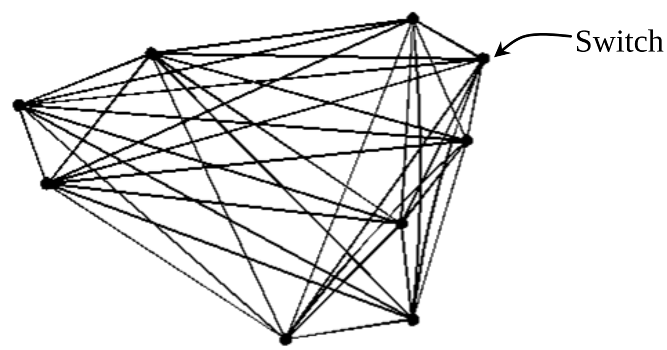


Figure 4-2: Mesh-Connected Network

PSTNs were initially developed as hierarchical networks. When demands of communication between particular switching offices increased, the basic hierarchical network trucks were augmented with *high-usage trunks* as shown in Figure 4-3. High-usage trunks are used for direct connection between particular switching offices with high volumes of traffic. They are likely to connect switching offices of the same hierarchy. In the case that these direct trunks are busy or their capacities are exceeded, overflows will be alternately routed through the backbone hierarchical network.

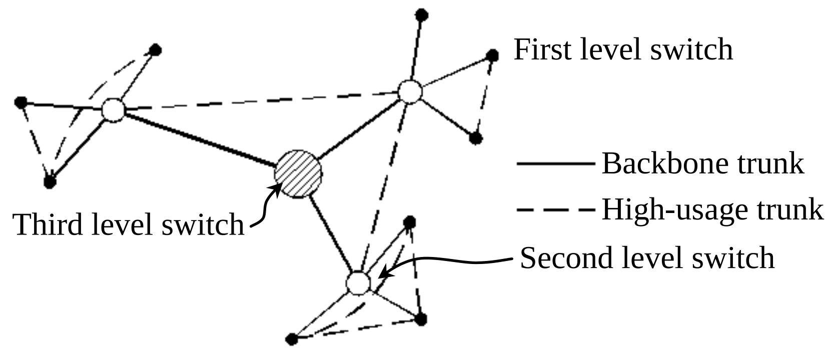


Figure 4-3: Hierarchical Network with High-Usage Trunks

In general, a PSTN can be separated into two main networks, local and toll networks. Local networks provide services in small geographic areas such as cities or counties, referred to as *local access and transport areas* (LATAs), while toll networks connect local networks together and provide long distance services. Each LATA interfaces with a toll network at a single point called a *point of presence* (POP). End offices in a LATA connect to a POP through intermediate offices called *access tandems* or *tandem offices* (AT&T Bell Laboratories 1983, Noll 1998, Bellamy 2000). A sample of this PSTN topology is shown in Figure 4-4. The scope of this research is limited to local networks and therefore toll networks will not be discussed further.

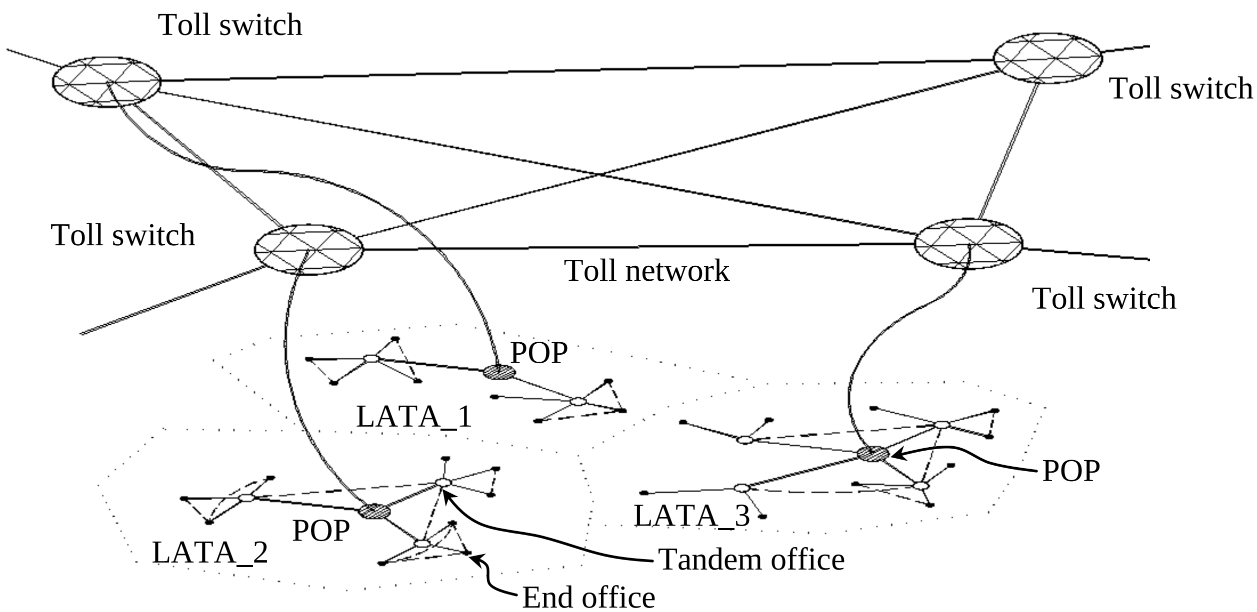


Figure 4-4: Public Switched Telephone Network (PSTN)

Mobile Telephone Network

In 1984, mobile telephone service was introduced in the United States to provide telephone service to portable telephone devices. Due to the increasingly affordable prices of services and devices, the number of subscribers grew rapidly. As a result, mobile telephone networks today are a major part of the PSTN and cannot be ignored.

Two-way radio transmission is used for mobile-to-mobile communication via *cell sites* or *base stations*. Physical landlines are used to allow communication between mobile telephones and traditional telephones supported on the PSTN.

In the early days of mobile telephone systems, a single high-power transmitter was used to provide services to a large geographic area in an attempt to minimize the number of cell sites. However, the capacity of the cell transmitter was limited due to restricted radio channels. To solve this problem, low-power transmitters were employed, to allow for radio frequency reuse in other nearby geographic areas. As a result, a number of cell sites are required each coverage small area. This can become a problem, in metropolitan areas where there is limited space for towers. Consequently, transmitters are mounted to existing structures such as building rooftops, power transmission towers, and elevated water storage tanks. As a result, the seismic performance of these transmitters becomes highly dependent upon the performance of the supporting structure.

One of the basic features of mobile telephone service which permits true mobility for mobile phone users is called *handoff*. This key feature utilizes dynamic tracking of the signal strength from the users so the calls can be continuously handled and transferred between cell sites while the users are moving. This greatly increases complexity and vulnerability of the service since a call involves a number of network components.

In modern mobile telephone systems, base stations are known as *base transceiver stations* (BTSs). A number of BTSs are connected to a base station controller (BSC) and together form a base station subsystem (BSS), as shown in Figure 4-5. A number of BSSs then connect to a tandem office of a PSTN through a *gateway mobile switching center* (GMSC) (Noll 1998). Mobile telephone systems can be considered to operate on top of PSTN facilities but in this study, the mobile telephone system and the PSTN will be considered together as a single voice telecommunication system.

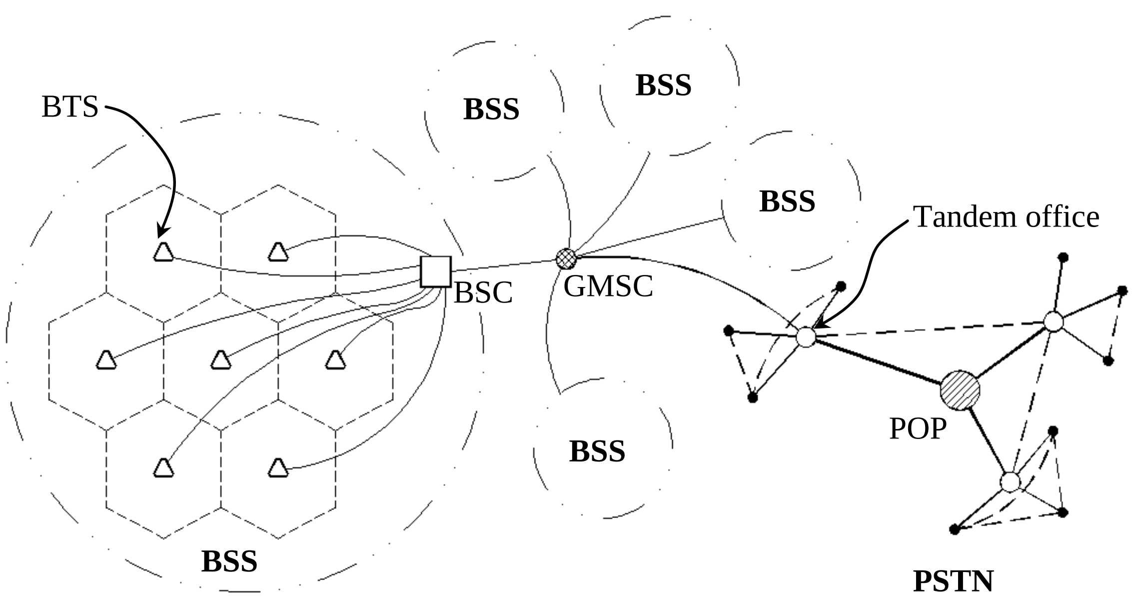


Figure 4-5: Mobile Telephone Network

Data transmission network

To transmit messages through telecommunication networks, three basic switching methods are currently used: *circuit*, *message*, and *packet*. Circuit switching occupies a dedicated connection for transmitting information, even though data is not always transmitted during the established connection. Because of this, circuit switching is not preferred. With message switching, messages are switched and transmitted in their entirety over the network. Packet switching divides the message into short bursts of fixed lengths, called *packets*, and switches and transmits them over a number of different paths before reaching the destination, where they are reassembled into the original message. The messages or packets sent through the network may be stored temporarily for some time along its transmission while waiting for the availability of channels (Noll 1998). A packet switching algorithm is more suitable for routinely data transmission. Therefore packet switching is commonly used by the SCADA system.

In practice, both dedicated and non-dedicated communication channels are used by the SCADA system in electric power system operation (Meliopoulos 2005). There are a number of media used for this purpose, from telephone circuits to microwave and fiber optic links. For simplicity, all data transmission used by the SCADA system in this research is assumed to be carried out over PSTN facilities. Packet-switching equipment is collocated at telephone switching offices (i.e., end offices, tandem offices, and POPs). Normally, data and voice are transmitted over the same trunks, sharing trunk capacity.

4.1.2 Telecommunication Network Model

Network Blocking Probability

Blocking probabilities of individual trunks and switching equipment have been presented in the previous chapter. However, a phone call through a large network generally involves a series of trunks and switches, each of which is selected from feasible alternatives. Therefore, the blocking probability of a phone call is the combined blocking probability of the necessary facilities along its routes between origin and destination. This probability is referred to as *end-to-end blocking probability*.

In general, there are a number of routes that connect a set of origins and destinations in a complex network. However, not all routes are used in practice. Short routes or routes that occupy minimum facilities are preferable, while the longer transmission routes usually result in a noisier traveling signal. To maintain quality of voice communication, lengthy routes are avoided. To reflect this practice, a set of simple routing rules are created to select the most likely routes between a pair of origin and destination and used in this research.

In order to understand the routing rules, two important terms, *path length* and *essential office* need to be introduced. The path length of a route is the number of links or trunks between origin and destination (O-D), while essential offices are offices whose deletion completely disconnects routes between a particular O-D set.

Although sophisticated routing rules are used in real telecommunication systems, this study uses the simplest rules that capture traffic to simulate network operation. Since quality of service highly depends upon the length of the route, the simplified routing rules limit the maximum path length of routes between each pair of essential offices. Figure 4-6 shows a simplified PSTN to illustrate the essential rules. For example, to establish a phone call between two subscribers who connect to end offices a and b, every possible route has to utilize end office a and b, and also tandem offices c and d. Since the deletion of either one of these tandem offices disconnects end offices a and b, the four offices between a and b are essential offices of the connection. For the routing rule that limits maximum path lengths between essential offices to two, there are two routes allowed between essential office a and c. They are $a \rightarrow c$ and $a \rightarrow f \rightarrow c$. Between essential office c and d, only routes $c \rightarrow d$, $c \rightarrow e \rightarrow d$, and $c \rightarrow h \rightarrow d$ are allowed and there is only one route $d \rightarrow b$ available between d and b.

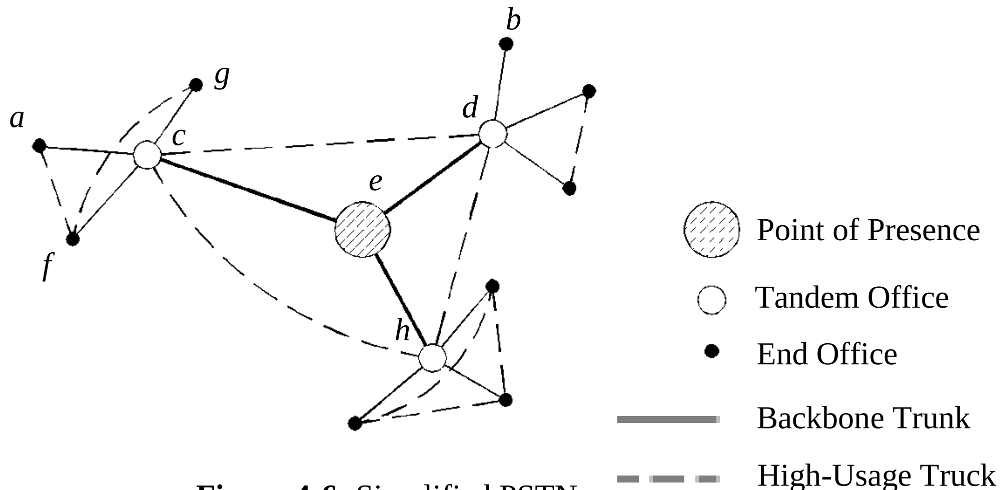


Figure 4-6: Simplified PSTN

The end-to-end blocking probability of each of the routes between each pair of essential offices can then be calculated as the probability of the serial system using,

$$P_{es} = 1 - \prod_{i=1}^{n} \left(1 - P_{b_i}\right) \tag{4-1}$$

where P_{es} is end-to-end blocking probability of a serial system, P_{b_i} is the blocking probability of trunk or switching office i existing along the route, and n is the total number of facilities along the route. The final end-to-end blocking probability between each pair of essential offices can be determined as the probability of a parallel system by,

$$P_{ep} = \prod_{i=1}^{n} P_{e_i} \tag{4-2}$$

where P_{ep} is the end-to-end blocking probability of a parallel system, P_{e_i} is the end-to-end blocking probability of route i, and n is the total number of routes between the essential offices. Finally, the end-to-end blocking probability between the origin and destination are calculated from the series of pairs of essential offices. In this case, end-to-end blocking probability between a and b is calculated by Equation 4-1 from the end-to-end blocking probability between office a and c, c and d, and d and b.

It should be noted that Equation 4-2 is derived from the assumption that the probabilities of parallel routes are statistically independent. This is true in large networks, whose alternate routes carry traffic from different sources. This assumption is reasonable for the size of the studied network. However, in smaller networks, the blocking probability of alternate routes tends to increase when main routes are blocked.

Figure 4-7 and Figure 4-8 show the simplified PSTNs used to investigate the effects of size, topology, redundancy and routing rules on the end-to-end blocking probability calculations. Since the networks represent LATAs, only a single POP is present in each of them. The size of a network is determined by the number of end offices in such networks. Figure 4-7 shows 5-, 10-, and 20-tandem-office PSTNs with 3 end offices attached to each tandem office. Figure 4-8 presents networks with the same sizes as the PSTNs in Figure 4-7 with different topology. Different degrees of dependencies are investigated for each network size. Zero redundancy means networks are hierarchically connected with only backbone trunks while 100% redundancy means networks are fully connected in PSTN fashion, which means only fully connected among tandem offices and among end offices that share the same tandem offices. Since there are a large number of possible networks that have degrees of redundancies between 0% and 100%, only a fraction of possible topologies is randomly selected for illustration.

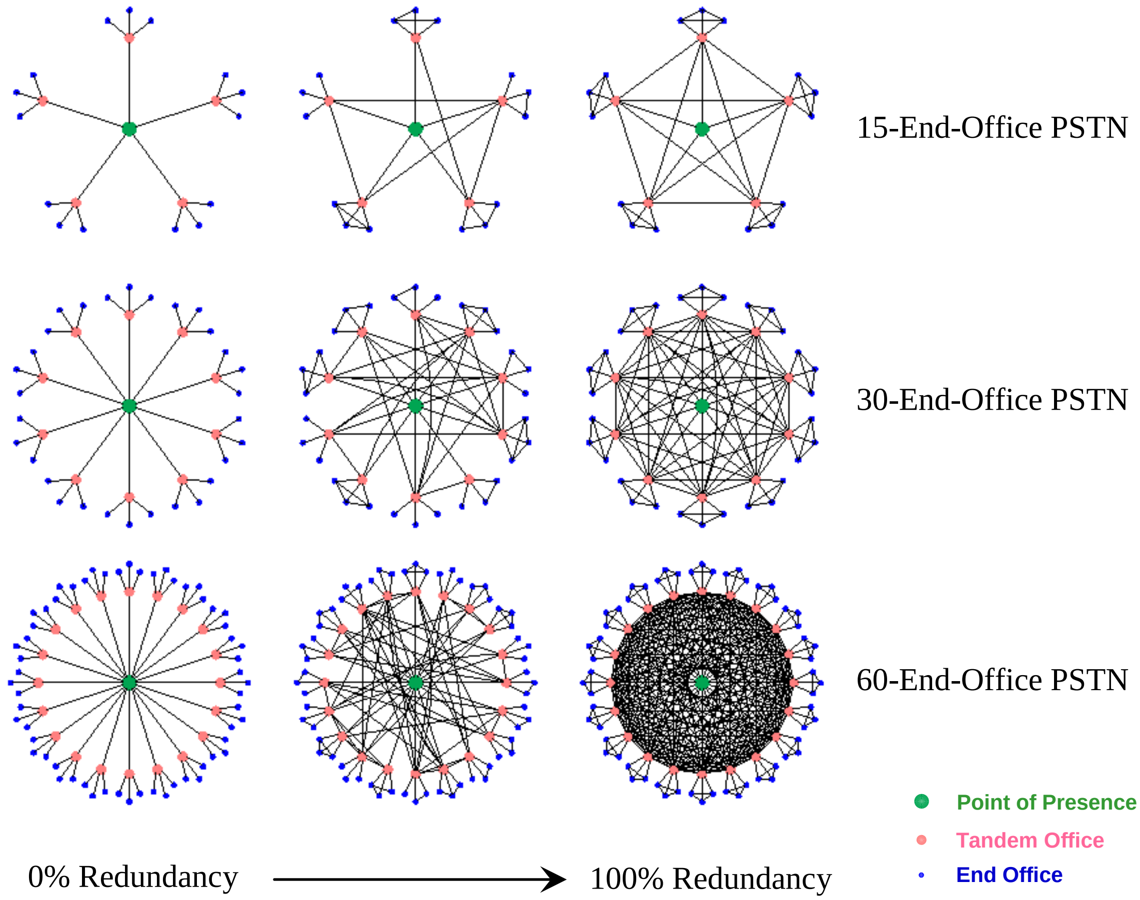


Figure 4-7: Simplified 5-, 10-, and 20-Tandem-Office PSTNs, with 3 End Offices per a Tandem Office

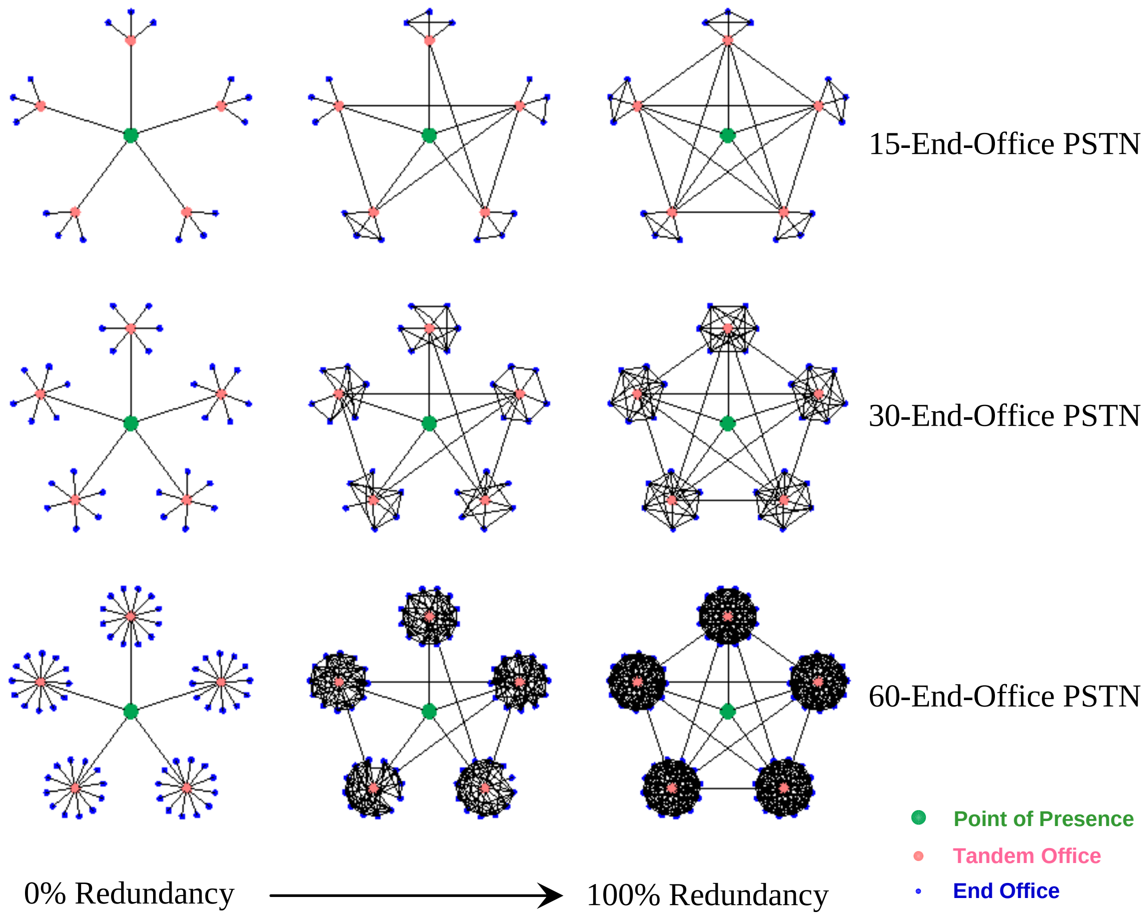


Figure 4-8: Simplified 5-Tandem-Office PSTNs, with 3, 6, and 12 End Offices per a Tandem Office

Figure 4-9 through Figure 4-12 present the network blocking probabilities of the simplified PSTNs shown in Figure 4-7 and Figure 4-8. Each mark represents an average end-to-end blocking probability for every pair of an O-D in a PSTN. The plots show average end-to-end blocking probabilities versus the degree of redundancy of the networks. The network blocking probabilities are calculated using the assumption that all components, both switches and trunks, are designed for a maximum blocking probability of 0.01 during BSBHs. These calculated network probabilities represent the probabilities of the networks operating at design traffic loads.

