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Hurricane Katrina: Damage Assessment of Power Infrastructure For Distribution, Telecommunication, and Backup

by

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EXECUTIVE SUMMARY

The U.S. power system infrastructure is traditionally considered to include transmission and distribution components of the utility grid. The actual system, however, is best characterized with at least four distinct networks: the transmission grid, the electrical distribution system, the telecommunication power infrastructure, and generator sets used as backup systems.

The transmission portion of the utility grid is composed of high-voltage lines running from power generation stations to substations where the voltage is stepped down into the distribution grid. Cables mounted on poles (usually shared with telecommunication networks) distribute electric energy to consumers. Although under normal conditions the electric utility grid is reliable, it is vulnerable to storms. Hence, extended outages over a large area are common outcomes of hurricanes. In the case of Hurricane Katrina, about 700,000 customers in Louisiana and almost 200,000 in Mississippi lost power. More electricity users suffered outages in Alabama, making the total number of affected customers greater than one million by the time the storm passed through the Gulf Coast on August 29, 2005.

The telecommunication power infrastructure has long used a mix of utility power and local dc power plants to achieve high reliability and extended operation. The utility is connected to the dc system bus via rectifier circuits, both at central office (CO) locations and at local power units. When the utility feed is lost, batteries act to maintain power. There is no time delay for changeover to the backup energy source, since the rectifier architecture provides an *OR* function for the sources. Battery backup in the telecommunication system is designed to maintain full function after loss of ac power for intervals of a few hours. If batteries become discharged, the local source shuts off and communication is lost within a small area. At the CO level, there may be additional generation equipment to maintain operation as long as fuel sources permit.

Telecom power systems in most locations are protected with robust enclosures intended to withstand icing, salt spray, and other severe weather conditions. In the event of widespread and extended flooding, as occurred in New Orleans and other communities, enclosures cannot prevent water ingress. It is possible that battery systems will be destroyed in such a circumstance, along with rectifier circuits and other power interface hardware.

The fourth network is an *ad hoc* collection of local resources with purely local control and no coordination. In many instances, this network also failed after Katrina. In a typical installation, a diesel generator fires up automatically after loss of ac power. After a few seconds when the engine is at speed, a transfer switch isolates the local power system and supplies power from the generator. The objective of the generator is to provide extended backup, although generator sets have much lower reliability than other resources, especially after operating for several hours. In many cases, these systems failed owing to water contact or physical equipment damage. A typical failure mode for permanent backup systems that survived the disaster, and temporary systems that were installed after the disaster, was simply running out of fuel following many hours or days of use. In these cases, restoration is a matter of refueling – a seemingly trivial task that is complicated by logistics, damage to highways, and post-storm access challenges. Many backup systems failed for lack of refueling because of flood damage, contamination, and shortages.

Damage to these networks was assessed a few weeks after the storm with an on-site survey along the Gulf Coast. After the survey, additional information was obtained from communication network operators, backup power suppliers, and public information resources through the press and government. This report describes survey results and places them in the context of information from other sources.

Bellsouth is the largest operator of traditional land-line telephony service in the area affected by Hurricane Katrina. The day after the eye of the storm made landfall almost 2.5 million lines were out of service. Of 33 COs that failed, two-thirds lost service due to lack of electric power caused mostly by fuel starvation of generator sets. The rest were destroyed by the hurricane's powerful storm surge. Wireless communication networks were also severely affected by the storm, although most of the switching centers escaped serious damage. Consequently, wireless network service was restored to an adequate level within a week, much faster than land-line services.

In general, the analyzed networks had similar geographical distributions of damage. Failure owing to direct infrastructure destruction by high winds or storm surge was found in Louisiana in Plaquemines Parish and the eastern half of St. Bernard Parish. Destruction also occurred along a 1 km strip of the Mississippi Gulf Coast between the Louisiana-Mississippi border and Biloxi Bay. Failure owing to flooding and security issues occurred in metropolitan New Orleans.

There is no single cause that explains Katrina's devastating effects on power and communication networks. Much of the primary damage was caused by storm surge. Although the winds were strong, the sustained wind speed at the time of Gulf Coast landfall had reduced to a strong category 3 on the Saffir-Simpson scale, compared to the peak category 5 level earlier in the Gulf of Mexico. The strong storm surge may explain why damage to electric substations and communication centers was far more severe than in other hurricanes. Although distributed portions of the networks were also severely damaged, wind effects were not out of the ordinary for a hurricane of the size and strength of Katrina.

The duration and severity of the outages was also caused by the Bellsouth wire network being a common transmission means for many communication networks and systems, including wireless networks and 911 services. The shared use of infrastructure, such as poles by electrical and communication networks, introduced a common point of failure that reduced the overall reliability and contributed to outages. Availability was reduced by relying on generator sets to provide backup power for long periods. Damaged roads and fuel supply disruptions made fuel delivery difficult or impossible and led to failure at several sites. Construction not suitable for hurricane-prone zones was another reason for extended outages. Examples of vulnerable construction were found in generator fuel tanks and in ground-level layouts of some sites in areas at risk of flooding or close to the coast.

Although effects of Hurricane Katrina were severe, many sites did not lose service. Two factors explain why. The most important was the dedication of network operator employees who showed remarkable commitment towards keeping the system running. A second was good fortune. Sometimes a few meters made the difference between a site being flooded or not.

Several recommendations can be implemented to mitigate damage from future storms as severe as Katrina. Some can be carried out in a short time, but others will take many years to implement. Mobile communication network transmission capacities and interconnection points between operators need to be increased to provide architectures that are more diverse. In the short term, links can be realized using microwave radios. Restoration means for destroyed COs need to be improved. Switch-on-wheels designs are a better option than digital loop carrier systems. The use of digital loop carrier systems to replace COs and damaged cables had the disadvantage of making the land-line network more vulnerable to future storms in the area affected by Hurricane Katrina. Network diversity can also be improved by minimizing shared infrastructure among different networks.

There are a number of options to improve network reliability when using generators for extended periods. Expanded battery capacity may solve the problem for outages lasting several hours. However, when the electric power is out for several days, many sites need larger fuel tanks. Access points for these tanks should be located high above ground to avoid possible flooding of the tank. Using natural gas or flexible-fuel diesel and natural gas generator sets might ease logistical requirements after a storm. Fuel consumption and needs can be reduced dramatically by installing solar panels at COs and cell sites. Use of a highly reliable "power of last resort" could support limited energy for wireless repeaters and support communication needs of first responders after extensive network damage. A long-term solution may involve the use of distributed generation systems to reduce dependency on the electric grid.

Restoration plans should be coordinated in advance with security officials to define alternative routes for delivering generators and fuel to damaged sites. Collaboration among tower owners and wireless communication operators during the planning phase should be expanded with the objective of equipping each cell site with one generator instead of wasting resources by delivering multiple generator sets to supply each individual operator at a tower site. Coordination among communication companies should be improved to establish "best practice" design and construction for areas subject to hurricanes.

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1 Introduction

On August 29, 2005, Hurricane Katrina struck the Mississippi and Louisiana coasts with winds over 200 km/h and storm surges up to 9 m in some areas. Devastating effects on utility power and telecommunication networks hampered early rescue and relief efforts, making them almost impossible in some areas. The impact on power and communication infrastructures and the consequences of extended outages in the aftermath of the hurricane illustrate the need for further contingency planning. In the past, there has been limited research on disaster damage and restoration of telecommunication systems or on how the reliability of communication systems in extreme conditions is related to power supply. Research on primary causes of failure under such circumstances is also limited.

