◆ Optimal Deployment of Power Reserves Across Telecom Critical Infrastructures

Gerard P. O'Reilly and Chi-Hung Kelvin Chu

Two of the fundamental critical national infrastructures, upon which all others rely heavily, are power and telecom. Emergency services, banking and finance, water, agriculture and food, the chemical industry, defense industrial base, public health, and government cannot run effectively without them for any sustained period of time. As a key infrastructure, central to all others, understanding and modeling the risk due to communications disruption is a high priority in order to enhance public safety and infrastructure resiliency. This paper presents an optimization model for deploying backup generator power within next-generation networks, which are deployed in an increasingly mobile, multi-service, and multi-vendor environment. It also examines how power reserves might be optimally deployed in the mobile telecom infrastructure during power disruptions or blackouts, in order to minimize the cascading of disruptions in the power infrastructure into the wider communications infrastructure. We will describe an example development of these coupled infrastructure models and their application to the analysis of a power disruption or blackout across a metropolitan area.

Introduction

The study of inter-dependencies among critical national infrastructures has come to the forefront in recent years [2, 4, 8, 10, 13, 15, 22]. Our interest has been in the communications infrastructure, and our recent focus has been on next-generation networks (NGNs) which have designs that could prove more reliable or less reliable than the current embedded base. On one hand, many NGN services are implemented on equipment which can be much more disaggregated and distributed than legacy network equipment, which often concentrated network functionality in one box. On the other hand, access to these NGNs is becoming increasingly distributed and closer to the customers. We see this now in wireless networks where access is provided through hundreds or thousands of cell sites spread throughout a given area. For wireline networks, a dominant access method will be through remote access arrangements handling just hundreds of customers each. Today, only about 20 percent of wireline customers are served through remote access arrangements, but this is postulated to grow to as much as 80 percent over time with the introduction of NGNs. Hence, as we move toward NGN deployment, a dominant percentage of both wireline and wireless customer access could be served via these arrangements in the future. Wireline remote access arrangements and cell towers for wireless access are generally powered by commercial electric utilities.

When commercial AC power is lost as a result of an outage, today, most remote devices and cell towers

Bell Labs Technical Journal 12(4), 127–142 (2008) © 2008 Alcatel-Lucent. Published by Wiley Periodicals, Inc.
Published online in Wiley InterScience (www.interscience.wiley.com) • DOI: 10.1002/bltj.20271

have only a small amount of backup power—at most, a few hours with battery backup—so they would go silent in a longer blackout. Should this occur, there would be no access to communications services, especially emergency services such as police, fire, and medical [14]. Cell phones will also lose power over time, though they can remain operational for a long time if sparingly used, or if recharged in a way other than from utility power, e.g., from a car battery.

In this paper, we show how to minimize the impact of a blackout on the telecommunications infrastructure by strategically deploying backup generators to a subset of nodes in areas where today they are not normally deployed. Local, state, and federal government may be interested in mandating minimal backup arrangements or subsidizing those arrangements in order to protect the communications infrastructure during an emergency or disaster situation.

We begin with a brief overview of next-generation networks in the communications infrastructure and follow with a discussion of power methods and requirements in communications networks. Next, we describe some recent power outages and present a model formulation of the problem to be solved. We show results for an example network and then provide our conclusions.

Panel 1. Abbreviations, Acronyms, and Terms

A—Amperes
AC—Alternating current
ATS—Automatic transfer switch
CO—Central office
DC—Direct current
DSL—Digital subscriber line
DSLAM—DSL access multiplexer
EIRP—Effective isotropic radiated power
HVAC—Heating, ventilation, and air conditioning
ILEC—Incumbent local exchange carrier
IMS—IP Multimedia Subsystem
IP—Internet Protocol
kW—kilowatt
kWh—kilowatt hour
NGN—Next-generation network
RBOC—Regional Bell Operating Company
UPS—Uninterruptible power supply
VAC—Volts of alternating current
VDC—Volts of direct current
VoIP—Voice over IP

Next-Generation Networks in Telecom

One example of a next-generation network layered architecture [17] for converged networks is based on the IP Multimedia Subsystem (IMS). It can be characterized by flexible data-driven session control, standardized interfaces, standardized and flexible applications, and common subscriber data. The architecture allows for:

1. Applications provided in centralized common pools, or distributed separately,
2. Session coordination or synchronization across applications,
3. Flexibility of core to coordinate end user experience, and
4. Multiple access networks, supporting multiple clients and endpoints.

Since NGNs combine aspects of the traditional telecom network and an information technology network, which power system architectures are best for NGNs, especially for access arrangements? In this converged architecture, applications will be common across access media, be it mobile radio, wireline, cable, or fiber-to-the-home or premise. The distributed access media will depend largely on power supplied from commercial sources in combination with battery reserve when the commercial power fails. In this paper, to protect against longer outages (i.e., blackouts), we propose a strategic deployment of backup generators staged to provide extended coverage for critical communications. It should also be noted that for the core network elements, geo-redundancy is usually provided to deal with large-scale disasters. In our case, this might include dual backhaul arrangements from cell sites, or from wireline remote nodes to multiple host switching centers.

Typical Power System for a Large Telecommunications Switching Office

The growth of telecommunications, data communications, and the Internet is impacting power systems in two ways. It has increased the demand for higher-capacity central office (CO) power plants, and it has energized the debate over the preferred method

for powering telecommunications. Direct current (DC) systems are currently used in telephone central offices, while uninterruptible power supply-protected alternating current (AC) systems are used in data communications.

Telecommunications equipment requires power to operate [18]. Since the telecommunications industry is a service industry, it is therefore necessary to have a reliable supply of power in order to provide service to customers with as few interruptions as possible. Although commercial AC power generally is very reliable, the interruption of power supply is a common phenomenon, sometimes extending a blackout to many hours over a large area. In order to protect telecommunications services from power interruptions, battery backup power is installed to maintain service for a short-term outage (typically 1 to 8 hours). However, prolonged commercial power interruptions (i.e., blackouts) will eventually cause the central offices to fail unless sufficient long-term power (often referred to as emergency, reserve, or auxiliary power) is provided by a standby generator, typically for up to several days. The auxiliary power supply can be permanently installed or may be portable to the premise in times of emergency.

Traditional telecommunications equipment generally requires −48 volts of DC (VDC) input power. Power systems, consisting of multiple parallel-redundant rectifiers, convert commercial AC power to −48VDC power, which then charges lead-acid storage batteries and supplies power to the critical load equipment. When other voltages are required, converters or inverters are used to provide the other required voltages from the −48VDC power plant. **Figure 1** shows an example of a typical traditional telecommunications power system using rectifiers and −48VDC battery systems to support the critical load equipment [6]. Virtually all critical information technology facilities include permanently installed engine-generator backup systems on site, plus their associated automatic transfer switches (ATS) to protect against sustained commercial AC power system failures.