The computational process for each point plotted in Figure 4-9 through Figure 4-12 starts from generating a network by randomly adding high-usage trunks to the backbone hierarchical network and then determining the redundancy of the network (the ratio of the number of high-usage trunks to the maximum possible number of high-usage trunks of the network). Next, all valid routes based on a given routing rule are determined for each pair of end offices. Then, the end-to-end blocking probability for each pair of origins and destinations is calculated using Equation 4-1 and Equation 4-2. The average end-to-end blocking probability of all possible pairs of end offices is finally determined to represent network blocking probability of the network.

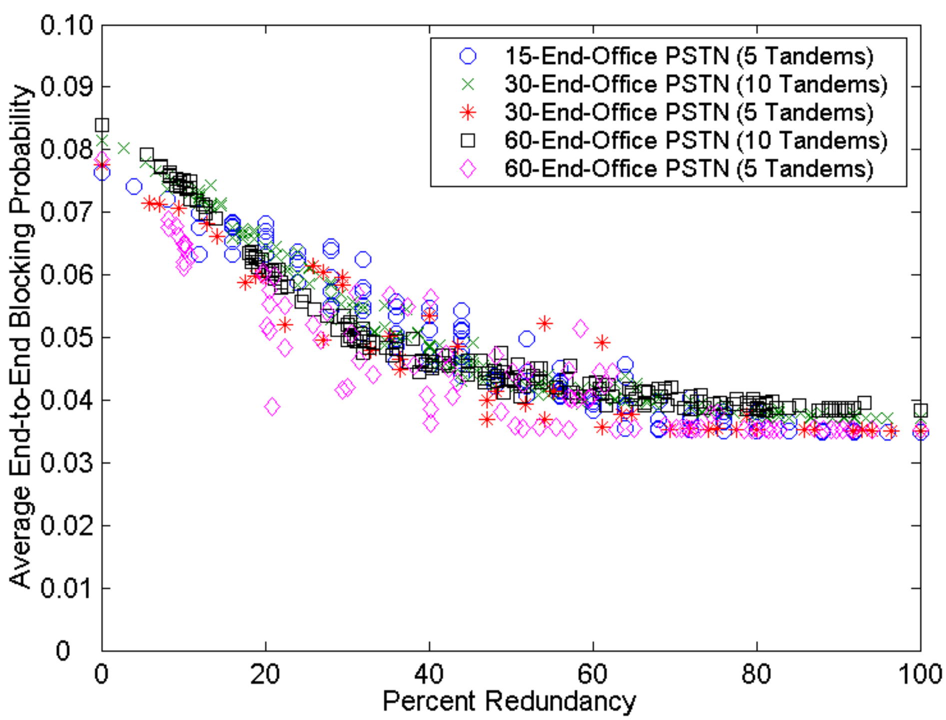


Figure 4-9: Average End-to-End Blocking Probability of PSTNs Utilizing 2-Maximum-Path-Length Routing Rule

Figure 4-9 shows the plot of average end-to-end blocking probability of the simplified PSTNs with the routing rule that limits path length between each pair of essential offices to two. This plot combines the network blocking probability of all PSTNs presented in Figure 4-7 and Figure 4-8. The result shows that the higher redundant networks have the lower network blocking probabilities which are caused by more available routs from additional high-usage trunks. This trend is obvious for PSTNs with low percent redundancy but not for those with high percent redundancy. From the plot, the size and topology of the PSTNs have a modest effect on their network blocking probabilities. The larger PSTNs or the PSTNs with more end offices have lower network blocking probabilities because larger PSTNs have more O-Ds which are directly connected, while the more centralized PSTNs or the PSTNs with more tandem offices have higher network blocking probabilities because paths of call routing are longer in such networks.

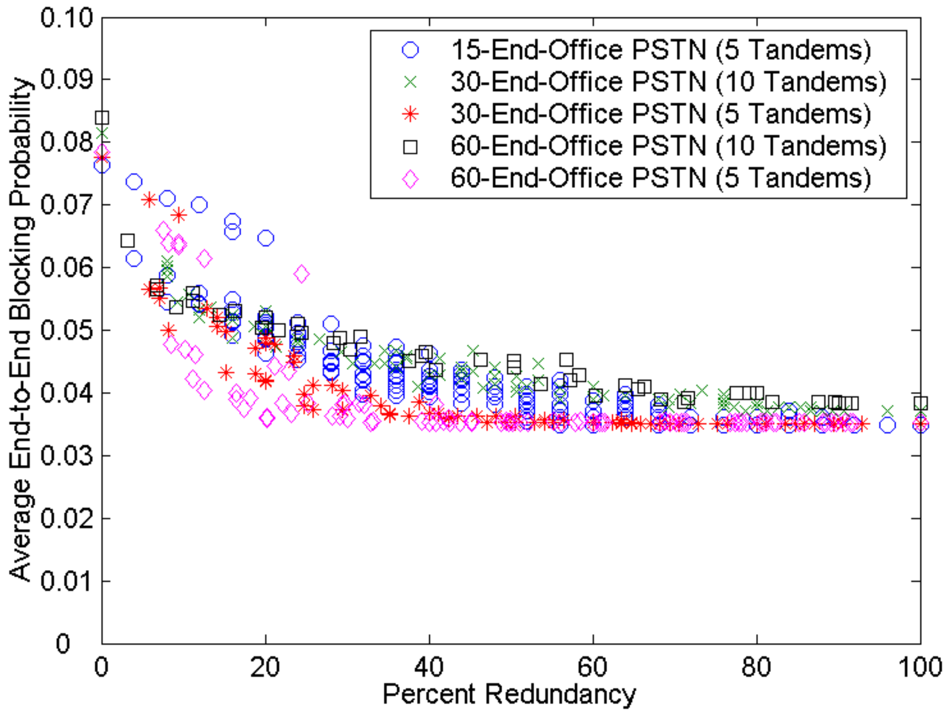


Figure 4-10: Average End-to-End Blocking Probability of PSTNs utilizing 3-Maximum-Path-Length Routing Rule.

Figure 4-10 presents the same plot as Figure 4-9 for the routing rule that allows maximum path length between essential offices of up to three. Figure 4-10 also demonstrates the same trends of network blocking probability as shown on Figure 4-9, however, with lower network blocking probabilities since the routing rule allows more routes for each O-D.

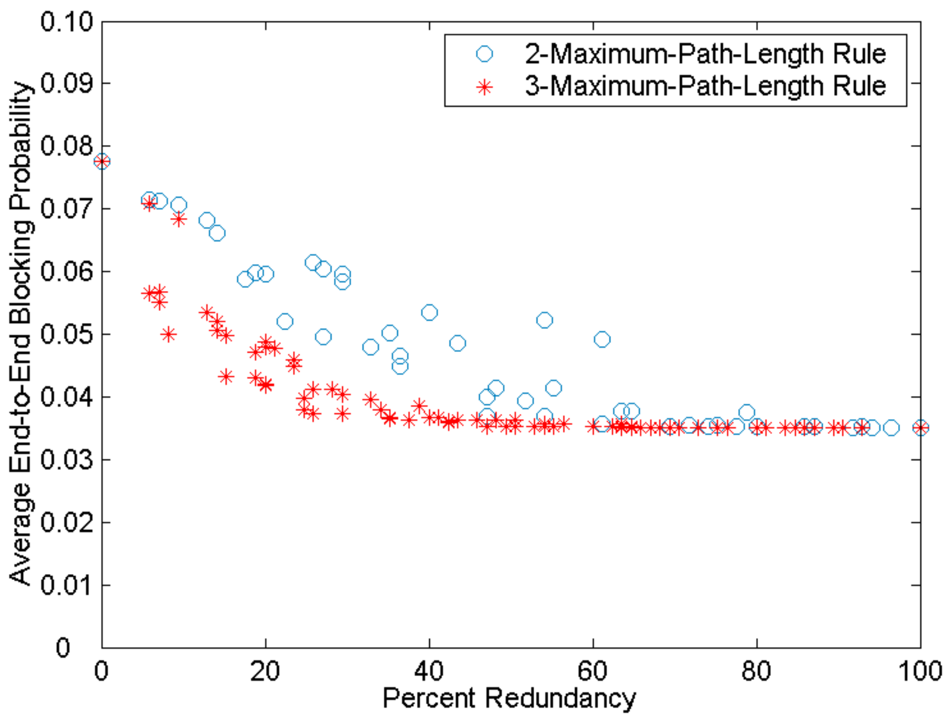


Figure 4-11: Average End-to-End Blocking Probability of 30-End-Office PSTNs with 5 Tandem Offices Utilizing 2- and 3-Maximum-Path-Length Routing Rules

Figure 4-11 and Figure 4-12 present the plots emphasizing the effects of routing rules on network blocking probabilities of 30- and 60-end-office PSTNs, respectively. The plots show that the network blocking probabilities of low redundant PSTNs are more sensitive to routing rules than those of high redundant PSTNs. The plots also suggest that larger networks are less sensitive to routing rules.

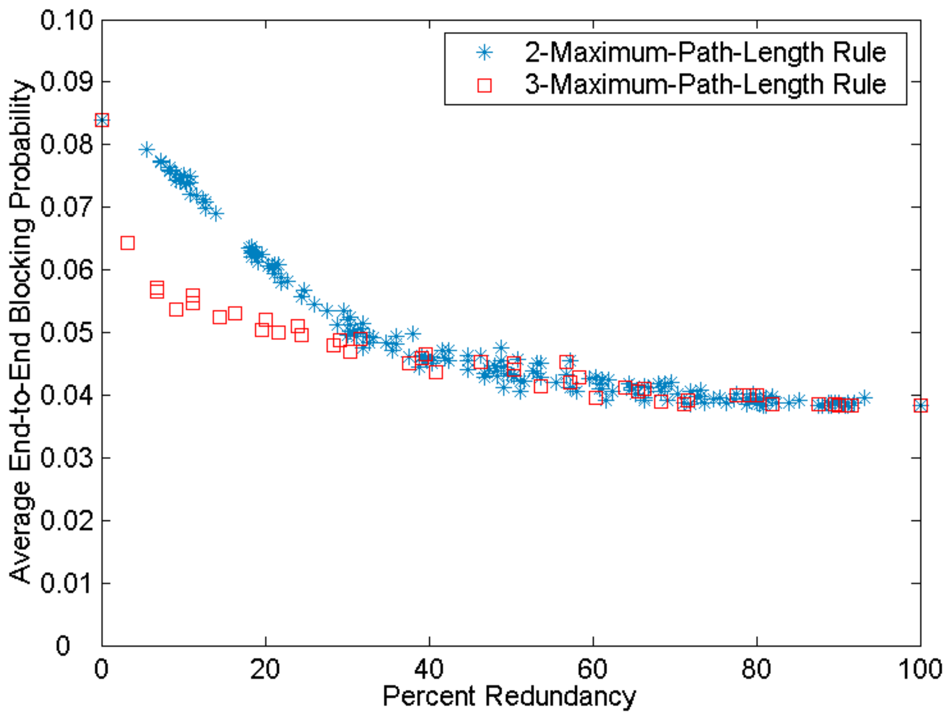


Figure 4-12: Average End-to-End Blocking Probability of 60-End-Office PSTNs with 10 Tandem Offices Utilizing 2- and 3-Maximum-Path-Length Routing Rules

It can be seen that the average end-to-end blocking probability or the network blocking probability, is not so sensitive to size and topology of the networks as to percent redundancy. Highly redundant PSTNs perform better than low redundant networks for any size and topology. The results also indicate some sensitivity of network blocking probability to the selection of routing rules in low redundant PSTNs. This information is useful for minimizing computational efforts in estimating performance indices of PSTNs. For example, either a 2- or 3-maximum-path-length routing rule is used in the analysis of a highly redundant PSTN in metropolitan area. The network blocking probability of the PSTN is expected to be the same. However, the required computing time of the network blocking probability analysis increases exponentially with the number of possible routes in the network. Therefore, it is logical to use 2-maximum-path-length routing rule in the analysis of the PSTNs to minimize computing time and still obtain acceptable estimation of the network blocking probability.

4.1.3 Seismic Performance Assessment of Telecommunication Systems

The seismic performance assessment of telecommunication systems consists of two main ingredients, the functionality assessment of network components and the interconnection among them. While the first ingredient was presented in the previous chapter, the mathematical model representing the second ingredient is discussed earlier in this chapter. For a given level of seismic demand, functionalities and blocking probabilities of telecommunication network components are estimated using network component fragility functions and component blocking probability curves, respectively. The performance of a given telecommunication network is then calculated from its topology and the estimated component functionality and blocking probability using the network blocking probability concept. In this study, network blocking probability is used to quantify performance of a telecommunication network.

Although the network blocking probability can be deterministically obtained for a given level of seismic demand, there is some degree of randomness and uncertainties in the models. In order to capture the inherent randomness and uncertainties, the seismic performance assessment of a telecommunication system is presented in term of fragility functions which is consistent with the general seismic functionality assessment of network components and other building structures. In this study, the sources of uncertainties of the calculated network blocking probability of a deterministic telecommunication network under a given seismic demand are due to the randomness of component functionality, component blocking probability, and the imperfect model of routing strategies. To determine the probability of exceeding a certain level of network blocking probability or a damage state, the Monte Carlo Simulation Method is used. A fragility function of a telecommunication network is obtained by repeating Monte Carlo Simulation for each level of seismic intensity. The comprehensive procedure of the fragility analysis is illustrated in Figure 4-13.

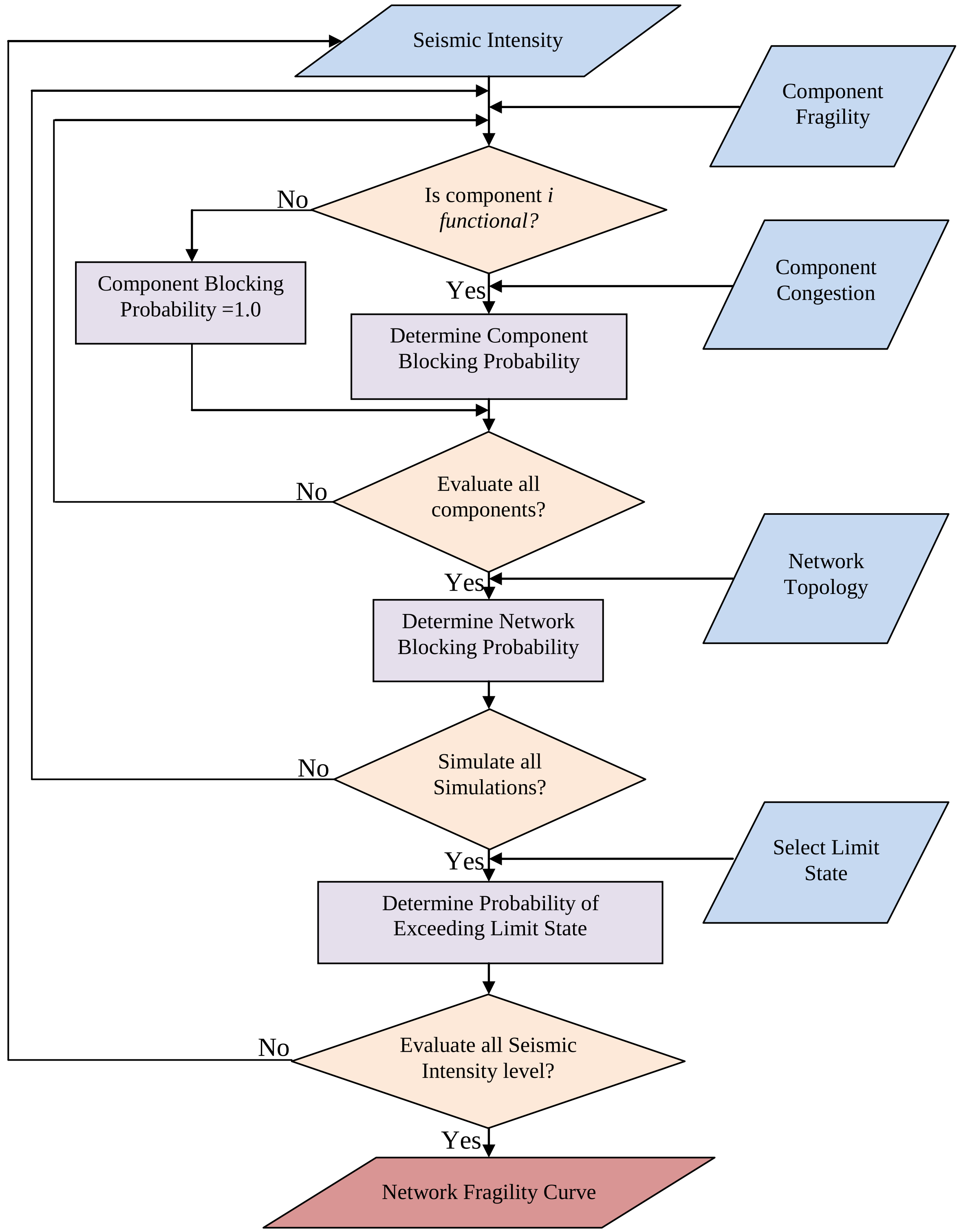


Figure 4-13: Fragility Analysis of Telecommunication Network

The fragility analysis of a telecommunication network consists of three major steps; (1) determine component blocking probabilities, (2) determine network blocking probabilities, and (3) determine the probability of exceeding a limit state. The first requires fragility functions of network components and a component congestion model. The second analyzes network topology and component blocking probability to obtain the overall network blocking probability. The first and the second steps are repeated for a given seismic intensity so that the probability of exceeding a limit state can be calculated in the last step. Figure 4-15 shows an example of output from the first two steps in the form of histograms of network blocking probabilities for each seismic intensity level. The results shown are obtained from the fragility analysis of a simplified 30-end-office telecommunication network with 5 tandem offices and 75% redundancy, shown in Figure 4-14 using the component fragility functions and the component congestion model presented in Chapter 3. By performing the final step on the distributions shown in Figure 4-15, the probability of exceeding each limit state for each seismic intensity level is calculated and the fragility surface is plotted in Figure 4-16.

Although the entire range of network blocking probability limit states can be calculated and shown in a fragility surface, it is more practical to consider only a few significant limit states in comparative studies because it is difficult to distinguish and present the differences between two fragility surfaces. The limit states of telecommunication networks are defined by network blocking probability. The limit states of telecommunication network considered in this study are similar to limit states of other building structures. Four limit states for fragility analysis of telecommunication networks are listed in Table 4-1.

It should be noted that the proposed limit states based on network blocking probability are used to represent the average number of retrial attempts required by a subscriber to complete a phone call. Other performance indexes such as average or maximum delay of a call, or the maximum number of retrial attempts can also be used to define limit states for fragility analyses of telecommunication systems, depending on the purpose of the analyses.

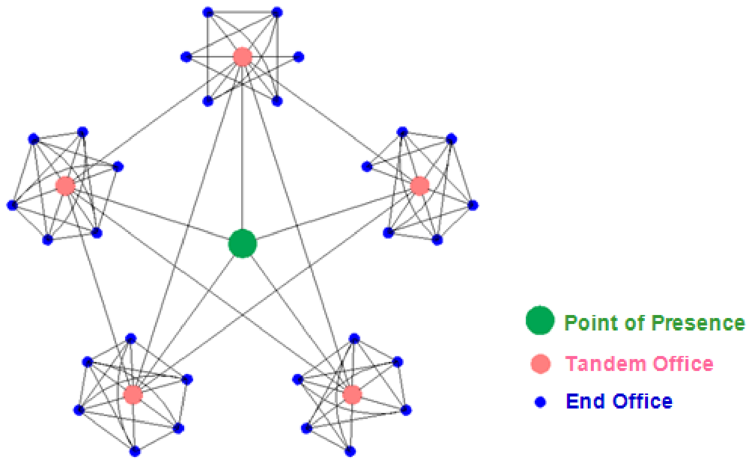


Figure 4-14: A Simplified 30-End-Office Telecommunication Network with 5 Tandem Offices and 75% redundancy

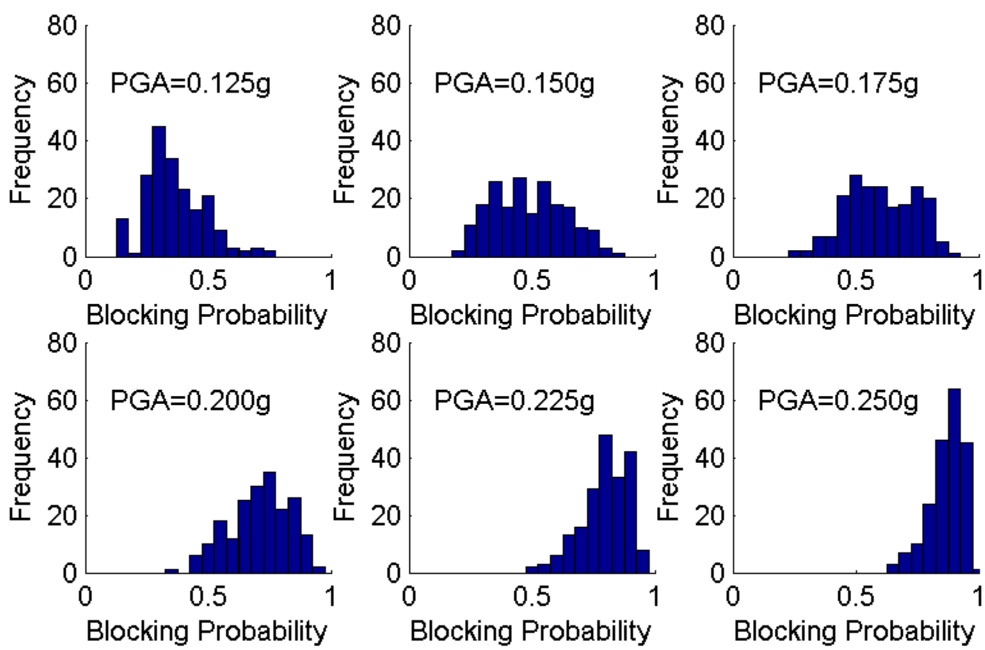


Figure 4-15: Histogram of Network Blocking Probabilities of The Simplified Telecommunication Network in Figure 4-14, Subjected to Uniform Seismic Hazard at PGA = 0.125g, 0.150g, 0.175g, 0.200g, 0.225g, and 0.250g.

