PNNL-28598

Coordination of Transmission, Distribution and Communication Systems for Prompt Power System Recovery after Disasters

Report – Grid and Communication Interdependency Review and Characterization of Typical Communication Systems

March 2019

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A. Tbaileh
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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Pacific Northwest National Laboratory
Richland, Washington 99352

Acknowledgments

The project is supported by funding from the U.S. Department of Energy (DOE) Office of Electricity as part of Advanced Grid Research & Development program. The Pacific Northwest National Laboratory project team thanks Dr. Ali Ghassemian from the DOE Office of Electricity for his continuing support, help, and guidance.

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1.0 Introduction

While progress has been made in increasing the resilience of power systems, major system disturbance and large-scale blackout risks still exist and are inevitable. Seven major blackouts in U.S. history lasted between 10 and 50 hours [1]. Figure 1.1 provides a comparison and synthesized statistical distribution of major outages in terms of normalized duration and percent of total load not served [2]. Power outages cost billions of dollars during those major events in the United States [3], and the cost increases exponentially as the duration of outage increases. The 2017 Puerto Rico power grid blackout became the largest in U.S. history in terms of customer hours. More importantly, the painfully slow recovery reminded the whole industry of the urgent need for better long-term and short-term grid planning as well as quicker restoration with necessary resources [3].

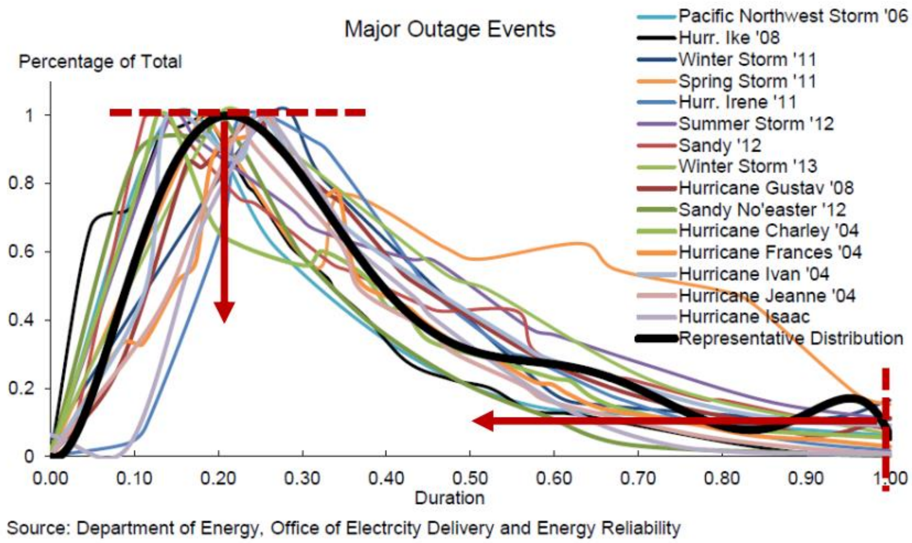


Figure 1.1. Major Outage Events [2]

Following an outage, it is critical to restore the system back to normal operating conditions quickly and efficiently. Communication networks are integral to modern power grid operations and are becoming increasingly critical as grid dynamics speed up and as more controls become closed-loop in form. Existing operation and control (particularly remote control) of power systems relies heavily on communication systems such as supervisory control and data acquisition (SCADA) systems. In 2015, Pacific Northwest National Laboratory published a formal technical report, “The Emerging Interdependence of the Electric Power Grid & Information and Communication Technology” [4], that examines the implications of emerging interdependencies between the electric power grid and Information and Communication Technology (ICT). Major findings of this report were highlighted as follows:

1. Electricity and ICT networks have become increasingly interdependent due to advances in sensor, network, and software technologies that enable more cost-effective means to interconnect grid devices. There is a strong need to increase wide-area situational awareness to coordinate both normal operation and restoration in a more dynamic grid resulting from increasing variable energy resources (VER) and distributed energy resources (DER).

2. The complexity of the utility industry has given rise to complexity in the supporting communication networks. There are two main dimensions: (i) multiple network types and a mix of private and public

infrastructure to support varying operational and security requirements; (ii) single-purpose networks with different organizational owners for different systems such as SCADA, AMI, voice, tele-protection, inter-control center communications, etc.

3. The Gridblocks Architecture (see Figure 1.2.) highlights this relationship between T & D & C networks, thus illustrating the combined system complexity.

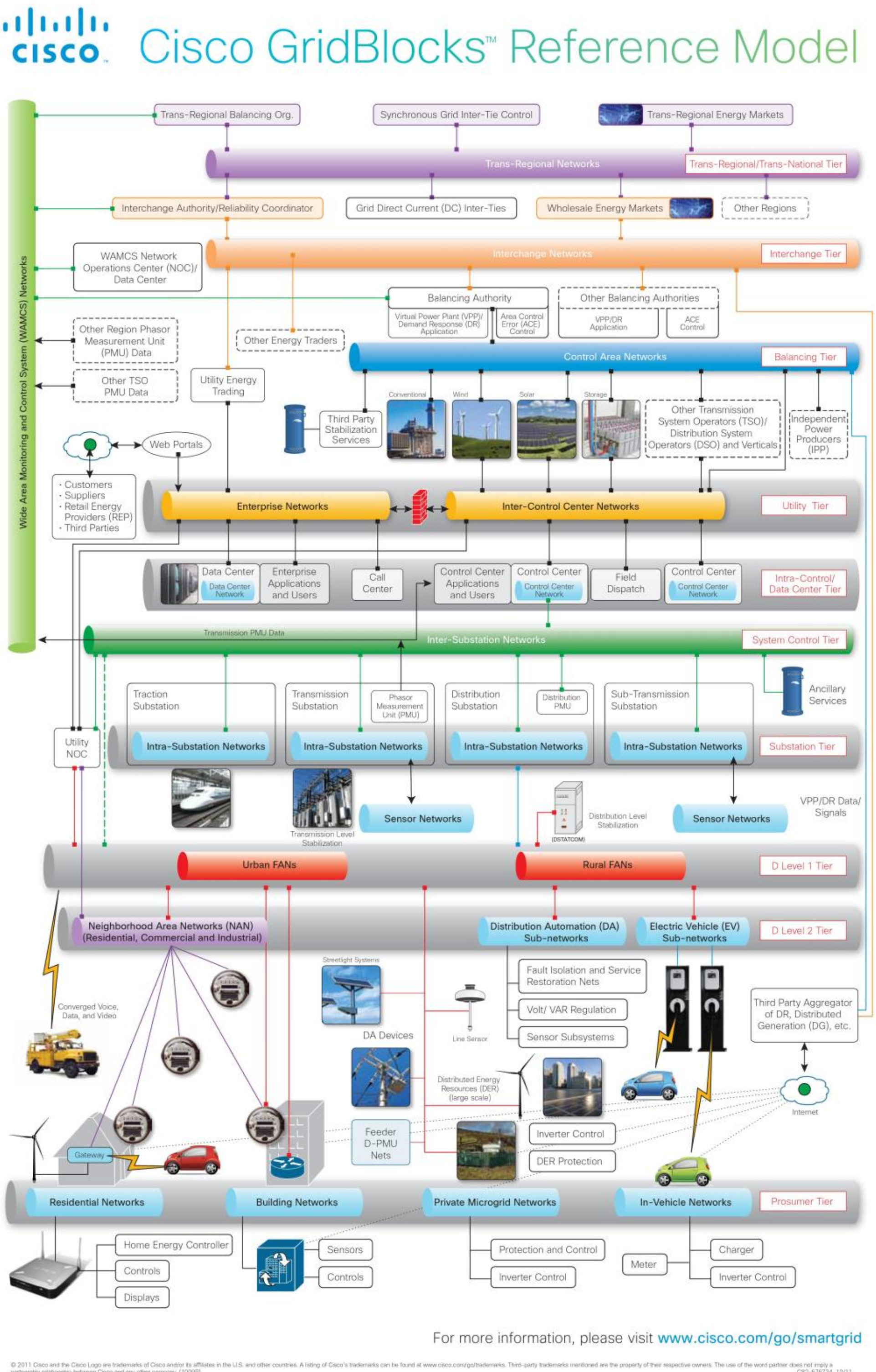


Figure 1.2. CISCO Gridblocks Reference Model [4]

Utilities are increasingly adopting data analytics in their operational systems to drive efficiency, reliability, and more informed decisions. These analytics are enabled by the data-rich environments that the increasingly intelligent devices and sensors provide. The data analytics that are included in the utility operational platform could provide different perspectives on the interdependency between systems, as well as interface requirements. Southern California Edison developed a smart grid reference architecture which classifies analytics in terms of logical relationships between data sources and usage [4]. In the process, the utility categorized analytics into six categories and end uses into eight categories, as shown in Figure 1.3. From this diagram, the number and complexity of the interfaces needed to support emerging data analytics are evident. This further emphasizes the dependence of communication networks that provide these connections to the utility operational systems.