Information technology equipment is traditionally powered by AC power, typically 120, 208, or 240 volts single phase AC in 60 hertz countries or 220–240 volts single phase AC in 50 hertz countries. Traditional information technology power systems include the use of AC uninterruptible power supply (UPS) systems with battery systems sized to provide either the necessary time for an orderly shutdown or

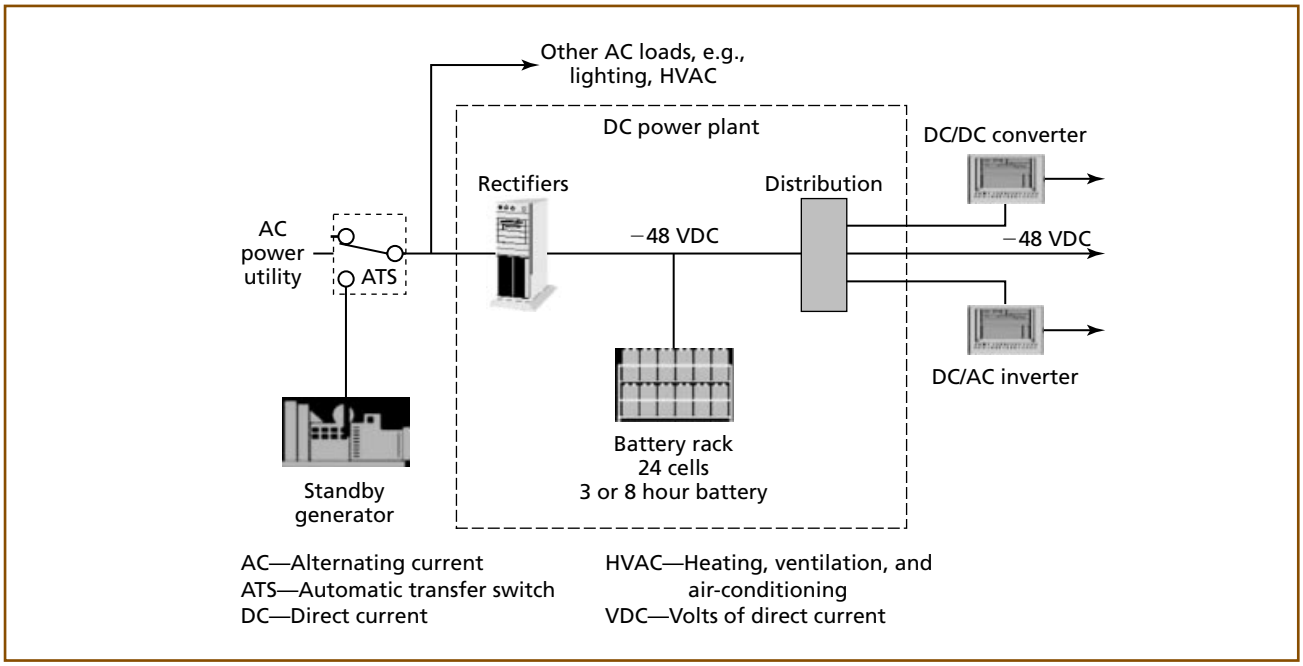

Figure 1.
Traditional telecommunications DC power system.

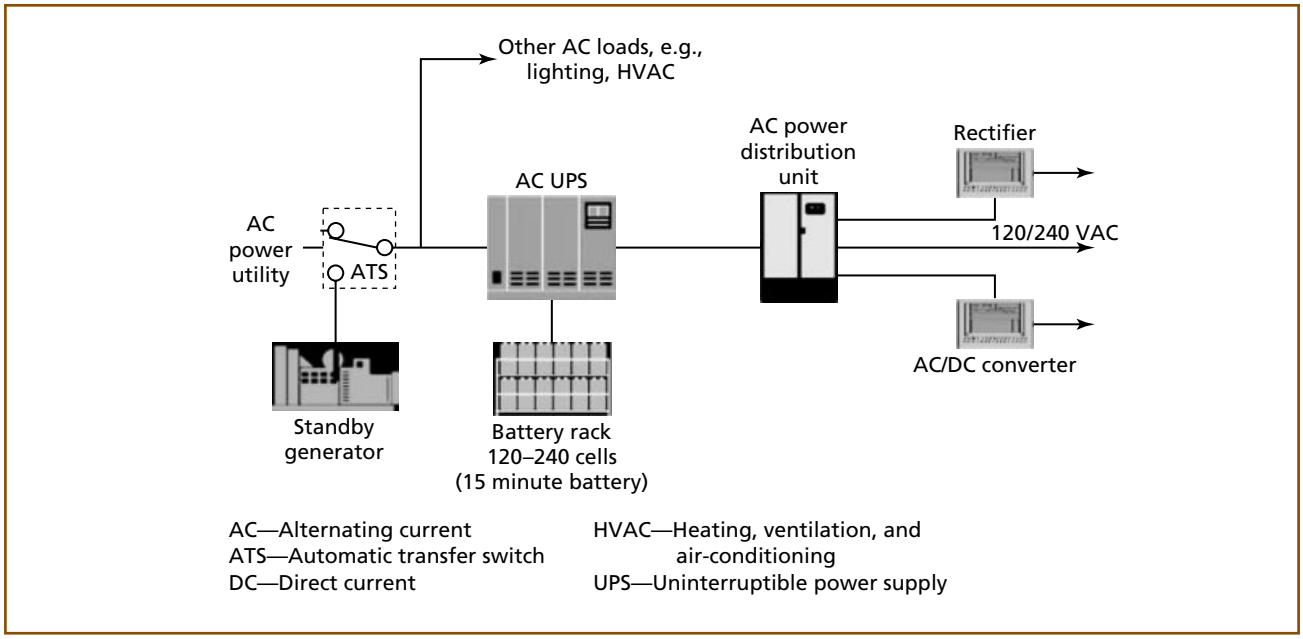

Figure 2.
Traditional information technology AC power system.

sufficient time to reliably start the standby engine-generator power systems. **Figure 2** shows a typical traditional information technology power system using AC UPS systems to support the critical load equipment [6].

Both traditional telecommunications and information technology facilities generally include other critical support equipment, such as lighting and air conditioning. This equipment must also be available for reliable operation of the telecommunications or information technology equipment. Depending on the susceptibility of these support systems to momentary power failures and the availability of standby generators, these critical support systems may be powered differently. For traditional telecommunications power systems without permanently installed standby systems, it is common to have these miscellaneous support loads powered from inverters that are connected to the −48VDC power system. With the convergence of telecommunications and information technology equipment, the critical electronic loads in any one facility will require both −48VDC power and one or more of the commercial AC power voltages. These systems are often operated in such a way that both types of loads are required for the site to remain operational.

This paper does not attempt to provide a blueprint for telecommunications power system design, but to provide an overview of the requirements for a telecommunications power plant.

DC Power System

The power load that the DC distribution system feeds is determined by the type, quantity, and mix of telecommunications equipment in an office. Once that load has been determined, a distribution system and a power source with adequate capacity to power the load, taking into account the distribution losses, must be available.

DC rectifier and battery plants. Figure 1 shows that telecommunications equipment requires a DC power source of various voltages and polarities. Since the DC power source comes from the AC power utility, the AC power must first of all be rectified into DC. Rectifiers therefore are the most important part of a DC power plant. The basic function of a rectifier is to convert AC to DC to supply the load demands and to charge the DC reserve batteries. Different technologies of rectifications commonly used in central offices are thyristor (SCR), controlled ferroresonant, and switchmode. Switchmode is very popular for remote locations because of its reduced weight and size.

DC/DC converter plants. There are other loads that require DC voltages other than the standard −48VDC. Many newer telecommunications systems utilize DC-to-DC converters to support these loads. These converters are constant power devices; i.e., during a power outage, as the battery voltage decreases, the current required to maintain operations increases. This increase in current may impact the available reserve time of the batteries and therefore must be considered very carefully during the design of the system.