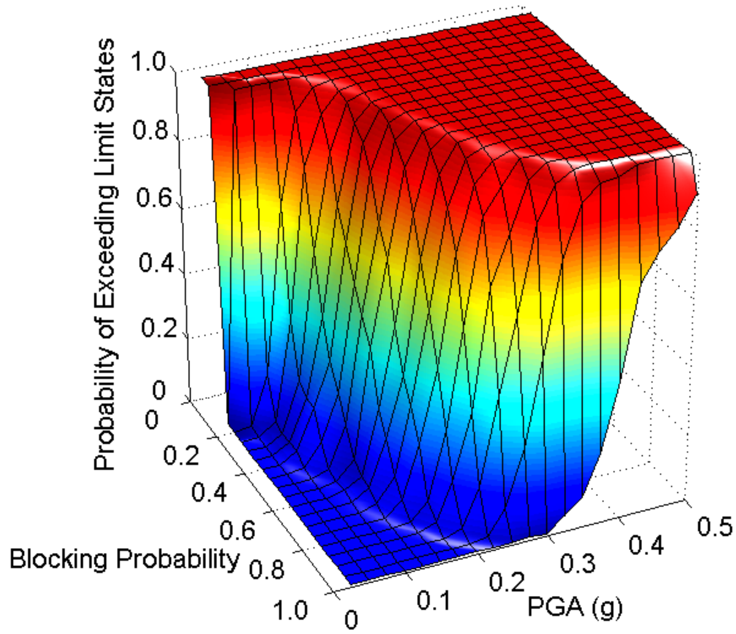


Figure 4-16: Seismic Fragility Surface of The Simplified Telecommunication Network in Figure 4-14, Subjected to Uniform Seismic Hazard.

Table 4-1: Limit States for Fragility Analysis of Telecommunication Networks

Limit State	Network Blocking Probability	Description
Slight Congestion	0.50	Average 2 attempts are required to make a successful connection on a telecommunication network.
Moderate Congestion	0.80	Average 5 attempts are required to make a successful connection on a telecommunication network.
Extensive Congestion	0.90	Average 10 attempts are required to make a successful connection on a telecommunication network.
Complete Block	0.99	Average 100 attempts are required to make a successful connection on a telecommunication network.

Figure 4-17 presents the fragility curves of the simplified telecommunication network for the four limit states. Since the distributions in Figure 4-15 are approximately normal or lognormal distributions, the fragility curves which are composite functions of those distributions are expected to be either normal or log-normal distributions, following the central limit theorem. The results from a K-S test for goodness of fit suggest that both normal and lognormal distributions are acceptable models for the fragility curves at a 5% significance level; however, a lognormal distribution is a little more suitable for the fragility curves. Thus curves are fitted to log-normal cumulative distribution functions (CDF) and each of them are represented by two parameters—median and dispersion. The parameters of the 4 fragility curves are summarized in Table 4-2.

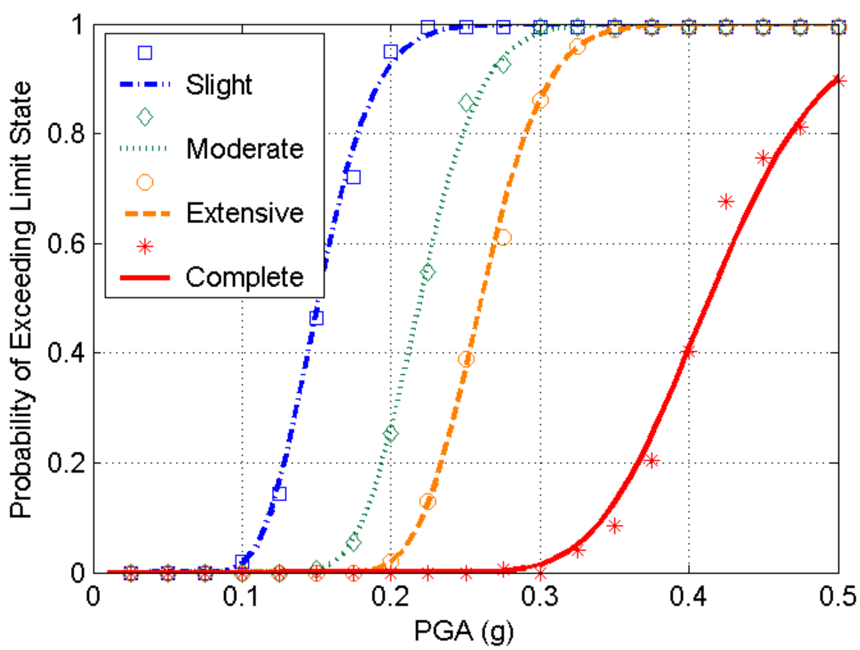


Figure 4-17: Seismic Fragility Curves of The Simplified Telecommunication Network in Figure 4-14, Subjected to Uniform Seismic Hazard.

Table 4-2: Lognormal Seismic Fragility Parameters of The simplified Telecommunication Network in Figure 4-14

Limit State	Median (g)	Dispersion
Slight Congestion	0.15	0.19
Moderate Congestion	0.22	0.15
Extensive Congestion	0.26	0.13
Complete Block	0.41	0.15

4.2 Electric Power System

In electric power engineering, electric power systems or power grids are generally divided into two subsystems—transmission and distribution systems. Transmission systems operate at high voltage in order to efficiently cover large geographical areas, while distribution systems operate at lower voltage and cover local customers or end users. In addition, their topology and configuration are significantly different. Transmission systems are more complex with a mesh-like topology. Distribution systems are simpler tree or looped networks. Due to the disparities, the two subsystems are generally considered separately. Although both transmission and distribution systems are essential to the functionality of power grids, this study focuses only on transmission systems because the disruption to power transmission tends to affect larger numbers of customers, including telecommunication operators, and could lead to cascading failure.

In modern society, continuous service of electric power infrastructure is crucial as electricity becomes a major source of energy for daily activities. An interruption could vastly affect society, economy, finance, and life safety. To prevent such disruptions, reliability assessment of electric power systems is essential. The results from t an assessment are used in planning, design, and operating the system to minimize the possibility of system failure.

The methodology used by electric power engineers for reliability assessment of electric power systems is discussed in the following sections. The discussion also includes the proposed modification and simplification of the methodology for seismic reliability assessment of the systems.

4.2.1 Reliability Assessment of Electric Power Systems

Reliability assessment of electric power systems concerns two issues—*system adequacy* and *system security*. System adequacy refers to the ability of an electric power system to generate and transmit electric power to satisfy demand in steady state, while system security is the ability of the system to maintain system functionality and stability after transient due to disturbance (Billinton and Li 1994). Both issues are equally important when reliability of the electric power system is of interest. However, the scope of this research is limited to the system adequacy. Only basic concepts of system security are briefly addressed in terms of *observability* later in this chapter.

4.2.2 Electric Power System Adequacy

In electric power engineering, reliability assessment is generally associated with four tasks—(1) determining component outage models, (2) selecting system states and calculating their probabilities, (3) evaluating the consequences of selected system states, and (4) calculating the risk indices (Li 2005). With slight modification, these tasks are adopted in this research for seismic performance assessment of electric power systems in an attempt to bridge the gap between electric power engineering and lifeline earthquake engineering.

The proposed tasks for seismic performance assessment of electric power systems are (1) determining component seismic fragility functions, (2) determining probabilistic models of seismic hazards affecting the systems, (3) determining disrupted topologies of the systems affected by seismic hazards, (4) evaluating performance of the disrupted systems, and (5) calculating probabilistic of exceeding limit states and determine fragility function. Table 4-3 presents the mapping between the tasks for electric power engineering reliability assessment and those for seismic performance assessment. The mapping clearly shows that the fundamentals remain the same. The modification only introduces seismic hazards into the procedure and presents results in the forms of seismic fragility function.

It can be seen that the seismic performance assessment of electric power systems and telecommunication systems follow the same outlines. The only major difference is the performance evaluation of the targeted systems. A more detailed discussion about the performance evaluation of electric power system is presented in the following section.

Table 4-3: Mapping between Tasks for Seismic Performance Assessment and Reliability Assessment of Electric Power Systems

Seismic Performance Assessment	Reliability Assessment
(1) Determining Component Seismic Fragility Functions	(1) Determining Component Outage Models.
(2) Determining Probabilities of Seismic Hazard Affecting The Systems	(2) Selecting System States and Calculating Their Probabilities.
(3) Determining Disrupted Topologies of The Systems Affected by Seismic Hazard	
(4) Evaluating Performance of the Disrupted Systems.	(3) Evaluating The Consequences of Selected System States.
(5) Calculating Probability of Exceeding Limit States and Fragility Functions of The Systems	(4) Calculating The Risk Indices.

Adequacy Evaluation of Electric Power Systems

In electrical engineering practice, optimal power flow analysis is generally used for adequacy evaluation of electric power systems. However, such an analysis is not practical in the lifeline earthquake engineering community because a detailed specification of the targeted networks is required, but this information is not publically available. This results in overly simplified methods which evaluate only performance of network components, and generally neglect system topology component and interaction.

In an attempt to better estimate performance of electric power system in seismic performance assessment, Dueñas-Osorio (2005) and Adachi (2007) employ the concepts of graph theory to capture topology of the network and simulate the interaction among network components. Dueñas-Osorio (2005) also proposed the used of basic network optimization analysis in seismic fragility analysis of electric power and water distribution systems. In this section, the optimal power flow analysis from electrical engineering is discussed along with its application on seismic performance assessment of electric power systems.

Optimal Power Flow Analysis

Billinton and Li (1994) define optimal power flow as finding a solution of power system operation and system states, including control variables and state variables, to optimize a given objective and to satisfy power flow equations and security constraints. Depending on the objective of the optimization, optimal power flow can be used for different purposes. The objective of optimal power flow analysis for reliability assessment can be minimizing load curtailment or minimizing cost of remedial action used to collect abnormal operating conditions (Li 2005, Yang et al. 2007). The optimal power flow can be formulated as follows:

$$\text{Min:} \quad f(x,u)$$

$$\text{Subject to:} \quad g(x,u) = 0 \tag{4-3}$$

$$h_{min} \le h(x,u) \le h_{max} \tag{4-4}$$

where $f(x,u)$ is an objective function of state variables, x, and control variables, u, $g(x,u)$ is a function representing summation of power flow at nodes, and $h(x,u)$ is security constraint functions.

Generally, optimal power flow analysis is a nonlinear optimization problem since the power flow equations include of trigonometric terms. As a result, optimal power flow analysis is complex and requires extensive computational effort. Since optimal power flow analysis must repeatedly be performed in a reliability assessment of an electric power system, there have been many attempts to simplify the power flow equations to improve the efficiency of the analysis and maintain the accuracy of the solutions. One of the recent attempts is quadratic power flow model (Kang and Meliopoulos 2002, Meliopoulos 2005, Yang et al. 2006, Tao and Meliopoulos 2011).

Quadratic power flow models utilizes the Kirchhoff's current law to formulate power flow equations in term of Cartesian coordinate state variables, while the traditional power flow models express power flow equations using power conservation in term of polar coordinate state variables. Accordingly, trigonometric terms are absent and the power flow equations become linear or quadratic. In addition, the solutions of the quadratic power flow model converge faster without compromising accuracy (Power Systems Engineering Research Center 2005, Yang et al. 2007).

Although the computational burden of solving optimal power flow problems is reduced by advances in electric power flow modeling, detail specification of targeted power grids and a full understanding of electric power engineering are still required. For this reason, the traditional optimal power flow analysis is not popular among lifeline earthquake engineers. More generalized optimal network flow models that relaxes intensive input requirement and maintain acceptable accuracy of the results are preferred. Figure 4-18 shows the comparison between real power flows in transmission lines of the 24-bus IEEE reliability test system (IEEE Reliability Test System Task Force 1979) obtained from traditional power flow equations and optimal network flow algorithm.

The optimal network flow algorithm used in this analysis is formulated as follows:

$$\text{Min:} \quad \sum(D \cdot p^2)$$

$$\text{Subject to:} \quad k(p, G, L) = 0 \tag{4-5}$$

$$l_{min} \leq l(p, G) \leq l_{max} \tag{4-6}$$

The objective of the optimization is to minimize the summation of the products between transmission line distance, D, and square of the real power flow in the transmission lines, p. $k(p, G, L)$ is functions representing summation of flow at nodes or buses, where G and

L are generated power and electric load, respectively. $l(p, G)$ is security constraint functions of the transmission lines and generation units.

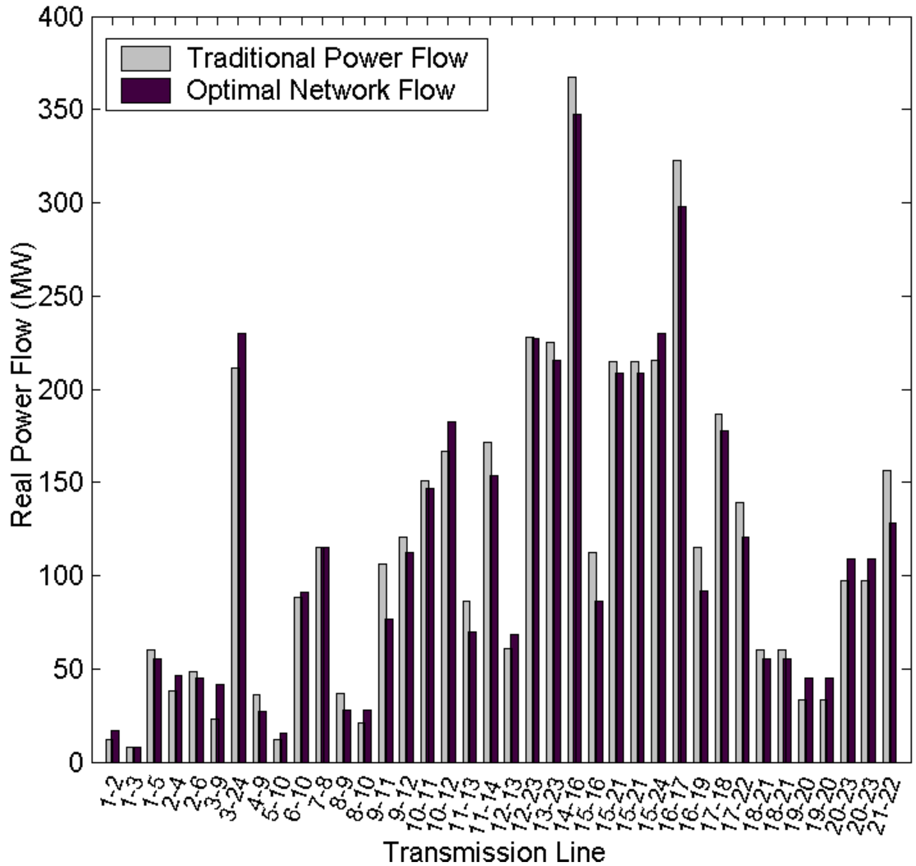


Figure 4-18: Real Power Flows in Transmission Lines of The 24-bus IEEE Reliability Test System (IEEE Reliability Test System Task Force 1979), Obtained by Traditional Power Flow Model and Optimal Network Flow.

The plot shows only some minor variations between the results from the two models. For lifeline earthquake engineering purposes, it therefore is reasonable to use optimal network flow model in lieu of the traditional electric power flow model to assess performance of electric power systems.

In a recent study, Dueñas-Osorio (2005) employs the concept of graph theory to characterize the topology of the network systems to quantify their performance under disruptive conditions. One of the most important proposed performance measurements is the *Service Flow Reduction, (SFR)*. This measurement parameter represents the ability of any generic transmission-distribution network systems (e.g. electric power grids, oil and gas distribution networks, and water distribution networks) to meet the demands of their end-users. The SFR obtained by performing optimal network flow analysis is used to quantify electric power system adequacy in this study.

4.2.3 Electric Power System Security

Electric power system security is highly dependent upon system monitoring and control. In order to maintain the stability of a power system, it is critical that the system is able to adjust itself to cope with disturbances, such as sudden changes in loads or loss of network components. Monitoring is an important function that provides information about the system state and detects such disturbances so that the proper control can be timely executed in an attempt to adjust and maintain system stability. From experience, the security of the power system can only be insured by continuous monitoring and control of the system (Meliopoulos 2005).

A *Control Center* is referred to as a facility which provides monitoring, control, and operation functions to manage an electric power system. Due to the complexity of modern power systems, these functions are all computer assisted. A control center manages a power system by monitoring and collecting state data from remote facilities in order to analysis and estimate the state of the overall system. Once the system state is obtained, appropriate commands are sent back to the remote facilities to control and operate the system according to the current state. The processes of monitoring and analyzing the system state are repeatedly performed in real time to ensure that the controls are up-to-date according to the current system state.

Monitoring and state estimation of a power system are of interest in this research because they rely on telecommunication infrastructure to transmit data from remote facilities to the control center. This demonstrates the interdependence between electric power control and operation and telecommunication systems. The discussion on the interdependencies between the two systems resumes in Chapter 5.

To provide additional background on monitoring and state estimation, Supervisory Control and Data Acquisition (SCADA) system, and State Estimation and Observability are presented in the following sections.

Supervisory Control and Data Acquisition (SCADA) Systems

To maintain stability, power systems should always satisfy two constraints: operating constraints and load constraints. Operating constraints include electric frequency, voltage, and power magnitude limits. Load constraints refer to the ability of generated power to match demands. To ensure that the system always follows these requirements, supervisory control and data acquisition (SCADA) systems are employed.

The SCADA system consists of two subsystems, control and data collection, as the name implies. The supervisory control system, located at the control center, displays the status of devices that are spatially distributed, and allows remote control of equipment such as transformers and circuit breakers at substations, and power generators at generation plants. The data acquisition subsystem provides interfaces between the control center and local facilities. It collects data monitored by and sent from these facilities over communication systems so that the status of the overall system can be analyzed. This analysis is called state estimation. Effective control and operation of electric power systems require accurate and reliable knowledge of the system state in real time. However, in catastrophic events, the communication system that supports SCADA may not fully function, and state estimation degrades. In the following section, state estimation and *Observability*, the ability to observe the state of the power system, are discussed.

State Estimation and Observability

The condition of an electric power system is uniquely defined by a set of variables called a state. The state consists of voltage magnitudes and phase angles at all nodes, referred to as buses in electric power engineering, except one voltage phase angle, which is set to zero as a reference. Therefore, a system with N nodes has $2N-1$ state variables. Knowing the state of the system, other quantities of interest such as real power and reactive power flow can be determined.

In practice, the state of the system is estimated at the control center from measured data sent from local facilities. The measurements are usually real and reactive power flow and voltage magnitudes. In normal operation, there are a number of redundant measurements received by the control center. The use of redundant measures ensures better quality and reliability of state estimation. However, when communication channels are not fully functional, there is a possibility that sufficient measurements will not be delivered to the control center. One important question then is whether or not the state of the system is still observable.

Consider a system with n states and m measurements. The general linear model of the measurement is

$$z = Hx + \eta \tag{4-7}$$

where z is a measurement vector, x is a state vector, H is an $m \times n$ matrix, and η is a measurement noise vector. The sufficient conditions to obtain a unique solution for x are $m \geq n$ and the rank of H is equal to n. Although H is constructed by sophisticated system identification procedures (Meliopoulos 2005) and is required to determine whether the state of the system is observable, it can be shown that the topology of H, which is more easily constructed from the set of measurements and the topology of the system, can be used in an equivalent way. The process by which the rank of H is deduced from its topology is known as *Topological Observability*.

To determine the Observability of a system by Topological Observability, the topology of H is determined using the sets of measurements and states. Then, the connectivity matrix of the state network is constructed as $H^T H$. The system is observable if and only if this network is connected, which means there are no isolated components and the rank of $H^T H$ is equal to the number of state variables.

In this study, Observability is considered as a performance measurement. As it determines whether systems states can be obtained from topology of the power systems and available local measurement, Observability is a performance measurement which implies system security.

In the event of an earthquake, it is very likely that Observability of the entire power system is not possible, and the system may be divided into islands to maintain serviceability in some portions of the system which are still observable and operable. Accordingly, *Partial Observability* of the system provides a better measurement parameter to represent the real performance of the system.

4.3 Summary

Chapter 4 provides the fundamental background of telecommunication systems and the reliability assessment of electric power systems. The discussions also include the mathematical representations which are used by individual systems to evaluate seismic performance of the system at the system level.

This research proposes the application of the network blocking probability to evaluate telecommunication system subjected to seismic hazard. The methodology is tested on synthesized networks which represent simplified telecommunication systems with various sizes and topologies. As expected, the results suggest that telecommunication networks with higher degree of redundancy operate at lower blocking probabilities. The results also indicate that network blocking probabilities of telecommunication networks do not depend on sizes or topologies of the networks.

