Leveraging a High Fidelity Switched Network Model to Inform System Dynamics Model of the Telecommunications Infrastructure

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A generic representation of the telecommunications infrastructure in a metropolitan area designed to be integrated into a much larger simulation of the seventeen key infrastructures[1] has been implemented in Vensim[2]. This Critical Infrastructure Protection Decision Support System (CIP/DSS) is designed to provide insights for the Department of Homeland Security (DHS) in making decisions about investments related to critical infrastructure protection[3]. Although a system dynamics representation was well suited to representing the dynamics and interdependencies in this complex system of systems, it was recognized early on that collaborations with key infrastructure domain experts and organizations would be important to the success of the project. This paper summarizes the results of a collaborative effort with Bell Laboratories, Lucent Technologies to leverage a detailed switched network simulation to inform the telecommunications system dynamics model in CIP/DSS.

Key Words: Critical Infrastructure, Telecommunications, System Dynamics

Introduction

The CIP/DSS (Critical Infrastructure Protection Decision Support System) project is developing a risk-informed Decision Support System that provides insights for making critical infrastructure protection decisions by considering all seventeen Critical Infrastructures and their primary interdependencies integrated with models of population, economics and simulations of possible scenarios impacting these infrastructures. CIP/DSS will assist decision makers in making informed choices by (i) functionally representing all seventeen critical infrastructures with their interdependencies, (ii) computing human health and safety, economic, public confidence, national security, and environmental impacts, and (iii) synthesizing a methodology that is technically sound, defensible, and extendable.

The purpose of the Information and Communications (I&C) sector module is to model the behavior of the telecommunications, data access and broadcast systems in a generic metropolitan area. It is important in modeling the urban environment to track the performance of wire-line (normal wire-based phone networks) and wireless communications, access to the Internet and corporate networks and the availability of broadcast radio and television under normal and off-normal conditions. The operation of these systems is such an integral part of a wide range of activities that the interdependencies with other infrastructures are often of critical importance. For the same reasons, telecommunication systems themselves are likely targets of intentional infrastructure attacks.

The Information and Communications (I&C) sector model makes use of five subsectors: Phone Call, Telecom, Data Network, Broadcast and Repair. The Phone Call and Telecom subsectors are concerned primarily with voice communications using both wire-line and wireless networks. The Data Network subsector looks at the Internet, corporate networks, and SCADA networks and the Broadcast subsector models including broadcast TV and radio systems, and the emergency broadcast system. The Repair model is concerned with network repair, call overloads, and investments in the telecommunications infrastructure. This paper is primarily concerned with a collaborative effort with Bell Laboratories, Lucent Technologies to leverage their N-SMART [4][5][6] network models (i.e., much more detailed discrete-event simulation models) to inform the behavior of the Phone Call and Telecom subsector system dynamic models, which are at a much higher level of aggregation.

N-SMART Network Model

The CIP/DSS modeling team is working in partnership with domain experts at Bell Laboratories, Lucent Technologies to make the models as relevant as possible while keeping them relatively simple because of the need to integrate the system dynamic models into a much larger set of models covering all key infrastructures. In particular, Bell Laboratories has built a detailed model of the switching network infrastructure in large metropolitan areas and a simulation of the network traffic load under normal conditions as well as with network failures and overload traffic patterns. The output of these models is being used as a guide to the desired high-level behavior of the Phone Call and Telecom sub-sector system dynamics modules in CIP/DSS.

The Network-Simulation Modeling and Analysis Research Tool (N-SMART) has been developed to support detailed wireline and wireless network simulations [4]. It studies telecom network readiness and traffic behavior on various disaster scenarios. It can create scenarios that demonstrate the pattern of telecom traffic loads and user behavior during the time of disaster, such as physical line disconnection and switching system failure.

N-SMART is a discrete event (call level, geographically based) telecom model that simulates capacities, blocking levels, retrials, and time to complete calls for both wireline and wireless networks. It models various network infrastructures, traffic load profiles, simulation scenarios, network management controls, and simulation engine parameters as inputs. Various simulation scenarios analyze how different traffic patterns, traffic loads, user behaviors, and disaster severities impact network performance and recovery. By analyzing the results of simulations, the tool shows how different telecom elements, such as bandwidth deficiency, switch processor overload, and user behavior, impact the performance of the network and its robustness. Figure 1 depicts the building blocks of the N-SMART-Voice simulation model, information input, and model output. N-SMART itself is much too detailed to be used directly in the CIP/DSS models. This is the reason for the higher level abstraction in the system dynamics models.