DC distribution. As shown in Figure 1, the primary DC distribution ties the rectifiers, battery, and loads together. The loads can be either a secondary DC distribution network, or equipment loads, or both. Overcurrent protection is provided at the power distribution panel before being handed off to the next level of DC distribution network. In most cases, the primary distribution is designed with redundant A/B feeds to ensure the reliability of the primary system.

Battery Reserve System

Several types of batteries are commonly found in telecommunications central offices [7]. These include lead-acid storage cells using lead-antimony, lead-calcium, or pure-lead, and valve regulated lead-acid cells. Although lead-antimony cells were the ones most commonly used in the past, they are no longer the preferred battery choice for power system designers.

Battery types.

- *Lead-antimony cells.* The lead-antimony cell is similar to a conventional lead-acid battery, except that antimony is added to the lead plates to increase its mechanical strength. These batteries have a higher self-discharge rate and require higher trickle currents compared to a conventional lead-acid battery.
- *Lead-calcium cells.* The lead-calcium cells have a lower discharge, lower trickle charge current, and require less maintenance than the lead-antimony cells. However, the condition of the lead-calcium cell is difficult to determine using the conventional specific gravity and voltage readings method.
- *Pure-lead cells.* These batteries are designed to minimize the physical deterioration associated with conventional design. The expected life of this type of battery is much longer than that of lead-antimony and lead-calcium.
- *Valve regulated lead-acid cells.* These cells are sometimes called sealed lead-acid cells. Under normal voltage and temperature operating conditions, they are expected to be virtually maintenance-free and gassing free. Although these cells may be referred to as sealed cells, they are vent-regulated to relieve excess internal pressure.

Sealed cells recombine evolved oxygen at the negative plates, eliminating the need for water and reducing ventilation requirements. That is why this type of battery is sometimes referred to as a recombination-type. Sealed cells are available in a variety of models designed for numerous applications. They range in capacity from 25 ampere-hours to over 4000 ampere-hours and have float voltages between 2.17 and 2.29 volts per cell. Some sealed cells have ampere-hour ratings that compare favorably with those of commonly used lead-acid flooded cells and are similar in size and weight.

In a central office environment, the battery of choice is typically a lead-acid 1680 amp hour cell. For remote confined locations, the battery of choice is valve regulated because of its compact size, current density, and low maintenance.

Battery reserve time. Battery reserve time is the amount of time a battery plant can supply DC power within the circuit voltage limits of the load equipment at the expected current drain. Traditional battery support times range from a minimum of 1 hour to over 24 hours, with typical battery support ranging from 3 to 8 hours. For the DC powered loads, if a location is easily accessible and a backup generator is available, then 3 hours of reserve power is typically required. For locations that have only battery backup, the battery reserve time is typically 8 hours. If an extended outage is expected, a portable generator will have to be used for powering the office.

Backup Generators for Long Term Outages

A wide variety of options must be considered for backup generators [21], including the following:

- Portable versus permanent generator installation,
- Generator engine fuel source, e.g., natural gas, propane, butane, liquefied petroleum gas, or gasoline, or diesel fuel,
- Automatic or manual control,

- Single, large versus multiple, small generators,
- Single-, sectional-, or dual-bus distribution, and
- Single-phase versus three-phase generators at 120-, 208-, 230-, 240-, 460-, or 480 volt output.

The following application questions must also be addressed when choosing or specifying a generator:

- What loads should be connected to a standby generator?
- What type of fuel best suits a particular application?
- What acoustic requirements and space requirements must be met?

The generator options are evaluated and selected with site-specific requirements in mind.

Large central offices will continue to employ both short term reserve power (batteries) and long term reserve power (generators), so redundancy is really not an issue for the core nodes in our NGNs. The backup power issue becomes important for smaller wireline remote sites, and for cell sites.

Remote unattended or partially attended plants. The current trend is to install unattended (or partially attended) plants, and many existing plants are also being converted for unattended or partially attended operation. This may require a standby generator to be equipped with automatic start and transfer capabilities.

Standby generator loads. There are three types of standby plant loads: essential, non-essential, and special.

1. *Essential loads.* Essential loads must operate during a prolonged commercial power outage and must be connected to the standby generator. The loads must be able to tolerate an interruption on the order of 5 seconds or more. Typical interruption times range from 10 to 90 seconds for automatic standby systems, and up to 15 minutes or more for manual systems. Some of the suggested loads that fall into the essential load category are listed below:
   a. Telephone equipment. The generator must maintain full operation of all recharge rectifiers in all DC plants in the building and all power needed for essential switching and transmission equipment and for other AC loads, such as:
      - Clocks and timers,
      - Convenience outlets located in the base of all central office equipment,
      - Status boards and equipment for network management,
      - Inverter plant powering protected and UPS loads,
      - Auxiliary equipment associated with the generator, and
      - Antenna deicers, ventilation equipment, navigating lights, and other ancillary equipment.
   b. Building equipment. The generator must maintain essential building facilities, including the following:
      - Sump pumps, house pumps, and fire pumps,
      - Heating and ventilating systems,
      - Cooling systems (e.g., when the ventilation system is inadequate or equipment temperature requirements cannot be met otherwise),
      - Essential lighting and ventilation for areas such as operator rooms, interior corridors, and lavatories,
      - Electronic security systems, and
      - Elevator service (e.g., provisional power to lower all elevators to the ground floors in multi-story buildings, and a minimum amount of power for elevator service.)

      In large, fully attended central office buildings, consideration should also be given to loads such as necessary dining room, cooking, and food refrigeration equipment; vending machines; and at least one elevator in buildings with three or more floors (local codes may be more stringent).
   c. Business office equipment. Power should be provided for:
      - Equipment necessary for protecting company revenues, including bill receipting and other business machines,
      - Visual signals on attendant-operated office equipment, and
      - Essential lighting.

d. Emergency lighting. Emergency lighting is suggested for operator positions, power equipment rooms, battery rooms, and engine rooms.

2. *Non-essential loads.* Non-essential loads are loads that are not required to operate during commercial power outages and therefore are not connected to the backup generator system.
3. *Special loads.* During commercial power failures, essential loads are switched to the standby generator. Standby power plants and their loads need to be tested to discover and resolve system problems before a power failure occurs. During these standby generator tests involving simulated power failures, certain types of loads are kept on the commercial AC power source and are not switched. These loads are classified as special power loads, which include the most important essential loads.

Typical Power Consumption by Office Type

Power consumption in a telecommunications node whether at a central office or a remote location can vary significantly depending on the type of installed equipment. The following sections provide an estimate of the power consumption for traditional telecommunications nodes and Internet hosting/server-based telecommunications sites. The power requirements for different types of facilities are significantly different from each other. See **Table I** for a summary. The last column, amp hours, is the amount needed by the generator to sustain 3 days (or 72 hours) without refueling.

Telecommunications central offices. In the United States, for example, the biggest incumbent local exchange carriers (ILECs) are the regional operating companies or regional bell operating companies (RBOCs). A typical RBOC owns about 3500 buildings and stations with about 780 million square feet of equipment space and uses more than 3 billion kilowatt hours (kWh) of electricity annually [11]. This amounts to approximately 100 kilowatts (kW) per building but varies widely. This includes all switching and transmission equipment together with network power and the associated subsystems, such as heating, ventilation, and air conditioning (HVAC); and the security, fire suppression, and building management systems that are connected to network management systems.