Moreover, the study of the effects of routing strategies used in the evaluation of telecommunication systems shows that only network blocking probabilities of the systems with low redundancy degree are sensitive to routing strategies. Routing rules that allow more routes between any pairs of origin and destination provide lower network blocking probabilities in low redundancy systems. At the end of the discussion on telecommunication systems, a procedure for creating a system fragility function for the telecommunication system is proposed.

In the second part of this chapter, reliability assessment of electric power systems is presented. Optimal power flow analysis and simplified network flow analysis are performed on the 24-bus IEEE reliability test system (IEEE Reliability Test System Task Force 1979) to quantify adequacy reliability of the system. Although there is some variation between the results from the simplified network flow analysis and the traditional optimal power flow analysis, it is reasonable to use the network flow analysis for the seismic performance analysis when detailed information of the system is unavailable or insufficient to perform the traditional optimal power flow analysis.

Besides application for individual evaluation of the system performance, the approaches presented in this chapter can also be used to evaluate interdependent telecommunication and power systems. The applications of the approaches to interdependent systems will be demonstrated later in Chapter 6.

CHAPTER 5

INTERDEPENDENCIES OF TELECOMMUNICATION AND ELECTRIC POWER SYSTEMS

Electric power transmission and telecommunication infrastructures are rapidly developed in response to the growth of demand in the modern world. Advanced technologies developed by each of the systems are exchanged and adopted by one another in order to improve services. They greatly benefit from each other in many ways. For example, telecommunication systems develop advanced switching equipment which relies increasingly on electric power, while electric power systems adopt telecommunication technology to collect real-time data from remote facilities for use in real-time operation of power grids. Such operation is engineered to provide timely adjustment of the power system configuration required to maintain stability of power grids during a disruption. This results in unavoidable interdependencies between the two systems. Although both systems benefit from the coupling, the interdependencies increase the vulnerability of the systems under disruptive conditions.

Electric power grids and telecommunication systems are related indirectly as well. For example, electric power grids are extensively dependent on monitored data transmitted over telecommunication network between control center and local facilities. Electric power customers rely on telecommunication network to notify problems with service in their area in case of blackout. In this chapter, the two critical interdependencies are discussed – electric power dependency of telecommunication system operations (Physical interdependency) and telecommunication dependency of power system operations (Cyber interdependency).

5.1 Telecommunication System Dependency on Electric Power System Operations

Interdependencies among infrastructure systems has been recognized and categorized by a few studies (Nojima and Kameda 1991, Rinaldi et al. 2001) which were discussed earlier in Chapter 2. The interdependency discussed in this section is classified in Functional disaster propagation (Category A) according to Nojima and Kameda (1991) or in Physical interdependency (Class 1) according to Rinaldi et al. (2001). This is because most equipment used in modern telecommunication infrastructure depends on electricity to operate. Even though there are some types of backup power systems for this equipment (i.e. backup generator and battery), these backup systems are designed only for a few hours of outage of commercial power and they often failed during catastrophic earthquakes.

Physical interdependency is mostly found between transmission-distribution (T-D) infrastructure systems when one system provides the lifeline for the other system, in this case, the electric power system is the provider for the telecommunication system. This type of interdependency is among the few interdependencies which have been studied within the last decades. Since physical interdependencies are straightforward, they are often visualized and formulated as physical links between two components of two different systems, i.e. electric power distribution substations in an electric power system and central offices in a telecommunication system.

There are three important components which are involved in simulating the physical interdependency between any two infrastructure systems in seismic fragility analysis. They are interdependent adjacency, interdependent probabilistic formulation, and coupling strength. Each is individually discussed in the following sections.

5.1.1 Interdependent Adjacency

Interdependent adjacency establishes physical links between network interdependent systems at the component level. These links represent the relationships between components. In the case of electric power and telecommunication systems, a link implies that functionality of a telecommunication central office is dependent upon electric power sent from the corresponding electric power substation. It must be noted that, in this case, the link only indicates a unidirectional relationship since the functionality of the electric power substation does not depend upon the corresponding central office in particular. The inverse relationship of the two systems (telecommunication dependency of power system operations) is discussed later in this chapter.

The interdependent adjacency matrix, IA, of the interdependent electric power and telecommunication systems is an $N_{power} \times N_{telecom}$ matrix, where N_{power} and $N_{telecom}$ are the sizes of electric power system and telecommunication system, respectively. The interdependent adjacency matrix is defined by:

$$IA_{i,j} = \begin{cases} 1 & \text{if } j \text{ central office depends on } i \text{ power substation} \\ 0 & \text{otherwise} \end{cases} \tag{5-1}$$

5.1.2 Probabilistic Formulation of Physical Interdependency

While the previous chapter presents independent fragility functions for network components, this section discusses the interdependent fragility functions for network components. It is logical to formulate physical interdependency from the component level because the relationships between the interdependent systems arise from their components.

When interdependency is the concern, the failure probability of a network component must be determined not only from the failure due to the main cause (seismic hazard in this case), but also from the failure due to interdependent relationships. Therefore, the power dependent failure probability of a telecommunication central office is defined by:

$$P(E_{t,int}) = P(E_{t,EQ} \cup E_{t,power}) \quad (5\text{-}2)$$

where $E_{t,int}$ is the event that the telecommunication central office interdependently fails, and it is the union of the event that the central office fails due to earthquake, $E_{t,EQ}$, and the event that it fails as a result from the failure of power substation, $E_{t,power}$. Since $E_{t,EQ}$ and $E_{t,power}$ are not mutually exclusive, the formula can be written as:

$$P(E_{t,int}) = P(E_{t,EQ}) + P(E_{t,power}) - P(E_{t,EQ} \cap E_{t,power}) \quad (5\text{-}3)$$

From the assumption that the two event, $E_{t,EQ}$ and $E_{t,power}$, are also statistically independent, the joint probability is equal to the product of the two probabilities and the interdependent failure probability is:

$$P(E_{t,int}) = P(E_{t,EQ}) + P(E_{t,power}) - P(E_{t,EQ}) \cdot P(E_{t,power}) \quad (5\text{-}4)$$

In Equation (5-4), $P(E_{t,EQ})$ can be obtained from the independent fragility functions presented in the earlier chapter and the $P(E_{t,power})$ can be derived using the concept of conditional probability. Since $E_{t,power}$ occurs only when the corresponding power substation fails due to an earthquake, $E_{p,EQ}$, the conditional probability is obtained:

$$P(E_{t,power} | E_{p,EQ}) = \frac{P(E_{t,power} \cap E_{p,EQ})}{P(E_{p,EQ})} \quad (5\text{-}5)$$

However, since $E_{p,EQ}$ is the sample space of $E_{t,power}$, the intersection of the two events is equal to $E_{t,power}$ or :

$$P(E_{t,power}) = P(E_{t,power}|E_{p,EQ}) \cdot P(E_{p,EQ}) \tag{5-6}$$

By substituting Equation (5-6) into Equation (5-4), the power dependent failure probability of the telecommunication is finally formulated as:

$$\begin{aligned} P(E_{t,int}) &= P(E_{t,EQ}) + P(E_{t,power}|E_{p,EQ}) \cdot P(E_{p,EQ}) \\ &\quad -P(E_{t,EQ}) \cdot P(E_{t,power}|E_{p,EQ}) \cdot P(E_{p,EQ}) \end{aligned} \tag{5-7}$$

From Equation (5-7), $P(E_{p,EQ})$ is obtained from the system analysis of the independent fragility function of the electric power substation, and $P(E_{t,power}|E_{p,EQ})$ represents *Coupling Strength* of the interdependencies between the two components which is discussed in the following section.

Once the interdependent probability $P(E_{t,int})$ is determined for each component of telecommunication systems, the congestion model is considered for each surviving components (blocking probability of 1 is assigned for failure components), and the process is repeated for the entire range of seismic intensities. The fragility function is then obtained and used in the power dependent fragility analysis of telecommunication systems.

5.1.3 Coupling Strength

Coupling strength, *Sc*, represents magnitude of interdependency between two network components. It is defined as a conditional probability as described in the previous section. In this case, coupling strength is the conditional probability of an event that a telecommunication component fails as a result of failure of the corresponding power substation.

Since coupling strength is a probability, it ranges from 0 to 1, where 0 means that the component are independent and 1 means that the component is fully dependent on the component of the other system. In the study of the interdependent telecommunication and electric power systems, coupling strength can be seen as a reliability index of the backup system of a telecommunication component, where low coupling strength implies that the backup system is reliable while high coupling strength indicates an unreliable backup system.

The coupling strength between a telecommunication central office and an electric power substation may be quantified by analyzing their outage records. From Equation 5-7, a coupling strength is a conditional probability of central office failure given that the corresponding substation fails, so the coupling strength can be estimated as a ratio of the number of outages of the central office due to substation outage to the total number of substation outages in a given time. These numbers may be obtained from typical outage records of the facilities.

Since a coupling strength can be considered as a reliability index of the power backup system used by the central office, another way of determining a coupling strength is to perform seismic performance analysis of the backup system. The probability that central office fails due to the failure of the corresponding electric substation $P(E_{t,power})$ may also be written as:

$$P(E_{t,power}) = P(E_{b,EQ} \cap E_{p,EQ}) \tag{5-8}$$

where $E_{b,EQ}$ is the event that the power backup system fails due to earthquakes and $E_{p,EQ}$ is the event that the corresponding electric power substation fails due to earthquakes (also defined above). Because these two events are statistically independent, Equation 5-8 can be rewritten as:

$$P(E_{t,power}) = P(E_{b,EQ}) \cdot P(E_{p,EQ}) \tag{5-9}$$

By substituting Equation 5-9 into Equation 5-6, the coupling strength $P(E_{t,power}|E_{p,EQ})$ is equal to $P(E_{b,EQ})$. Therefore, coupling strength can also be quantified by determining seismic performance of power backup systems used in central offices.

Quantifying coupling strength between network components is one of the most important tasks in the study of infrastructure interdependencies. However, this task is beyond the scope of this study. Only sensitivity analysis of seismic performance of the interdependent systems is performed. The results of the analysis are presented in the next chapter.

5.2 Electric Power System Dependency on Telecommunication Systems Operations

This research proposes a framework for studying the interdependency between the electric power and telecommunication infrastructure systems under seismic conditions. The primary interdependency is due to cyber dependency, and it is developed through electric power system control and operations which extensively utilize SCADA systems for monitoring and managing geographically distributed facilities. As one of the most vital elements of SCADA systems, failure of the telecommunication infrastructure impacts reliability and stability of electric power grids.

Cyber interdependency is considered as one of the most critical threats to modern infrastructure systems as a result of the rapid development of information technology and the telecommunication infrastructure. Despite the fact that reliability of telecommunication infrastructures in normal operation has greatly improved in recent years, the systems are seldom designed to withstand extreme conditions such as natural disasters (i.e. earthquakes, hurricanes, and tornados) or terrorist attacks. Disruptions to telecommunication systems in such events affect the performance of other infrastructure systems while they are most needed for recovery from the catastrophic events.

The following sections present the treatment of the cyber interdependency between electric power and telecommunication systems subjected to seismic hazard. The proposed framework is developed based on high-level assumptions and the basic concepts of observability.

5.2.1 Cyber Interdependency Analysis

Unlike physical interdependency, the effects of cyber interdependency on the target infrastructure systems are not straightforward. Although interdependent adjacency can sometimes be established at component levels, the impacts of the interdependency are seldom localized. However, the same two-step approach used in developing the model for physical interdependency is also valid for cyber interdependency. First the relationship must be defined and then the consequences are determined.

In the case of telecommunication and electric power systems, one of the relationships between them is through the use of the SCADA systems in electric power controls and operations. Monitored measurements at local facilities are transmitted over the telecommunication infrastructure to the control center or, in other words, between two central offices in the telecommunication systems. Therefore, the relationship between the two systems can be simply defined at the component level between local electric power substations and the control center, and telecommunication end offices.

Telecommunication infrastructures provide connections between remote facilities and the control center of power grids. Failure of telecommunication systems implies loss of connections between them. Since the local measurements are essential to the estimation of the power system states in order to maintain system stability, the quality of the state estimation and stability of the power grid can be compromised if measurements are not delivered on timely basis. Unlike the case of physical interdependency, failure of a telecommunication end office serving a power substation does not directly affect the functionality of the particular substation; instead, it influences the stability of the entire electric power system. In order to capture the impacts of lose of measurements in electric power state estimation, the concepts of topology observability and partial observability are employed.

5.2.2 Observability

The objective of the observability analysis is to determine whether state estimation analysis of the target electric power system can be performed from the set of available measurements. Justification is made by the calculation of the rank of the H matrix from the set of the linear power flow model (Equation 4-7). The system is observable only if the rank of H is equal to the number of state variables ($2N - 1$ state variables for N-bus power systems).

There are a number of studies utilizing the concept of graph theory to formulate observability analysis. By constructing two graphs, one for physical topology and the other for measurement topology of a electric power system, observability of the system can be evaluated by determining a minimum spanning tree (Mori and Tsuzuki 1991). The existence of the minimum spanning tree in the two graphs is equivalent to the necessary condition required for an observable system (Krumpholz et al. 1980, Monticelli and Wu 1985a, Jain et al. 2005).

The topological analysis using graph theory concepts also allows the determination of observable subnetworks. This graph theory based algorithm is very useful for this research because observability of the entire electric power system is highly unlikely under seismic conditions. It is logical to determine the largest portion of the system in order to minimize the loss when the stability of the entire system is not possible.

This study adopts the concept of partial observability as an indicator to illustrate another aspect of the interdependency between telecommunication and electric power systems besides physical interdependency. It should be noted that observability does not imply operability or stability of electric power systems but it is essential in system operation. However, it is a good performance measurement indicating whether the attempt to maintain stability of the system is still possible during disastrous events.

5.3 Summary

Telecommunication and electric power systems are infrastructure systems which are highly interdependent. The two aspects of the interdependencies between the two systems are power dependency of telecommunication (physical interdependency) and telecommunication dependency of electric power system operations (cyber interdependency). The physical interdependency is directly established from three important components: (1) interdependent adjacency – the representation of the physical links between components of the two systems, (2) probabilistic formula – the probabilistic relationship defining effects of the interdependency at the component level, and (3) coupling strength – the conditional probability which quantifies intensity of the interdependency. The cyber interdependency between electric power grid and telecommunication system arises through the SCADA systems used in electric power system operations. SCADA depends on telecommunication system to provide the necessary communication between remote facilities and the electric power control center. Unavailable communication channels during disasters can compromise the ability of an electric power system to maintain its stability. This research adopts the concepts of state estimation and observability to illustrate cyber interdependency of electric power systems. Observability is proposed to be used as a performance index in this work. The proposed model defines a relationship between electric power substations and control center, and telecommunication end offices. The following chapter presents and discusses the applications of the proposed models on the test base systems in Shelby County, TN.

CHAPTER 6

NETWORK RESPONSE TO SEISMIC DISRUPTION AND MITIGATION STRATEGIES

Shelby County, TN is located approximately 60 miles to the south of the New Madrid Seismic Zone (NMSZ). It has been selected by the Mid America Earthquake Center (MAEC) as a study region for integrated seismic loss assessment and consequence-based earthquake risk management because of its population density, buildings and infrastructure inventory, and location (MAEC 2006). Several studies on the interdependencies of the electric power and water systems (Dueñas-Osorio 2005, Leelardcharoen 2005, Dueñas-Osorio et al. 2006, Adachi 2007, Duenas-Osorio et al. 2007a, Duenas-Osorio et al. 2007b, Kim et al. 2007, Adachi and Ellingwood 2008, 2009b) have been done using this testbed.

In this chapter, a new study on the interdependencies between the electric power and telecommunication systems in the region is presented in order to demonstrate the application of the proposed methodology. The chapter briefly introduces the electric power and telecommunication system in the Shelby County testbed. Next, the responses of the two interdependencies – the electric power dependency of the telecommunication system and the telecommunication dependency on the electric power system operations – are presented along with sensitivities of the interdependent responses. The chapter concludes with studies of seismic mitigation strategies for the coupled infrastructures.

6.1 Shelby County Testbed

6.1.1 Electric Power System

Figure 6-1 shows the simplified electric power transmission system in Shelby County, TN (Shinozuka et al. 1998, Dueñas-Osorio 2005, Leelardcharoen 2005, Adachi 2007) used in this chapter. The system comprises 45 nodes (buses), including 3 gate stations (generation nodes), 5 medium voltage substations (intermediate nodes), and 37 distribution circuits (end nodes). The nodes are interconnected by 139 transmission lines. The fragility functions of the network components are defined in Table 4-1.

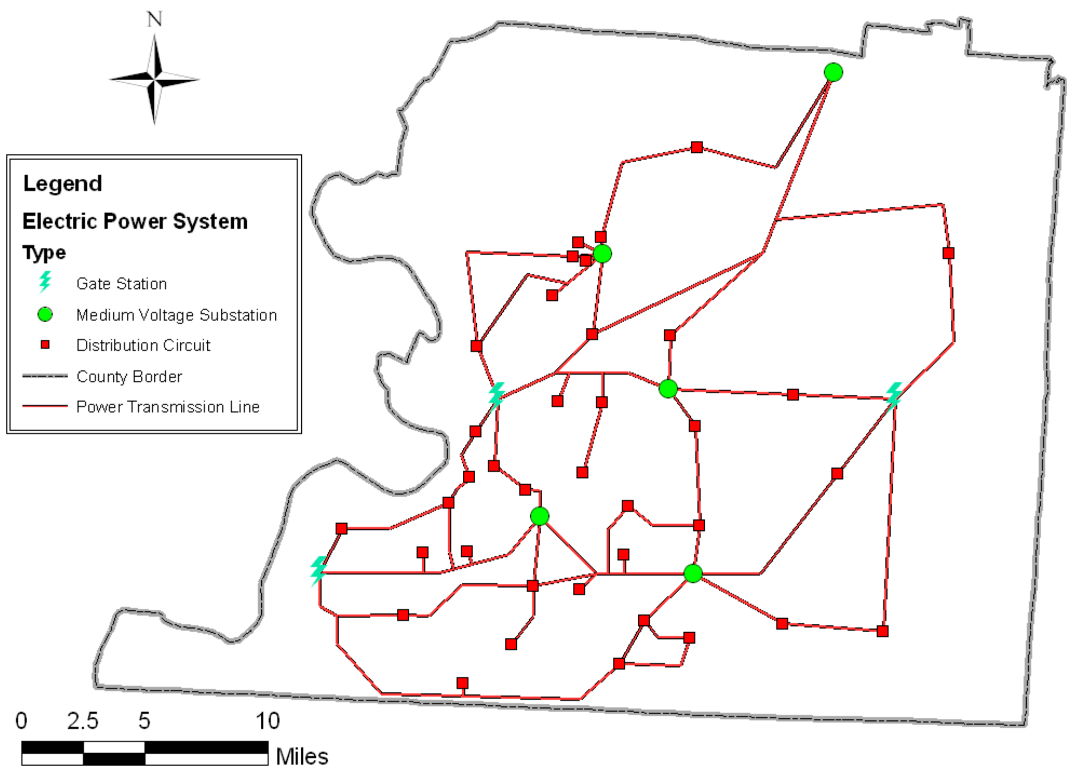


Figure 6-1: Electric Power System in Shelby County, TN

6.1.2 Telecommunication System

The backbone heirarchical telecommunication network in Shelby County, TN is shown in Figure 6-2 (high-usage trunks are not shown for clarity). This network is synthesized from the locations of central offices in the county available in an online central office lookup tool (Marigold Technologies 2007). The system represents a local access and transport area (LATA) with a point of presence (POP), 4 tandem offices, and 34 end offices (39 central offices in total). The system has 168 trunks (38 backbone trunks and 130 high-usage trunks) and 77.4% redundancy. The log-normal fragility functions for the telecommunication system components are listed in Table 3-2.

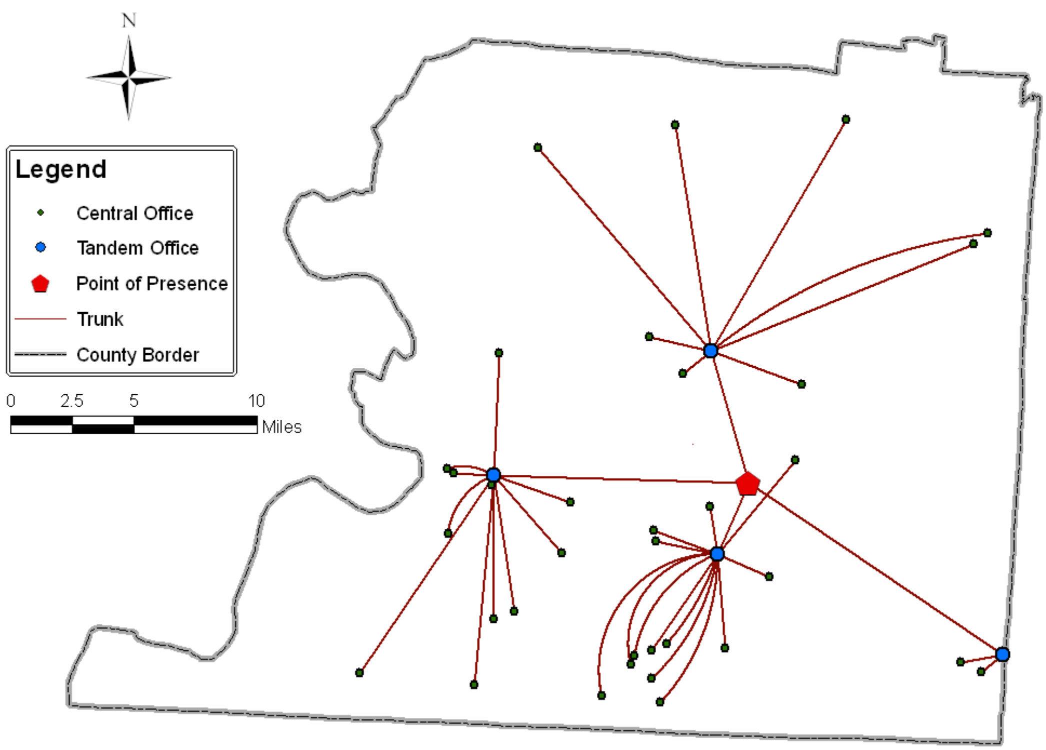


Figure 6-2: Backbone Hierarchical Telecommunication Systems in Shelby County, TN

6.2 Electric Power Dependent Responses of Telecommunication System

This section presents the physical interdependent responses of the electric power and the telecommunication systems in the Shelby County testbed. In this case, the functionality of the telecommunication network components is dependent on electric power sent from local electric power substations at deterministic coupling strengths and locations. The interdependent adjacency and the coupling strengths are defined in the following subsection before the presentation of the interdependent response of the system.