The impact of Hurricane Katrina on the U.S. Gulf Coast caused heavy damage to infrastructure networks. One of the most serious effects was complete loss of communication, caused both by direct damage and loss of electrical supply. Communication loss hampered rescue efforts, stymied attempts to coordinate early responses, and made calls for aid impossible from the hardest-hit areas. It was only by September 2, four days after the storm crossed the coast, when military-grade communication networks (often satellite-based) began to have an impact as substitutes. A parish sheriff from a particularly hard-hit area in Louisiana reported during a CNN broadcast that his biggest needs were drinking water and communication. A description of the effects of Hurricane Katrina was delivered by Lt. Gen. Russell Honore, the military commander in charge of recovery and relief operations [1]:

> "What this storm did was a classic military operation. The storm gathered strength, attacked the coast of Louisiana-Mississippi with overwhelming force. One of the things in a military attack you want to do is to cut the enemy's ability to communicate. It took out all cell phones and regular phone service. The other thing this storm did is to cut the road network. As the storm moved north it protected its left flank by leaving a flood. Again, classic military attack: take the enemy's eyes out, take his ears out, then fix him so he can't maneuver."

Clearly, in the U.S. communication networks have become essential tools for safety at many levels. There are many open questions about how communication system dependencies on power networks and power supply affect reliability under extreme conditions. In the future, communication dependence is likely to grow even more as broadband networks become common.

1.1 The storm

Katrina was an extraordinarily powerful and deadly hurricane that carved a wide swath of catastrophic damage and inflicted high loss of life. It was the costliest and one of the five deadliest hurricanes ever to strike the United States. Katrina first caused fatalities and damage in southern Florida on August 25, 2005 at about 6:00 p.m. local time as a Category 1 hurricane on the Saffir-Simpson Hurricane Scale. After reaching Category 5 intensity over the central Gulf of Mexico, Katrina weakened to a strong Category 3 storm shortly before making landfall on the northern Gulf Coast on August 29th at 5:00 am local time, near Buras, Louisiana. The central pressure yields an important indication of hurricane strength, with a lower central pressure indicating a stronger storm. Katrina's minimum central pressure of 920 mb is the lowest on record in the Atlantic basin for Category 3 hurricanes, and at that time was the third lowest pressure of any hurricane making landfall in the continental US. Hurricane Katrina was not only extremely strong but also extensive with a storm surge of 3 m as far as Mobile, Alabama and hurricane force winds extending 120 km eastward. New Orleans experienced sustained surface winds weaker than a Category 3 storm at ground level with increased wind speeds at higher floors of tall buildings [2]. Even so, the damage and loss of life inflicted by this massive hurricane in Louisiana and Mississippi were staggering. Significant effects extended into the Florida panhandle, Georgia, and Alabama.

Considering the scope of its impact, Katrina was one of the most devastating natural disasters in United States history. Estimates of the insured property losses caused by Katrina range between $20 and $60 billion. The American Insurance Services Group (AISG) estimates that Katrina is responsible for $38.1 billion of insured losses in the United States. A preliminary estimate of the total damage cost of Katrina is assumed to be roughly twice the insured losses, or at least $75 billion. This figure would make Katrina the costliest hurricane to occur in the United States. Even after adjusting for inflation, the estimated total damage cost of Katrina is roughly double that of Hurricane Andrew (1992). Normalizing for inflation and for increases in population and wealth, only the 1926 hurricane that struck southern Florida is on the same order as Katrina in terms of damage cost. The Insurance Information Institute reports that, mostly due to Katrina but combined with significant impacts from the other hurricanes striking the United States in the same year, 2005 was, by a large margin, the costliest year ever for insured catastrophe losses in this country.

1.2 On-site survey and project scope

This study extends the knowledge of catastrophic disaster effects on the electrical power supply and the impact on telecommunication power infrastructure including backup systems [3-5]. Information is presented from an on-site survey and other relevant sources. The on-site survey was conducted on October 17-23, 2005 in the area highlighted on the map shown in Fig. 1.1. This region follows the I-10 corridor between Mobile and New Orleans. It also includes areas adjacent to US 90 and Louisiana highway 39.

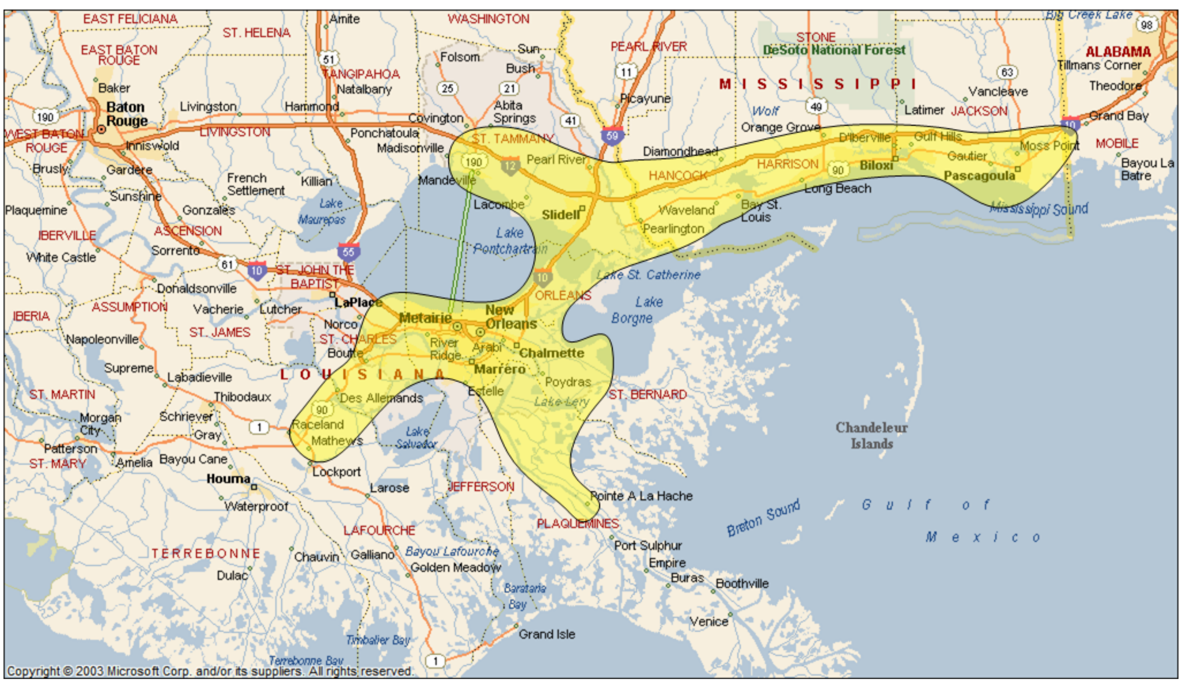

Fig. 1.1. On-site survey territory

The tasks carried out during the survey included:

- Determine the extent of restoration already in place, areas in which the process is in progress, and areas not yet in progress. Identify a suitable geographical sample of each type of area.
- Assess the status in each sample area. Identify working and non-working telecom and large backup power units
- Survey battery-based and fuel-based backup to determine the degree to which repair or replacement will be required in place of routine recharge or refueling.
- To the degree possible, gather spot data to support maps of the extent of telecom power outages.
- Use digital still and video images to record status of:
    - Cellular telephone sites
    - Fixed-line telephony central offices
    - Electric power substations
    - Electric power transmission and distribution
    - Emergency backup power systems

Two graduate students, Alexis Kwasinski and Wayne Weaver, both with industry experience, performed the on-site survey. As with everyone and everything affected by Katrina, logistical, transportation, communication, and housing were major challenges in carrying out the survey. Due to destruction, refugee housing, and emergency personnel housing, the closest hotel available was in Orange Beach, AL, almost 200 miles east of New Orleans. Transportation was an issue since many roads and bridges were damaged. For example, the I-10 bridge over Lake Pontchartrain, a major artery into the city of New Orleans, was heavily damaged in the storm. At the time of the survey the south bridge spans had been restored to working condition (see Fig. 1.2), but the north spans were still under repair. This caused extended delays in travel to and from New Orleans.