Depending on the equipment and size of the central office, typical maximum power supply ratings for the switching and transmission equipment range from 50 amperes (A) to 800 A [11, 19], which is equivalent to 2.5 kW to about 40 kW. The typical power requirement for switching equipment on average is estimated to be approximately 1 kW per 1000 lines (however, during busy days such as Mother's Day, the power consumption can be as high as 4 kW per 1000 lines). Power requirements for the transmission equipment associated with switching equipment, and the recharge power needed for the batteries, are both approximately one-fifth that of the switching equipment itself, or approximately 0.5 kW in total [1]. For a CO of moderate size, handling 20,000 lines, the total power consumption will be about 30 kW.

Table I. Example power consumption of various nodes.

Office type	Power consumption/unit	Example size	Power consumption	Amp hours of reserve required
Large central office	2.0 watts/line	50,000 lines	100 kW	144,000
Medium central office	1.5 watts/line	20,000 lines	30 kW	43,200
Small central office	1.0 watts/line	4,000 lines	4 kW	5760
Data center	200 watts/sq.ft.	40,000 sq.ft.	8,000 kW	691,200
Wireline DSLAM remote site	1.5 watts/line	1000 lines	1.5 kW	108
Wireless base station	4.0 watts/user	1500 users	6.0 kW	432

DSLAM—Digital subscriber line access multiplexer
kW—Kilowatt

Data centers, Internet hosting, and server-based telecommunications sites. Typical data centers, Internet hosting sites, and server-based telecommunications sites usually have a mix of AC-powered loads in the range of 85 to 95 percent of the total electrical load (kW) with only 5 to 15 percent of the total electrical load (kW) being DC-powered. The size of typical sites tends to be in the 10,000 to 100,000 square foot range with power densities of the electronic equipment in the range of 35 to 100 watts per square foot [20]. In today's data center environments, the highest density racks can exceed 200 watts per square foot, so designers are specifying new data centers to handle heat loads of 350 and even 500 watts per square foot [16].

With these requirements, the critical power system sizes tend to fall in the range of 350 kW to over 8 megawatts (MW). At −48VDC, these power levels equate to 7000 amps to over an astounding 160,000 amps. At 480 volts of alternating current (VAC) 3-phase, these same power levels equate to a more manageable 420 amps to over 9600 amps. This is why data telecommunications sites are generally powered by AC instead of DC.

The Internet has increased the demand for second residential lines, broadband access lines via digital subscriber line (DSL) or cable, data services, and accelerated co-location and the deployment of power-hungry high speed fiber networks. This has caused an upsurge in CO power loads and a demand for higher capacity (3000 A to 10000 A) plants that is expected to grow at 20 to 25 percent annually for next few years [16].

Remote access arrangements. High speed Internet access for data only or for combined voice and data using Voice over Internet Protocol (VoIP) is typically provided by DSL to the customer premise, and due to limited range, it is concentrated on remote systems called DSL access multiplexers (DSLAMs) located in the access plant between the customer premise and the central office. The typical power consumption for a DSLAM is on the order of 1500 watts serving approximately 1000 lines.

Wireless base stations. For cell phones, access to the network is provided through base stations. Depending on the configuration of the base station, the power requirements may vary significantly from one to another. A typical Alcatel-Lucent OneBTS® base station can support 140 simultaneous users per carrier and handle up to 11 carriers, so the total number of potential users is approximately 1,540.

Table II. Example base station power consumption.

Example base station types	Calculated DC power (watt)	Measured DC power
CDMA 4.0 Compact	~2600	~2700
CDMA 4.0 ModCell	~6000	~5500
UMTS ModCell 4.0	~12500–13000	~7000–9000

CDMA—Code division multiple access
DC—Direct current
UMTS—Universal Mobile Telecommunications System

Since the power consumption of a base station depends heavily on the configuration and the type of wireless network it supports, **Table II** provides a sample of the power requirements calculated and/or measured for various networks. As the table shows, the power consumption for a base station is quite significant and is comparable to that of a typical small-sized central office.

Power Outages

Power outages occur frequently, and significant ones happen every few years. For example, an outage in 2003 affected a large portion of the eastern United States [23]. Approximately half of power outages are caused by bad weather, such as storms or hurricanes [12]. The other half are caused by network overloads, procedural errors, and similar occurrences. Our intention here is not to model power outages—that has been done elsewhere [3]—but rather to show how to mitigate their effects on the telecommunications infrastructure by providing backup generators strategically placed at nodes where they traditionally have not been provided.

Model Formulation

Our goal is to minimize the total cost of providing backup generators to a metropolitan area that experiences a blackout lasting more than 4 hours, the point at which most short-term battery power

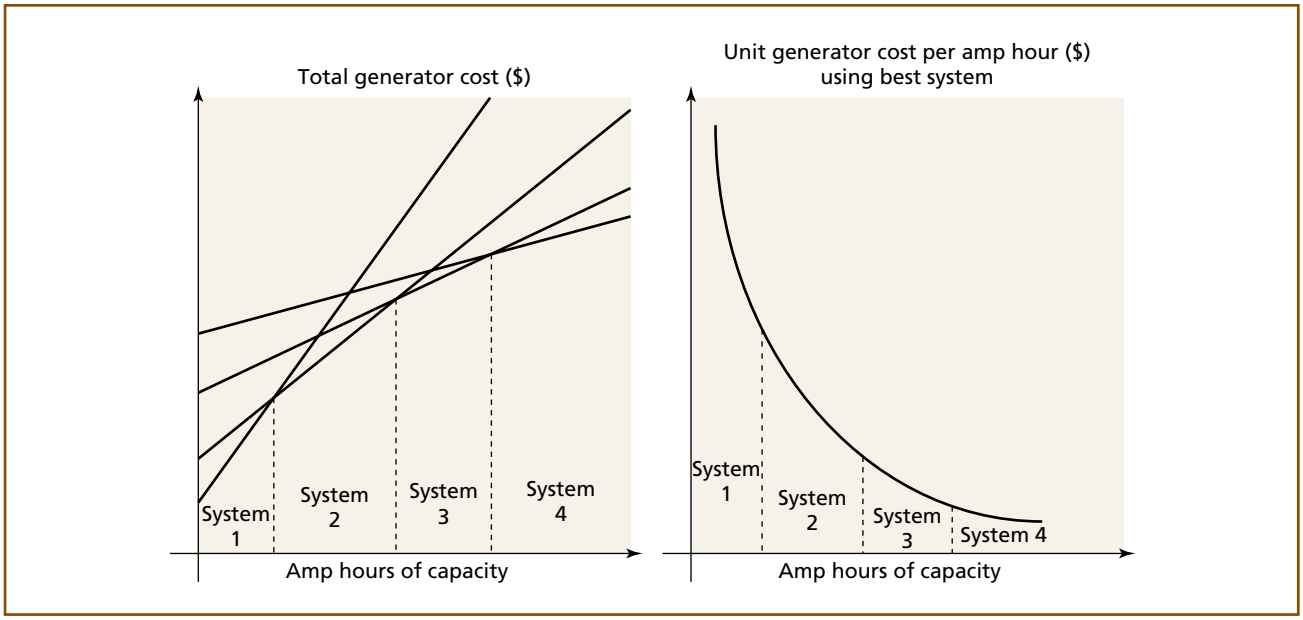

Figure 3.
Total cost and unit cost of generators.

reserves would have been depleted. Generators come in various sizes. **Figure 3** shows four different systems with different cost curves. We assume that a given system will incur a fixed start-up cost and a variable cost per amp hour.