6.2.1 Interdependent Adjacency and Coupling Strength of Electric Power and Telecommunication System in Shelby County, TN

The relationship between telecommunication central offices and electric power substations is established from the fact that central offices run on electric power. In practice, a power substation provides electricity within a well-defined local area or a service area. Therefore, it is logical to assume physical interdependencies between an electric power substation and a central office located in its service area (Figure 6-3).

A coupling strength between interdependent network components is unique for each pair of interdependent adjacent components. It is likely that the more critical facilities are equipped with more reliable backup power systems. For example, a coupling strength for a POP is less than one for a tandem office while the coupling strength for a tandem office is less than one for an end office. This study uses the assumption that the coupling strength for a POP to an electric power substation is 0.25 less than the one for a tandem office and the one for tandem office is 0.25 less than the one for an end office. It should always be noted that coupling strengths are probabilities and must be greater than 0 but less than 1.

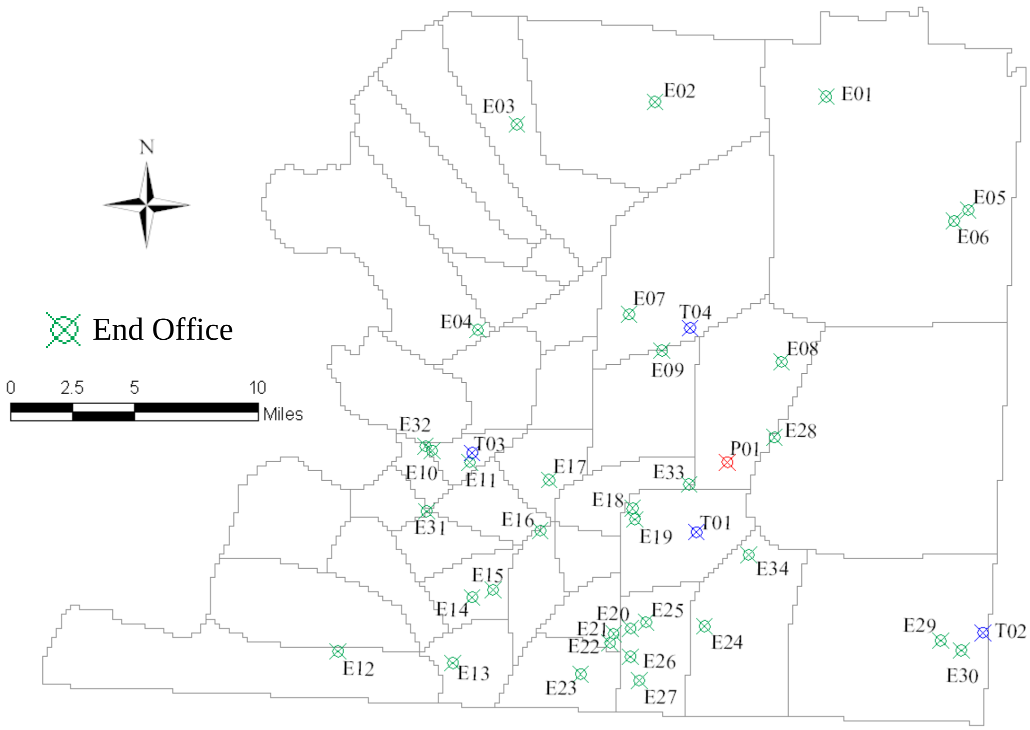


Figure 6-3: Shelby County Telecommunication Central Offices in Electric Power Service Areas

6.2.2 Electric Power Dependent Fragility of Telecommunication System

In this section, electric power dependent responses of the telecommunication system in Shelby County, TN subjected to a uniform seismic hazard are presented. The probabilistic responses of the system are illustrated in terms of log-normal fragility functions obtained from numerical simulations. The results include fragility curves for the interdependent systems with various assumed coupling strengths between network components and various redundancy levels within telecommunication systems.

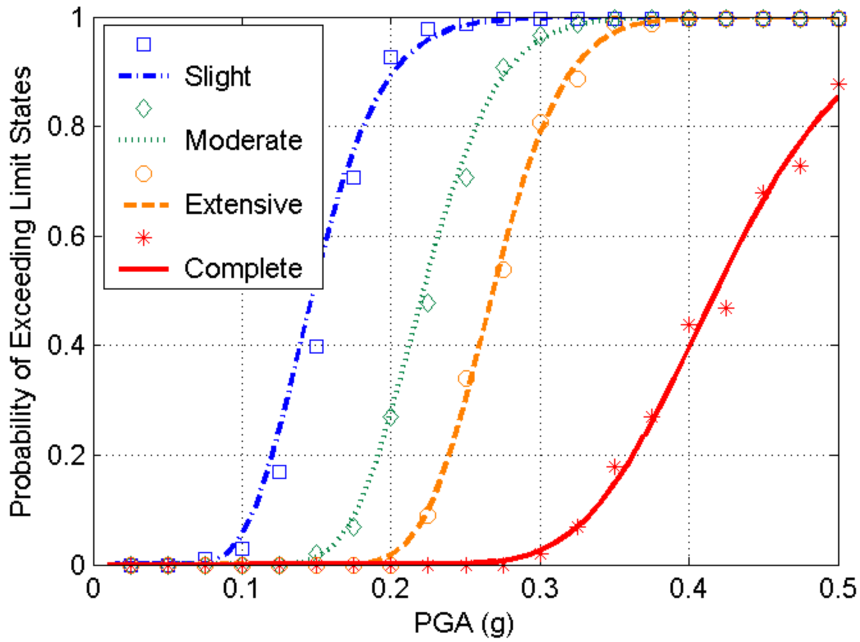


Figure 6-4: Independent Fragility Curves of Shelby County Telecommunication System for Four Limit States

Figure 6-4 shows the fragility curves of the independent system (Coupling Strength = 0.0). The four curves represent the four limit states defined earlier in Chapter 4 (Table 4-1). In this example, 300 simulations are performed at each PGA in order to obtain the probability of exceeding the limit states. The plot data are fitted to log-normal distributions with acceptable fitness confirmed by the Kolmogorov-Smirnov (K-S) test for goodness of fit (Ang and Tang 2007).

The fragility curves indicate that, at 0.25g PGA, there is a 35% probability that the telecommunication system blocking probability will exceed 90% (extensive limit state), and a 90 % probability that the system blocking probability will exceed 80% (moderate limit state). The plot also indicates that there is a 40% probability that the system will be completely blocked at over 0.4g PGA.

It should be noted that the telecommunication fragility medians used this study range from 0.26g to 0.40g and the dispersions range from 0.50 to 0.60 (Table 3-2). While the system fragilities have similar ranges of medians, the fragility dispersions of the system are significantly less (0.17 to 0.24). The drop of the dispersion is due to the interconnection among network components (the combination of parallel and serial systems). This result is consistent with the previous studies of infrastructure system fragility (Dueñas-Osorio 2005, Dueñas-Osorio et al. 2006, Kim et al. 2007, Leelardcharoen et al. 2011)

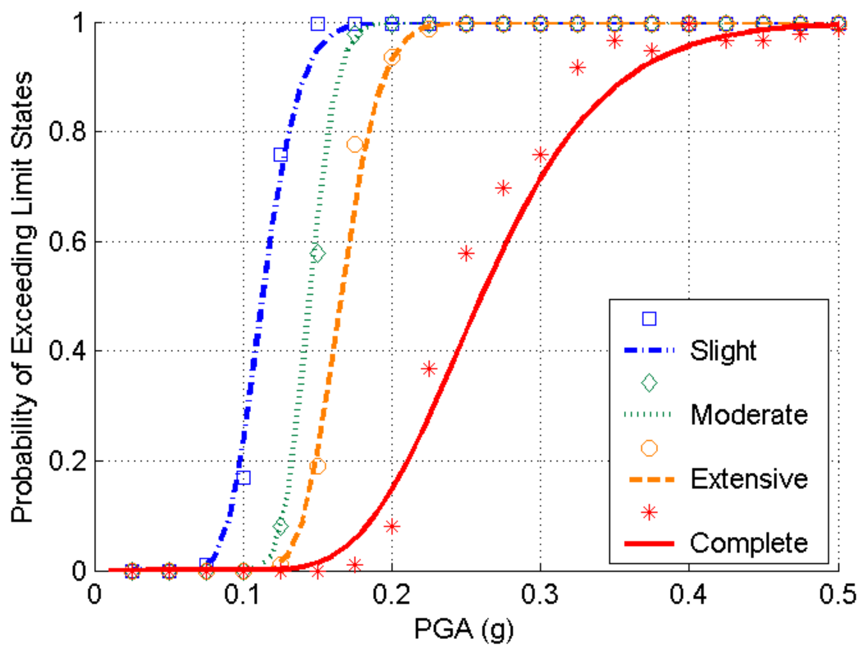


Figure 6-5: Interdependent Fragility Curves of Shelby County Telecommunication System with Coupling Strength = 0.25 for POP, 0.50 for Tandem Offices and 0.75 for End Offices

Figure 6-5 and Figure 6-6 present plots of the interdependent fragility curves of the electric power dependent telecommunication systems with medium coupling strength (0.25 for POP, 0.50 for tandem offices, and 0.75 for end offices) and extremely high coupling strength (1.0 for all central offices), respectively. It can be seen that interdependent systems are more vulnerable to a seismic hazard than the independent systems (Figure 6-4) because the curves shift to the left. At the 0.25g PGA, the probability of exceeding the extensive congestion limit state (90% blocking probability) becomes 100% (for both Figure 6-5 and Figure 6-6) instead of 35% observed earlier in the independent system with the same configuration (Figure 6-4). The plots also show that the interdependent telecommunication system reaches severe limit states at lower seismic intensities. For example, compared to the independent system, the interdependent system (with medium and high coupling strength) reach the 40% probability of exceeding limit state of complete block (99% blocking probability) at 0.25g and 0.19g instead of 0.4g. These results support the statement that the interdependencies cannot be ignored in seismic assessment analysis of infrastructure systems.

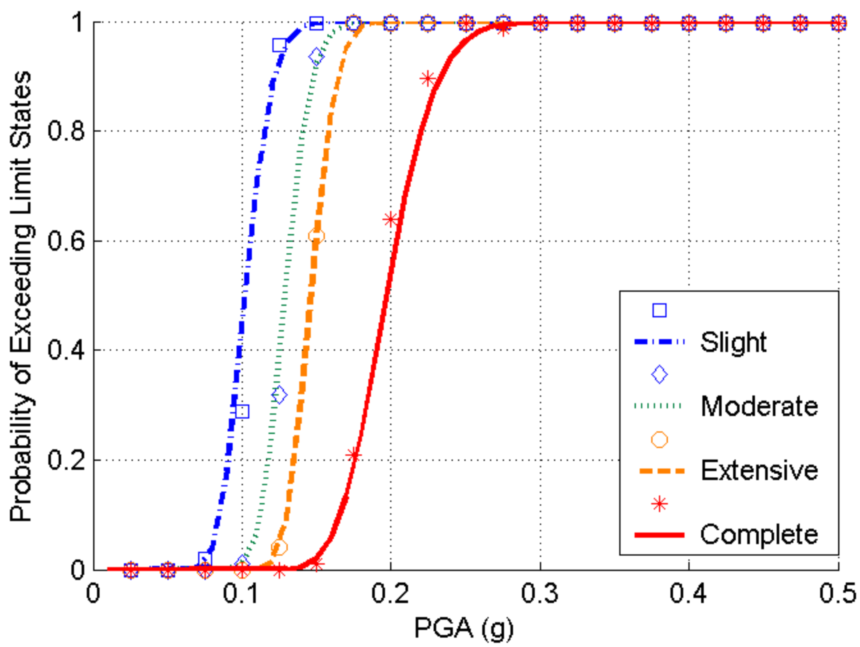


Figure 6-6: Interdependent Fragility Curves of Shelby County Telecommunication System with Coupling Strength = 1.0 for All Central Offices.

To enhance the understanding of the influence of the interdependencies on seismic responses of the two systems, the sensitivity of the seismic fragility parameters are presented in Figure 6-7 and Figure 6-8.

From Figure 6-7, the relationship between the fragility medians and the coupling strengths is almost linear. As expected, the medians decreases as the coupling strengths increase. The plot suggests that the medians of the complete blocking limit state are more sensitive to the coupling strength of end offices because its graph has a steeper slope.

This is because the fragility of the power substations dominates the fragility function of the telecommunication central offices. Instead of operating at higher blocking probability, the central offices become completely out of order and influence the overall system performance.

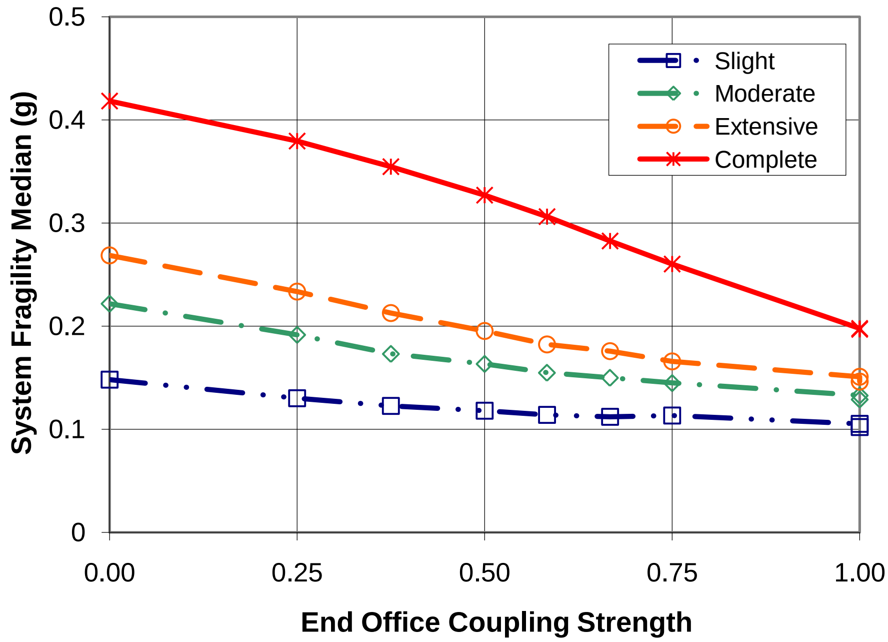


Figure 6-7: Sensitivity of Interdependent Fragility Median of Shelby County Telecommunication System to Coupling Strength

The sensitivity of the fragility dispersion is plotted in Figure 6-8. Higher coupling strength results in lower dispersion of the slight and moderate congestion limit states; however, the dispersions of the more severe congestion limit states have different trends. There are peaks observed between coupling strengths of 0.50 and 0.75. This is caused by the increased number of possible states of the system as the coupling strength introduces fragility of electric power substations to the interdependent system.

Earlier in Chapter 4, the effects of the redundancy of telecommunication system to the system blocking probability are investigated for a simplified telecommunication system as a potential mitigation strategy. The results (Figure 4-9, Figure 4-10, and Figure

4-11) suggest that an increase in the system redundancy only affects the systems that originally have less than 50% redundancy. Since the testbed telecommunication system has a 77% redundancy from the beginning, adding more links to increase system redundancy does not improve the performance system since Figure 6-9 shows no increase of the fragility medians. Figure 6-10 also confirms the increase in dispersion when there are more possible states of the system available resulting from the additional trunks or connections to increase redundancy.

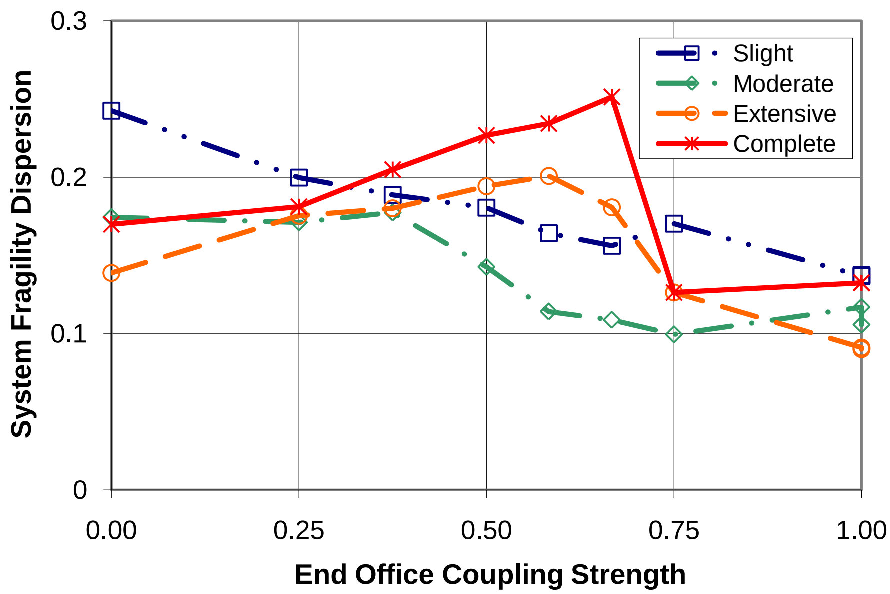


Figure 6-8: Sensitivity of Interdependent Fragility Dispersion of Shelby County Telecommunication System to Coupling Strength

Besides the overall system performance, the local response should also be considered. Figure 6-11, shows the average End-to-End blocking probability at each end office. The blocking probability is averaged from End-to-End blocking probability between that end office and all other end offices in the system. Since they are averaged, the plot only shows slight variation of the average blocking probability. Figure 6-11 provides insights on local performance of the system. It can be used to identify the end office which best performs (low blocking probability) during earthquake in order to locate important facilities that heavily depend on telecommunication infrastructure such as an emergency call center and an electric power control center.

Figure 6-11, also indicates significant increase of the average blocking probability at higher coupling strengths, *Sc*. This emphasizes the importance of interdependent analysis in studies of infrastructure systems.

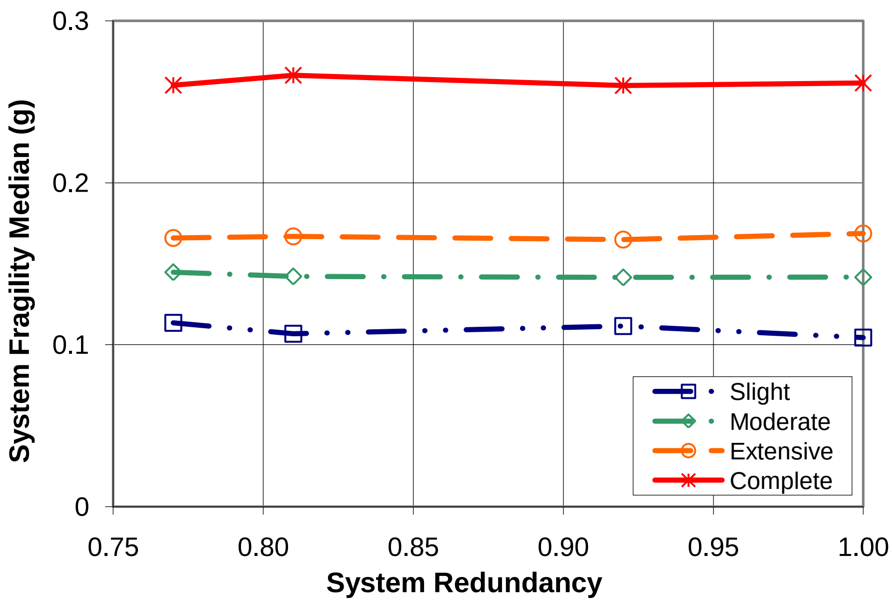


Figure 6-9: Sensitivity of Interdependent Fragility Median of Shelby County Telecommunication System to System Redundancy (Coupling Strength = 0.25 for POP, 0.50 for Tandem Offices and 0.75 for End Offices)

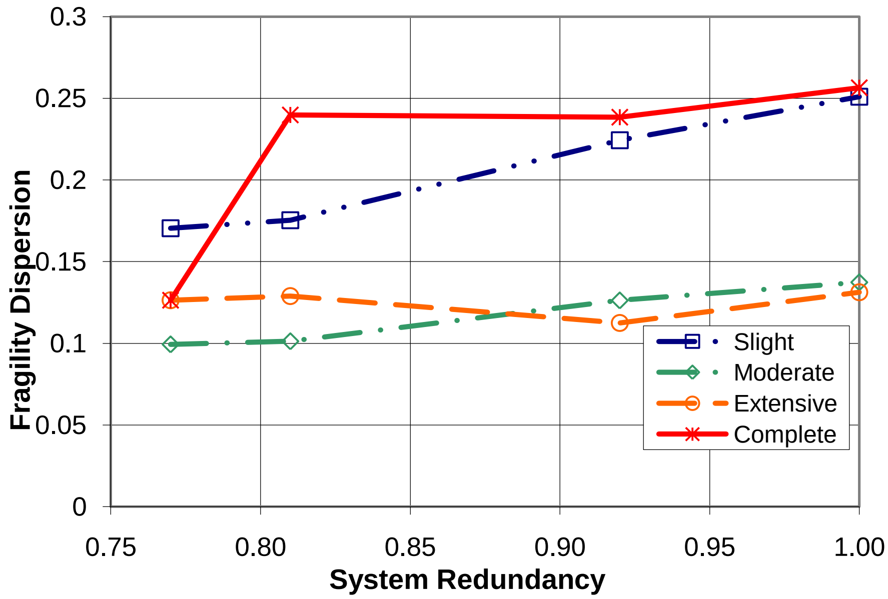


Figure 6-10: Sensitivity of Interdependent Fragility Dispersion of Shelby County Telecommunication System to System Redundancy (Coupling Strength = 0.25 for POP, 0.50 for Tandem Offices and 0.75 for End Offices)

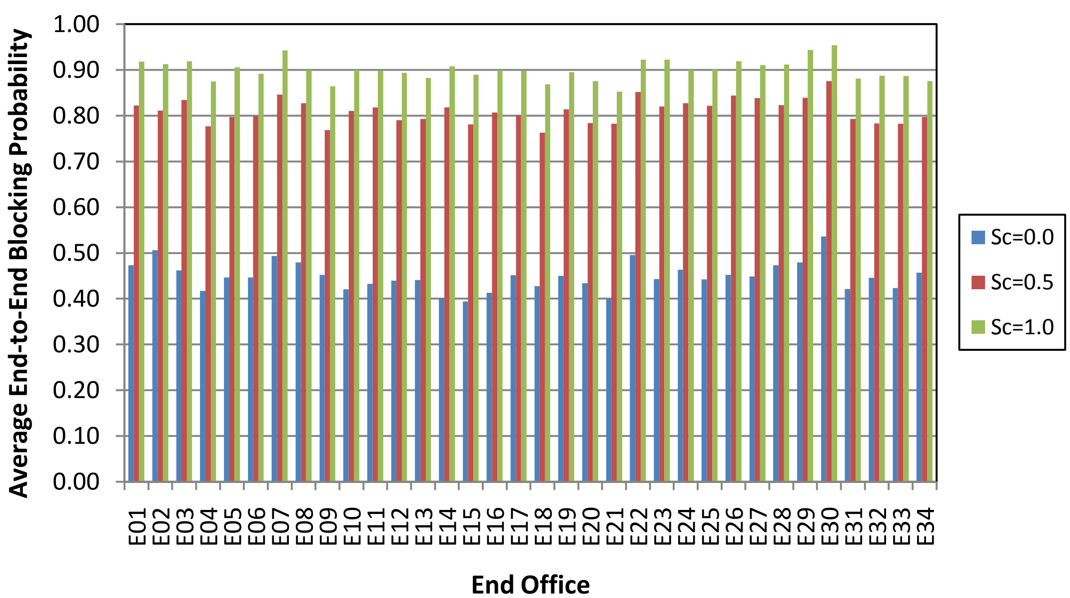


Figure 6-11: Local Average End-to-End Blocking Probability for End Offices of the Original System Subjected to PGA of 0.15g

6.3 Telecommunication Dependency of Electric Power System Operations

The analysis of the telecommunication dependent electric power system in Shelby County is presented in this section. This analysis is performed under the assumption that all of the communication between local facilities and the electric power control center are done over the public telecommunication infrastructure. It is assumed that each electrical substation has a connection to a nearby end office. The monitored measurements at a local substation are sent frequently through this end office over the telecommunication network to the destination end office and to the control center to which it is connected. In the event that the blocking probability between the end office at the substation and the end office at the control center reaches a high value due to seismic-induced congestion, the measured data may become out of date or lost. The loss of measurement data or even delayed data could result in less reliable state estimation, a partially observable system, or an entirely unobservable system. The quality of state estimation is beyond the scope of this study. Rather, this analysis focuses on whether or not the system is observable, and if not, the size of the maximum observable island or subnetwork is explored to provide insight into the necessary conditions for power operations.