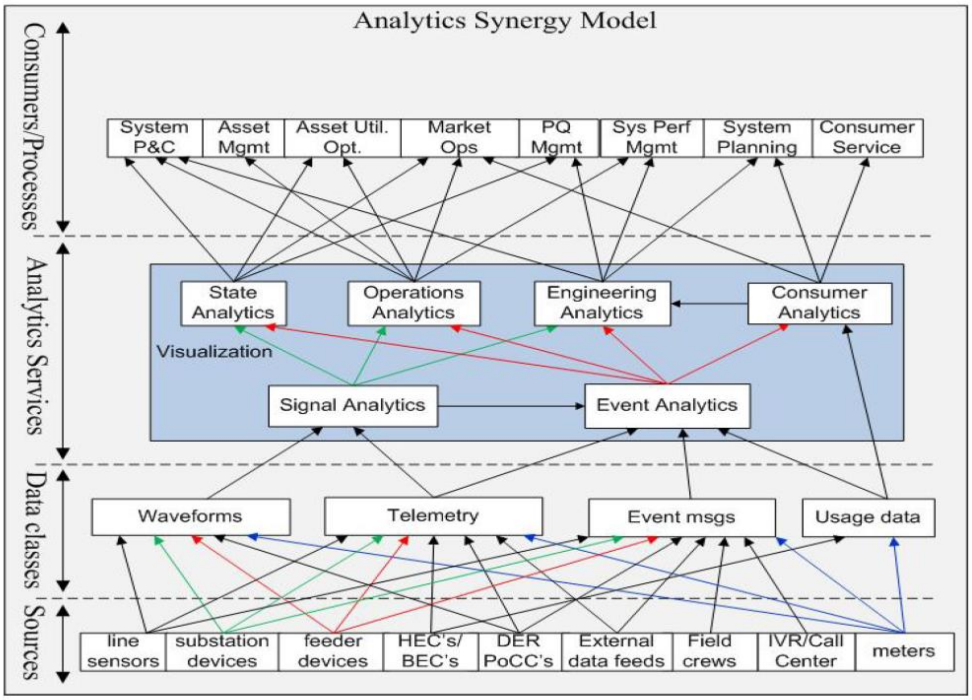


Figure 1.3. SCE Analytics Classification Schema

It is clear that the power grid's dependence on communication systems is only increasing due to the need for coordination and situational awareness across the complex structure of entities and systems that comprise the grid. The benefits of including communication systems in restoration planning and implementation efforts include:

1. Coordination of communication system restoration efforts in accordance with real-time situational awareness priorities of T&D operations. By ensuring resources are invested in highest value links first, overall restoration efficiency can be increased.

2. Ensuring a consistent view of the wide-scale grid state. With network connectivity restored to critical SCADA, devices, and other systems, and through appropriate sharing of key data, the various organizations involved in system restoration can minimize the risk of incongruent actions.

3. Providing timely updates to the various stakeholders involved so that decisions can be made in a timely and consistent manner.

4. Enabling broader options for distribution resources to participate in overall restoration efforts through more timely communication to distributed resource controllers or operators.

Therefore, it is essential to consider communication system restoration along with the grid restoration scheme in post-disaster/emergency system restoration. Unfortunately, the interdependence and support of communication systems have barely been considered in existing restoration plans in the industry. For this, there are three main reasons: (1) limited focus on the interdependence between the physical grid and the communication system among grid operators and communication system operators; (2) lack of established models for the communication systems used for power system control and operation; (3) lack of an adequate integrated decision-support tool. These limitations and the challenging task of individual system restoration limit the ability of grid and communication system operators to expand coordination beyond systems for which they are responsible.

In this report, we first review communication technologies and systems for the grid as well as their roles (impact) in restoration, aiming to fill the knowledge gap of interdependence between the physical grid and the communication system. Then we review methods of creating synthetic power system models and proposed improvements to one potential method that will be considered in the next phase of the project. Lastly, we identify several key characteristics and metrics of typical communication systems based on analysis of an actual communication system. This provides input for developing or generating synthetic communication systems.

2.0 Interdependency between Power Grids and Communication Networks: A Review

In this section, the PNNL research team provides a comprehensive literature review of existing research regarding the interdependency of grid and communication networks. We noticed that transmission and distribution systems are treated separately or not considered simultaneously in the existing grid and communication interdependency studies. That is, either transmission and communication, or distribution and communication networks are considered in existing research efforts. Thus, subsections below are organized in such a way to reflect current categorizations.

2.1 Transmission and Communication Networks

One of the most important communication systems supporting the power industry is SCADA. Existing operation and control (particularly remote control) of transmission systems relies heavily on SCADA. SCADA has been used to collect measurements from field sensors, such as programmable logic controllers (PLCs) and remote terminal units (RTUs). Moreover, it enables the system operators to interact with various control equipment and devices through human machine interface (HMI) or advanced control functions in the control room. Inter-control center protocol (ICCP) has been the dominant communication protocol for data exchange occurring between multiple control center energy management systems (EMS), power plant distributed control systems (DCS), SCADA in transmission systems, and distribution systems. Below are some reviews of existing work where interdependency or integration of transmission and communication networks has been considered.

In [5], researchers from PNNL studied the cyber vulnerability of power system substations. The cyber vulnerability model was formulated based on the Petri net model, a mathematical tool that can be used to perform probabilistic analysis of cyber events. A typical substation network model was considered in this study as a local area network (LAN) and further integrated into the IEEE 57-bus system as a wide area network (WAN). There are no physical characteristics of the communication network considered in this study, and the simulation is limited to the mathematical model for stochastic petri net. Thus, the integration of the transmission system and communication network in this research is tailored for a cyber vulnerability study.

In 2008, a researcher from the Italian ENEA Casaccia Research Center investigated the potential impacts on the internet network for research (GARR) backbone during 2003 Italian electrical grid failures [6]. For the network modeling, an undirected GARR graph has been developed for a GARR dedicated to linking universities and research institutions. All communication nodes are considered as an autonomous system (AS-level) router with packet forwarding and receiving functions. A prototype model for Italian high-voltage (380 kV) electrical transmission network has been developed to represent its topology with an undirected graph. A suitable "Quality of Service" (QoS) of the electrical network has been defined as a function of the pre-defined perturbation (power system contingencies) considering DC power flow solutions. The interdependency of the two networks has been modeled based on the hypothesis that nodes geographically close are functionally related; modeling was performed by correlating geographical positions manually. Moreover, the dynamic response between two networks has been linked by a sufficient power dispatch at one electric power node and an on/off status of one communication network node. Simulation results indicated that a fault in the electrical grid could cause amplified impact on the communication network due to interdependency.

Another grid and communication interdependence model for Italy was developed [7] to evaluate the cascading failure. A framework has been developed to analyze the interdependency based on the information of a 2003 blackout in Italy, in which an iterative process was proposed to mimic the cascading failure.

The last decade has seen growing interest in applying GPS-synchronized phasor measurements from phasor measurement units (PMUs)) into control room applications. PMUs has higher and stricter requirements for communication systems. The potential impact of the communication networks for PMUs on the grids has been evaluated to ensure wide-area situational awareness. In [8], a sample communication network of the California Power Grid has been analyzed to minimize the network cost when designing the communication network for both the substation and wide area IEC 68150 standard is adopted for the substation network design. Guidelines from the North American Synchro-Phasor Initiative (NASPI) are adopted for the synchrophasor information-sharing mechanism among regional power grid control centers Tree and mesh network structures for the communication systems have been considered. Comparative numerical results show that the reliable mesh design has advantages in terms of the number of links and total link distance needed. Electric power reliability is quantified in terms of availability of power to the customer; in contrast, communication network reliability is usually discussed in terms of 2-terminal, k-terminal, or all-terminal reliability [9]. The first is the most basic case, where a sender *s* and a receiver *t* can communicate with each other with a certain guarantee. The k-terminal case is when a set of *k* nodes in the network can communicate. Finally, all-terminal refers to the case when all nodes can communicate with all other nodes.

The interdependency of the power system and communication has also been considered in bulk power system restoration research [10]. The dependency between the electrical network and the communication network during restoration is modeled through restoration constraint on the activation of each node, which requires restoring each node for both networks. We believe this is a very strong assumption regarding the interdependency that is not applicable for most real-world grid and communication systems. The formulation is simplified as topology restoration, with detailed physical constraints for the electrical network but only an on/off model for the communication network.

Researchers from Lawrence Livermore National Laboratory and multiple universities studied the transmission and communication system interdependency from cascading failure perspective. [11]. In particular, the electric power and communication networks have been studied to evaluate the potential impact from cascading failures, which could begin in either network and propagate into other networks. Though the cascading failure model might be significantly different from the restoration strategy design, it shows the close coupling between different networks, especially when both networks are inherently tied to geography; as a result, the topologies of both networks are often highly correlated. Three different power communication coupling patterns were considered to represent the failure propagation of one node between two networks. Simulation results suggest that robustness can be enhanced by interconnecting networks with complementary capabilities if modes of internetwork failure propagation are constrained.

2.2 Distribution and Communication Networks

Compared to the bulk power and communication systems, the interdependence on distribution system and communication networks is historically weak, mainly because there are much less communication requirements for operating traditional distribution. Up to date, the communication networks in the distribution systems are to send the status of the switches and RTUs to utilities' control rooms and allow the operators in the control rooms to send signals to the switch to change the configuration. The original design of distribution networks did not account for two-way power flows, dynamic demands, or reliable two-way communication.

The distribution systems operation has been changing in recent years. Many power distribution systems have been challenged by more distributed, intermittent energy sources, such as solar and wind. In some scenarios, utility operators and control systems cannot 'see' nontraditional energy resources, such as rooftop solar, wind turbines, fuel cells, and storage.

To address the challenges, much more real-time data from the DERs and feeders should be accessed by the utility's distribution management system (DMS) to coordinate distributed resources with utility infrastructure, local autonomous controls, and centralized controls [12]. Thus, more sensors have been deployed to monitor the status of the DERs and the feeders; in this context, more advanced, two-way communication systems to transmit a large volume of data between the grid edge and the control rooms are needed.