The total cost of a generator of type j for A amp hours, where j = 1, . . . J, is given by

$$GC_j\,(A) = a_j + b_j\,A \qquad (1)$$

where a_j is the fixed startup cost and b_j is the variable incremental cost per unit.

For any given system size, for amp hours required, we would choose the system which carries the minimum total cost. The unit cost by system is shown on the right side of Figure 3, which makes it obvious which system should be used.

Let

N = number of nodes in the network that could be powered during an extended blackout.

P_i = power requirements in amp hours for a backup generator for nodes i = 1, . . . N

For a given P_i, we would pick the minimum cost generator type j, or

$$GC\,(P_i) = \min\,(GC_j\,(P_i)\,) \text{ over } j = 1, \ldots J \qquad (2)$$

If all nodes were equipped with a generator, then the total cost of generator equipment for power backup during blackouts would be

$$\text{Total Cost(TC)} = \sum_{i=1}^{N} GC(P_i) \qquad (3)$$

Now, summing this over all potential nodes in a metropolitan area, it would amount to hundreds of millions of dollars, which is not affordable.

As such, proper placement of backup generators requires some decisions.

Let

x_i = 1 if a generator is deployed at node i
= 0 if a generator is not deployed at node i (4)

Let $X = \{x_1, x_2, \ldots x_N\}$ the set of 0, 1 decision variables representing whether backup generator would be placed at that location.

So our optimization problem is to minimize the total cost or

$$\text{Minimize TC}\,(X) = \sum_{i=1}^{N} GC(P_i)x_i \qquad (5)$$

subject to a set of constraints on coverage of the metropolitan area, and capacity of the nodes serving that area.

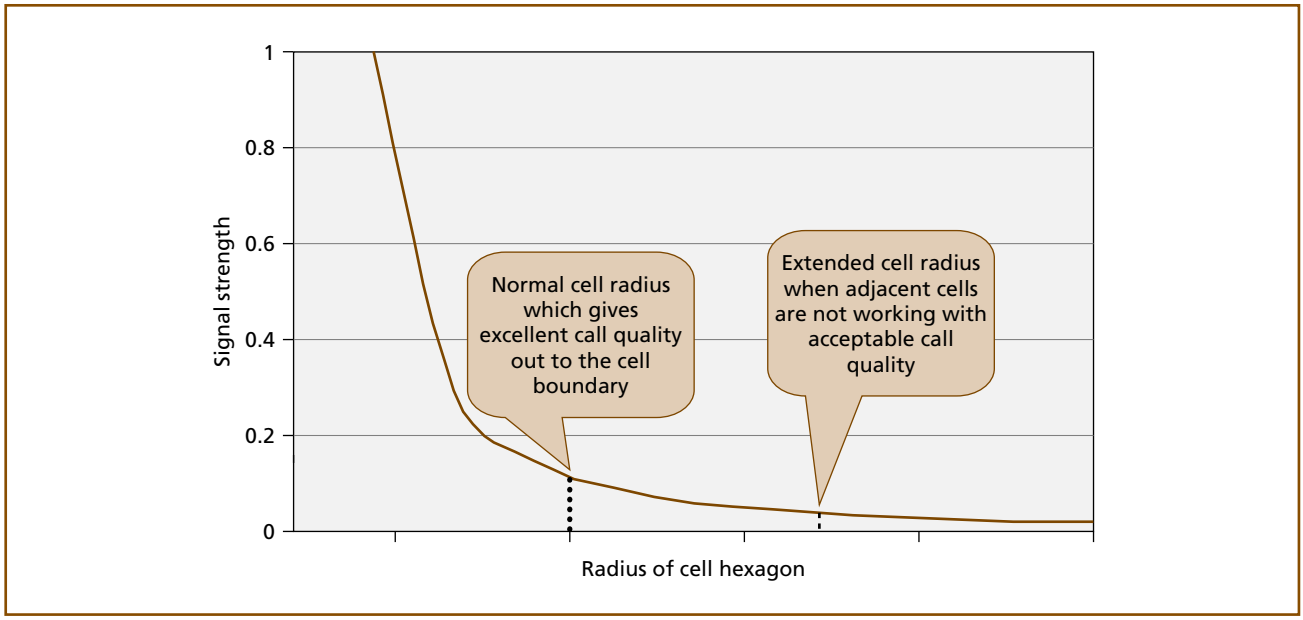

Figure 4.
Signal strength decreases with distance.

Wireless Signal Strength vs. Distance

The Okumura-Hata model [9] of propagation for dense metropolitan areas is shown below:

$$\log_{10}(R/1000) = \frac{PL - 69.55 - 26.16 \log f + 13.82 \log h_b + C_h}{44.9 - 6.55 \log h_b} \quad (6)$$

where:

R: cell radius in meters (m)

PL: propagation loss or path loss effective isotropic radiated power (EIRP) in dB

f: carrier frequency (MHz), e.g., 900 MHz or 1800 MHz

h_b: base station effective antenna height above ground in the range 30 to 200 m

h_m: mobile station antenna height above ground in the range 1 to 10 m

$C_{h:}$ correction factor for the mobile station antenna height
$= 3.2 \log (11.75\, h_m)^2 - 4.97$

Typically, a region is planned with a uniform layout of cell hexagons when everything is working. In actual practice, the cell sizes vary by population and building density, with cells in dense urban areas being the smallest at hundreds of meters in radius, to urban, suburban, and rural cells spanning many miles in radius. Excellent call quality is provided to the cell boundaries when everything is working. **Figure 4** shows an example of the signal strength as a function of distance. It shows the potential extended range of a cell site when its adjacent cells aren't working. For a given radius of a cell site serving area, mobile customers farther away can be served at a larger radius with acceptable service.

Let R_i = extended radius of each node i giving acceptable call quality. **Figure 5** shows that the extended radius is generally bigger than the size of the normal hexagon serving area of the cell site. So, an adjacent out-of-service cell without a standby generator may be covered by a working cell with a standby generator.