6.3.1 Measurement Network of Electric Power System in Shelby County, TN

This analysis assumes a deterministic set of measurements located throughout the system. The set includes 38 power injection measurements (one for each generation node and each intermediate substation, and 30 measurements at distribution circuits) and 108 branch measurements (about 78% of the total of 139 branches). Each of the measurements is connected to a telecommunication end office. In normal daily operation, this set of the measurements is assumed to be sufficient to observe the entire system with some redundant measurements to ensure quality of the state estimation. In this analysis, it is assumed that observability is independent of the power flow or the function of the substation. Therefore, observability only implies that the system is reliably controllable which does not always mean that electricity can be delivered. For instance, a system might be 50% observable after an earthquake but electricity might be delivered to only 70% of the observable subnetwork due to physical damage to some of the substations in the subnetwork.

Finally, it should be noted that this analysis is performed under these high-level assumptions (e.g. the measurements at substations and transmission lines are real and reactive power only, no voltage magnitude is measured and the placement of the measurements is random while the placement of measurement in the real system is consciously engineered) because this work aims to provide a foundational framework for cyber interdependency analysis. A more comprehensive analysis should be developed in future work.

6.3.2 Telecommunication Dependent Fragility of Electric Power System Operations

Figure 6-12 through Figure 6-15 present the telecommunication dependent fragility curves of the Shelby County electric power system for various assumed locations of the control center. The limit states for the fragility functions are 25%, 50%, 75% and 100% unobservability. It should be noted that these sets of fragility curves are derived from the assumption that the measurement data are lost when the local measurement cannot be transmitted to the control center in a timely basis defined as within 5 minutes from the time that each measurement is taken. In this case, the setup time of each connection is assumed to be 30 seconds and each blocked attempt is reconnected immediately until successful. From this set of assumptions, the measurement will be considered lost when there are more than 10 retrial attempts to connect to the control center or equivalently that the end-to-end blocking probability is 90% (extensive congestion limit state) between the end office at the local measurement location and the one at the control center.

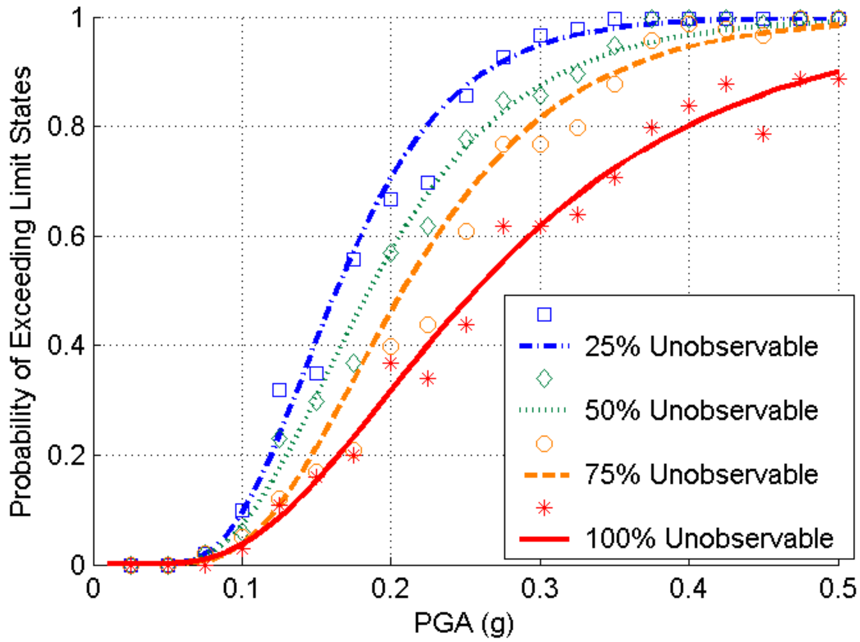


Figure 6-12: Telecommunication Dependent Seismic Fragility Curves of Electric Power system Operation for System with Control Center at E01 Central Office (Figure 6-3)

Each figure provides the relationship between seismic intensity and the probability that the electric power system is partially unobservable more than some certain percentages. For example, Figure 6-12 suggests that, at 0.2g PGA, there is a 70 % probability that more than 25% of the entire electric power system becomes unobservable due the loss of local measurements which cannot be transmitted to the control center, or there is a 32 % chance that the power system will be completely unobservable due to the same cause. The plot also indicates that for a given 60% probability, the system is likely to be more than 25%, 50%, 75% or completely unobservable at 0.18g, 0.20g, 0.22g, and 0.30g PGA, respectively. In other words, the fragility curves represent the vulnerability of the electric power control center to perform state estimation which is a critical task required for reliable operation and control of the power grid.

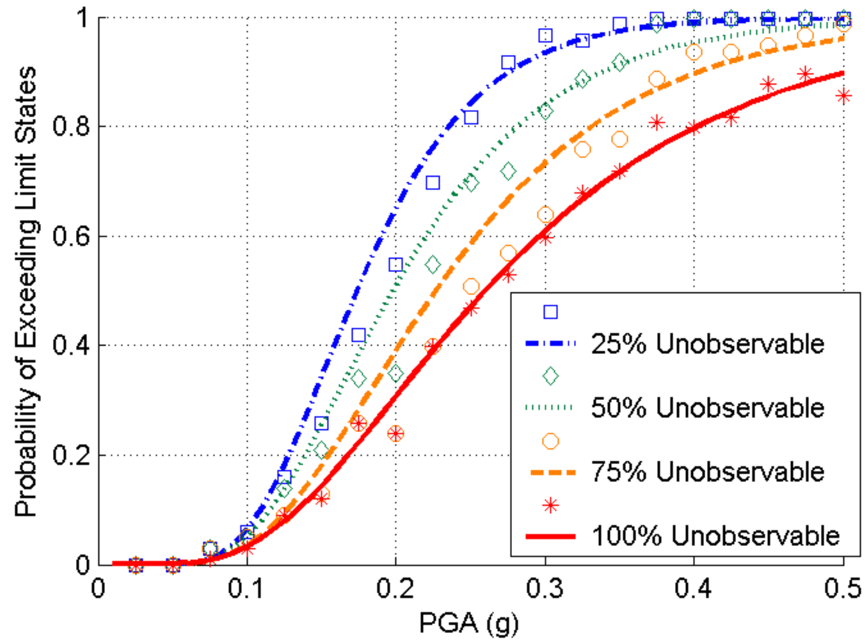


Figure 6-13: Telecommunication Dependent Seismic Fragility Curves of Electric Power system Operation for System with Control Center at E10 Central Office (Figure 6-3)

In normal daily operations, there are always some measurements that are lost due to the malfunction of meters or the loss of connections. In such cases, the control center will estimate the measurements from recently received data and use it to perform state estimation. However, under seismic stresses, it is highly likely that the topology of the system will be altered due to the loss of remote substations or other facilities. In this situation, the estimated measurement used in the normal daily operation is not likely to represent the lost measurement. Therefore, it is more likely that portions of the electric power system become unobservable due to the loss of measurements after an earthquake than on normal days.

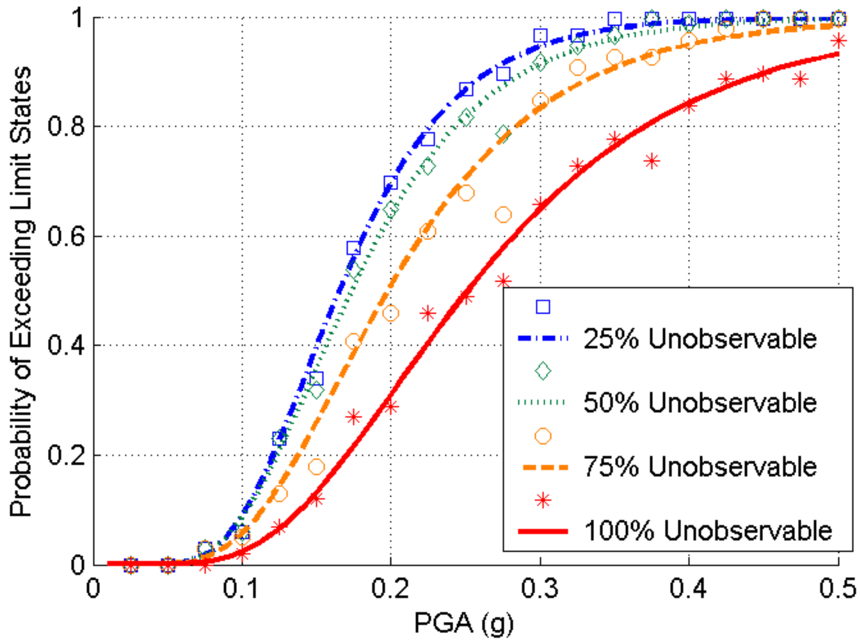


Figure 6-14: Telecommunication Dependent Seismic Fragility Curves of Electric Power system Operation for System with Control Center at E20 Central Office (Figure 6-3)

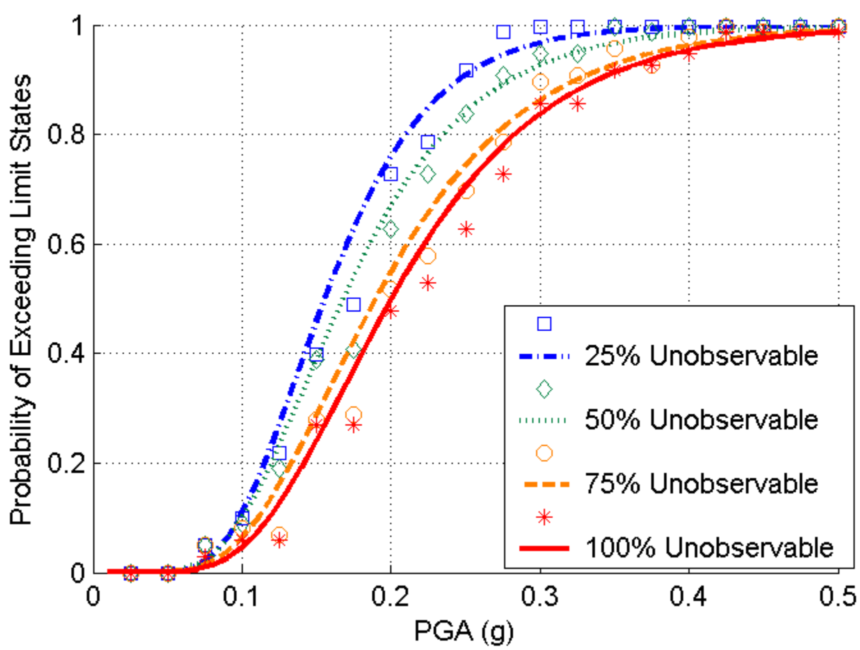


Figure 6-15: Telecommunication Dependent Seismic Fragility Curves of Electric Power system Operation for System with Control Center at E30 Central Office (Figure 6-3)

The connections between local measurements and the control center are vital to observability of the power grid and dependent upon the performance of telecommunication infrastructure. As seen in Figure 6-11, some end offices perform at a lower blocking probability than others. Therefore the location of the end office associated with the control center will influence the observability of the power system. Figure 6-12 through Figure 6-15 show the different fragility curves of the systems whose control centers are located at different locations and are therefore associated with different end offices. From the plots, there are slight variations among the first three systems while the last system is significantly more vulnerable than the others. The sensitivities of the log-normal fragility parameters to the properties of the end offices associating with the control centers are presented in Figure 6-16 through Figure 6-19.

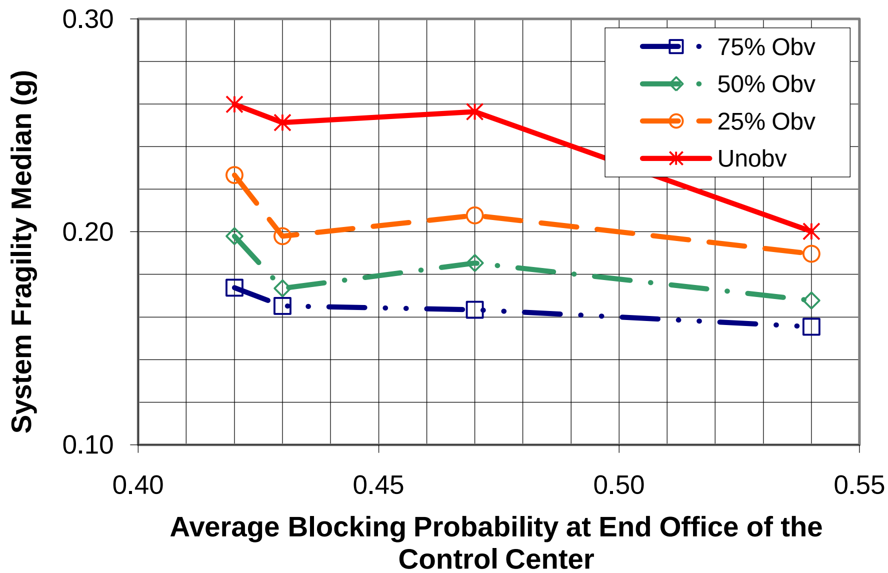


Figure 6-16: Sensitivity of the Interdependent Fragility Median of Shelby County Electric Power system to Average Local Blocking Probability of the Control Center End Office.

Figure 6-16 is the sensitivity plot of the interdependent fragility median for the Shelby County power system. It indicates, as expected, that the fragility median tends to be lower (more vulnerable) when the control center is associated with an end office which operates at a high blocking probability. The same trend is also found in the sensitivity of the fragility dispersion (Figure 6-17). It is also noted that both the median and dispersion of the fragility curve of the most severe limit state (100% unobservable) are more sensitive to the average blocking probability.

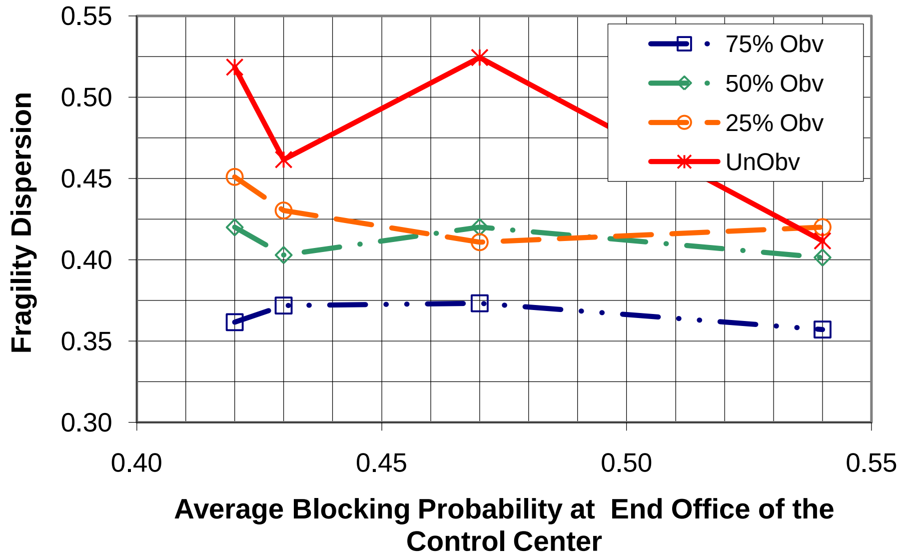


Figure 6-17: Sensitivity of the Interdependent Fragility Dispersion of Shelby County Electric Power system to Average Local Blocking Probability of the Control Center End Office.

In Figure 6-18 and Figure 6-19, the sensitivity of the fragility median and dispersion to the vertex degree of the control center end office are presented. As expected, the observability of the power system is more reliable (higher median and higher dispersion) when the control center connects to an end office with high vertex degree. This is because high vertex degree represents high number of alternative routes which increases the chances that more measured data can be delivered to the control center. Therefore, it is desirable to locate the control center near an end office with more connections. This information is expected to be useful in the process of selecting the control centers for a newly designed electric power system.

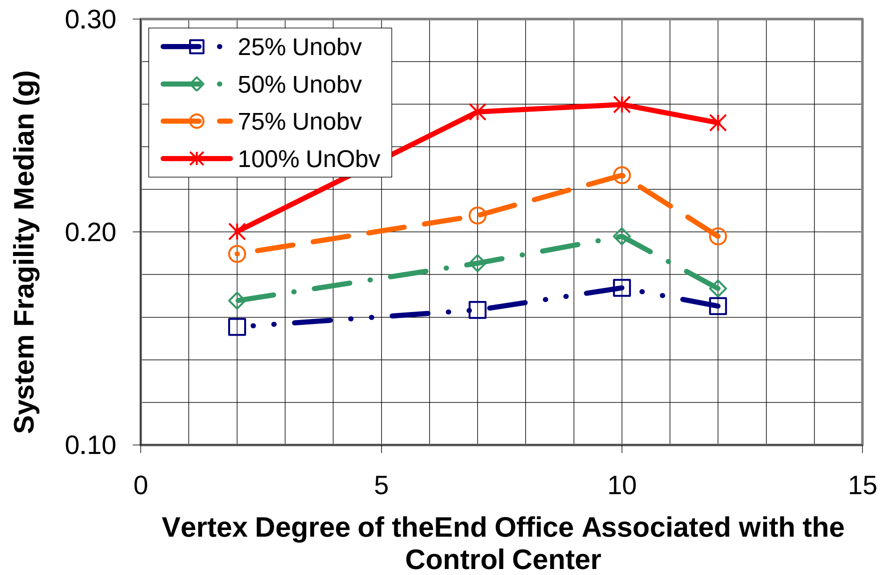


Figure 6-18: Sensitivity of the Interdependent Fragility Median of Shelby County Electric Power system to Vertex Degree of the Control Center End Office.

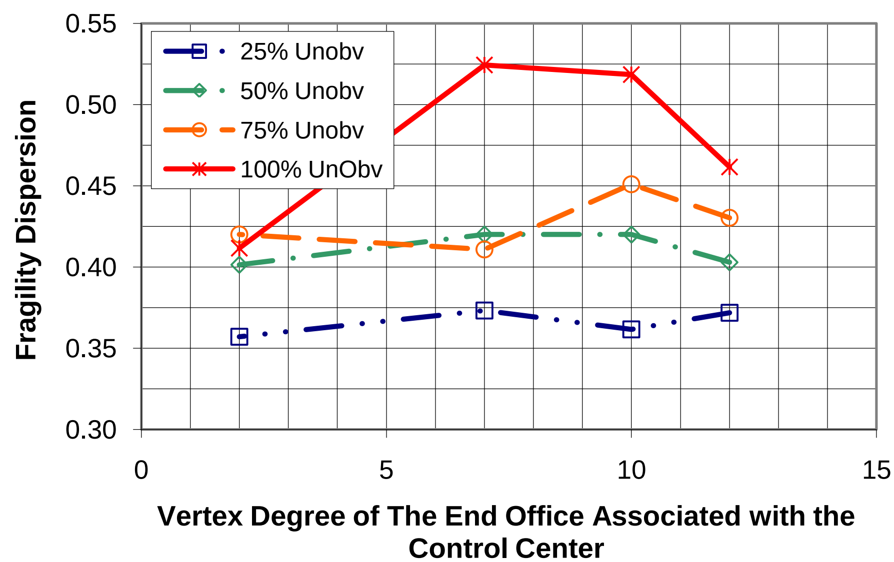


Figure 6-19: Sensitivity of the Interdependent Fragility Dispersion of Shelby County Electric Power system to Vertex Degree of the Control Center End Office.