After the on-site survey was conducted, extensive data gathering was carried out via private companies such as Caterpillar, Alltel, Sprint, TMobile, Cingular, and BellSouth as well as from government agencies including the Federal Communications Commission (FCC), the US Geological Survey, the Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers, the National Oceanic and Atmospheric Administration (NOAA), and the US Department of Energy. Satellite and aerial imagery [6-10] was used to determine the status of the affected area shortly after the storm had passed. Additional on-site data, network information, personal accounts and various other data have been gathered and integrated into this report.

Fig. 1.2. I-10 bridge over Lake Pontchartrain

2 Communication System and Electric Power System Background

Many communication networks operate within in a region. The networks of interest for this report are the public switched telephony network (PSTN), the mobile communication network, satellite communication networks, and broadcasting systems such as cable television (CATV), emergency services, and commercial radio and TV systems. New telecommunication means such as voice over Internet protocol (VOIP) or telephony over Internet are not analyzed, because they are not physical networks but rather services that operate over one of the networks mentioned above.

A natural disaster can affect the operation of these networks in many ways. A direct impact implies destruction or damage to one or more key network elements. An indirect impact implies that network operation is hampered because some necessary external factor has failed. This report focuses on the electrical power supply. To give a better understanding of communication network relationships with electrical power, possible failure modes, and recovery means, a description of communication networks and electrical power systems is presented next.

2.1 The public switched telephony network (PSTN)

The PSTN is the traditional landline telecommunication system in which subscribers with fixed telephones are interconnected through cables by a commutating element called the *switch*. Other names given to the PSTN are fixed-telephony network, wire-line telephony network and *plain old telephone system* (POTS) network. Companies that provide POTS services are called a *competitive local exchange carrier* (CLEC).

A switch is the most important element of a PSTN. The function of a switch is to link two network subscribers by commutating calls. The building that houses the switch is called a *central office* (CO). In many ways, a CO is analogous to a substation in an electric utility grid, serving as the primary connection point to consumers as well as an interconnection to bulk communication infrastructures. Each CO covers a portion of the CLEC territory. This geographical region is called a *CO area* and is determined based on the number of potential subscribers, geographic limitations and demographic characteristics. The location, usually a CO in the most populated zone within its area to minimize connection length to subscribers, must be close to important routes to minimize linkage distance to other COs.

The CO also contains other communication equipment, including transmission systems necessary to connect the CO to other COs. Fig. 2.1 shows the basic communication elements of a CO. Calls are commutated in the switch matrix. Copper cables to subscribers are terminated in vertical blocks in the *main distribution frame* (MDF). These cable terminations are connected with cross-connect jumpers to horizontal terminal blocks that are also located in the MDF. Several positions in the horizontal blocks of the MDF are then connected to switch line modules (LM) where the signals of some LMs are combined in multiplexing units (MUX) to produce a single signal in order to reduce the switch matrix complexity. The multiplexed signals are processed in interface modules (IM) that separate the MUX units and the switch matrix. The switch matrix is also connected through IM and de-MUX units to trunk modules where high capacity links are terminated in the switch. These trunks are then connected through the transmission distribution frame (TDF) to the transmission system, where most of the trunk signals are routed to other COs and communication centers. The entire system is controlled with process controllers and managed from administration terminals.

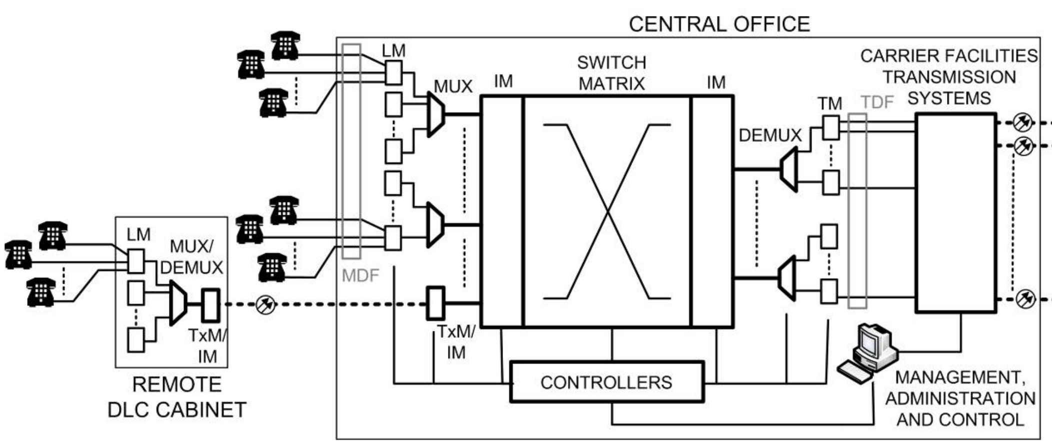

Fig. 2.1. CO main communication components with a remote DLC

Fig. 2.1 also shows an alternative to connect subscribers through a multiplexed remote terminal, a digital loop carrier (DLC) system. The DLC is placed away from the CO in metallic cabinets containing the line modules, multiplexing unit, and a transmission and interface module (TxM/IM), which connects the cabinet to the CO, generally using fiber-optic cable. While a copper wire connection between a subscriber and its CO cannot expand for more than 3.5 to 4 km, a fiber-optic cable between a DLC cabinet and a CO can reach lengths of 7 to 10 km. The most popular DLC systems, usually installed inside Type-80 cabinets, are the subscriber loop carrier SLC-96 and SLC-5 manufactured by Lucent Technologies.

Sometimes, a switch can be operated with its main processing unit located in another CO, shown in Fig. 2.2. In this configuration, it is said that the latter is the host switch of the former, called the *remote switch*. In case the host switch fails, the remote switch is 95 % self-sustainable [11] and can still process local calls. The main reason to use remote switches is to optimize the traffic within its serving area.