Coverage for an Area

Another set of constraints involve coverage, that is, providing communications services during a blackout to a certain fraction of the population, which could be as much as 100 percent. Coverage is defined for an area when working nodes cover demand in an area for non-working nodes. It should also be noted that while the coverage area for a given cell site is expanded, its call-carrying capacity (or bandwidth)

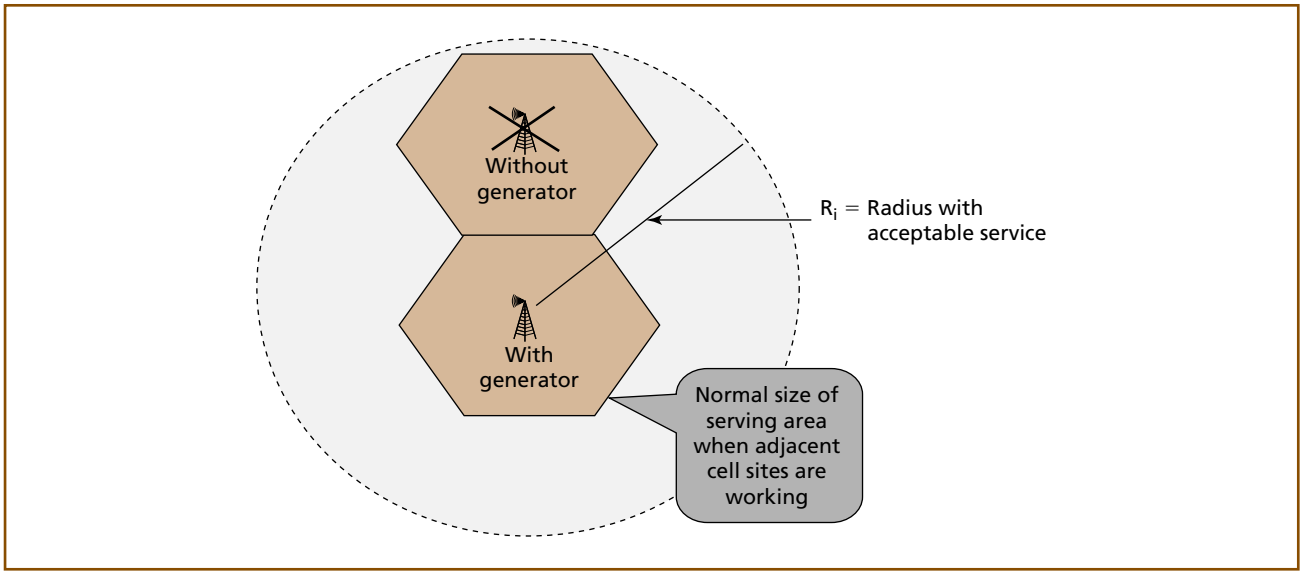

Figure 5.
Potential servicing area of a cell site with a generator.

is not expanded. Hence, with an expanded area and more demand, congestion may result, but calls can still get through.

Expansion of a coverage area can only be done with wireless systems, as wireline nodes have fixed boundaries. For example, if a cell tower isn't working, another adjacent cell tower may cover its area if its radius is big enough.

Let

L_i = location of node i in the network (by latitude and longitude, for example)

For wireless nodes, node j is covered by node i if distance (i,j) $< R_i$.

C_{ij} = 1 if node i covers node j, i = 1, . . . N, and j = 1, . . . N, a square matrix

Note: for all wireline nodes, if they are to be considered in the analysis,

C_{ij} = 1 for all i = j i = 1, . . . N, and j = 1, . . . N
= 0 for all i ≠ j

D_j = level of peak demand (say during busy hour) for node j for j = 1, . . . N

Coverage of demand for the whole area is defined as

$$\sum_{j=1}^{N} D_j \, Max_i \, (C_{ij} x_i) \tag{7}$$

where the max is over i = 1, . . . N.

Recall that the x_i are the decision variables on where generators would be placed. This avoids double counting of nodes that might be covered more than once.

Let

C = coverage factor for a whole area, at 100 percent when everything is working.

During a blackout, since it may be cost prohibitive to cover 100 percent of the area, an objective might be set somewhat lower, say at 50 percent or 75 percent coverage. As such the coverage constraint is

$$\sum_{j=1}^{N} D_j \, Max_i \, (C_{ij} \, x_i) \geq C \sum_{j=1}^{N} D_j \tag{8}$$

Now, coverage is one thing, but service providers also require sufficient capacity in the selected nodes to effectively service the area being covered. Hence, a minimum capacity might be required during the blackout across the nodes with backup generators.

Let

CAP = fraction of total capacity that must be provided during the blackout, say 40 percent. CAP could be as high as 100%.

$$\sum_{j=1}^{N} D_j x_j \geq \text{CAP} \sum_{j=1}^{N} D_j \tag{9}$$

As a result, the optimization problem is to minimize equation (7), subject to coverage constraint (8) and capacity constraint (9). This can be a rather large mathematical programming problem with j running into the thousands, and difficult since it is both non-linear and integer. Such large problems can be reasonably solved by using packages such as Excel Solver [5]. For any given non-linear, integer problem instance, optimal solutions are usually not guaranteed, so in practice, one seeks a good solution from many different starting places (feasible solutions which are easy to find in this problem), and then chooses the best overall solution.

Example Analysis on a Small Network

To make this example tractable, a small area of a city was chosen with just 49 cell sites, arranged in a 7 × 7 hexagonal pattern, an example of which is shown in **Figure 6** with a solution showing 11 generators spread throughout the area. Note that cell site boundaries are usually not so neatly organized as in Figure 6, but the methodology applies with any arrangement of cell sites. For this example, we have ignored the fixed wireline sites (central offices) with fixed boundaries, since all of those will have backup generators and serve the wireline demand within their wirecenter boundary. We have also ignored the wireline remote arrangements for simplification because a standby generator at one of those remote sites cannot be used to extend service beyond the serving boundary for that remote site. The methodology allows for their inclusion if desired.

Normally, a city will have hundreds or thousands of cell sites. For simplicity here, we assume that all cell sites have the same size in boundary but can have different demand levels. The optimal cost results are shown in **Figure 7** as a function of the capacity of the sites with generators. Obviously, the more sites with generators, the more costly the solution. More importantly, **Figure 8** shows the percent of population coverage versus a given capacity of the nodes with generators. If we want to have 100 percent of the capacity available, we would need to

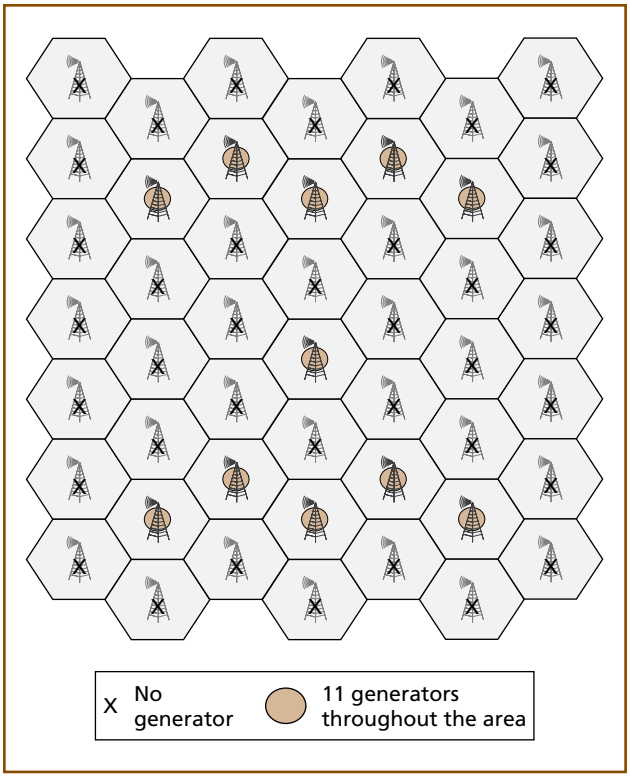

Figure 6.
Selection of sites for 30 percent capacity covering 80 percent of population.

put a backup generator at every site and incur the largest cost. This is likely to be cost prohibitive. In fact, we can cover 50 percent of the population with just under 20 percent of the capacity equipped with generators, and we can cover more than 80 percent of the population with just over 30 percent of the capacity equipped with backup generators. After that point, there are diminishing returns to increasing coverage at larger and larger costs. In fact, Figure 6 shows the solution where 11 sites out of 49 have backup generators. These sites contain 30 percent of the capacity of the original network but cover approximately 80 percent of the population in a blackout. The cost for this coverage would be about $4 million, as shown in Figure 7. If we were to demand 100 percent coverage of the population, the cost would increase to more than $16 million, so an extra $12 million would yield only an additional 20 percent increase in population covered.