6.4 Seismic Mitigation Strategies for Interdependent Systems

The previous section presents the results of the two interdependent analyses performed on the Shelby County testbed telecommunication and electric power systems. Some of the sensitivity analysis results suggest factors which affect performance of the interdependent systems. This useful information is reviewed again in this section in an attempt to provide basic guidelines for seismic mitigation strategies.

6.4.1 Electric Power Dependency of Telecommunication Systems

The results from the analysis show a strong correlation between coupling strength and fragility of the interdependent systems. Therefore it is logical that decreasing the coupling strength between a telecommunication central office and an electric power substation is one of the high priority actions in attempts to mitigate seismic effects on the interdependent telecommunication system. This can be achieved by installing more reliable electric power backup systems which are designed for seismic hazards.

Another mitigation action is to increase the redundancy of the telecommunication system. The results from the study indicated that increasing redundancy (adding more connections or trunks) to a low redundant telecommunication system may significantly reduce the blocking probability of local central offices and the overall system. However, the improvement in the performance of systems with high redundancy is insignificant. This is because more routes provided by the additional connections do not contribute to system performance due to the constraints of the routing rules.

The study also demonstrates poor system performance of the interdependent telecommunication system when electric substations with high vertex degree exist in the interdependent adjacency. This implies that there are many central offices which are dependent on one substation. This situation is not desirable but yet may be unavoidable, especially in high population areas. In cases where this condition cannot be controlled, reducing coupling strength should be the alternative mitigation strategy.

Improving fragilities of network components is also an important seismic mitigation action. In practice, it is impossible to improve all the components at the same time. More study on the contribution of individual components is required to establish more efficient strategies for maximizing the improvement of the system performance given limited resources.

Because one of the seismic effects on telecommunication systems is the seismic-induced communication demand, increasing the capacity of network components (e.g. central offices and trunks) is another reasonable mitigation action. However, it should be noted that the efficiency of this mitigation strategy depends on the seismic performance of the components to withstand seismic-induced physical damage because the additional capacity will become useless if the components are not functional. Therefore, improving fragility functions and increasing capacities of network components should be done in parallel.

The deployment of alternative independent telecommunication systems such as two-way radio communication systems and satellite telephone systems is one of the most efficient post-disaster mitigation actions. This strategy has been used by most of emergency service agencies and utilities during the recovery process after disaster events.

Recently, some computer scientists at Georgia Institute of Technology have developed a new telecommunication system called LifeNet. The system uses computer software to allow connections among computers and smart phones which are WiFi enabled. It operates independently from the primary telecommunication infrastructure and is specifically designed to provide communication when the primary telecommunication system is not available during disaster (Georgia Institute of Technology 2011).

6.4.2 Telecommunication Dependency of Electric Power Operations

From the study of telecommunication dependency of electric power operations, the observability is completely dependent on the performance of the telecommunication infrastructure. Therefore, the mitigation actions discussed earlier for the interdependent telecommunication influence the observability indirectly.

Another mean of improving observability of an electric power system is to reduce the degree of dependency between the two systems. This may be done by providing other means of connections between local measurement and the control center which are not operated on public networks, but such connections must be robust to seismic hazard to avoid seismic-induced interference that can block or cause delay in data transmission.

There are some recent studies (Meliopoulos et al. 2006, Mohagheghi et al. 2007, Stefopoulos et al. 2007) on utilizing global positioning system (GPS) signals to locally monitor voltage phase angles (one of the two state variables). This approach allows localized state estimation in lieu of the traditional centralized state estimation at the control center. This results in an observability of the electric power systems which is less dependent on data transmission over the telecommunication infrastructure.

6.5 Summary

The analyses of the two interdependencies: (1) electric power dependency of telecommunication system and (2) telecommunication dependency of electric power operations discussed in Chapter 5 are applied to the Shelby County testbed telecommunication and electric power systems. The testbed systems are synthesized from publically available data. Component fragility and congestion models derived in Chapter 3 are used as the inputs for the analyses. The results illustrate the application of the cyber interdependency analysis to an electric power system and demonstrate the amplification of the vulnerability of the system due to these interdependencies. Sensitivity analyses of the system to interdependence parameters such as coupling strength, vertex degree of interdependent adjacency, and redundancy ratio are performed. The results from the study indicate that seismic performance of telecommunication systems is highly sensitive to coupling strength. Fragility medians of a telecommunication system can be overestimated by up to100% if its dependency on electric power system is not considered. The influence of telecommunication system redundancy on seismic performance is also studied. The results confirm that increases in the redundancy of telecommunication systems only improve the seismic performance of low redundant systems. The results from cyber interdependent system analysis also demonstrate the influence of the telecommunication end office associated with the electric power control center. The study suggests that electric power observability of power grids is more reliable if the control center is associated with an end office with high vertex degree. This is because more connections to the end office increase the chance that measured data are delivered to the control center. In the end of this chapter the results from the study are used to establish preliminary recommendations for seismic mitigations such as reducing coupling strengths, increasing system redundancy, improving component fragilities and capacities, providing alternative telecommunication systems, relocating the electric control center, and utilizing localized state estimation.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

Modern society and economies depend heavily on the electric power and telecommunication infrastructures. Disruptions of these two critical lifelines are not desirable but yet are unavoidable, especially during natural disasters. The consequences to the individual infrastructures of such events have been widely studied; however, the interdependencies between these two systems have not been sufficiently explored. Due to the rapid improvement in technology, these two infrastructure systems are becoming increasingly interdependent. Failure of one system is likely to shift vital influence to the other. Therefore, understanding interdependencies between electric power and telecommunication systems is considered one of the most critical tasks in an attempt to minimize disruptions and mitigate negative effects to society and economies.

This final chapter summarizes the results from the present investigation of the interdependent response of electric power and telecommunication systems. It also discusses the significance of this study, its applications, and its contributions to the research communities. Finally, this chapter suggests some relevant future work which is essential to the advancement of infrastructure interdependency field.

7.1 Conclusions

There have been a number of studies on the effects of earthquake hazard on critical infrastructure systems. Most of this published work focuses on individual performance of individual network systems and tries to improve overall system performance by strengthening individual network components without considering the interaction within the systems. There are only a few attempts to try to understand the interaction within these systems and there are even fewer studies addressing the interdependence across different systems. In the last two decades, some studies (Nojima and Kameda 1991, Rinaldi et al. 2001, Rinaldi 2004) have explicitly recognized and categorized interdependencies between infrastructure systems. However these studies do not explore in depth interdependent effects on the performance of the systems, although there are a few more recent studies (Dueñas-Osorio 2005, Dueñas-Osorio et al. 2006, Duenas-Osorio et al. 2007a, Duenas-Osorio et al. 2007b, Kim et al. 2007) on the interdependencies between transmission and distribution infrastructure systems such as electric power systems, potable water systems, and oil and gas transmission systems. The studies of the interdependencies between telecommunication infrastructure systems, which are queuing network systems, and the other critical infrastructure systems are still rare. Therefore, this work is aimed at creating a foundational framework for the study of the telecommunication infrastructure and its interdependency with other systems.

One of the first tasks to evaluate the seismic performance of infrastructure systems is to understand the seismic hazard and its effects on the systems. Strong ground motion from a seismic hazard causes physical damage to both electric power and telecommunication network components, and this leads to a rise in communication demand on telecommunication systems. In this study, fragility functions are used as probabilistic representations of physical damage while traffic theory is proposed to capture the effect of high communication demands. Due to the nature of telecommunication systems, traffic theory is the most suitable concept for quantifying their seismic performance by using blocking probabilities as performance indexes.

This study recognizes three different sources of seismic-induced demand: (1) communication among subscribers within earthquake affected area, (2) communication between emergency service agencies and subscribers in earthquake affected area, and (3) communication attempts from subscribers outside earthquake affected area. From the demographic signature of the target area of study, these three sources are mathematically modeled using a renewal process with Weibull probability distribution as interarrival time, holding time, and interarrival of retrial demand. Unlike normal daily communication demands which are modeled using traditional Poisson process, the renewal process with a Weibull distribution is preferable in the disastrous situation where the demands are driven by a correlated cause and lack a memoryless property. From these demand models, it is possible to establish the relationships between seismic intensity and level of blocking probability for telecommunication components which are used in the evaluation of the overall system performance. The renewal process congestion model demonstrates component blocking probabilities of up to 2% higher than the Poisson process model. The results also indicate the importance of retrial attempts to component blocking probability. The component blocking probability can be underestimated by 1.3% if retrial attempts are not considered in the simulation.

In order to perform system evaluation analysis, understanding topology and the nature of the systems is vital. The goal of electric power systems is to transmit and distribute electricity from generation units which are normally located in remote areas to end users in cities or industrial areas, while telecommunication systems aim to provide connections to subscribers over shared resources. The distinction between the two systems must be recognized in the evaluation of the interdependent system.

In practice, electrical engineers use a physics based power flow algorithm to analyze and design electric power grids. The algorithm is simple to understand and apply but it requires detailed input of the system; however, most of this detailed information about power grids are sensitive to public security and are rarely available. In this study, a simplified optimal network flow analysis is utilized to evaluate electric power systems in lieu of the electric power flow algorithm in an attempt to relax the intensive input requirement. The proposed optimal network flow analysis and the traditional power flow analysis are tested on the 24-bus IEEE reliability test system. The results from the optimal network flow and the power flow algorithm agree with acceptable tolerance.

Unlike an electric power system, a telecommunication system is not a transmission-distribution network. Its subscribers access the system for connections to other subscribers, so a telecommunication system behaves like a queuing network. Because not all subscribers use service of telecommunication network at the same time, the systems are engineered so that a number of subscribers share limited resources. It has always been the goal in design of telecommunication systems to provide minimum resources while trying to achieve an acceptable Grade of Service (GOS) during normal daily operation. As a result, the systems become vulnerable to rare events when communication demands are abnormally high.

In order to evaluate the performance of a telecommunication system, it is important to understand how telecommunication systems manage resources or route connections between origins and destinations. Since the birth of communication infrastructure systems, routing algorithms have been continuously improved and have become highly sophisticated. However, a basic objective is to route a connection over the shortest path possible to minimize the use of resources and maximize quality of the connection. From this fundamental objective, this study develops a simple routing to simulate the operation of telecommunication system for seismic performance evaluation of the systems subjected to the loss of components and the concurrent increase in communication demand. This results in the newly developed framework for seismic fragility analysis of telecommunication systems employed in this work.

In the study of the interdependencies between telecommunication and electric power systems, the relationship between the systems must be clearly defined. This study focuses on two types of interdependencies: (1) electric power dependency of telecommunication systems and (2) telecommunication dependent of electric power systems operation.

The first dependency is defined as physical coupling between network components of the two systems. The failure of electric power substations affects telecommunication central offices directly. This relationship is straightforward and similar to dependencies between other transmission-distribution infrastructure systems. This type of dependency is characterized by three important components: (1) interdependent adjacency, (2) probabilistic formulation, and (3) coupling strength. The interdependent analysis is performed for the Shelby County infrastructure systems. The results indicate significant degradation of the telecommunication system performance due to the interdependency. The seismic performance of telecommunication system can be overestimated by up to 100% when the interdependency is not properly considered. This can be seen in the fragility function for the network components, but it is clearer in the sensitivity of the telecommunication system seismic fragility median to coupling strength. Therefore, improving the coupling strength is one of the most effective mitigation actions. This can be achieved by providing more reliable power backup or additional power resources. In the study of low redundancy telecommunication system, the results suggest improvement of system performance by increasing the redundancy such as by adding connections within the systems. However, this mitigation strategy is not efficient for high redundancy (more than 50%) systems such as the Shelby County telecommunication system and perhaps other telecommunication systems in metropolitan areas. This is because the additional connections do not contribute to performance of the systems due to the constraints of the routing rules. This study also suggests that high vertex degree in the interdependent adjacency results in a vulnerable interdependent telecommunication system because many telecommunication central offices depend on only one power substation. When the substation fails, it is likely that the functionality of the central offices that depend on it would be affected. However, this situation may be unavoidable, especially in metropolitan areas where many central offices are located in the same service area of an electric power substation. In this case, additional or more reliable power backup systems for these central offices are required in order to reduce the coupling strength for seismic mitigation.

The second dependency is a cyber interdependency. This type of interdependency relates to information technology. For an electric power system, the cyber interdependency arises from the use of SCADA systems to provide reliable system control and operation. A SCADA system allows the electric power control center to collect measurement data from geographically distributed sensors in the network and to perform state estimation. The results from state estimation are used by the control center to determine a course of action to maintain stability of the overall system. However, there are some situations when the SCADA system fails to collect sufficient data to perform accurate state estimation. In this case, the control center may not have an accurate state estimation of the system and this may result in improper control actions which can affect the stability of the power system.

In an earthquake, it is very likely that the communication infrastructure is compromised. In this situation, failure in telecommunication system may affect the performance of the SCADA system and therefore the observability of the system (the ability of the control center to perform state estimation). From this complex relationship, a cyber interdependency analysis is developed using high-level simplifying assumptions such as types and locations of measurements and connections between the measurements and end offices in order to provide a foundational framework for the study of this type of interdependency. This analysis is then applied to the Shelby County testbed. The results from the test case demonstrate the influence of the local performance of the telecommunication system on the electric power system observability. The topological properties of the telecommunication end office associated with the electric power control center can be used to estimate reliability of the observability. The study indicates that locating the control center near the end office with high vertex degree may improve reliability of electric power system observability by up to 30%. Suggestions on how to relax cyber interdependency are suggested based on the results from the study.

One of the greatest challenges in this study is obtaining the specification of electric power and telecommunication systems. Even though, the application of the proposed framework can be demonstrated through the systems synthesized and estimated from basic information such as population, service areas, and distance of transmission lines, the advantages of this framework can be further enhanced when applying it to the systems with complete sets of detailed configurations. The availability of the detailed specification (e.g. voltage and power rating of transmission lines and substations, and capacity of generation units for electric power systems, or the real capacity of central offices and trunks, the number of subscribers per an end office, and the exact connections between central offices for telecommunication systems) allows more precise algorithm to be used in lieu of the simplified algorithm used in this study (e.g. physical power flow analysis in lieu of optimal network flow analysis).

7.2 Applications and Future Research

The proposed methods are basic tools for assessing the seismic response of two critical infrastructure systems. These methods physical and cyber interdependencies between the systems into account in an attempt to provide more accurate results simulating the real situation. Due to the inherent uncertainty of the problem the methodologies are developed based on probability concepts. This research focuses on developing the algorithms which apply to telecommunication systems and its interdependencies with other infrastructure systems. As one of only a few studies in this area, this work is expected to provide a foundational framework for future study on cyber and other type of interdependencies among infrastructure systems. Finally, the algorithms and simulation developed in this study are aimed to aid decision making processes in urban planning and seismic mitigation investment.

This study initiates new ways to model the interdependent issues between infrastructure systems under stresses. However, there are some important issues which need to be addressed in any future research. These include:

- Collection of usage data from a telecommunication system in order to validate and refine seismic-induced congestion models.
- Development of models to estimate the existing coupling strength between network components.
- Development of models to address the dependency of the telecommunication infrastructure on recovery after an earthquake.
- Application of the proposed method in multi-hazard situations.
- Investigation of the higher-order interdependency between infrastructure systems to simulate and investigate cascading failure.
- Investigation of effects of localized improvements on overall system performance in order to develop algorithms to maximize system performance by improving a limited number of components.
- Exploration of the localized or decentralized state estimation algorithm sensitivity and vulnerability to seismic hazards.
- Development of comprehensive models to evaluate both adequacy and security of electric power system performance under seismic hazards.
- Development of the model representing mobile telephone systems at the base station subsystem level (including a number of cell towers and devices used by subscribers).
- Development of the model representing electric power distribution systems.
- Investigation of the effects of cyber interdependencies on the smart grid.

REFERENCES

Abrahamson, N. A., and W. J. Silva (1993). Attenuation of Long Period Strong Ground Motions. Proceedings of the 1993 Pressure Vessels and Piping Conference, July 25, 1993 - July 29, 1993, Denver, CO, USA, Publ by ASME.

Abur, A. (2004). Power System State Estimation Theory and Implementation. New York, N.Y., Marcel Dekker.

Adachi, T. (2007). Impact of Cascading Failures on Performance Assessment of Civil Infrastructure Systems. PhD, Georgia Institute of Technology.

Adachi, T., and B. R. Ellingwood (2008). "Serviceability of Earthquake-Damaged Water Systems: Effects of Electrical Power Availability and Power Backup Systems on System Vulnerability." Reliability Engineering and System Safety **93**(1): 78-88.

Adachi, T., and B. R. Ellingwood (2009a). "Serviceability Assessment of a Municipal Water System under Spatially Correlated Seismic Intensities." Computer-Aided Civil and Infrastructure Engineering **24**(4): 237-248.

Adachi, T., and B. R. Ellingwood (2009b). "Serviceability Assessment of Electrical Power Transmission Systems under Probabilistically Stated Seismic Hazards: Case Study for Shelby County, Tennessee." Structure and Infrastructure Engineering **5**(5): 343-353.

Adachi, T., and B. R. Ellingwood (2010). "Comparative Assessment of Civil Infrastructure Network Performance under Probabilistic and Scenario Earthquakes." Journal of Infrastructure Systems **16**(1): 1-10.

Adamson, S. C. G., Steven P. (1993). "Analysis of Two Trunk Congestion Relief Schemes."

Alber, J., and M. Poller (2006). Observability of Power Systems Based on Fast Pseudorank Calculation of Sparse Sensitivity Matrices. IEEE Power Engineering Society Transmission and Distribution Conference, PES TD 2005/2006, May 21, 2006 - May 24, 2006, Dallas, TX, United states, Institute of Electrical and Electronics Engineers Inc.

Amin, M. (2000). "Toward Self-Healing Infrastructure Systems." IEEE Computer Magazine **33**(8): 44-53.

Ang, A. H.-S., and W. H. Tang (2007). Probability Concepts in Engineering-Emphasis of Applications to Civil and Environmental Engineering, Wiley.

Applied Technology Council (1985). Earthquake Damage Evaluation Data for California. Redwood City, California, Applied Technology Council (ATC)**:** 492.

Applied Technology Council (1991). Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States. Redwood City, California, Applied Technology Council (ATC)**:** 440.

Archuleta, R. J., W. B. Joyner, and D. M. Boore (1979). "Methodology for Predicting Ground Motion at Specific Sites." Geological Survey Circular (United States)(Compendex): 26-36.

ASCE (2011). Lifelines Performance Assessment Preliminary Summary: Tohoku Off Shore Earthquake & Tsunami, Japan.

AT&T Bell Laboratories (1983). Engineering and Operations in the Bell System. Murray Hill, New Jersey.

Atkinson, G. M., and D. M. Boore (1990). "Recent Trends in Ground Motion and Spectral Response Relations for North America." Earthquake Spectra **6**(1): 15-35.

Atkinson, G. M., and D. M. Boore (2006). "Earthquake Ground-Motion Prediction Equations for Eastern North America." Bulletin of the Seismological Society of America **96**(Compendex): 2181-2205.

Balijepalli, N. V., Subrahmanyam, S.; Richter, Charles W.; Christie, Richard D.; Longo, Vito J. (2005). "Distribution System Reliability Assessment Due to Lightning Stroms." IEEE Transaction on Power Delivery **20**(3).

Beavers, J. E. (2003). Advancing Mitigation Technologies and Disaster Response for Lifeline Systems : Proceedings of the Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering, August 10-13, 2003, Long Beach, California. Reston, Va. : , American Society of Civil Engineers.

Bellamy, J. C. (2000). Digital Telephony. Coppell, Texas, John Wiley & Sons, Inc.

Billinton, R., and W. Li (1994). Reliability Assessment of Electric Power Systems Using Monte Carlo Methods New York, Plenum Press.

Billinton, R. K. S. C., N.; Chu, K.; Debnath, K.; Goel, L.;Khan, E.; Kos, P.;Nourbakhsh G.; Oteng-Adjei, J. (1989). "A Reliability Test System for Educational Purposes - Basic Data." IEEE Transaction on Power Systems **4**(3): 7.

Bobbio, A., R. Terruggia, A. Boellis, E. Ciancamerla, and M. Minichino (2007). A Tool for Network Reliability Analysis. 26th International Conference on Computer Safety, Reliability, and Security, SAFECOMP 2007, September 18, 2007 - September 21, 2007, Nuremberg, Germany, Springer Verlag.

Bolt, B. (1993). Abridged Modified Mercalli Intensity Scale, Earthquakes - Newly Revised and Expanded, W.H. Freeman and Co.**:** 331.

Booker, G., J. Torres, S. Guikema, A. Sprintson, and K. Brumbelow (2010). "Estimating Cellular Network Performance During Hurricanes." Reliability Engineering and System Safety **95**(Compendex): 337-344.

Breuer, L., and D. Baum (2005). An Introduction to Queueing Theory and Matrix-Analytic Method. Dordrecht, Netherlands, Springer.

Brooks, J. D., Rod "Analyzing Security Assessment Schemes in Traditional Networks."

Campbell, K. W. (2003). "Prediction of Strong Ground Motion Using the Hybrid Empirical Method and Its Use in the Development of Ground-Motion (Attenuation) Relations in Eastern North America." Bulletin of the Seismological Society of America **93**(Compendex): 1012-1033.

Campbell, K. W., and Y. Bozorgnia (1994). "Empirical Analysis of Strong Ground Motion from the 1992 Landers, California, Earthquake." Bulletin of the Seismological Society of America **84**(Compendex): 573-588.

Cancho, R., C. Janssen, and R. Solé (2001). "Topology of Technology Graphs: Small World Patterns in Electronic Circuits." Physical Review E **64**(4).

Carreras, B. A., V. E. Lynch, I. Dobson, and D. E. Newman (2004). "Complex Dynamics of Blackouts in Power Transmission Systems." Chaos **14**(3): 643-652.

Chang, S. E., H. A. Seligson, and R. T. Eguchi (1995). Estimation of Economic Losses Caused by a Disruption of Lifeline Service. San Francisco, CA, USA, ASCE**:** 48.

Chassin, D. P. P., Christian (2005). "Evaluating North America Electric Grid Reliability Using the Barabasi-Albert Network Model."