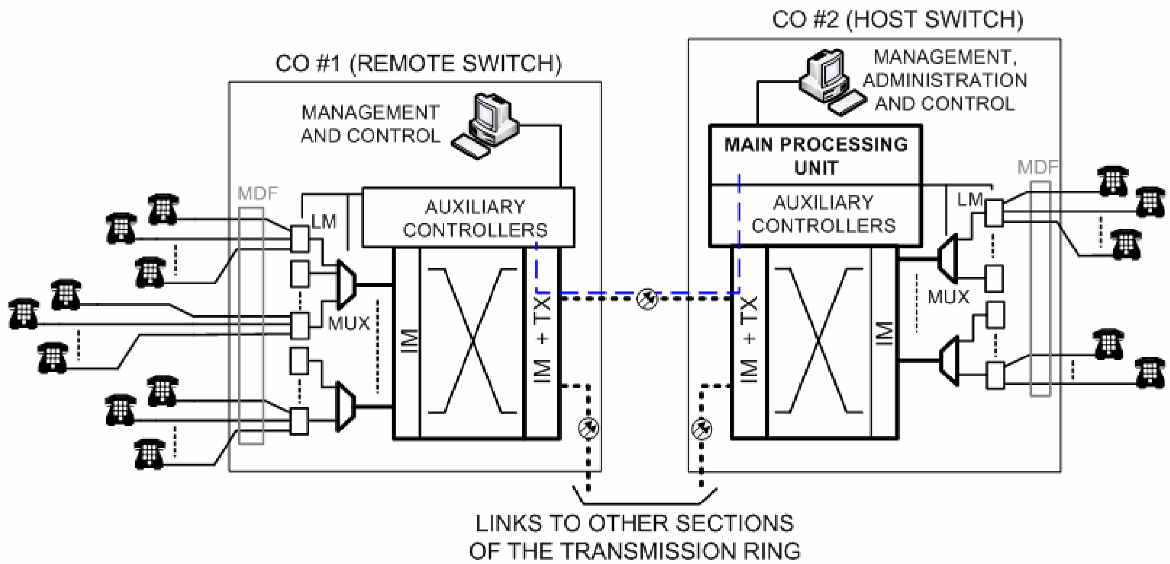

Fig. 2.2. Remote switch and its host architectures

The CO also contains all the ancillary services essential for the system to operate, among them, the direct current (dc) power plant. As shown in Fig. 2.3, the power plant receives alternating current (ac) electrical power and rectifies it into dc electrical power. It is distributed to a global power distribution frame (GPDF), the other system power distribution frame (PDF), and to inverters that feed the management terminals with ac power. The GPDF and PDF hold the fuses that protect the system in case of a short circuit in the equipment frames. The switch, transmission systems, and management terminals are the main power plant loads. The CO power plant also feeds subscriber telephones with copper wires when they are directly connected to the MDF. Fig. 2.3 also shows that the DLC cabinet requires a separate power plant that receives the ac power from a local connection.

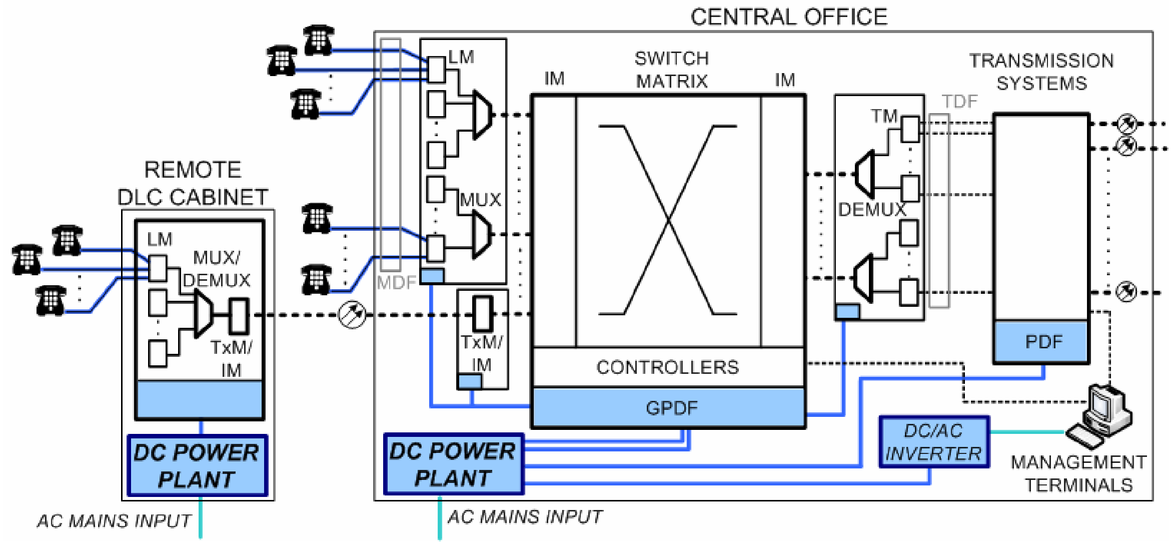

Fig. 2.3. CO and DLC main components showing the electrical supply scheme

One of the main functions of the power plant is to provide energy to the system even when there is an outage in the ac utility grid. This is accomplished by including batteries directly connected in parallel to the load and a combustion engine/electric generator set (genset) in a stand-by mode connected through a transfer switch to the ac mains input. Fig. 2.4 shows a basic scheme of a telecom switch power plant. During normal operation, the system is fed from the electric grid through rectifiers that converts the ac mains into dc power. The function of the batteries during an electric utility grid outage is to provide power to the system for a short time until the genset starts and the transfer switch connects the generator to the rectifier input. In this manner, as long as the genset has enough fuel and does not fail, the CO can operate normally until the electrical utility power is restored. In normal operation, DLC cabinets have the same power plant structure without the genset.

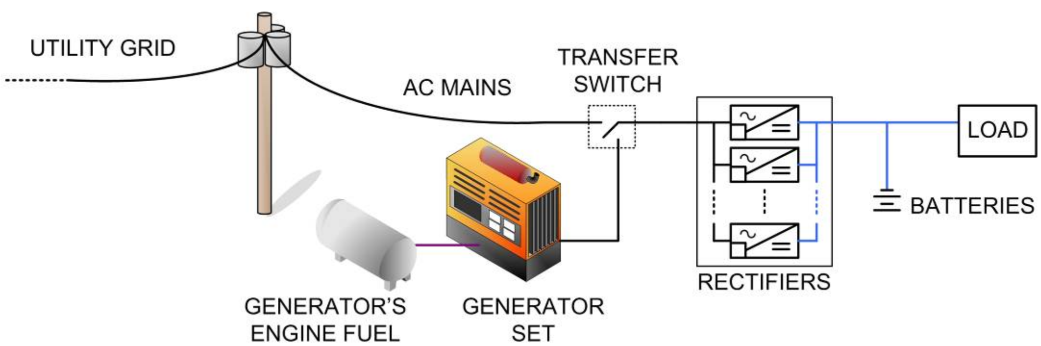

Fig. 2.4. Basic elements of a telecom power plant and connection scheme

One problem with batteries is their very high density – they are made with lead. A CO battery string may weigh well over 1 tn/m^2, a standard floor-loading value for dwellings. For this reason batteries are usually placed at ground level, where it is easier to reinforce the floor. Another problem is the difficulty of replacing batteries, as they need to be maintained charged while stored. If they are not, they eventually discharge and end up being permanently damaged. Thus, battery manufacturers keep only a small battery inventory. Lead times for large orders may reach up to 4 weeks. The rest of the CO equipment is mainly printed circuit boards and metallic frames, which can be easily stored and produced rapidly.

One of the most important characteristics of the PSTN is its extremely high reliability with downtimes, usually less than a minute per year. This has both commercial and emergency (911 system) implications. Fig. 2.5 shows a scheme of the enhanced 911 (E911) system with its three main elements: the PSTN, the public safety answering points (PSAPs), and the E911 offices. In the E911 system, the PSTN carries the call to the PSAP, as routed by the corresponding E911 office. Since CO areas do not generally coincide with PSAP areas, the system includes the E911 offices that route the calls to the corresponding PSAP center of the calling party. In Fig. 2.5, both party A and party B belong to CO X, located in PSAP area B. When party B calls 911, there is no issue because CO X, PSAP B and calling party B are all located within the same PSAP area. However, when party A, located in PSAP area A calls 911, the E911 office #1 routes the call through CO X to PSAP A. The system is also programmed to reroute 911 calls to backup E911 offices in case the primary one ceases to operate. For example, in Fig. 2.5, E911 office #2 is the E911 CO #1 backup.

In the PSTN not all the COs have the same importance. To reduce the cost in transmission links, the PSTN architecture has a radial configuration in which several COs are connected through another switch called a *tandem office*. Hence, tandem switches are more important than regular switches called *class 5 CO* or *local offices* (LO) that handle subscriber calls. Fig. 2.6 presents an example of how tandem offices interconnect class 5 COs. The figure shows that party D can talk to party C only through tandem office Y. In the same way, party E can talk to party A only through tandem office X. Moreover, party A and party B can only talk through tandem offices X and Y. When the traffic between two class 5 offices is high enough, they can be directly connected with high-usage trunks. For example, in Fig. 2.6 party F and party G can be connected without passing tandem office X. The importance of a tandem office becomes evident in Fig. 2.6. When tandem office Y fails, the subscribers of the five class 5 COs connected to it will only be able to talk to other subscribers of the same LO. Usually, tandem switches do not interconnect subscribers, but they do connect class 5 switches to other higher hierarchy centers.