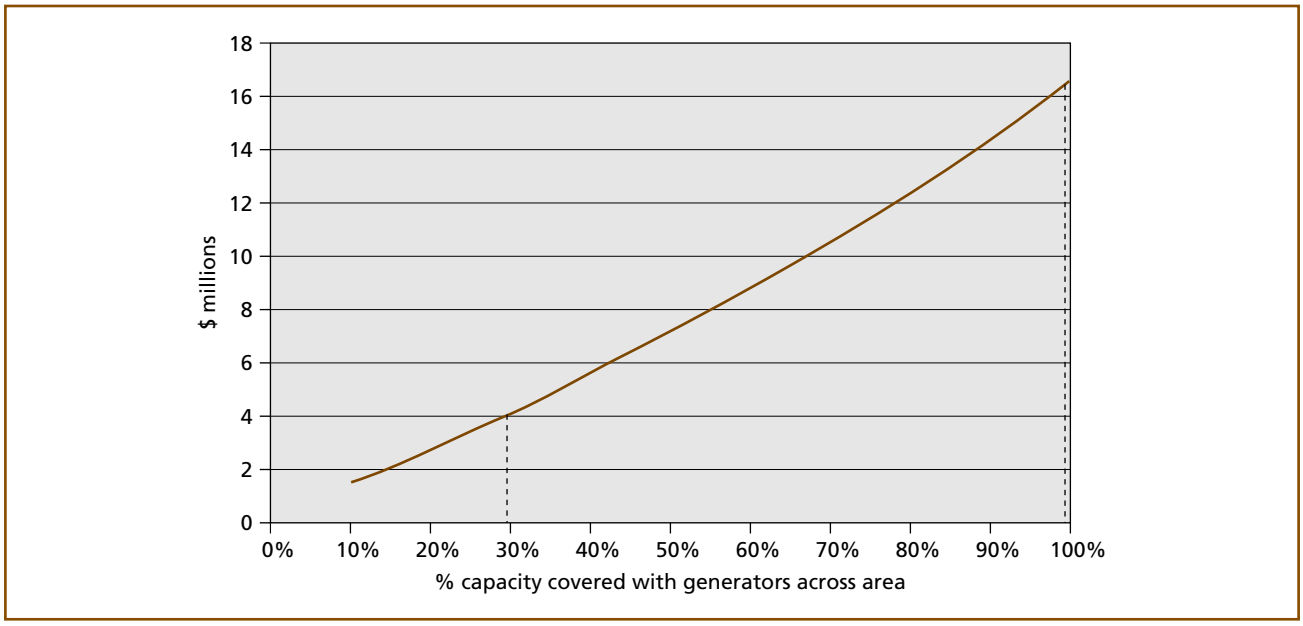

Figure 7.
Optimal cost as a function of capacity covered.

Conclusions

For next-generation networks, where remote access arrangements dominate, we can expect to see a transition regarding backup arrangements. While today wireline access continues to work during a blackout and cell service may go down except in those locations where generators are placed, in the future, certainly the wireline and wireless central offices will continue to have backup generators, but the remote nodes (DSLAM sites or cell sites) will not, unless

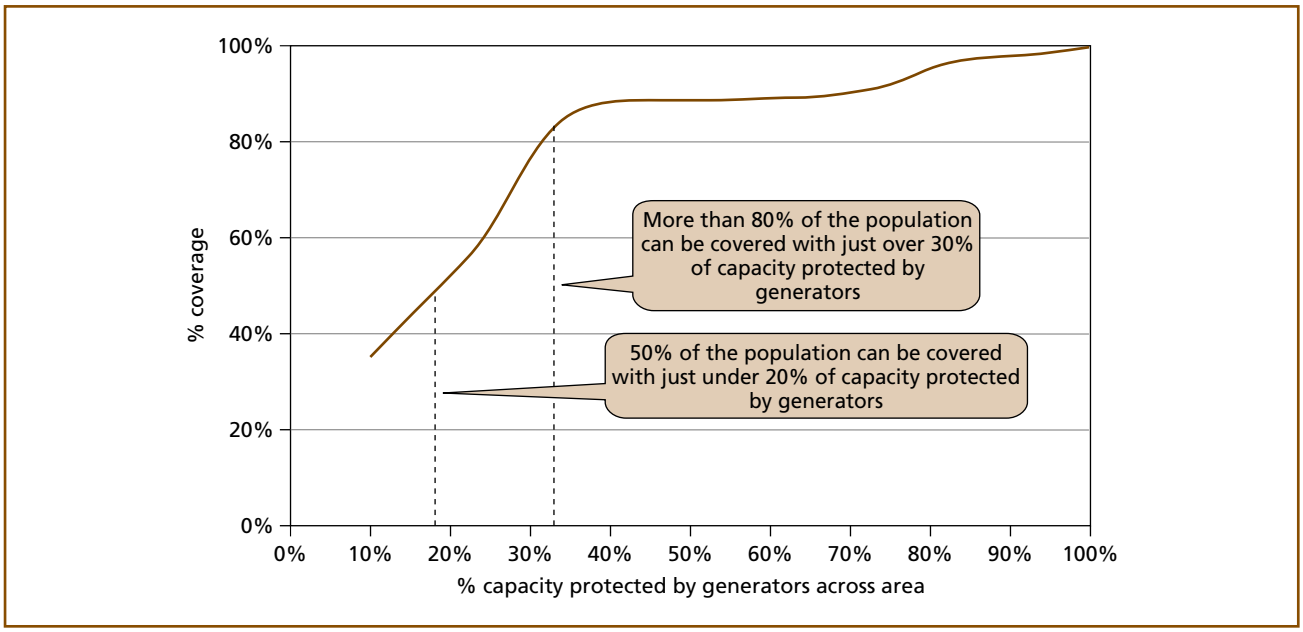

Figure 8.
Population covered as a function of capacity covered.

generators are strategically placed. Hence, it will be cell service, where generators might be deployed, that backs up landline service. It is also a fact that more and more people, particularly the younger generations, may only have wireless access and no wireline access in their residences. Or, they may have VoIP for their home, which would be knocked out if there is a commercial AC failure (unless they have UPS at home, which most residences will not have).

Backup generators for cell towers are not normally deployed today, and there is little economic incentive to deploy these costly arrangements for blackout events. However, for societal purposes in giving access to emergency services during a blackout, it may be the greater good to supply this level of cross-infrastructure backup. As such, the governments of cities and states may want to subsidize these arrangements in order to protect communications throughout their areas during these emergency situations.

References

[1] Advanced Micro Devices, "Power and Cooling in the Data Center," 2005, <http://enterprise.amd.com/Downloads/34146A_PC_WP_en.pdf>.

[2] W. E. Beyeler, S. H. Conrad, T. F. Corbet, G. P. O'Reilly, and D. D. Picklesimer, "Inter-Infrastructure Modeling—Ports and Telecommunications," Bell Labs Tech. J., 9:2 (2004), 91–105.