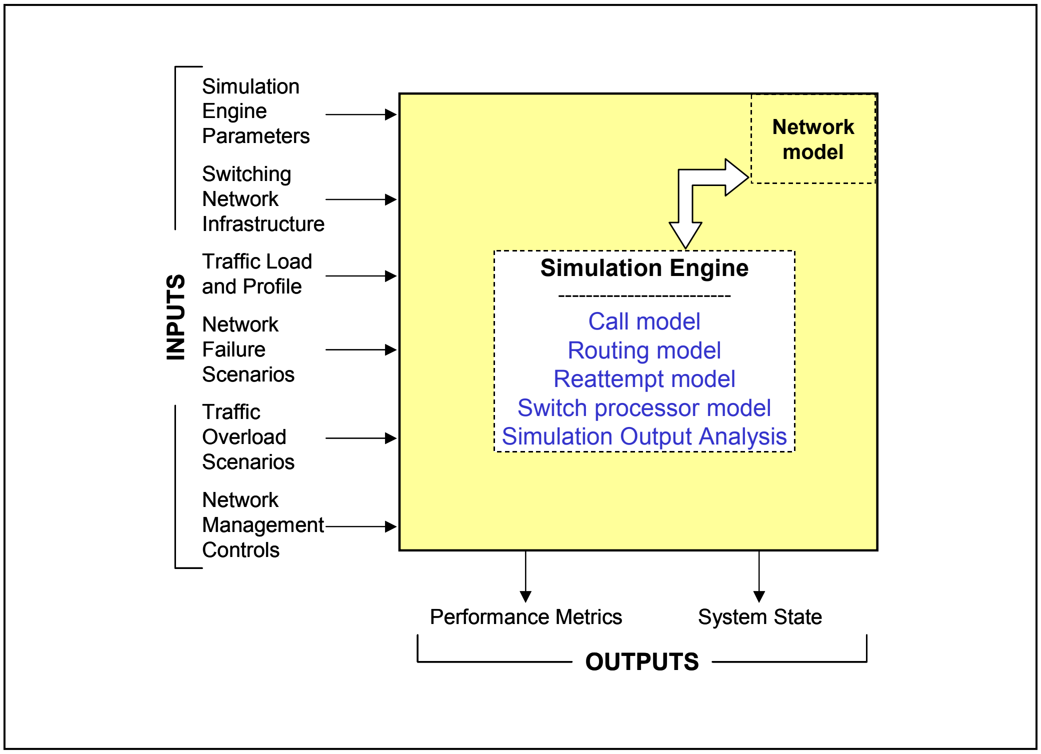

Figure 1: N-SMART Model

The simulation engine consists of algorithms to generate events related to calls, re-attempts, network failures, processor overloads, and simulation output. It works on the detailed topology of the nodes and links in the Metropolitan Network model to simulate calling throughout the area. See [4][5][6] for much of the details.

Telecommunications System Dynamics Model

The telecom system dynamics model is required to represent the main activities of the Information and Communications sector and the primary interdependencies with other infrastructure sectors. The model is designed to handle off-normal conditions such as natural disasters, terrorist attacks, large-scale accidents, and cyber attacks. It also must be responsive to changes in call demand, including large overloads on the capacity of the networks, and damage to the switches, trunks and national backbone network.

Operational levels of telephone systems including priority systems, private networks including SCADA, broadcast systems and access to the Internet are represented in the model. Metrics used to characterize the state and performance of the systems must include the availability of the different telecommunications services, network capacities, and call volumes and costs associated with system operations. The dependence of the system on other infrastructures, especially electricity, fuel, government activities, transportation, and financial services are integrated into the overall system model. In addition interdependencies between subsectors of the Information and Communications sector (wire-line and wireless telecommunications, switching facilities and private networks, telecommunications and Internet access) is represented.

The Public Switched Telephone Network (PSTN) wire-line and wireless networks are modeled in the Phone Call and Telecom subsectors. The Phone Call subsector keeps track of the number of call attempts and compares that to system capacity (switches and trunks) and estimates the number of blocked calls due to problems in the switches and trunks and busy signals. Blocked calls then become additional call attempts based on how many calls are re-attempted. Calls successfully admitted into the system, based on a comparison of demand and capacity, are passed to the Telecom subsector. This subsector also estimates revenue lost due to incomplete calls.

The Telecom subsector keeps track of total demand including a long-distance load. This demand forms the basis for initial call attempts in the Phone Call subsector. The Telecom subsector also determines the availability of wire-line and wireless communications based on the admitted calls from the Phone Call subsector and the demand. Priority calls and repair costs are also tracked in this subsector.

The telecommunications networks are allowed to undergo degradation and repair. For voice communications, the wireless network's condition depends in part on the condition of the PSTN. The condition of the two networks determines the system capacity which, when combined with the demand on the system, determines the availability of telecom communications. Demand includes a daily variation and long-distance demand from the national model as well as possible call volume overloads due to events.

Costs estimated in the model include revenue lost due to incomplete calls, infrastructure repair costs and investment costs in the infrastructure. The cost functions were estimated with the assistance of domain experts at Argonne National Laboratory and Bell Laboratories, Lucent Technologies but use very simple scaling relationships. Further work is needed in this area.