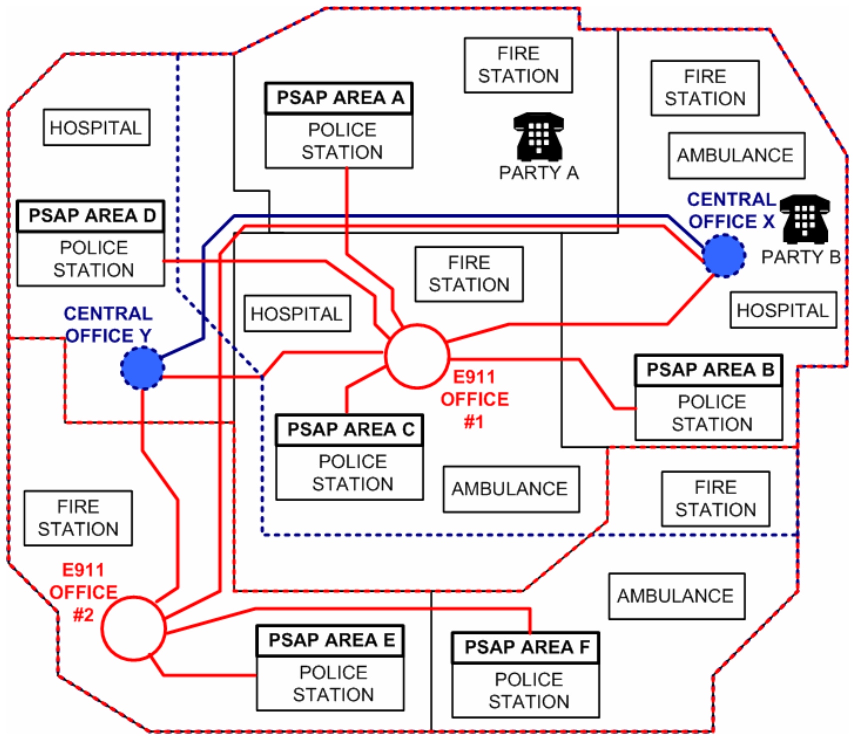

Fig. 2.5. E911 system representation

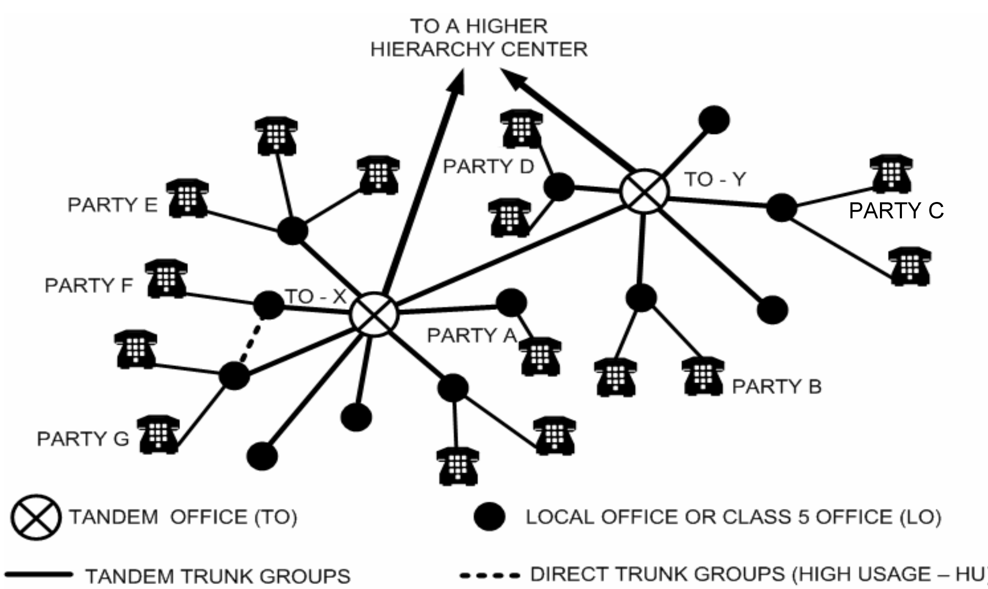

Fig. 2.6. Typical CO connections in a city

The elements of the PSTN within a CO area are divided into outside plant and inside plant components. All the elements located outside the CO up to the vertical blocks of the MDF are part of the outside plant. The remaining elements situated inside the CO are part of the inside plant. For historical reasons, sometimes transmission fiber-optic cables and microwave antennas are considered neither part of the inside nor the outside plant. The outside plant is extremely vulnerable to natural disasters and, for this reason, needs to be considered as part of any study of natural disaster effects on communication systems. The basic terminology used for outside-plant hardware is shown in Fig. 2.7: poles, manholes, a cable entrance facility, serving area interfaces, line drops, feeders, and distribution cables.