[3] B. A. Carreras, D. E. Newman, and I. Dobson, "Evidence for Self-Organized Criticality in a Time Series of Electric Power System Blackouts," IEEE Trans. Circuits Syst. I Regul. Pap., 51:9 (2004), 1733–1740.

[4] S. H. Conrad, R. J. LeClaire, G. P. O'Reilly, and H. Uzunalioglu, "Critical National Infrastructure Reliability Modeling and Analysis," Bell Labs Tech. J., 11:3 (2006), 57–71.

[5] Frontline Systems, Excel Solver V7.1, <http://www.solver.com>.

[6] T. M. Gruzs and J. Hall, "AC, DC or Hybrid Power Solutions for Today's Telecommunications Facilities," Proc. 22nd Internat. Telecommun. Energy Conf. (INTELEC '00) (Phoenix, AZ, 2000), pp. 361–368.

[7] K. Hoshijima, K. Sekiya, T. Yamashita, K. Matsumoto, Y. Kuwata, and S. Furubo, "Power Supply System for High-Speed Broadband Telecommunications Equipment in a Central Office," Proc. 18th Internat. Telecommun. Energy Conf. (INTELEC '96) (Boston, MA, 1996), pp. 383–390.

[8] D. J. Houck, E. Kim, G. P. O'Reilly, D. D. Picklesimer, and H. Uzunalioglu, "A Network Survivability Model for Critical National Infrastructures," Bell Labs Tech. J., 8:4 (2004), 153–172.

[9] International Telecommunication Union, Radiocommunication Sector, "Prediction Methods for the Terrestrial Land Mobile Service in the VHF and UHF Bands," ITU-R Rec. P.529–2, Oct. 1995, pp. 5–7, <http://www.itu.int>.

[10] A. Jrad, H. Uzunalioglu, D. J. Houck, G. O'Reilly, S. Conrad, and W. Beyeler, "Wireless and Wireline Network Interactions in Disaster Scenarios," Proc. IEEE Military Commun. Conf. (MILCOM '05) (Atlantic City, NJ, 2005), vol. 1, pp. 357–363.

[11] D. Kong and F. de Kock, "Affordable and Reliable Power Systems for Telecommunications in Africa," Proc. 19th Internat. Telecommun. Energy Conf. (INTELEC '97) (Melbourne, Austral., 1997), pp. 141–145.

[12] North American Electric Reliability Corporation (NERC), Disturbance Analysis Working Group (DAWG) Database, Blackouts in North America, <http://www.nerc.com/~dawg/database.html>.

[13] G. O'Reilly, D. Houck, F. Bastry, A. Jrad, H. Uzunalioglu, W. Beyeler, T. Brown, and S. Conrad, "Modeling Interdependencies Between Communications and Critical Infrastructures," Proc. Working Together: R&D Partnerships in Homeland Security (Boston, MA, 2005).

[14] G. O'Reilly, H. Uzunalioglu, S. Conrad, and W. Beyeler, "Inter-Infrastructure Simulations Across Telecom, Power, and Emergency Services," Proc. 5th Internat. Workshop on Design of Reliable Commun. Networks (DRCN '05) (Ischia, It., 2005), pp. 387–393.

[15] G. P. O'Reilly, D. J. Houck, E. Kim, T. B. Morawski, D. D. Picklesimer, and H. Uzunalioglu, "Infrastructure Simulations of Disaster Scenarios," Proc. 11th Internat. Telecommun. Network Strategy and Planning Symposium (NETWORKS '04) (Vienna, Aus., 2004), pp. 205–210.

[16] N. Osifchin, "An Infrastructure for Telecommunications Power in a New Era in Public Networking," Proc. 3rd Internat. Conf. on Telecommun. Energy Special (TELESCON '00) (Dresden, Ger., 2000), pp. 23–28.

[17] H. Pant, C.-H. K. Chu, S. H. Richman, A. Jrad, and G. P. O' Reilly, "Reliability of NGNs with a Focus on IMS Architecture," Bell Labs Tech. J., 12:4 (2008), 109–125.
[18] K. F. Rauscher, R. E. Krock, and J. P. Runyon, "Eight Ingredients of Communications Infrastructure: A Systematic and Comprehensive Framework for Enhancing Network Reliability and Security," Bell Labs Tech. J., 11:3 (2006), 73–81.
[19] M. Rush, "Telecom/Office Hybrids: Staying Flexible in an Uncertain Market," New York Commercial Real Estate J., Apr. 2001.
[20] Telcordia Technologies, "LSSGR: Power, Section 13," GR-513-CORE, Issue 1, FR-64 Component, Sept. 1995.
[21] J.-C. Tetart, "France Telecom Latest Trends in Central Office Power," Proc. 22nd Internat. Telecommun. Energy Conf. (INTELEC '00) (Phoenix, AZ, 2000), pp. 373–378.
[22] United States, The White House, The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets, Washington, D.C., Feb. 2003, pp. 6, 47–79, <www.whitehouse.gov/pcipb/physical.html>.
[23] United States and Canada, U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, Natural Resources Canada, Ottawa, Apr. 2004.

(Manuscript approved October 2007)

GERARD P. O'REILLY is a distinguished member of technical staff in Bell Labs' Network Performance and Reliability Department in Murray Hill, New Jersey. He received a B.S. in mathematics from Manhattan College, and an M.S. and Eng.Sc.D. in operations research from Columbia University in New York, New York. Dr. O'Reilly has been a developer, systems engineer, technical manager, and district manager in Bell Labs, AT&T Labs, and AT&T's International Network Planning Group. He also served as an Adjunct Professor of Telecommunications at Stevens Institute of Technology, teaching switching and signaling. His current focus includes working with Sandia National Labs and the U.S. Department of Homeland Security on inter-infrastructure vulnerabilities and simulations. He served for 12 years as associate editor of switching for the IEEE Transactions on Communications, has written over 45 technical papers and technical talks, holds 2 patents, and was an editor of a book on survivable networks.

CHI-HUNG KELVIN CHU is currently a senior planning analyst in Resource Planning at Con Edison Company of New York, Inc. He was formerly a member of technical staff in the High Reliability Network Architecture and Services Group at Bell Labs in Holmdel, New Jersey. During his tenure at Bell Labs, he researched and developed new methodologies, approaches, and tools to assess the end-to-end reliability of advanced broadband networks. Most recently, he was involved in a reliability-based network engineering program incorporating and integrating reliability assessment into advanced network design, as well as developing an integrated framework for network reliability assessment. He has been engaged in a variety of projects involving different technologies from different countries, from optical to wireless networks, and from metro access, to large national core networks, to large undersea cable systems. For the past 28 years, he has been involved in the application of computer-based probabilistic and deterministic reliability assessment techniques, including system modeling and simulation, to the planning, operation, risk assessment, and management of telecommunication and power/energy systems. He received his Ph.D. in electrical engineering from the University of Saskatchewan in Saskatoon, Canada. Dr. Chu has published over 50 papers in the application of probabilistic techniques in both telecommunications systems and power (energy) systems in publications including the IEEE. He serves as a reviewer for several publications of the Institute of Industrial Engineers (IIE) and the International Journal of Electrical Power & Energy Systems. He is a senior member of the IEEE. ◆