Use Case Diagram

A use case diagram describing the use cases at the highest level of the Information and Communications sector model is shown in Figure 2. Three main actors are used to represent the actions of the analyst and interactions with other metropolitan sector models and the national-level telecommunications model. The analyst controls investments in labor (for repair operations), redundant fiber and pre-placed telecommunications switches and, with the other sector models actor, influences the loads on the system.

After the Analyst has set the initial conditions for a scenario, the Information and Telecommunications Simulation computes the evolution of the telecommunications system with time at a resolution of one time step per minute for approximately six weeks to a year, depending on the scenario. The system computes the load on the various telecommunications systems based on input from the analyst (scenario) and interactions amongst the telecommunications subsectors and other infrastructures as well as the national network. The loads are compared with system capacities at each time step to determine the busy, blocked and admitted calls and availability of the telecom systems.

The telecommunications loads are computed based on a normal diurnal cycle, a standard call volume based on population and system capacity, long-distance call loads and potential call overloads whose level varies as a function of time. Calls that are re-attempted are calculated based on the number of busy connections and calls blocked due to issues at the switches and trunks and added to the total attempted call volume. Call overloads are determined by the details of the scenario. Total call load is recomputed each time step and is factored into the computation of telecom system dynamics.

Telecom system capacity is calculated based on the normal switching capacity in the metropolitan area, call loads on the system and damage to the switches, trunks and national backbone network. Switch capacity engaged in overhead tasks (setting up and tearing down calls) is driven primarily by the total number of call attempts while the number of calls in service determines the load on the trunks. Comparisons that are made to normal system capacities in concert with the call volumes determine the number of admitted calls in the telecom system dynamics.

The analyst determines any damage to the telecom system capacities through the scenario definition. Damage is measured in terms of a reduction in normal system capacity for the metropolitan area, which is typically 80% to 95% of the normal peak handling requirements. Damage occurs to telecom switches and trunks and the national backbone network which in turn reduces the capacity of Internet access and private networks including SCADA. Capacity returns to normal levels over time based on repair activities and investments in the robustness of the system. Note that telecom networks already have many back-up and failover systems in place to handle failures. For example, the transport network, over which trunks and private lines run, is usually built on fiber optic rings. A single cut of a ring usually goes un-noticed by customers since there is usually 1+1 protection.