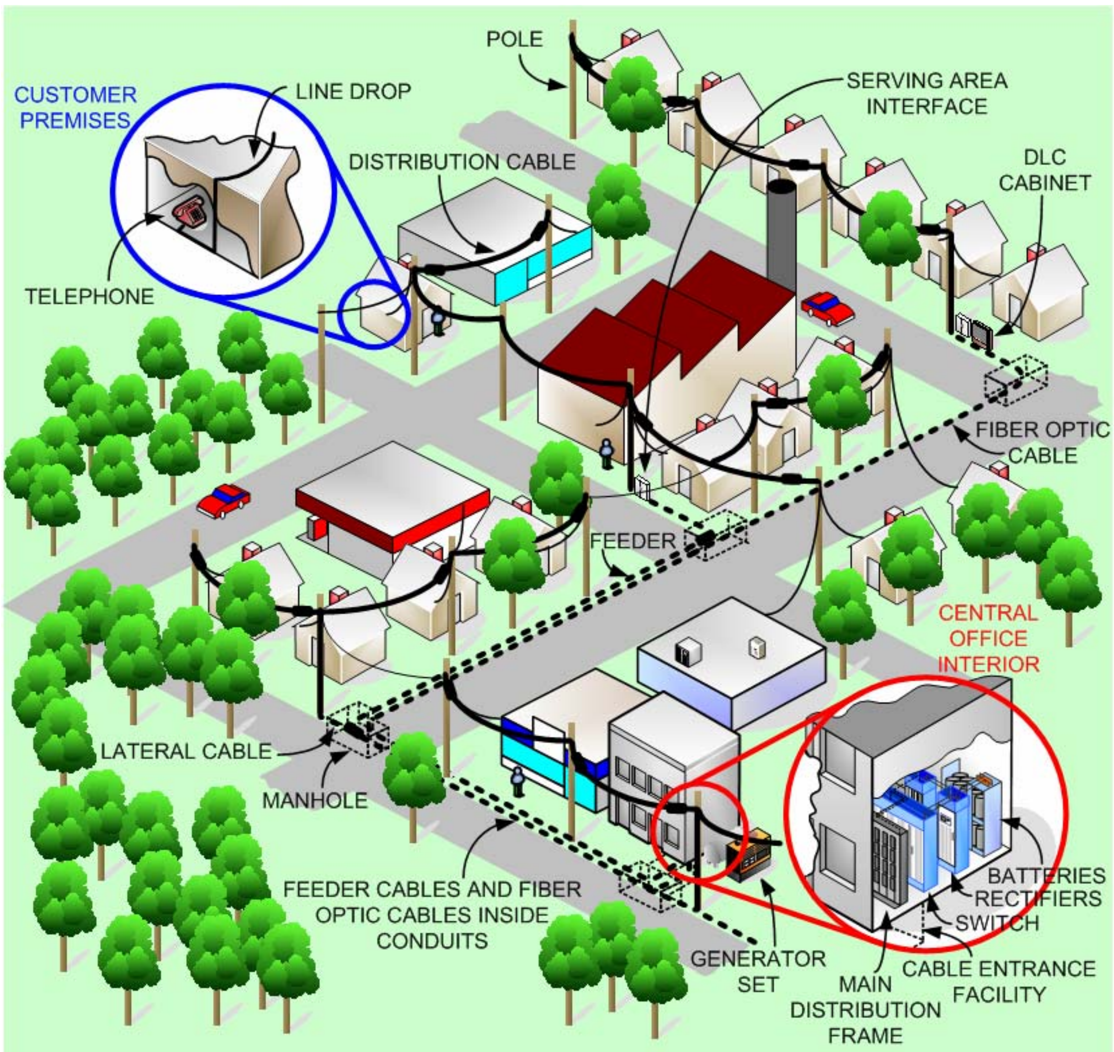

Fig. 2.7. Main outside-plant elements of a CO.

2.2 Mobile communication network

In a mobile communication network the fixed wire connection between the CO and the subscribers is replaced by a radio link. This radio link utilizes a frequency or a code assigned at the time of establishing the call. Once the call has ended, the frequency or code is freed and can be used by other subscribers. Another difference from a fixed-telephony service is that subscribers can still maintain a communication when they are moving. Other names for mobile communication networks are *cellular telephony, wireless telephony networks* or simply a *cellular network.*

Fig. 2.8 shows the main elements of a mobile communication network: the mobile telephony-switching center (MTSO) and the cell sites. The MTSO is also called a *mobile switching center* (MSC). A user will communicate through a radio link to a cell site, which in turn is connected to the MTSO with a fiber-optic cable, a microwave link, or, in special cases, a satellite link. Having a satellite link between the MTSO and the cell site is different from a satellite mobile communication, in which the satellite itself acts as a cell site. It is not very common to use satellite links in mobile communication networks and not all equipment manufacturers support this application. In the rare cases that it is used, the cell site is in distant locations that are very complicated to reach by land, such as very high mountains or Antarctica. The entire mobile communication network coverage area is divided into regions called *cells* that ideally have the form of a hexagon. Cell sites are located in the intersecting point of three cells. Each cell site covers the surrounding area, which is divided into 3 sectors, each of them corresponding to 1/3 of each of the adjacent cells to the cell site, as in cell site #10 shown in Fig. 2.8. Usually, the same location is shared by cell sites of different operating companies that install their base stations in different shelters or platforms and place their antennas in the same tower at different heights. Fig. 2.8 also exemplifies a typical call: When user A calls user B, the call goes through cell site #5 via a radio link and continues to the MTSO through a fiber-optic cable. Then the MTSO routes the call to cell site #8 using a microwave link, and the call connection is finally established via a radio link between cell site #8 and user B. A key characteristic of mobile communication is that users may move without having the call disconnected. This characteristic is represented with user C. In the figure, user C is driving through the south-north sector of cell site #1, represented in green, and entering the north-north sector of cell site #6. At this point, the network controllers transfer the call path from cell site #1 to cell site #6 in a process called *handoff*.

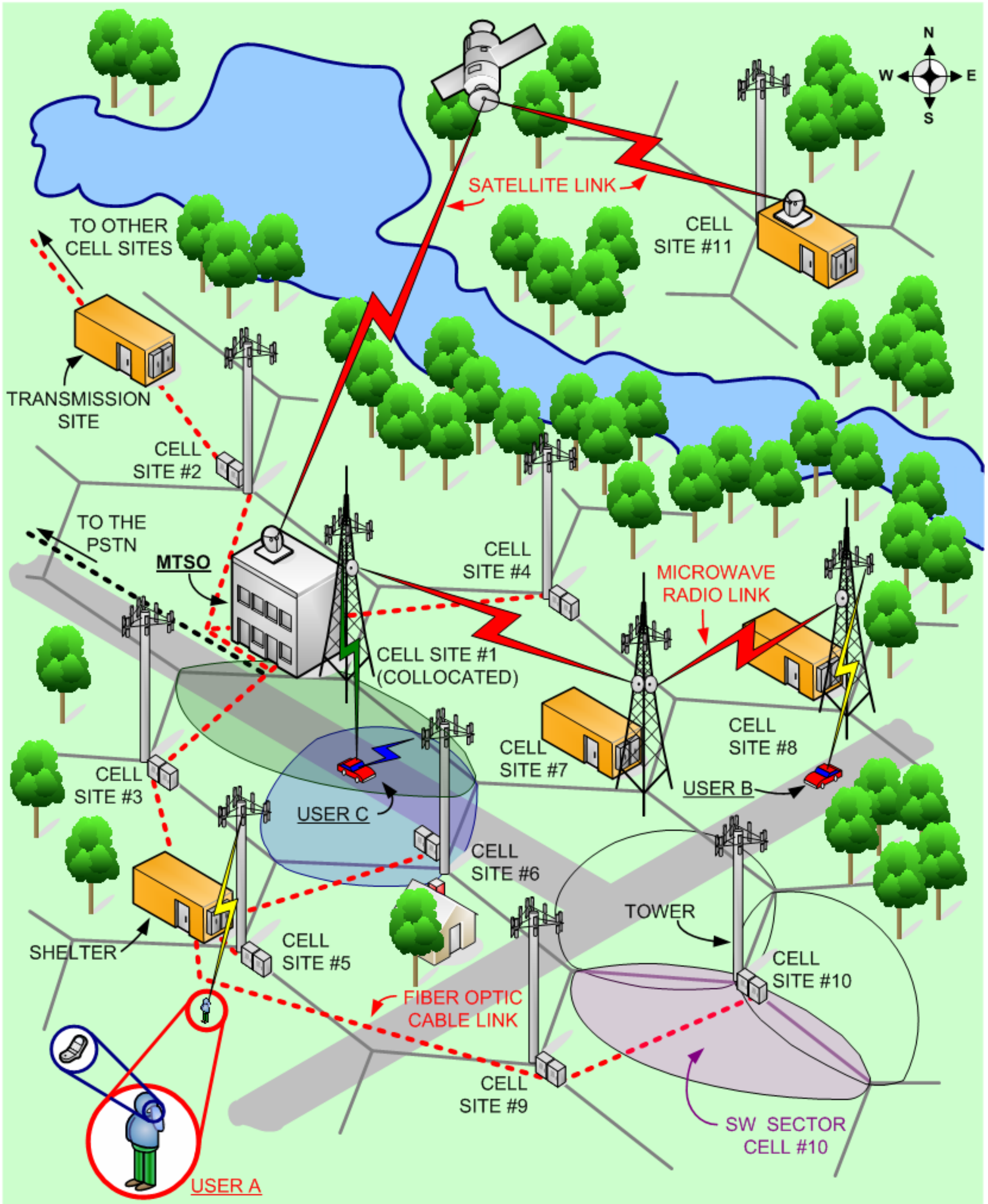

Fig. 2.8. Mobile-communication network scheme

A mobile communication switch is similar to those used in the PSTN, as shown in Fig. 2.9. One difference is that in MSCs, switches do not have line modules since all the links to other COs and to the cell sites are through trunks. Another difference is that MSC switches incorporate a cell site controller that manages the calls between the MTSO and the cell sites and in between cell sites. One of the cell site controller functionalities is, for example, the handoff. The customer database in also dynamically handled differently so that the system can keep track of the user locations to allow incoming calls to be routed to the appropriate cell. Fig. 2.9 also shows that in some ways a cell site and a DLC cabinet are alike in the sense that both act as fixed remote subscriber concentration nodes. Yet, while DLC cabinets have a fixed connection to the subscriber using copper wires, cell sites have a flexible connection using radio links. Fig. 2.9 also shows that the cell site electronic equipment and its housing are called a *base station* (BS).