Five different communication architectures have been evaluated to meet the complex requirement from Smart Grid in [13] they are given as follows:

1. **Direct Connected Network:** the simplest architecture, each smart meter has a dedicated connection to the data hub inside a substation, often referred to as a "hub and spoke" network. No aggregator is present, and the communication links may be wired or wireless. The effectiveness of this architecture depends on the size of the neighborhoods involved and data volume/rate.
2. **Network with Local Access Aggregators:** aggregating smart meter data at a neighborhood level before transmitting them to the data hub inside a substation. It is based on the Neighborhood Access Network (NAN) and reduces data rate and bandwidth requirements, as well as total number of direct connections to the substation.
3. **Network with Interconnected Local Access Aggregators:** Besides the proposed structure in 2), this architecture connects adjacent NAN networks with interconnected trunks. This could facilitate effective sharing of distributed energy resources (DER) available in adjacent neighborhoods during an islanding event.
4. **Mesh Network:** Besides the proposed structure in 2), this architecture leverages wireless radio frequency (RF) technology to connect smart meters within a neighborhood. Due to cyber-security concerns, a hybrid connection with wired and wireless technology is preferred.
5. **Internet Cloud (Internet of Things):** this architecture facilitates the use of Cloud services to gather, store, and analyze huge volumes of data and make it available for those with appropriate levels of access.

There are several metrics that should be adopted for communication network performance; they are:

1. Bandwidth or Data Rate;
2. Latency;
3. Security;
4. Scalability;
5. Resilience;
6. Reliability;
7. Interoperability;
8. Distance Reach;

9. Existing Geographic Coverage;
10. Cost of Ownership.

Three different communication technologies, including wired broadband technology, Power Line Communication (PLC), and Long-Term Evolution (LTE) have been evaluated based on the abovementioned algorithms, with corresponding physical characteristics. Recommendations could be given based on the algorithm requirement and communication technology characteristics.

The efforts reviewed above are mainly focusing on how communication systems should be designed and developed to support the distributions with high penetration of DERs in the near future. Similar to the ongoing research on the interdependency between power transmission and communication networks, researchers also investigated the application of graph theory and complex network analysis in the power distribution network. In [14], the information/energy transmitted between the electrical and communication nodes has been categorized into four types:

1. Electrical node to another electrical node: representing normal power flow in power systems;
2. Communication node to another communication node: representing data flow between routers;
3. Electrical node to one communication node: representing energy supply for communication node;
4. Communication node to one electrical node: representing monitoring/control actions issued by operators.

To accommodate multiple infrastructures modeling with an adjacency matrix, a complex-value has been incorporated into the adjacency matrix to allow modeling communication and power distribution infrastructures in different spaces while preserving their characteristics. With this transformation, all the nodes in both networks could be considered in the same adjacency matrix, and conventional graph analytics can be applied for further analysis. A typical French Distribution Network has been used for simulation, which includes 14 power-buses, 17 lines, seven distributed generations, nine loads and three transformers HTB/HTA; on the other hand, the communication network involves two routers, one WiMax base station (BS), eight multiplexers, and 26 links including ADSL, PSTN/ISDN, optic fiber and Ethernet technologies, along with a private-owned LAN-GigaEthernet.

The integration of the power systems network and communication has significant impact for grid operation and control, especially when facing natural disasters. Canadian researchers from the University of British Columbia have designed a disaster response planning platform considering the interdependence between grid and communication networks [15]. This platform provides decision support and an interactive simulation environment for planners to evaluate specific scenarios while selecting appropriate control strategies and disaster responses. There are three major components in this platform, which are given as follows:

1. DR-NEP: a web service module that enables different simulators to communicate results to each other via a common enterprise service bus (ESB) and a database;
2. I2Sim: an event-driven, time-domain simulator for modeling infrastructure interdependencies considering resource allocation during a disaster at multiple hierarchical levels;
3. WebSimP: a service-based module to interface with different domain simulators, which in this study are an electrical adapter and telecommunication adapter.

The authors configured a power distribution system, a corresponding SCADA system, and an I2Sim disaster model. The distribution system has 165 buses, 22 circuit breakers and 46 loads, including critical public loads such as hospitals, industrial loads such as water pumping stations, and residential loads.

Correspondingly, the SCADA system has one main control center (MSC), a disaster recovery SCADA center (DRS), 44 remote terminal units (RTUs) in HV substations, and 9 RTUs in MV substations; moreover, all the substations and RTUs in the SCADA system are connected by a proprietary network (DPN) and public backup telecommunication network (PSTN). Different study scenarios have been analyzed considering the top priorities of hospital and water pumping station operation during disasters.

It should be noted that when designing the communication network for power distribution systems, both the physical structure and properties of a communication network should be evaluated thoroughly; moreover, the algorithms that are integrated for DMS should also be evaluated. German researchers have conducted a comparison of three different algorithms in the simulation environment called SiENA [16]. These three algorithms are given as follows:

1. COHDA: a heuristic for completely distributed energy management;
2. Power-Matcher: Multi-Agent System (MAS) approach for market-based supply demand matching;
3. PrivADE: a Privacy-Preserving algorithm for DMS.

Based on the existing research, researchers from the National Renewable Energy Laboratory (NREL) investigated the applicability of different communication technologies for smart grid applications [17]. In general, different technologies, including wireless and wired solutions, could be utilized in NS-3 for the hybrid network architectures. NS-3 is a discrete-event network simulator for Internet systems, targeted primarily for research and educational use [18]. The communication network could be divided into three layers:

1. Home Area Networks (HAN): can use Zigbee, low-power wireless personal area networks (LoWPAN) and power line communication (PLC); PLC includes broadband PLC and narrowband PLC;
2. Neighborhood Area Networks (NAN): Ethernet cable, WiFi or WiMAX;
3. Wide Area Network (WAN): fiber optics.

Different test cases have been selected to verify the feasibility, scalability, and reliability of hybrid networks with different technologies in the context of designing an appropriate architecture for the coordination of DER and energy storage systems (ESS). The attributes and parameters of Open System Interconnection (OSI) layers have been reviewed for different technologies for smart grid applications, in which average network latency and average packet size were used as metrics for system quality of service (QoS).

With the reviews above, existing distribution and communication interdependence research can be summarized as follows:

1. Most research has been focused on identifying appropriate communication systems to support distribution operations and increasing DER. Coordination in normal operations or in recovery across the two networks has not received much attention.
2. Research in interdependence during restoration efforts has been limited and focused on simulations to drive improvements in the planning stage of recovery efforts.

2.3 Communication Model Review

In the last two subsections, we reviewed researches on grid and communication interdependency. To support the task of developing synthetic communication models for coordinated restoration studies in this project, in this section, our review is intended to cover communication models in a general sense. Indeed, some of the literature we review will not propose new generative models in themselves, but rather discuss critical aspects of the communication modeling process. Other work we discuss may propose standalone communication models at varying levels of abstraction (from fully specified, operational systems, to completely abstract, topology-focused graph models) or only describe communication models in relation to coupled communication-power systems. As these topics are all interrelated, our goal in this section is to take a broad overview of the work considered.

A summary has been generated to provide an overview of 12 existing research models; the common attributes shown in those models are categorized to reflect the interdependence of multiple networks, including power system transmission systems, power system distribution systems, the communication network, and, more importantly, the modeling "depth" in each communication model. Here the "depth" indicates the level of modeling details for the communication network, which includes the following three levels:

1. Topology of communication network;
2. Physical characteristics of communication network;
3. QoS of communication network.

Besides the abovementioned three levels, there are two important attributes of a communication network model needed to represent the basic modeling approach, which are:

1. Delay modeling;
2. Modeling environment/software.

The PNNL research team performed a comprehensive literature review; the results and corresponding conclusions are presented in the following subsections.

2.3.1 Inter-dependency Review for Different Networks

For the 13 research models that we have reviewed, the inter-dependency among different networks has been considered. However, some of the research only considers a portion of the power systems, such as just the transmission grid or distribution grid. Table 2.1. lists the detailed analysis through different perspectives of inter-dependency. Although a communication model has been considered in all studies, only one [10] evaluates power system restoration; even so, its focus is on the transmission system, not including the distribution system. Similarly, there is only one research work that examines T & D & C inter-dependency, but not specifically for restoration. Therefore, there is clearly a gap within the research community of not performing a holistic analysis on power system restoration based on the T & D & C network integrated study.

Table 2.1. Inter-dependency Review for Different Networks

Reference	Year of Research	Trans-mission Model	Distri-bution Model	Communi-cation Model	T & C Inter-dependency	D & C Inter-dependency	T & D & C Inter-dependency	Restoration
[6]	2008	Yes	No	Yes	Yes	No	No	No
[7]	2010	Yes	No	Yes	Yes	No	No	No
[13]	2013	No	Yes	Yes	No	Yes	No	No
[14]	2013	No	Yes	Yes	No	Yes	No	No
[15]	2013	Yes	Yes	Yes	Yes	Yes	Yes	No
[5]	2014	Yes	No	Yes	Yes	No	No	No
[8]	2016	Yes	No	Yes	Yes	No	No	No
[10]	2017	Yes	No	Yes	Yes	No	No	Yes
[11]	2017	Yes	No	Yes	Yes	No	No	No
[16]	2017	No	Yes	Yes	No	Yes	No	No
[12]	2018	No	Yes	Yes	No	Yes	No	Yes
[17]	2018	No	Yes	Yes	No	Yes	No	No
[18]	2018	No	Yes	Yes	No	Yes	No	No

2.3.2 Review of Attributes in Communication Network Modeling

It has been shown that much existing research considers the communication model; these efforts have set corner stones for the inter-dependency studies of the power system and communication networks. It should be noted that those communication network modeling efforts have been limited by the research scope or the study scenarios. As a result, the modeling "depth" in each communication model might be different, and various features of the communication models have been tailored or customized to fulfill the requirements from the grid side. Here the "depth" indicates the level of modeling details for a communication network, which includes three different levels that are given as follows:

1. Topology of communication network;
2. Physical characteristics of communication network;
3. QoS of communication network.