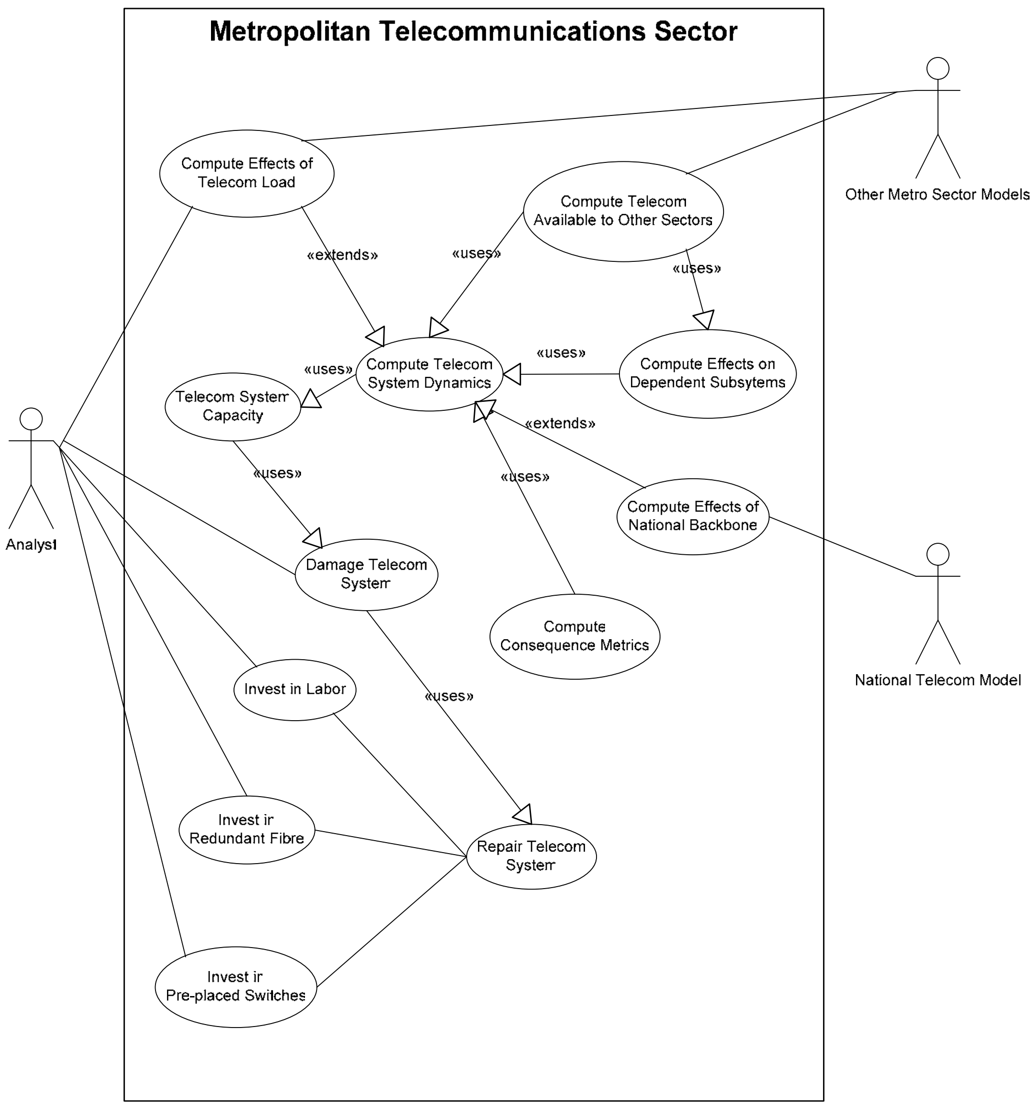

Figure 2: Information & Telecommunications Use Case Diagram

The effects of interdependencies between various telecommunications systems are determined at each time step. Wireless communications can be impacted by the wire-line network and the transfer of call load when the wire-line system becomes overloaded. Since many private networks typically pass through large transport hubs, where switching facilities are collocated, damage to these buildings affects private networks including SCADA. A significant fraction of

Internet access is obtained through dial-up access to the telephone system using analog modems, so that, a problem with telecommunications, is allowed to propagate to Internet access. Broadcast systems are modeled as largely independent of other telecommunications systems although an interruption in another infrastructure such as the electric system is allowed to affect both communications and broadcast systems.

Phone Call Model

The primary subject of this paper concerns the phone call model and how the Bell Laboratories, Lucent N-SMART model was used to inform the behavior of the model. The phone call system dynamics model is discussed in more detail below.

Major Processes

The central process in the Phone Call subsector model is the calculation of the effective switching capacity in the metropolitan area. This process directly determines the number of admitted calls, the key metric of the model, as the minimum of the effective switching capacity and the number of attempted calls. The effective switching capacity also determines the number of calls blocked at the switches, which adds to the number of call attempts.

Three key sub-processes determine the effective switch capacity:

- Damaged capacity of the switches (normal capacity if no damage)
- Capacity of the switches tied up with overhead
- Total volume of attempted calls

The damaged capacity is determined using the capacity reduction computed in the Repair subsector and the normal capacity of the switches. Switch capacity on overhead is determined based on the results of a network model from Bell Laboratories, Lucent Technologies for a variety of damage and overload scenarios. The total volume of calls is determined by the volume of calls attempted for the first time (obtained from the Telecom subsector model) and the number of reattempted calls based on the number of calls blocked in the system due to overloaded or damaged switches, trunks or as a result of busy signals. The effective switching capacity is the difference between the total capacity and the capacity busy on overhead tasks but is corrected to allow for the amount of switch capacity busy on overhead tasks to saturate as the number of attempted calls exceeds the total capacity of the system.

The second major process determines the number of reattempted calls in the system. Three different categories of reattempted calls are tracked – busy lines, calls blocked in switches and calls blocked in trunks. Each reattempt category begins with a number of blocked calls. Depending on a reattempt probability, the volume of abandoned calls in that category is calculated. The number of reattempted calls in each category is determined using an average wait time for the callers.

The third major process estimates lost revenue based on the cumulative number of calls reattempted in the system, wire center lines lost, and the loss of use of any private networks passing through switching centers. Reattempted calls are accumulated as a function of time with a fraction of them considered lost to the system, resulting in reduced revenue compared to normal conditions.

Primary Stocks

Note: Terminology: The variables in Figure 5 typically have Ica: in front of them. The I refers to the Information and Telecom Sector, and the "ca" refers to the phone call sub-sector model. This is a common nomenclature used across all the CIP/DSS sectors.

The stocks in the Phone Call subsector are the number of calls in service (Ica: Calls in Service), three separate stocks keeping track of the number of blocked calls waiting to be reattempted for each of the three blocked call types (e.g., Ica: Switch Blocked Callers Waiting for the switches) and the cumulative number of reattempted calls (Ica: Cumulative Reattempts).

The calls-in-service stock is fed at the rate that calls are admitted into the system and is depleted by the number of calls being completed. The stocks for blocked calls are fed by the rate of blocked call generation and depleted by both the rate of call abandonment and the rate at which calls are reattempted. The cumulative reattempted call stock is fed by the reattempted call rate and is not depleted.

Feedback Loops

There are three feedback loops in the Phone Call subsector model. In each case the feedback involves the total number of call attempts, where the number of call attempts influences a factor, which in turn influences the number of call attempts. The three factors which feedback to call attempt volume are:

- Calls blocked at switches
- Calls blocked at trunks
- Busy signals

The number of calls blocked at switches increases with the number of attempted connections, which in turn increases the number of reattempted calls due to switch blocking which increases the number of attempted connections. This is a positive feedback loop as illustrated in Figure 3.