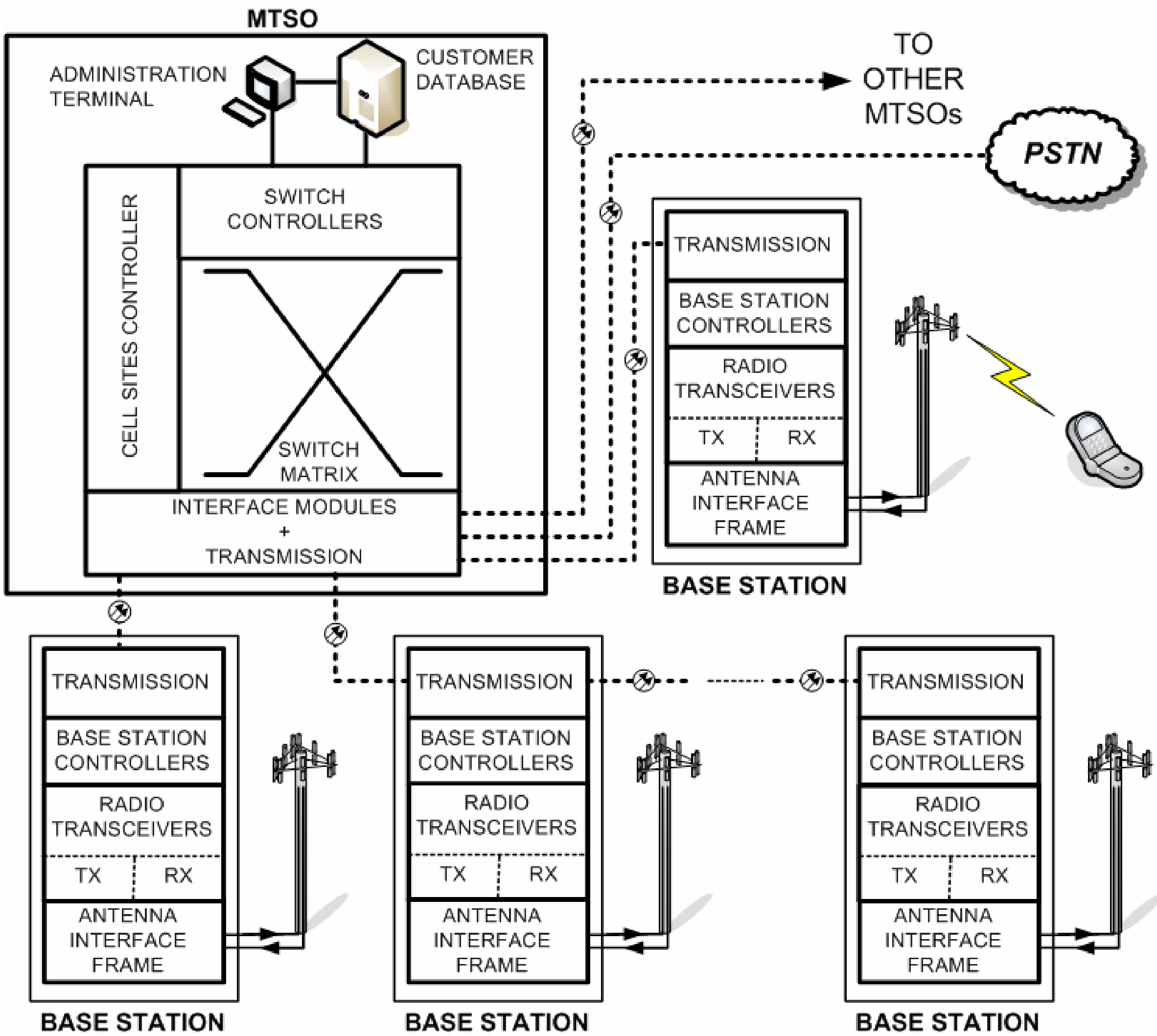

Fig. 2.9. MTSO and cell sites main communication components

The electrical power supply of MTSOs and cell sites is also very similar to PSTN systems. As Fig. 2.10 shows, the only difference in the electrical power distribution in a MTSO when compared with a PSTN switch is that subscriber telephones are no longer fed directly from the CO. For this reason, cell phones need to have their own batteries. The basic elements of an MTSO power plant and its connections are the same as already shown in Fig. 2.4. Base stations also have the same power plant architecture, although many cell sites do not include a permanent generator set.

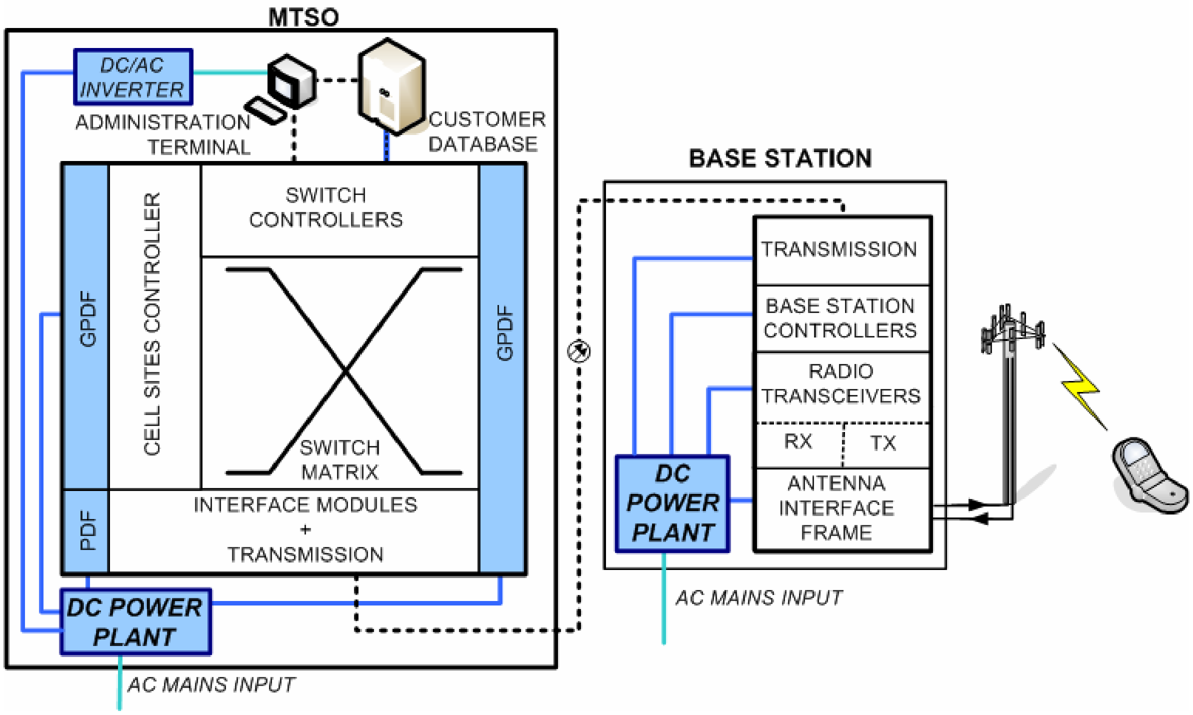

Fig. 2.10. Mobile communication network scheme

Fig. 2.11 shows the basic architecture of a cellular network including two full MTSOs, A and B; 5 remote switches (RS), A1, A2, B1, B2 and B3; and several cell sites represented by hexagons. The cellular network remote MSCs are equivalent to those of the PSTN, but the host switches add functions to the main processing ones: the host controls its respective remote switches' cells as well as performing the main processing unit functions. For example, in Fig. 2.11 the cell sites in the light-yellow area are controlled by MTSO B, but each switch performs the commutation process within its corresponding area bounded by a doted line. Since a host switch concentrates some of the functions of a remote switch, the loss of service in the former is more critical than an outage in the latter.