In Table 2.2, all 13 studies have been analyzed using the abovementioned three levels, as well as the two main attributes that reflect the inter-dependency between power system networks and communication networks. Those two main attributes are given as follows:

1. Node mapping method among different networks;
2. Node constraint logic among different networks.

Using the three modeling levels and two main attributes, we performed comprehensive review of all 13 models and demonstrated that they vary from each other. Therefore, a generic methodology has not been proposed to systematically evaluate the impact of interdependency among different networks, especially when considering the impact during power system restoration.

Observations from **Error! Reference source not found.** could provide some insights regarding the xisting progress on communication network modeling within the grid context, which are:

1. Topology analysis is popular and almost included in every research model;
2. Limited research for power system distribution networks considers the physical characteristics of the communication network, while none of the power system transmission networks consider it. One exception is that the PMU network, which is usually considered as a separate communication network for utilities due to its late emergence compared to the SCADA network;
3. Limited research considers the QoS when modeling a communication network; they might vary significantly from each other due to the broad definition of QoS;
4. The inter-dependency among different networks has been realized through node mapping. This method is very popular and used by almost all research teams;
5. Some of the research models provide the description of node constraint logic. Node constraint is based on node mapping; any pair of nodes that is mapped in power system networks and communication networks could impact each other through pre-defined logic to propagate their current status to different networks through the node mapping method and node constraint logic.

Table 2.2. Review of Attributes in Communication Network Modeling

Reference	Year of Research	Consider Topology in Communication Network	Consider Physical Characteristics of Communication Network	Consider QoS in Communication Network	Consider Node Mapping Among Different Networks	Consider Node Constraint Among Different Networks
[6]	2008	Yes	No	Yes	Yes	Yes
[7]	2010	Yes	No	No	Yes	Yes
[13]	2013	Yes	Yes	No	No	No
[14]	2013	Yes	No	No	Yes	Yes
[15]	2013	Yes	Yes	Yes	Yes	Yes
[5]	2014	Yes	No	No	Yes	No
[8]	2016	Yes	Yes	Yes	Yes	Yes
[10]	2017	Yes	No	No	Yes	Yes
[11]	2017	Yes	No	No	Yes	Yes
[16]	2017	Yes	Yes	Yes	Yes	Yes
[12]	2018	N/A	N/A	N/A	N/A	N/A
[17]	2018	Yes	Yes	Yes	Yes	No
[18]	2018	Yes	Yes	Yes	Yes	No

2.3.3 Review of Functions of Communication Network Modeling

Based on the data transmitted by the communication network and the expected function and impact of communication network integration, we provide the comparison for these 13 research models from various aspects, which are given in Table 2.3.

It should be noted that only one study specifically mentioned the industry standards that were adopted when designing and evaluating the communication network, while others failed to provide this information or simply ignored it in their research. Based on the knowledge of the PNNL research team, there are a number of industry standards that need to be complied with by the utility for various applications in power system operation and control. Therefore, a gap exists between the research and utility practice to fully understand the existing industry standards for communication network modeling.

Most communication network modeling efforts focus on the SCADA network, and a limited number of them focus on smart meter data; one concentrates on PMU data transmission. Moreover, only half of the research work takes the communication delay into account, and some of them adopt very simple assumptions for communication delay.

Lastly, the modeling of communication networks has been integrated into all kinds of power system analyses; this indicates the potential impact of communication network modeling on all aspects of power system analysis, especially when facing multi-discipline research and complex system control.

Table 2.3. Review of Function of Communication Modeling

Reference	Year of Research	Consider Industry Standards?	Consider SCADA Data	Consider PMU Data	Consider Smart Meter Data	Consider Delay?	Application Scenario
[6]	2008	No	Yes	No	No	Yes	Critical Infrastructure
[7]	2010	No	Yes	No	No	No	Cascading Failure
[13]	2013	No	Yes	No	Yes	Yes	Concept Design
[14]	2013	No	Yes	No	No	No	Vulnerability Analysis
[15]	2013	No	Yes	No	No	Yes	Natural Disaster Response
[5]	2014	No	Yes	No	No	No	Cyber Security
[8]	2016	Yes	No	Yes	No	Yes	Communication Reliability Enhancement
[10]	2017	No	Yes	No	No	No	Hurricane Restoration
[11]	2017	No	Yes	No	No	No	Cascading Failure
[16]	2017	No	Yes	No	Yes	Yes	Market Signal in DMS Operation
[12]	2018	N/A	Yes	No	Possible	N/A	Automated Restoration in DMS
[17]	2018	No	Yes	No	Yes	Yes	Communication Technology Profiling and Comparison
[18]	2018	No	Yes	No	Yes	Yes	Communication Parameter Calibration

2.3.4 Conclusion and Recommendation for Modeling Communication Network

In the preceding sections, a comprehensive literature review has been performed regarding the communication network modeling of power systems. Based on this review, major conclusions are given as follows:

1. There is clearly a gap for the research community to perform a holistic analysis on the power system restoration based on the T & D & C network integrated study;
2. Topology analysis is popular and included in almost every research model, while the physical characteristics and QoS of communication networks have only been considered by a limited number of researchers;

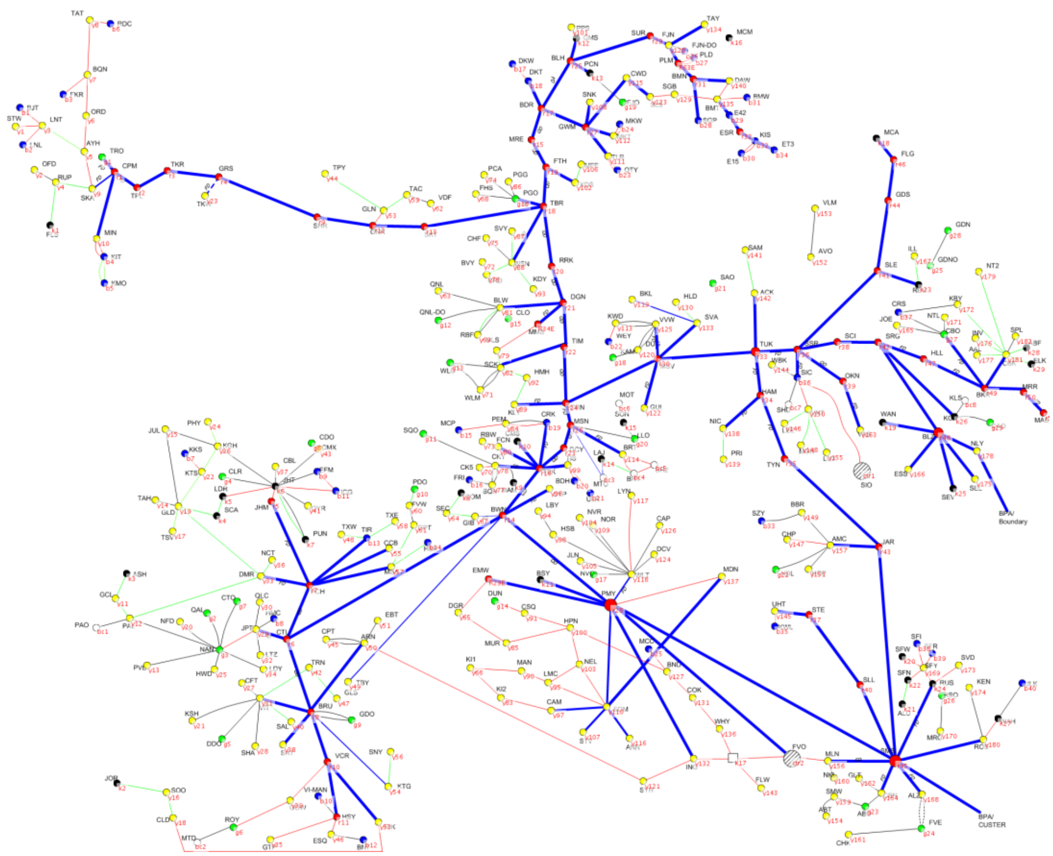
3. Node mapping among different networks is the fundamental method for the inter-dependency study. This method is very popular and used by almost all research teams;
4. Some of the research models provide the description of node constraint logic. The mapped nodes could impact each other through pre-defined logic to propagate their current status to different networks through the node mapping method and node constraint logic;
5. A gap exists between the research and utility practice, preventing complete understanding of the existing industry standards for communication network modeling;
6. The functions of the communication network model can be differentiated by the data the model transmits, and the specific needs of the multi-discipline analysis.

The close interdependence among different networks demonstrates the possible impacts each network can have on the other in state of failures, including cascading failures. Inter-dependence could be reinforced due to cross-system functional dependencies and geographical topology similarities. The literature review shows the great potential for our ongoing project to advance research in this area through novel coordination methods to support power system restoration.

3.0 Characterizing and Developing Communication System Models

3.1 Characterizing Communication Networks: A Realistic Communication Network Example

We consider the topology model of a realistic utility communication system and analyze its underlying graph topology. This network corresponds to a topology available from a presentation to RASRS by Bouacar Diallo and Ralph Barone from BC Hydro [30]. Based on the topology, PNNL research team has extracted the graph connectivity information by using software to parse the graph from the PDF image. The network topology is presented below in **Error! Reference source not found.**, with vertex labels ritten near each vertex in red.