The number of calls blocked at trunks and due to busy signals decreases with increasing attempted connections, which in turn reduces the number of attempted connections. These are negative feedback loops. An example for the case of busy signal calls blocked is illustrated in Figure 4.

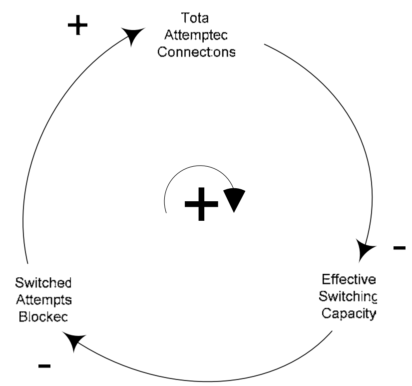

Figure 3: Positive Feedback on Total Attempts Due to Switch Blocking

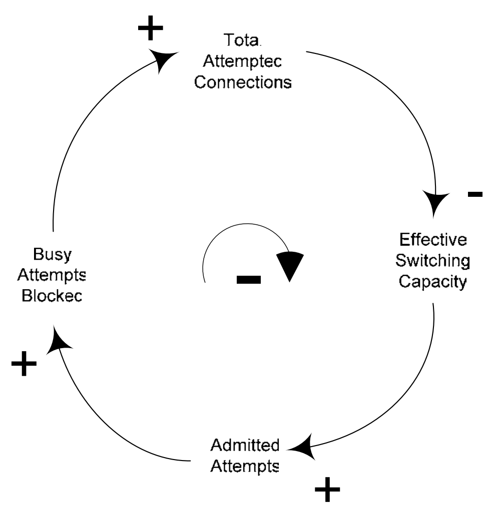

Figure 4: Negative Feedback on Total Attempts Due to Busy Signals

Interdependencies

Interdependencies between the telecommunications model and other sector models are illustrated in Table 1. The table shown applies to a generic scenario involving the destruction of a switching station in a metropolitan area. Dependency in the effects is read from left to right in the table, starting with the destruction of the switch and the direct affects of that destruction including a decrease in the metropolitan area switching capacity and injuries resulting from the destruction.

Other sectors affected include emergency services [E], public health [P], transportation [T], government [G], banking and finance [B], water [W], postal [O], food [F], energy [X] and other subsectors of the information and telecommunications sector [I].

Table 1: Interdependencies with Other Sectors

Cause	*Effect*	*Effect*	*Effect*	*Effect*	*Effect*
Destruction of telecom network	Fatalities [M]	Corpses [P]			
	Injuries [M]	Rescues [E]	Hospitalization [P]	Fatalities [P]	Corpses [P]
				Disabilities [P]	
				Hospital Beds [P]	
	Evacuations [M]	Evacuations [T]	Traffic Congestion [T]	EMS Effectiveness [E]	
				Government Response [G]	
	Destruction [M]	Insurance Claims [B]			
		Reconstitution [M]			
	Switch Capacity [I]	Wireline [I]	Government Response [G]		
			Hospital Effectiveness [P]		
		Wireless [I]	Government Response [G]		
			Hospital Effectiveness [P]		
		Radio [I]			
		Television [I]			
		Corporate Network [I]	ATM Machines [B]		
			Business Operations [B]	Revenue Loss [B]	
		Internet [I]			
		SCADA [I]	Electric Power [X]	Water Treatment [W]	
				Food Processing [F]	
				Mail Operations [O]	
				Government Response [G]	
				Hospital Effectiveness [P]	

Model Design

A diagram of the System Dynamics model of the Phone Call subsector is shown in Figure 5. Interdependency variables originating from other sectors are depicted in red while metrics are color coded purple. Variables appearing in brackets originate from other subsectors in the model.

The layout of the diagram is as follows. The switch capacity calculation is shown in the upper right, blocked calls in the lower right, trunk capacity in the upper right with lost revenue below.