Clements, K. A., G. R. Krumpholz, and P. W. Davis (1982a). "Power System State Estimation with Measurement Deficiency: An Algorithm That Determines the Maximal Observable Subnetwork." IEEE transactions on power apparatus and systems **PAS-101**(Copyright 1983, IEE): 3044-3052.

Clements, K. A., G. R. Krumpholz, and P. W. Davis (1982b). "State Estimator Measurement System Reliability Evaluation - an Efficient Algorithm Based on Topological Observability Theory." IEEE transactions on power apparatus and systems **PAS-101**(Compendex): 997-1004.

Conrad, S. H. O. R., Gerard P. "An Overview of Energy and Telecommunications Interdependencies Modeling at Nisac ".

Cortereal, M., and L. Gouveia (2007). "Network Flow Models for the Local Access Network Expansion Problem." Computers & Operations Research **34**(4): 1141-1157.

David, G. R., J. A. Douglas, and J. Larry (2006). Impact of Distributed Energy Resources on the Reliability of Critical Telecommunications Facilities. Telecommunications Energy Conference, 2006. INTELEC '06. 28th Annual International.

Dobson, I. N., D. E.; Carreras, B. A.; Lunch, V. E. (2002). "An Initial Complex System Analysis of the Risk of Blackout in Power Transmission Systems."

Dorogovtsev, S. N. M., J. F. F. (2002). "Evolution of Networks." Advances in Physics **51**(4): 109.

Dueñas-Osorio, L. (2005). Interdependent Response of Networked Systems to Natural Hazards and Intentional Disruptions. Doctor of Philosophy Dissertation, Georgia Institute of Technology.

Duenas-Osorio, L., J. I. Craig, and B. J. Goodno (2007a). "Seismic Response of Critical Interdependent Networks." Earthquake Engineering and Structural Dynamics **36**(2): 285-306.

Duenas-Osorio, L., J. I. Craig, B. J. Goodno, and A. Bostrom (2007b). "Interdependent Response of Networked Systems." Journal of Infrastructure Systems **13**(3): 185-194.

Dueñas-Osorio, L., K. Leelardcharoen, J. I. Craig, and B. J. Goodno (2006). Failure of Interdependent Networks. The 8th National Conference in Earthquake Engineering, San Francisco, CA.

Elmakias, D. (2008). New Computational Methods in Power System Reliability Berlin, Heidelberg, Springer-Verlag Berlin Heidelberg.

Erlang, A. K. (1925). "Probability Theory Applied to Telephony." Annales des Postes, Telegraphes et Telephones **4**: 617-644.

Erlang, A. K. (1926). "Calculations of Probabilities in Telephony." Revue Generale de l'Electricite **20**: 270-278.

Exposito, A. G., and A. Abur (1998). "Generalized Observability Analysis and Measurement Classification." IEEE Transactions on Power Systems **13**(3): 1090-1095.

Exposito, A. G., A. Abur, and E. R. Ramos (1995). On the Use of Loop Equations in Power System Analysis. Proceedings of the 1995 IEEE International Symposium on Circuits and Systems-ISCAS 95. Part 3 (of 3), April 30, 1995 - May 3, 1995, Seattle, WA, USA, IEEE.

Faza, A., S. Sedigh, and B. M. McMillin (2007). "Reliability Modeling for the Advanced Electric Power Grid."

Faza, A., S. Sedigh, and B. M. McMillin (2008). "The Advanced Electric Power Grid-Complexity Reduction Techiques for Reliability Modeling."

Faza, A., S. Sedigh, and B. M. McMillin (2009). "Reliability Analysis for the Advanced Electric Power Grid from Cyber Control and Communicaiton to Physical Manifestations of Failure."

FEMA (2004). Fema 450: The 2003 Nehrp Recommended Provisions for New Building and Other Structures. Washington D.C., Federal Emergency Management Agency (FEMA).

Fink, G. V. (1994). Innovative Network Modeling and Simulation Tool. IEEE MILCOM.

Fioriti, V., S. Ruzzante, E. Castorini, A. Di Pietro, and A. Tofani (2009). Modelling Critical Infrastructures in Presence of Lack of Data with Simulated Annealing - Like Algorithms. 28th International Conference on Computer Safety, Reliability, and Security, SAFECOMP 2009, September 15, 2009 - September 18, 2009, Hamburg, Germany, Springer Verlag.

Frost, V. S. M., Benjamin (1994). "Traffic Modeling for Telecommunications Networks." IEEE Communication Magazine.

Georgia Institute of Technology. (2011). "Georgia Tech Researchers Demo Disaster Communications System " Retrieved August 17, 2011, from http://www.gatech.edu/newsroom/release.html?nid=69356.

Ghiraldi, A. Z., Ervino "Survivability of Reliable Telecommunications Equipment Enclosures through Natural Diasters."

Glass, R. J. B., Walt E.; Stamber, Kevin L. "Advanced Simulation for Analysis of Critical Infrastructure- Abstract Cascades, the Electric Power Grid, and Fedwire."

Guimerà, R., A. Arenas, A. Díaz-Guilera, and F. Giralt (2002). "Dynamical Properties of Model Communication Networks." Physical Review E **66**(2).

Gutenberg, B., and C. F. Richter (1941). "Seismicity of Earth." Geological Society of America -- Special Paper: 131.

Gutenberg, B., and C. F. Richter (1949). Seismicity of Earth and Associated Phenomena. Princeton, NJ, United States, Princeton University Press.

Heller, M. (2001). Interdependencies in Civil Infrastructure Systems. The Bridge. **31:** 9-15.

Houck, D. J., E. Kim, G. P. O'Reilly, D. D. Picklesimer, and H. Uzunalioglu (2004). "A Network Survivability Model for Critical Nation Infrastructures." Bell Labs Technical Journal 8(4): 153-172.

Hwang, H., and J. Huo (1997). "Attenuation Relations of Ground Motion for Rock and Soil Sites in Eastern United States." Soil Dynamics and Earthquake Engineering **16**: 363-372.

Hwang, H., H. Lin, and J.-R. Huo (1997). "Site Coefficients for Design of Building in Eastern United States." Soil Dynamics and Earthquake Engineering **16**: 29-40.

IEEE Reliability Test System Task Force (1979). "Ieee Reliability Test System." IEEE transactions on power apparatus and systems **PAS-98**(6): 8.

Institute of Electrical and Electronics Engineers (2005). Ieee Recommended Practice for Seismic Design of Substation. New York, New York, Institute of Electrical and Electronics Engineers.

International Telecommunication Union. (2009). "Free Statistics." Retrieved July 4, 2009, from http://www.itu.int/ITU-D/ict/statistics/.

Jain, A., R. Balasubramanian, and S. C. Tripathy (2008). Topological Observability: Artificial Neural Network Application Based Solution for a Practical Power System. 40th North American Power Symposium, NAPS2008, September 28, 2009 - September 30, 2009, Calgary, AB, Canada, IEEE Computer Society.

Jain, A., R. Balasubramanian, S. C. Tripathy, B. N. Singh, and Y. Kawazoe (2005). Power System Topological Observability Analysis Using Artificial Neural Networks. 2005 IEEE Power Engineering Society General Meeting, 12-16 June 2005, Piscataway, NJ, USA, IEEE.

Jayaram, N., and J. W. Baker (2009). "Correlation Model for Spatially Distributed Ground-Motion Intensities." Earthquake Engineering & Structural Dynamics **38**(15): 12.

Jrad, A., G. O'Reilly, S. H. Richman, S. Conrad, and A. Kelic (2007). Dynamic Changes in Subscriber Behavior and Their Impact on the Telecom Network in Cases of Emergency. MILCOM 2006, 23-25 Oct. 2006, Piscataway, NJ, USA, IEEE.

Jrad, A., H. Uzunalioglu, D. J. Houck, G. O'Reilly, S. Conrad, and W. Beyeler (2005). Wireless and Wireline Network Interactions in Disaster Scenarios. MILCOM 2005: Military Communications Conference 2005, October 17, 2005 - October 20, 2005, Atlatnic City, NJ, United states, Institute of Electrical and Electronics Engineers Inc.

Kang, S. W., and A. P. Meliopoulos (2002). Contingency Selection Via Quadratized Power Flow Sensitivity Analysis. 2002 IEEE Power Engineering Society Summer Meeting, July 21, 2002 - July 25, 2002, Chicago, IL, United states, Institute of Electrical and Electronics Engineers Inc.

Kim, Y., B. F. Spencer, J. Song, A. S. Elnashai, and T. Stokes (2007). Seismic Performance Assessment of Interdependent Lifeline Systems, Mid-America Earthquake Center**:** 39.

Krumpholz, G. R., K. A. Clements, and P. W. David (1980). "Power System Observability: A Practical Algorithm Using Network Topology." IEEE transactions on power apparatus and systems **PAS-99**(4): 1534-1542.

Laprie, J.-C., K. Kanoun, and M. Kaaniche (2007). Modelling Interdependencies between the Electricity and Information Infrastructures. 26th International Conference on Computer Safety, Reliability, and Security, SAFECOMP 2007, September 18, 2007 - September 21, 2007, Nuremberg, Germany, Springer Verlag.

Leelardcharoen, K. (2005). Interdependent Performance of Power Ans Water Networks. Student Leadership Council Online Magazine. Urbana, Il, Mid-America Earthquake Center. **5:** 1-23.

Leelardcharoen, K., L. Dueñas-Osorio, J. I. Craig, and B. J. Goodno (2011). Seismic Fragility Analysis of Telecommunication Systems. 11th International Conference of Applications of Statistics and Probabilistic in Civil Engineering, ETH Zurich, Switzerland, CRC Press.

Lemaréchal, C., A. Ouorou, and G. Petrou (2010). "Robust Network Design in Telecommunications under Polytope Demand Uncertainty." European Journal of Operational Research **206**(3): 634-641.

Li, W. (2005). Risk Assessment of Power Systems: Models, Methods, and Applications Piscataway, NJ, IEEE Press.

Liu, K. S. (1980). "Direct Distance Dialing: Call Completion and Customer Retrial Behavior." The Bells System Technical Journal **59**(3): 295-311.

MAEC. (2006). "Research Projects and Goals." Retrieved March 18, 2011, from http://mae.cee.uiuc.edu/projects/research_projects.html.

Marigold Technologies. (2007). "Central Office Lookup Tools." Retrieved October, 13, 2007, from http://www.marigoldtech.com/lists/co.php.

McGuire, R. K. (1995). "Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop." Bulletin of the Seismological Society of America **85**(5): 1275-1284.

McGuire, R. K. (2001). "Deterministic V.S. Probabilistic Earthquake Hazards and Risks." Soil Dynamics and Earthquake Engineering **21**: 377-384.

Melchers, R. E. (1999). Structural Reliability Analysis and Prediction. London, John Willey & Sons.

Meliopoulos, A. P. S. (2005). Power System Modeling, Analysis, and Control. Atlanta, Georgia.

Meliopoulos, A. P. S., G. J. Cokkinides, F. Galvan, and B. Fardanesh (2006). Gps-Synchronized Data Acquisition: Technology Assessment and Research Issues. 39th Annual Hawaii International Conference on System Sciences, HICSS'06, January 4, 2006 - January 7, 2006, Kauai, HI, United states, Institute of Electrical and Electronics Engineers Computer Society.

Min, P. S. H., Manjunath (1990). "End-to-End Planing Model for Optimal Evolution of Telecommunication Network." 200-206.

Mohagheghi, S., R. H. Alaileh, G. Cokkinides, and A. P. Sakis Meliopoulos (2007). Distributed State Estimation Based on the Supercalibrator Concept - Laboratory Implementation. 2007 iREP Symposium- Bulk Power System Dynamics and Control - VII, Revitalizing Operational Reliability, August 19, 2007 - August 24, 2007, Charleston, SC, United states, Inst. of Elec. and Elec. Eng. Computer Society.

Monticelli, A., and F. F. Wu (1985a). "Network Observability: Identification of Observable Islands and Measurement Placement." IEEE transactions on power apparatus and systems **PAS-104**(5): 1035-1041.

Monticelli, A., and F. F. Wu (1985b). "Network Observability: Theory." IEEE transactions on power apparatus and systems **PAS-104**(5): 1042-1048.

Mori, H., and S. Tsuzuki (1991). "A Fast Method for Topological Observability Analysis Using a Minimum Spanning Tree Technique." IEEE Transactions on Power Systems **6**(2): 491-500.

National Science Foundation. (1997). "Nsf Funds Earthquake Research Centers in Calfornia, Illinois and New York."   Retrieved June 1, 2008, from http://www.nsf.gov/news/news_summ.jsp?cntn_id=102833.

Newman, D. E. N., Bertrand; Dobson, I.; Lynch, V. E.; Gradney, Paul (2005). Risk Assessment in Complex Interacting Infrastructure Systems. 38th Hawaii International Conference on System Sciences.

Nojima, N., and H. Kameda (1991). Cross-Impact Analysis for Lifeline Interactions. The Third United States Conference on Lifeline Earthquake Engineering, Los Angeles, CA, USA, Publ by ASCE, New York, NY, USA.

Noll, A. M. (1998). Introduction to Telephones and Telephone Systems. Los Angeles, California, Artech House.

O'Reilly, G., A. Jrad, R. Nagarajan, T. Brown, and S. Conrad (2007). Critical Infrastructure Analysis of Telecom for Natural Disasters. Networks 2006: 12th International Telecommunications Network Strategy and Planning Symposium, November 6, 2006 - November 9, 2006, New Delhi, India, Institute of Electrical and Electronics Engineers Inc.

O'Reilly, G., B. Uzunalioglu, S. Conrad, and W. Beyeler (2005). Inter-Infrastructure Simulations across Telecom, Power, and Emergency Services. 5th International Workshop on Design of Reliable Communication Networks 2005, October 16, 2005 - October 19, 2005, Island of Ischia, Naples, Italy, Inst. of Elec. and Elec. Eng. Computer Society.

O'Reilly, G. P., D. J. Houck, E. Kim, T. B. Morawski, D. D. Picklesimer, and H. Uzunalioglu (2004). Infrastructure Simulations of Disaster Scenarios. Networks

2004 - 11th International Telecommunications Network Startegy and Planning Symposium, June 13, 2004 - June 16, 2004, Vienna, Austria, VDE Verlag GmbH.

Obal, W. D. I. S., William H. (1993). "A Model-Based Foundation for Evaluation Large Scale Telecommunication Systems."

Population Division, U. S. C. B. (2009). "Geographic Comparison Table, Tennessee by County." Retrieved June 26, 2009, from http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US47&-_box_head_nbr=GCT-T1&-ds_name=PEP_2009_EST&-_lang=en&-redoLog=false&-format=ST-2&-mt_name=PEP_2009_EST_GCTT1_ST2&-_sse=on.

Power Systems Engineering Research Center (2005). Comprehensive Power System Reliability Assessment. A. P. Meliopoulos.

President's Commission on Critical Infrastructure Protection (1998). Presidential Decision Directive 63 (Pdd-63) on Critical Infrastructure Protection. The White House. Washington D. C.

Rinaldi, S. M. (2004). Modeling and Simulating Critical Infrastructures and Their Interdependencies, Big Island, HI., United States, Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ 08855-1331, United States.

Rinaldi, S. M., J. P. Peerenboom, and T. K. Kelly (2001). "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies." IEEE Control Systems Magazine **21**(6): 11-25.

Rosato, V., L. Issacharoff, F. Tiriticco, S. Meloni, S. De Porcellinis, and R. Setola (2008). "Modelling Interdependent Infrastructures Using Interacting Dynamical Models." International Journal of Critical Infrastructures **4**(Compendex): 63-79.

Schiff, A. J. (1995). Northridge Earthquake Lifeline Performance and Post-Earthquake Response. Technical Council on Lifeline Earthquake Engineering, ASCE**:** 1-329.

Schiff, A. J. (1997). Post-Earthquake Investigation of Lifelines. Reston, VA, ASCE.

Schiff, A. J. (1999). "Hyogoken-Nanbu (Kobe) Earthquake of January 17, 1995 - Lifeline Performance." Technical Council on Lifeline Earthquake Engineering Monograph(14): 1-332.

Schiff, A. J. (2004). "Documenting Damage, Disruption, Interdependencies and the Emergency Response of Power and Communication Systems after Earthquakes." International Journal of Critical Infrastructures **1**(1): 100-107.

Schiff, A. J., and A. Tang (2000). Chi-Chi, Taiwan, Earthquake of September 21, 1999 : Lifeline Performance Reston, VA, American Society of Civil Engineers.

Shimomura, T., and T. Takada (2004). Estimation for Seismic Ground Motion Using Macro-Spatial Correlation Model. 3rd Asian-Pacific Symposium on Structural Reliability and Its Applications

Shinozuka, M., A. Rose, and R. T. Eguchi (1998). Engineering and Socioeconomic Impact of Earthquake - an Analysis of Electricity Lifeline Disruptions in the New Madrid Area. Buffalo, NY, Multidiciplinary Center for Earthquake Engineering Research Center.

Snow, A. P., G. R. Weckman, and K. Chayanam (2006). "Modeling Telecommunication Outages Due to Power Loss." International Journal of Industrial Engineering : Theory Applications and Practice **13**(Compendex): 51-60.

Song, J., and S.-Y. Ok (2009). "Multi-Scale System Reliability Analysis of Lifeline Networks under Earthquake Hazards." Earthquake Engineering & Structural Dynamics: n/a-n/a.

Stefopoulos, G. K., R. H. Alaileh, G. J. Cokkinides, and A. P. Sakis Meliopoulos (2007). On Three-Phase State Estimation in the Presence of Gps-Synchronized Phasor Measurements. 2007 39th North American Power Symposium, NAPS, September 30, 2007 - October 2, 2007, Las Cruces, NM, United states, Inst. of Elec. and Elec. Eng. Computer Society.

Takada, T., and T. Shimomura (2004). Macro-Spatial Correlation Structural of Seismic Gound Motion of the 1999 Chi-Chi Earthquake. 9th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability.

Tang, A. K. (1998). Factors Affecting Congestion (Change of Traffic Pattern) of Telecommunication Systems and Networks. The Workshop on Performance

Criteria for Telecommunication Services Under Earthquake Conditions, Stanford University, Stanford, California.

Tang, A. K., and A. J. Schiff (1996). Method of Achieving Improved Seismic Performance of Communications Systems. New York, NY, ASCE.

Tao, Y., and A. P. S. Meliopoulos (2011). Optimal Power Flow Via Quadratic Power Flow. 2011 IEEE/PES Power Systems Conference and Exposition, PSCE 2011, March 20, 2011 - March 23, 2011, Phoenix, AZ, United states, IEEE Computer Society.

Taylor, C. E. (2002). Acceptable Risk Processes : Lifelines and Natural Hazards. Reston, VA, American Society of Civil Engineers.

The Associated Press. (2009). "2.8 Earthquake in Memphis, Tn." Retrieved December 12, 2009, from www.volunteertv.com/news/headlines/37746299.

U.S. Census Bureau. (2009). "2005-2009 American Community Survey 5-Year Estimates." Retrieved August 15, 2011, from http://factfinder.census.gov/servlet/ACSSAFFFacts?_event=&geo_id=01000US&_geoContext=01000US&_street=&_county=&_cityTown=&_state=&_zip=&_lang=en&_sse=on&ActiveGeoDiv=&_useEV=&pctxt=fph&pgsl=010&_submenuId=factsheet_1&ds_name=DEC_2000_SAFF&_ci_nbr=null&qr_name=null&reg=null%3Anull&_keyword=&_industry=.

USEIA. (2009). "Electricity Net Generation: Electric Power Sector, 1949-2009." Retrieved July 28, 2011, from http://www.eia.gov/totalenergy/data/annual/txt/ptb0802b.html.

USGS. (2009, August 31, 2009). "2009 Psha Interactive Deagregation." Retrieved July 20, 2011, from http://eqint.cr.usgs.gov/deaggint/2008/documentation.php?PHPSESSID=cqklvd22rm7pa958kv09841g15

Wang, M., and T. Takada (2005). "Macrospatial Correlation Model of Seismic Ground Motions." Earthquake Spectra **21**(4): 1137-1156.

Werner, S. D., D. K. Ostrom, and C. E. Taylor (2002). Planning of Unified Lifeline Risk/Reliability Platform for Seismic Risk Decision Making. Richmond, California, Pacific Earthquake Engineering Research Center (PEER)**:** 48.

Wong, F. (1998). Concentration, System Modeling, and Telecommunications Performance. The Workshop on Performance Criteria for Telecommunication Services Under Earthquake Conditions, Stanford University, Stanford, California.

Yang, F., A. P. S. Meliopoulos, G. J. Cokkinides, and G. Stefopoulos (2007). "A Bulk Power System Reliability Assessment Methodology." European Transactions on Electrical Power **17**(4): 413-425.

Yang, F., A. P. S. Meliopoulos, G. J. Cokkinides, and G. K. Stefopoulos (2006). Contingency Simulation Using Single Phase Quadratized Power Flow. 2006 9th International Conference on Probabilistic Methods Applied to Power Systems, PMAPS, June 11, 2006 - June 15, 2006, Stockholm, Sweden, Inst. of Elec. and Elec. Eng. Computer Society.

Yao, B.-H., L.-L. Xie, and E.-J. Huo (2004). "Comprehensive Study Method for Lifeline System Interaction under Seismic Conditions." Acta Seismologica Sinica English Edition **17**(2): 211.

VITA

Kanoknart Leelardcharoen was born in Chiang Mai, Thailand in 1980. He graduated Bachelor of Engineering in Civil Engineering from Chulalongkorn University in Bangkok, Thailand in 2002. Soon after graduating, he joined an international company as a civil/structural engineer involved in the design of a nuclear power plant in a high seismic zone. After practicing engineering for two years, he came to Georgia Institute of Technology in pursuing his graduate studies. Kanoknart enrolled as a master student in the School of Civil and Environmental Engineering in the fall of 2004. During his master program, he joined a group of graduate students who conducted research in earthquake engineering for the Mid-America Earthquake Center (MAEC). His research focused on seismic performance assessment of interdependent infrastructure systems. In 2005, He earned his Master's degree and decided to continue his graduate studies and research work with the institute. He started his doctoral program in the spring of 2006. His current research is focusing on interdependencies between critical infrastructures and telecommunication systems.