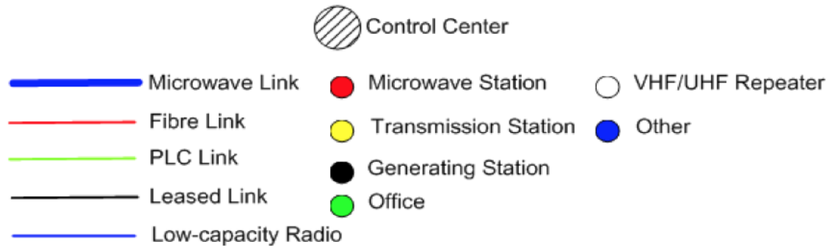


Figure 3.1. Network Topology of a Realistic Communication Network Example

3.1.1 Graph Analytic Metrics

In order to analyze the graph topology of this network, we utilize several analytic tools from network science. We list the metrics we consider below and provide informal definitions of these avoiding notation. We divide these into two categories: global metrics (measurements reflect a property of the graph as a whole) and local measurements (measurement about the vertices or edges of the graph).

Global Metrics:

- **|V|, |E|:** how many vertices and edges there are, respectively.
- **Density:** the ratio of number of edges to vertices. For sparse graphs, this ratio is close to 1; for dense graphs, this ratio is closer to |V|.
- **Diameter:** the most hops you would ever need to take to get from one vertex to another. “Six degrees of separation" means the graph diameter is 6.
- **Average distance**: the average number of hops you need to take to get from one vertex to another.
- **Spectral gap:** the spectral gap constant is a numerical measure between 0 and 1 of graph “bottleneckedness”. A “bottleneck” means one can divide the graph into two parts such that not many edges cross between these two parts, relative to how many edges are in these parts. Smaller values indicate a tighter bottleneck.
- **Clustering coefficient:** a numerical measure between 0 and 1 of how interconnected neighbors of a given vertex are. For instance, if a vertex has 10 neighbors, and every pair of these neighbors are also connected to each other, then the clustering coefficient is maximal and equal to 1. If none of their neighbors are connected, the clustering coefficient is 0. Note that while this is a local, vertex-based measure, we can derive a global measure by averaging over all vertices.
- **Assortativity coefficient:** a numerical measure, between -1 and 1, of the tendency of vertices of a certain degree to connect with vertices of the same degree. If a network is disassortative, then its assortativity coefficient is negative, meaning that high-degree vertices tend to link to low-degree vertices (such as in a star topology).

Local Metrics:

- **Vertex-based.** We consider three different types of graph vertex-centrality measures. Each of these measures how “central" a vertex is within the graph but based on different criteria. Below, we give an informal “definition" of what each metric is attempting to answer.
  - **Betweeness centrality**: how frequently is this vertex on a shortest path between pairs of other vertices?

– **Eigenvector centrality**: if we consider all possible paths (not just shortest paths), how frequently do we encounter this vertex?

– **Closeness centrality:** on average, how close is this vertex (in terms of shortest path length) to other vertices?

- **Edge-based**

  – **Edge betweenness centrality**: how frequently is this edge on a shortest path between pairs of other vertices?

Because the above centrality metrics have different units, it is not helpful to compare them by just reporting the raw scores. Instead, we normalize each centrality score so that its entries sum to 100.

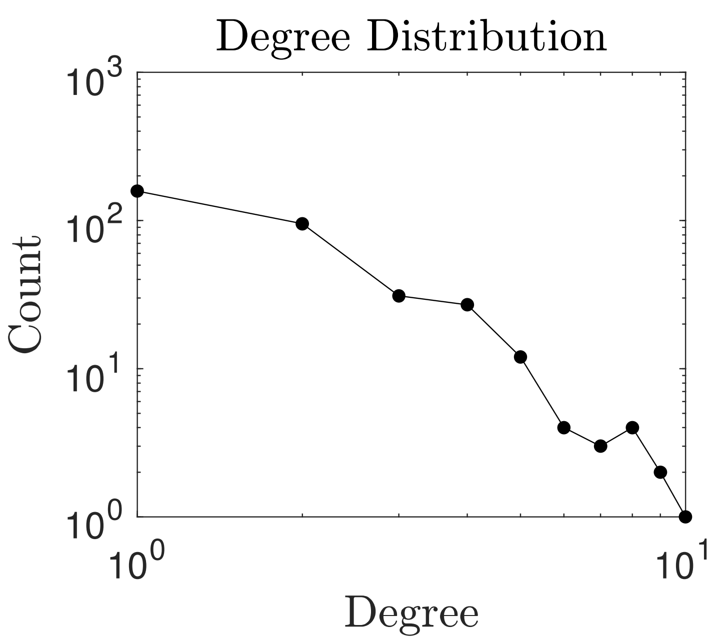
3.1.3 Global Topology Properties of a Realistic Communication Network

We first compute the global scalar metrics we identified earlier, and present these in the table below. We also plot the degree distribution

Table 3.1. Global Scalar Graph Metrics for a Realistic Communication Network

Global Metrics						
$(\|V\|, \|E\|)$	Density	Diameter	Avg. Dist.	Clus. Coeff.	Assortativity	Spectral gap
$(343, 357)$	1.04	28	11.47	0.05	-0.22	1.16 e–3

Table 3.2. Node degree distribution of a Realistic Communication Network



Discussion. The network consists of 343 nodes, which can represent microwave, transmission, or generation stations, offices, VHF/UHF repeater, control centers, or other types of nodes. There are 357 edges, which represent either microwave, fiber, PLC, or leased links. The density value of 1.04 suggests this network is sparse and is more consistent with a linear, or $n \cdot \log(n)$ sparsity relationship, rather than the quadratic value posited by Metcalfe's law. The large diameter and average distance, as well as low clustering coefficient, are all indicative of the tree-like nature of this graph: there are relatively few cycles or cyclic structures in this graph. The spectral gap suggests the graph may be easily partitioned into two roughly equally sized pieces by deleting only a few edges. Finally, turning our attention to the degree distribution, we see that the majority of the vertices in this network—over 200 out of the 343—are incident to either 1 or 2 edges. The largest degree is 10, and the number of vertices for each degree decreases more or less monotonically, as is typical for graphs derived from complex systems.

3.1.4 Local Properties of the a Realistic Communication Network Graph

We present data on the centrality measures with the two tables below. We consider both the extremal centrality values (i.e. which vertices score the highest under each measure) as well as the average behavior for each vertex type.

Table 3.3. The Top 5 Nodes Achieving the Largest Centrality Values for Each Notion of Centrality. The nodes are identified by their label, and their type is also listed.

	Degree		Betweeness		Closeness		Eigenvector	
Rank	*Node*	*Type*	*Node*	*Type*	*Node*	*Type*	*Node*	*Type*
1	`k6`	Generating	`r14`	Microwave	`r16`	Microwave	`r28`	Microwave
2	`r28`	Microwave	`r24`	Microwave	`r23`	Microwave	`y110`	Transmission
3	`y118`	Transmission	`r22`	Microwave	`r14`	Microwave	`y132`	Transmission
4	`r45`	Microwave	`r16`	Microwave	`r26`	Microwave	`r45`	Microwave
5	`y110`	Transmission	`r18`	Microwave	`r24`	Microwave	`y118`	Transmission

Table 3.4. The Average Centrality Values for Nodes of a Given Type a Realistic Communication Network. The average percentiles for those values are also reported. Betweeness, closeness, and eigenvector centrality values are normalized so that the sum total is 100.

	Degree		Betweeness		Closeness		Eigenvector	
Type	*Value*	*Percentile*	*Value*	*Percentile*	*Value*	*Percentile*	*Node*	*Percentile*
Microwave	3.52	72 %	1.50	87 %	0.33	63 %	0.49	50 %
Transmission	1.97	33 %	0.08	35 %	0.30	53 %	0.33	55 %
Generating	1.83	27 %	0.06	28 %	0.28	46 %	0.24	51 %
Office	1.55	21 %	0.04	20 %	0.25	44 %	0.10	47 %
VHF/UHF	1.38	24 %	0.01	15 %	0.27	50 %	0.01	41 %
Other	2.00	17 %	0.03	15 %	0.25	33 %	0.03	37 %

Discussion. For degree, betweenness, and closeness centrality, microwave station nodes have, on average, the highest centrality values. In particular, the high betweenness centrality scores suggest these nodes are very frequently on the shortest path between other nodes. This is consistent with the intuition from the visualization that the red vertices form much of the backbone of the network's topology. Microwave station and transmission station nodes also constitute the majority of the top five rated nodes across the four centrality types considered. That we see a separation in these values across the node types suggests the roles of these vertices in the real network are, to an extent, reflected in the underlying graph topology.

Centrality Score Visualization. We summarize the centrality score results by presenting visualizations below. We note the layout of these visualization was made to clarify the topology of the network. Thus, these visualizations do not utilize the same (x,y) coordinates as in the original network to plot the nodes, but do represent the same underlying graph in terms of the graph connectivity. In all three visualizations, the sizes of the vertices in the visualization are proportional to their centrality score. In the case of the betweenness centrality visualization, we note the edges are also drawn proportional to their edge centrality score.