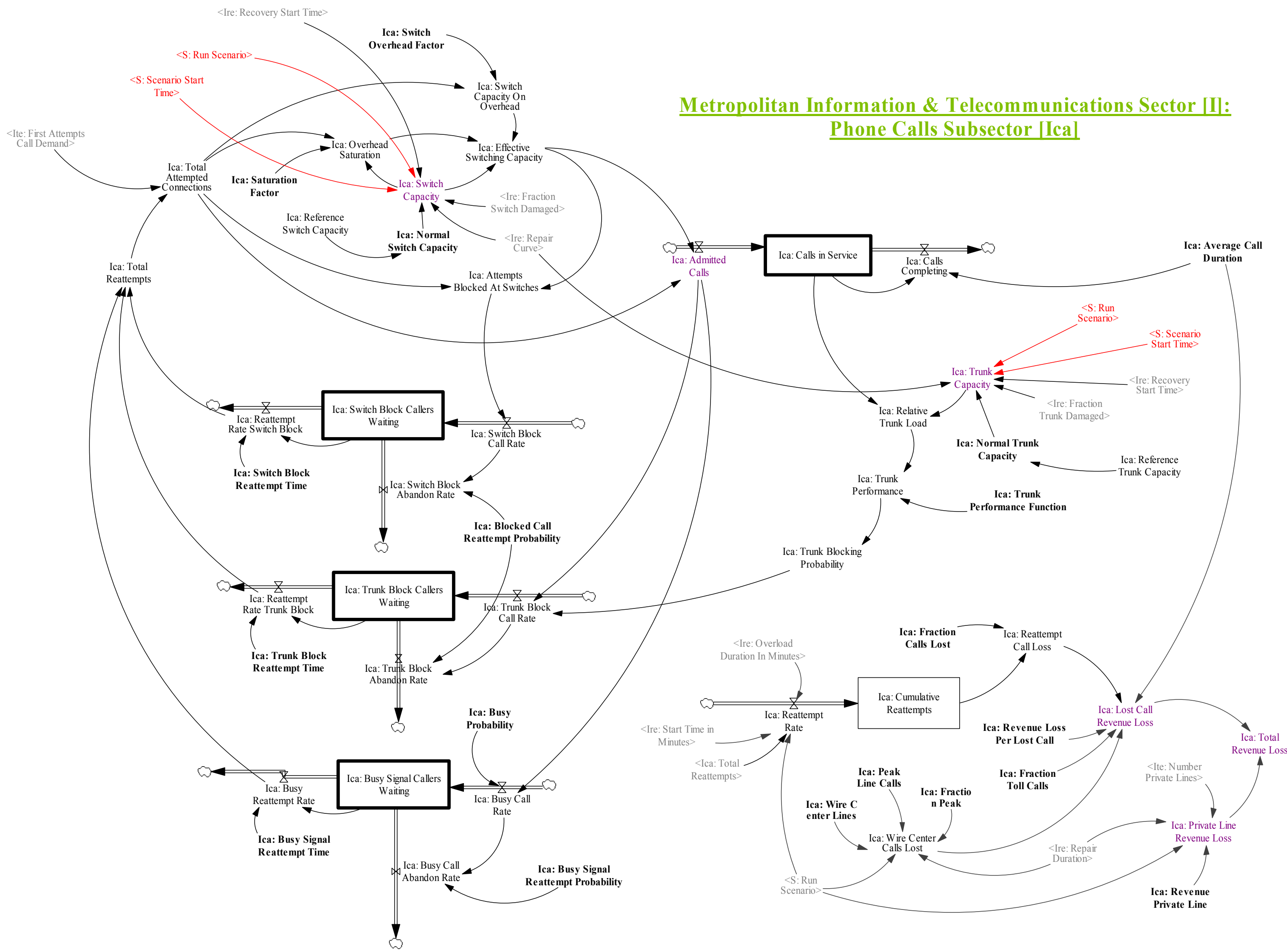

Figure 5: System Dynamics Model of the Phone Call Subsector

Bell Laboratories, Lucent Technologies Collaboration and Model Performance

The CIP-DSS modeling team collaborated with telecommunications experts in both the private sector and the federal government to design a telecommunications scenario to demonstrate the CIP-DSS models, incorporate results from specialized and detailed models, and obtain input data for the CIP-DSS models.

Bell Laboratories, Lucent Technologies and the National Communications System (NCS); have been working with the CIP-DSS team since the beginning of the project. Bell Laboratories uses the N-SMART detailed model of the switching network infrastructure in large metropolitan areas to simulate the network traffic load under normal conditions as well as with network failures and overload traffic patterns.

The major data sources for this subsector were derived from the Bell Laboratories, Lucent Technologies network models of wire-line and wireless communications as well as metropolitan level specifications for telecommunications, including some high level unit costs. Results from the Phone Call and associated Telecom and Repair subsector models were calibrated and tested using output from the network model for Seattle, Washington for a number of scenarios including various levels of call overloads, main building damage and combinations. Comparisons are shown in Figures 6 and 7 for a four times call overload example.

Figure 6 shows the normal operations comparison depicting the normal diurnal behavior of call volumes for admitted and busy calls with no disruption. Clearly there is a very good match since the same input parameters are used in both cases.

In Figure 7 a similar call volume comparison is shown but with a first attempt call volume that is four times the normal level (one of the more stressful network disruptions). Although the shapes do not match precisely, the magnitude and location in time for the major peaks and valleys in the call volume are in fairly good agreement. Similar comparisons were made for cases where a major switching center was out of service and where a combination of call overload and the loss of a switching center are used.