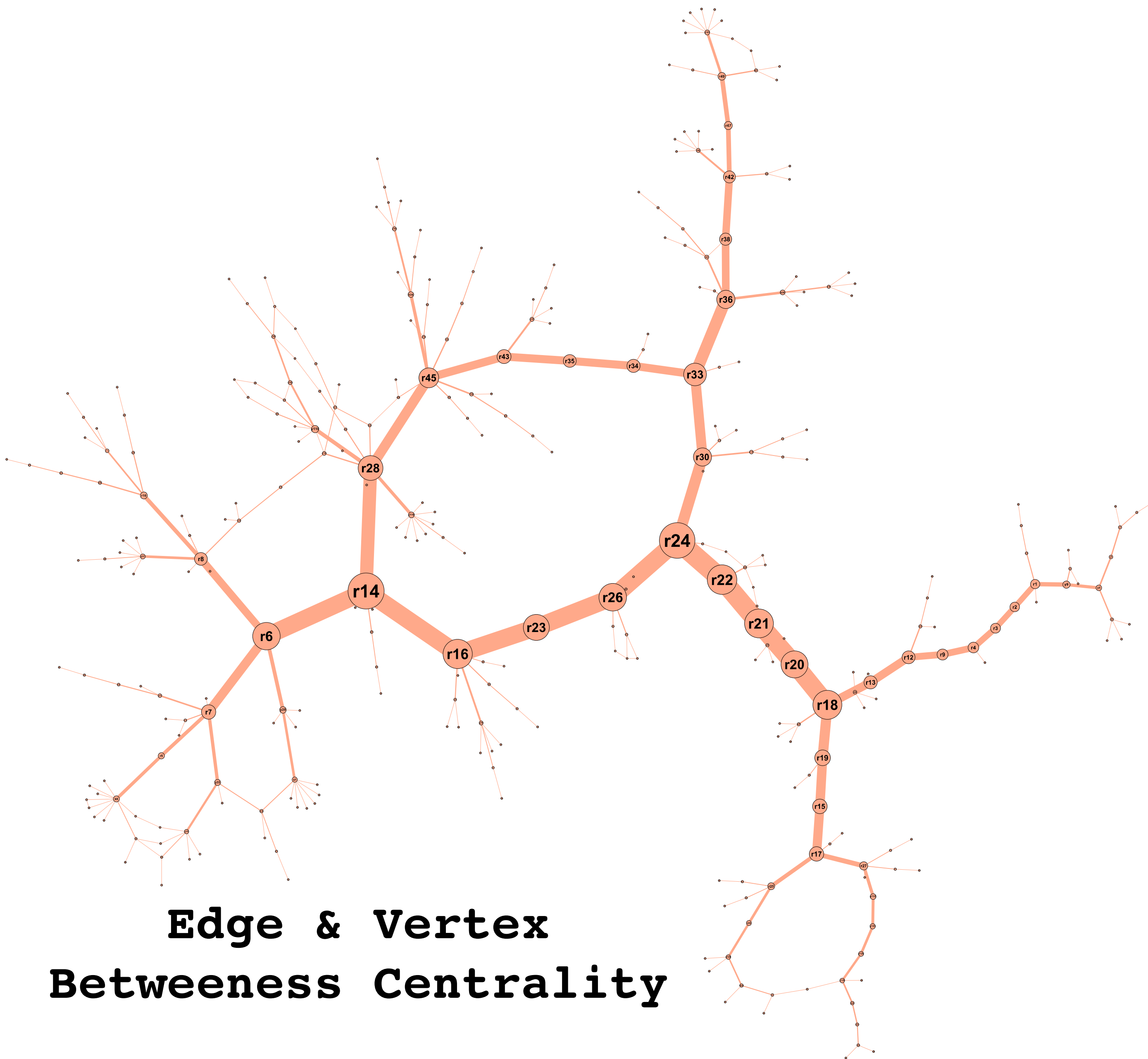


Figure 3.2. Edge and vertex betweenness centrality visualization of the communication topology.

Figure 3.3. Closeness centrality visualization of the communication topology.

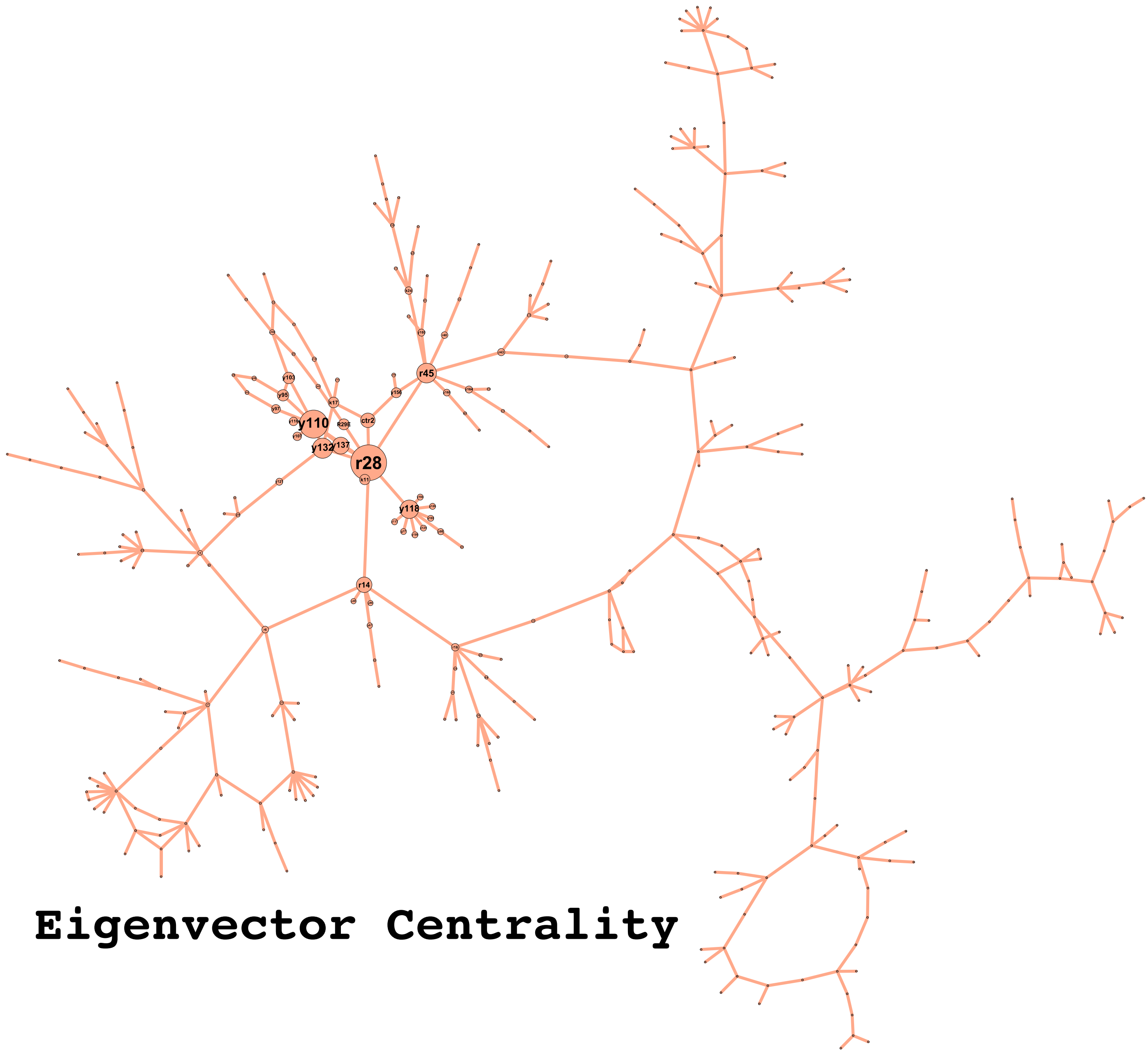


Figure 3.4. Eigenvector centrality visualization of the communication topology.

3.2 Synthesized Communication Network Model

With the characterizations of the communication networks, we could leverage them as input to develop synthesized communication network models such that the synthesized models would have the same or very similar characterizations. In this section, we describe several abstract graph theoretic properties typical of communication networks. We use these observations in developing a scheme for synthetically generating realistic communication network graph topologies at varying scales. We utilize the Chung-Lu model as the kernel of our proposed method, describe several efficient implementations of this model, and illustrate its application with a few experiments. Finally, we briefly suggest a procedure for linking collections of given graphs to form a composite network and apply this to a 700-bus system with nine areas.

3.2.1 Key Graph Theoretic Properties

Here, we identify some key graph theoretic properties of communication networks. Rather than focus our attention on specific types of communication networks, we aim to identify very general, abstract properties that tend to be widely exhibited by communication networks. In doing so, our hope is that we can apply these observations when designing a generative model for producing "realistic" synthetic communication network graph topologies that are broadly applicable.

- **Sparsity:** The sparsity of a graph is the number of edges in the graph relative to the number of vertices n. Metcalfe's law asserts that the number of edges in telecommunication networks is proportional to n^2. An even larger growth rate of 2^n was proposed by Reed. However, as argued in [22], there is strong evidence that both Metcalfe's law and Reed's law are inaccurate overestimations of the density of communication networks. As an alternative, the authors of [22] propose that the number of edges in a communications network is proportional to $n \cdot \log(n)$.
- **Degree distribution:** The degree of a vertex is the number of edges that contain that vertex as an endpoint; the degree distribution summarizes these vertex degree counts by specifying the number of vertices of degree k. With regard to communication networks, it has been observed that the distribution of vertex degrees tends to be heavily-tailed. Loosely speaking, this means that there are many low-degree vertices and few high-degree vertices. For instance, one type of heavily-tailed distribution is Zipf's distribution, which posits that the frequency of degree k vertices is inversely proportional to k.
- **Diameter:** One so-called "small-world" [28] property typical of communication networks is having low shortest path lengths between vertices. This phenomenon is sometimes colloquially referred to as "six degrees of separation." More precisely, the graph's diameter (the longest shortest path) is posited to be proportional to $\log(n)$.

3.2.2 The Chung-Lu Model

The Chung-Lu (CL) model [20] is a generative graph model. This model provides wide control over some properties we described above, including the sparsity of the graph, as well as its degree distribution. While diameter is not a directly tunable input of the model, the CL model also tends to output graphs with the small diameter typical of communication networks. In this section, we provide a formal description of the Chung-Lu model, describe efficient algorithms for generating Chung-Lu graphs in practice, and devise a scheme for generating the Chung-Lu model inputs synthetically, under which realistic communication network graph topologies can be generated at varying scales.

The Chung-Lu model is parametrized by a "desired vertex degree" vector, $d = (d_1, \ldots, d_n)$, where n is the desired number of vertices. Given these inputs, the Chung-Lu model generates a graph $G = (V, E)$ according to the following: for each possible pair of vertices, the probability of an edge is given by

$$\Pr(\{v_i, v_j\} \in E(G)) = \frac{d_i \cdot d_j}{\sum_{i=1}^{n} d_i},$$

Algorithm 2. Chung-Lu Graph

Input: list of N weights, $W = w_0, \ldots, w_{N-1}$, sorted in decreasing order
Output: Chung-Lu graph $G(V, E)$ with $V = \{0, \ldots, N-1\}$

```
E ← ∅
S ← Σ_u w_u
for u = 0 to N − 2 do
   v ← u + 1
   p ← min(w_u w_v / S, 1)
   while v < N and p > 0 do
      if p ≠ 1 then
         choose r ∈ (0, 1) uniformly at random
         v ← v + ⌊ log(r) / log(1−p) ⌋
      if v < N then
         q ← min(w_u w_v / S, 1)
         choose r ∈ (0, 1) uniformly at random
         if r < q/p then
            E ← E ∪ {u, v}
         p ← q
         v ← v + 1
```

(a) The Miller-Hagberg efficient Chung-Lu implementation [26]

Algorithm 3: $\mathcal{O}(|\text{Edges}|)$ Chung-Lu Algorithm

```
for k = 1 to m do
   Draw node i with probability k_i/2m;
   Draw node j with probability k_j/2m;
   /* Add edge (i, j) to the graph */
   if i ≠ j then
      a_ij = a_ji = 1;
   else
      a_ii = 2;
   end
end
```

(b) The "fast" Chung-Lu implementation [29]

Figure 3.5. Two Algorithms Implementing the Chung-Lu Model.

where, to guarantee this is indeed a valid probability, we require that the square of the maximum desired degree does not exceed the sum of the desired degrees. Note that in expectation, each vertex achieves its (user-specified) desired degree since

$$\mathbb{E}(\text{degree of } v_i) = \sum_{j:j\neq i} \Pr(\{v_i, v_j\} \in E(G)) = \frac{d_i}{\sum_{i=1}^{n} d_i} \cdot \sum_{j:j\neq i} d_j = d_i.$$

In practice, generating a Chung-Lu graph by "flipping a coin" (i.e. generating a random number) for each of the n^2 possible edges is too expensive. One simple alternative, called "fast Chung-Lu" by the authors in [23] is to instead draw the endpoints of m edges independently and proportionally to their desired degree, with replacement. In other words, the probability of picking vertex v_i as an endpoint of an edge is given by

$$\Pr(v_i \text{ chosen as edge endpoint}) = \frac{d_i}{\sum_{i=1}^{n} d_i}.$$

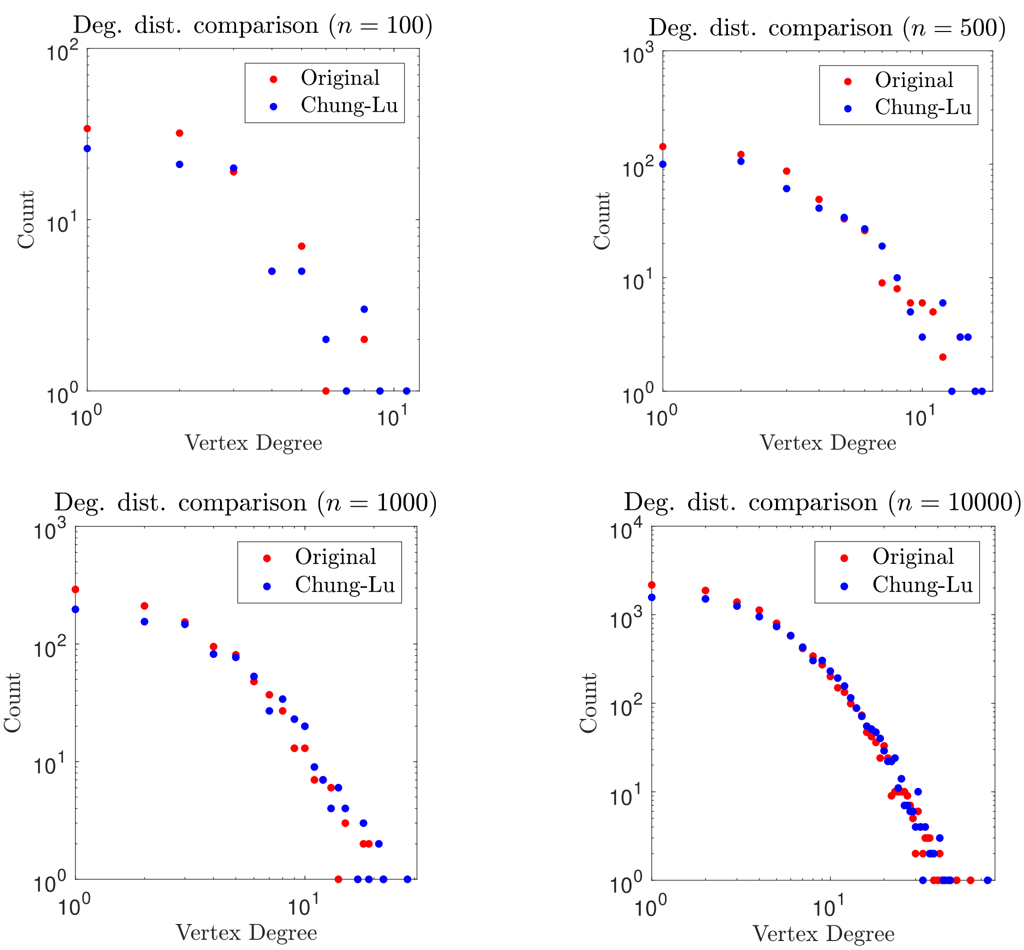
Consequently, we still have that each vertex achieves its desired degree d_i in expectation since

$$\Pr(\{v_i, v_j\} \in E(G)) = 2 \cdot m \cdot \Pr(v_i \text{ chosen as edge endpoint}) \cdot \Pr(v_j \text{ chosen as edge endpoint}) = \frac{d_i \cdot d_j}{\sum_{i=1}^{n} d_i},$$

where we used the handshaking lemma identity. Observe that this implementation requires $O(m)$coin flips, as opposed to $O(n^2)$. Since, for many real-world networks, $m \ll n^2$ this implementation is faster than the naive approach. However, one drawback of this implementation is that self-loops (i.e. edges of the form $\{v, v\}$) are now possible. Nonetheless, in practice, these tend to be few and are simply discarded in post-processing. An alternative implementation avoiding this issue of self-loops was proposed by Miller and Hagberg [26]. For an in-depth comparison of these and other related variants of the Chung-Lu model, see [29]. We present pseudo-code of the fast Chung-Lu algorithm in Figure 3.5b as well as Miller and Hagberg's implementation in Figure 3.5a.

3.2.3 Synthetic Input Generation Scheme

In order to generate an instance of the Chung-Lu model, we need to specify the user-inputted desired degree sequence. When fitting the Chung-Lu model to a given graph, we can simply extract the desired degree sequence from the data. However, in applications it may often be the case that such data is unavailable, or that we may wish to *scale* these inputs to generate graphs of any given size. In this section, we describe the scheme we utilize to generate arbitrarily-sized Chung-Lu graphs.