The approach taken here is to calibrate the telecommunications model for a few cases where detailed results of the Bell Laboratories, Lucent model are available, which then allows the CIP-DSS model to work through a continuum of cases relevant to the scenarios run against the CIP-DSS models and integrate those results with the other sector models.

As the Bell Laboratories, Lucent model has been broadened to incorporate greater detail in wireless communications, the impact of the long distance network and other areas; ongoing efforts will incorporate those results into the CIP-DSS modeling efforts.

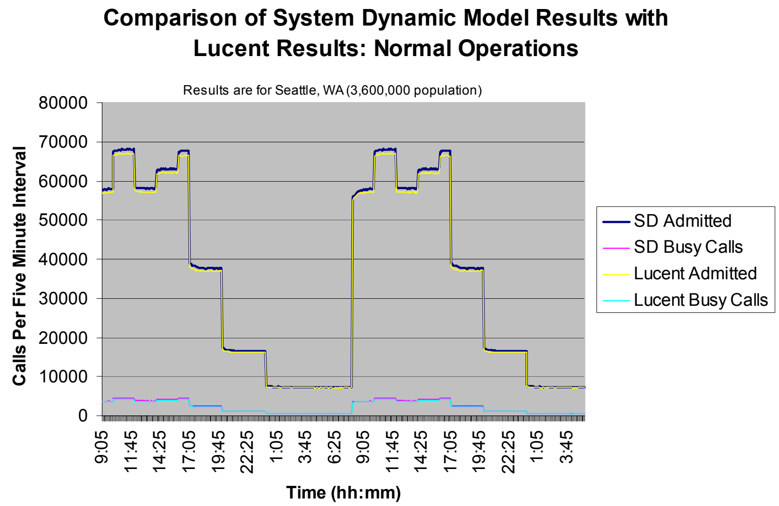

Figure 6: Result Comparison for Normal Operations

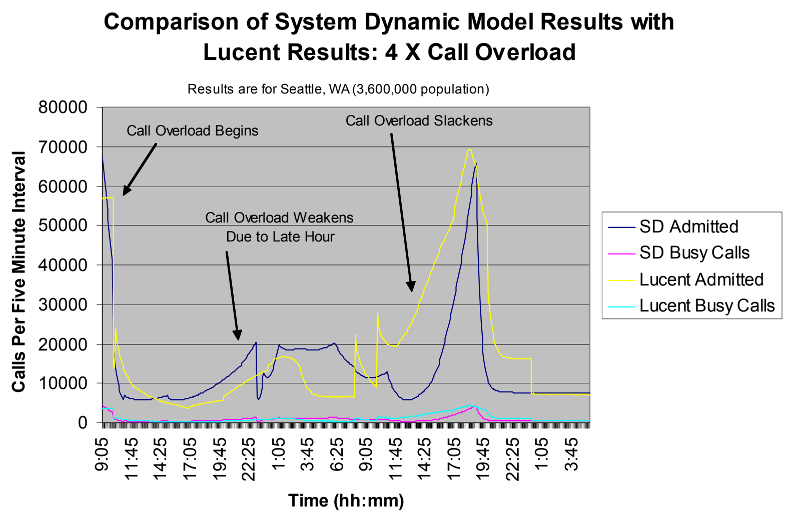

Figure 7: Result Comparison with 4 X Call Overload

Example Runs

The output from a sample run on the telecommunications scenario is shown below to illustrate results produced by the Systems Dynamics telecommunications model. This is a case where a key switching center in a major metropolitan area has been damaged and there is a concurrent call volume overload due to the incident. The overload overwhelms the reduced capacity of the metropolitan area and the damaged switching center also causes some interruption in the national backbone network, affecting long distance service. Telecommunications availability, the ratio of calls admitted to the system to the attempted calls, is pictured in Figure 8. Availability is actually a metric from the Telecom subsector but reflects behavior largely driven by the Phone Call subsector. Three primary regimes of behavior can be seen. At first the availability behavior is dominated by the call overload (call volume greatly exceeds the switching capacity) with availability dropping to 5% at peak calling times. Once the call overload abates, behavior improves dramatically for a few days as the long distance connectivity continues to recover, lowering the overall metropolitan area first attempts because of the lower long distance initiated calls. Availability drops again in the extended period between recovery of the long distance network and the continuing repair of the switching system. The Government Emergency Telecommunications System (GETS) for wire-line and the Wireless Priority Service (WPS) for wireless networks are ways for getting important calls through these networks when they are under stress. If the network is working but overloaded, these calls get priority.