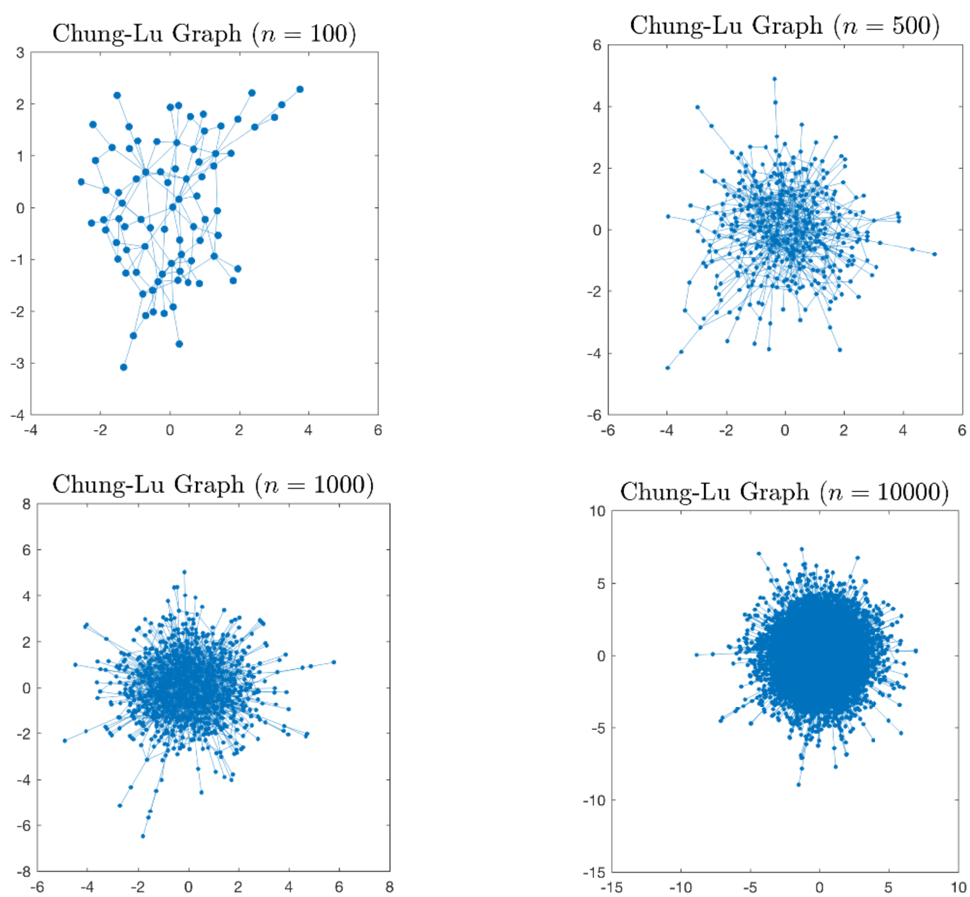


Figure 3.6. Top 4 Plots: Examples of synthetic degree distributions generated for different values of *n* according to the scheme (in red) compared against the degree distribution of the output Chung-Lu graph (in Blue). Bottom 4 Plots: Visualizations of the output Chung-Lu Graphs.

We adopt a flexible framework for synthetic input generation suggested in [23]. In particular, we use a generalized log-normal degree distribution, where the number of degree d vertices satisfies

$$n_d \propto \exp\left(-\left(\frac{\log d}{\alpha}\right)^{\beta}\right),$$

for some parameters α, β. As implemented in the generation software package (http://www.sandia.gov/~tgkolda/feastpack/#1), one may conduct a parameter search to locate the optimal α and β given target values for average degree and maximum degree, denoted $\bar{d}$ and $dmax$, respectively. Because average degree is twice the ratio of number of edges to vertices, the choice of $\bar{d}$ as a function of n reflects an assumption of how a graph's *density* varies (see [25] for more on this). In short, we must specify

- n, the number of vertices
- $\bar{d}$, the average degree
- $dmax$, the maximum degree

Thus, in order to scale our model inputs to graphs on different numbers of vertices, we must determine how to approximate $\overline{d}$ and $dmax$ as functions of n. Given that we lack additional information about the communication networks in question, here we seek guidelines aimed at “generic” complex networks. In [27] one such suggestion for how the maximum degree may vary with n for power-law networks is

$$d_{\max} \sim n^{1/\psi},$$

where ψ is the power-law exponent. Next, we turn our attention to average degree. We begin by recalling that average degree can be written as twice the ratio of the number of edges to the number of vertices. Hence, how average degree changes is the same as how the ratio of edge to vertex counts changes. On this topic of the relative edge *sparsity*, some have argued [24] that the number of edges may vary superlinearly in the number of vertices, and even suggest some networks follow a power-law densification.

We now apply this generation scheme, taking ψ =2 (and hence $dmax = \sqrt{n}$) and $\overline{d} = \frac{1}{2}\log n$. We note that this choice in average degree is consistent with the sparsity typical of communication networks suggested by [22]. We generate synthetic degree distributions for each of n =100, 500, 1000, and 10000 according to the scheme described above. In Figure 3.6. Top 4 Plots: Examples of synthetic degree distributions generated for different values of *n* according to the scheme (in red) compared against the degree distribution of the output Chung-Lu graph (in Blue). Bottom 4 Plots: Visualizations of the output Chung-Lu Graphs.

, we plot the original degree distribution against that of the output Chung-Lu graph and a visualization of the Chung-Lu graph for each such n. Observe that the scheme's generated degree distributions are heavy-tailed (as one would expect of communication networks), and that the graph outputted by the Chung-Lu model provides a close match of the desired input degree distributions.

3.2.4 Linking Chung-Lu Graphs

In applications, one might sometimes wish to generate a number of differently sized Chung-Lu graphs and link them together to form one composite network. By “linking two Chung-Lu graphs together" we mean adding edges that have one endpoint in one graph, and another endpoint in the other. For instance, consider a 700-bus system with nine areas: here, the Chung-Lu model may be applied to generate a graph for each area, and then we may wish to link all the areas together via cross-area edges. In this section, we briefly describe a procedure for how to link these graphs together and apply this method to sample 700-bus system data.

Algorithm 1 Fast Bipartite CL

```
procedure FBCL({d_i^u}, {d_j^v})
    m ← ∑_i d_i^u
    E ← ∅
    for k = 1,...,m do
        Randomly select i ∈ U proportional to d_i^u/m
        Randomly select j ∈ V proportional to d_j^v/m
        E ← E ∪ (i, j)                              ▷ Duplicate edges discarded
    end for
return E
end procedure
```

Figure 3.7. Fast Bipartite Chung-Lu Implementation [21]

By linking two (or more) Chung-Lu graphs, we are generating a *bipartite graph* between them. Recall that a bipartite graph is one for which vertices can be partitioned into two sets such that edges are only possible between vertices in different sets. We propose linking graphs by using a bipartite version of Chung-Lu, suggested in [21]. Much like the Chung-Lu model, here the user must specify the desired degree sequences, except now there are two such desired degree sequences (one for each partition). For example, in linking together two area graphs A and B, the inputs are the desired degrees of vertices in area A (with respect to B) and the desired degrees of vertices in area B (with respect to A).

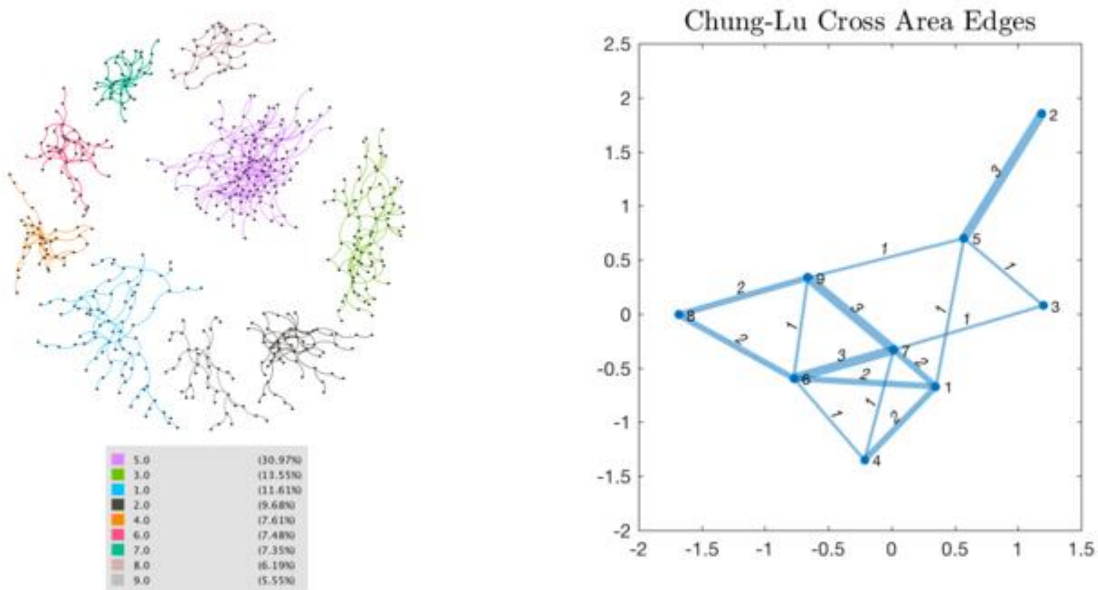


Figure 3.8. Left: Visualization of synthetically generated 700 bus system with 9 areas. The legend reports which colors represent which areas, and the percentage of vertices in the network that are in that area. Right: Visualization of cross-area edges. Each vertex (labeled by area number) corresponds to an area graph, and edges (labeled by multiplicity) correspond to cross-area edges, with thickness proportional to the number of cross-area edges.

In Figure 3.7, we present the pseudo-code specification of the fast bipartite Chung-Lu model. Here, d_u^i denotes the desired degree of vertex i in partition u. Extracting this information from the 700-bus data for each of the 36 pairs of areas, we apply this model to link together the graphs visualized in Figure 3.8. The output is visualized in Figure 3.8b, where each area graph in Figure 3.8a is represented as a vertex, and edges between these vertices represent the cross-area edges inserted by the method.

4.0 Conclusion and Next Steps

In this report, we first reviewed communication technologies and systems for the grid as well as their roles (impact) in restoration, aiming to fill the knowledge gap of interdependence between the physical grid and the communication system.

Based on the review on communication systems, major conclusions are given as follows:

1. There is clearly a gap for the research community to perform a holistic analysis on the power system restoration based on the T & D & C network integrated study;
2. Topology analysis is popular and included in almost every research model, while the physical characteristics and QoS of communication networks have only been considered by a limited number of researchers;
3. Node mapping among different networks is the fundamental method for the inter-dependency study. This method is very popular and used in almost all research teams;
4. A gap exists between the research and utility practice, preventing complete understanding of the existing industry standards for communication network modeling.

We also proposed several key characteristics and metrics of typical communication systems based on analysis of an actual communication system. These metrics and characteristics will be used as input for developing or generating synthetic communication systems in the next phase.

Lastly, we reviewed methods of creating synthetic power system models and proposed improvements to one potential method that will be considered in the next phase of the project.

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