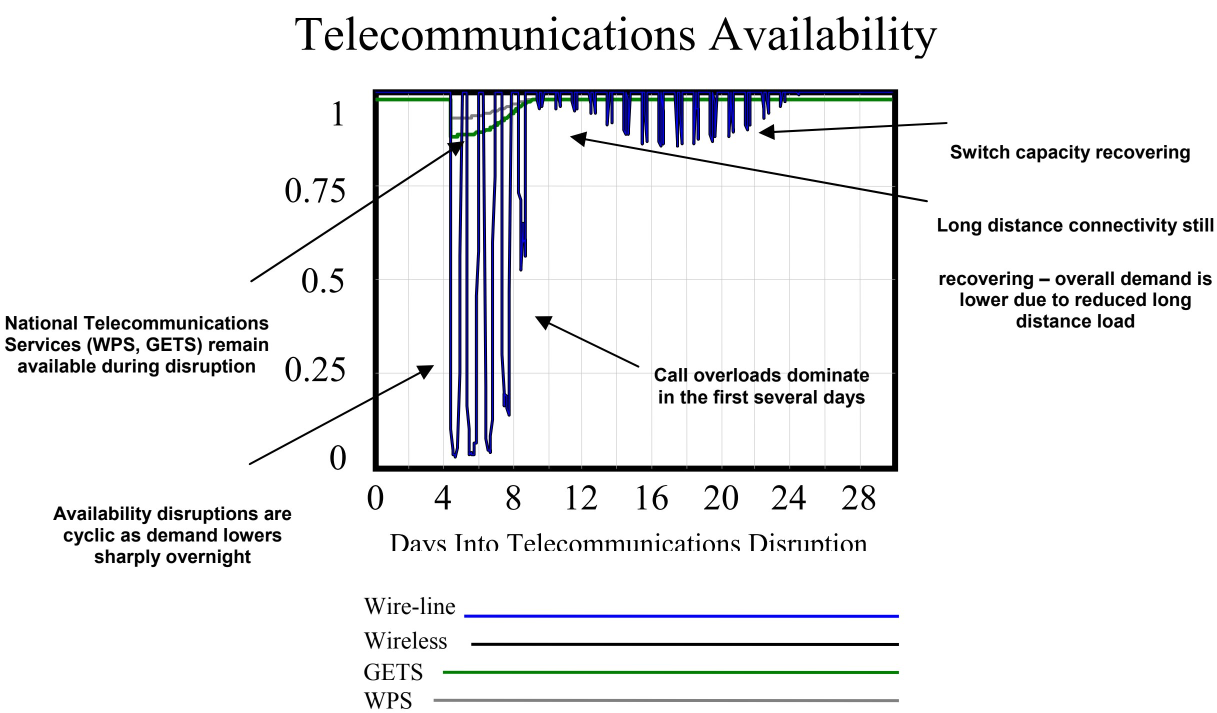

Figure 8: Telecommunications Availability

Figure 9 shows the admitted call volume for the same case. Note that the wireless network is affected also but recovers faster. The wireless network is affected because the call overloads in the wire-line network drive customers to their cell phones, which overloads the wireless network as well. Many wireless phone calls also pass through the wire-line switching network for completion.

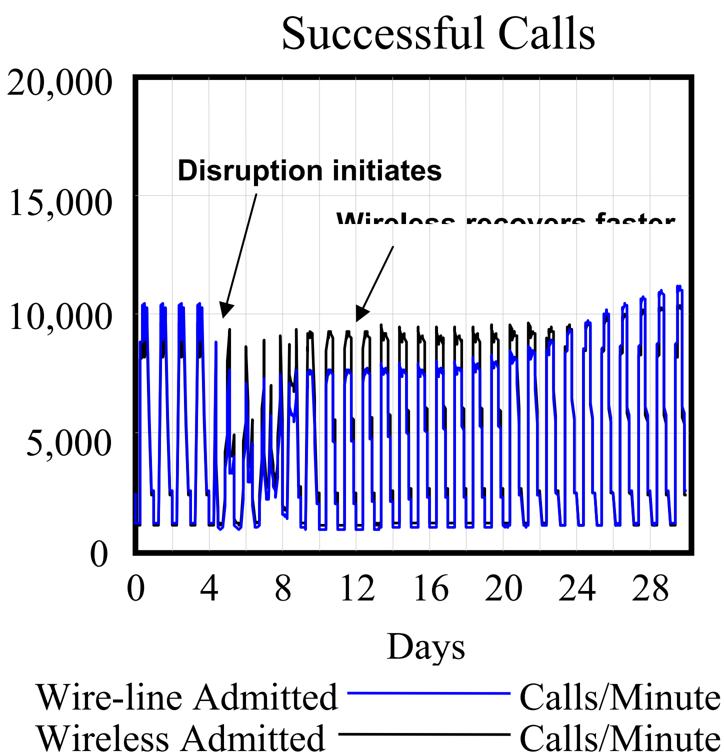

Figure 9: Admitted Call Volume with a 4 X Overload

Conclusions

We have found that aggregated telecommunications representations using systems dynamics models can be used in place of more detailed call-by-call discrete event simulations. Subsequently, these models fit nicely into more general systems dynamics models where critical national infrastructures are simulated together. This allows for a better understanding of the cascading effects of disruptions across infrastructures.

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