Fig. 2.11 also shows a common characteristic of communication networks called *network diversity*, which implies that there is more than one path linking two nodes. For example, cell sites B21, B22, B23 and B24 are connected with RS B2 in a ring, so there are two paths linking RS B2 with any of the four cell sites. RS B3 also has two paths to MTSO B: one passes through cell site B31 and the other through cell sites B32 and B22 and RS B2. In some cases, network diversity cannot be implemented. For example, cell site A23 has only one path to RS A2 passing through cell site A22. If for any reason cell site A22 fails, the area covered by cell A23 will also lose service. The same situation is observed with RS B1 connected to its host switch, MTSO B, using the PSTN transmission links.

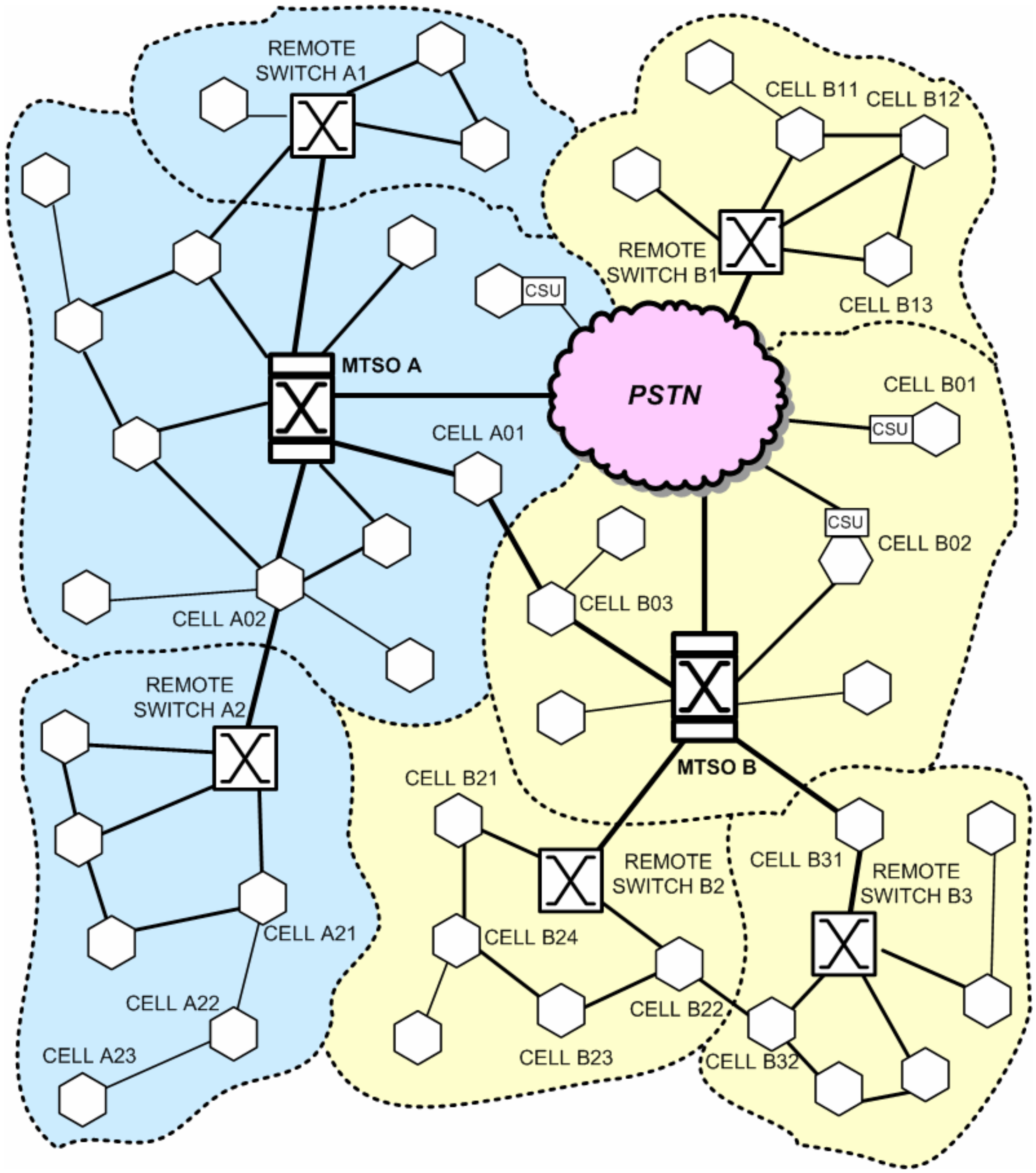

Fig. 2.11. Mobile communication network scheme

The cellular network has several connection points to the PSTN called *channel service units* (CSU). Mobile communication networks need to have links with the PSTN to make calls possible between a wireless phone and a wire-line telephone. However, some of the connections are necessary just to link cell sites and switches with the rest of the mobile communication network. One example of such a connection is the one already mentioned in RS B1. Another example is cell site B01. Hence, the PSTN is a critical point of failure for the entire communication system. If the PSTN fails, not only wire-line subscribers may lose service but also a significant portion of the wireless network may become isolated or even lose service.

As previously mentioned, satellite mobile communication is similar to regular mobile communication networks. The only difference is that the cell sites are replaced by satellites orbiting the earth and powered by solar energy and batteries. The switches are still located on land and are powered by the electric utility.

2.3 TV and radio systems

Traditional TV and radio systems broadcast signals from a main station using antennas. These antennas are quite vulnerable to high winds. However, if they fall, the transmission can easily be shifted to some other location within the broadcasting area with an appropriate antenna. Traditional radio and TV systems are useful during a disaster aftermath to broadcast messages of public interest, such as information about the location of food and water distribution centers. But public broadcasting systems only transmit information in one direction, so they have limited usefulness during disasters. Two-way private radio systems, such as those used by police and other emergency services, are more useful. As in all telecommunication systems, both the emitter and the receiver need to be powered, either by some local connection to the electric grid or with batteries.

More relevant for this report are cable TV (CATV) networks because most of such existing networks allow for bidirectional signal flow. Hence, it is possible not only to have TV signals or data broadcasted from the main transmission station to the subscribers but also to have data signals transmitted back from the subscribers to the transmission station. Thus, bidirectional CATV networks support several applications such as regular internet and internet phone services, commonly referred to as *voice over IP* (VOIP) services.

Fig. 2.12 shows the basic architecture and elements of a CATV network. The main transmission station is called the *head-end* (H/E). To support Internet-based applications, the H/E is connected to the PSTN though at least one fiber-optic link. The H/E is linked with the subscribers with fiber-optic cables up to optical nodes and then with coaxial cables. Since the signal loses quality as it moves along the coaxial cable, it needs to be improved by using amplifiers. Depending on the size of the coaxial cable, the number of subscribers and the topology, typically, in cities, the amplifiers are placed every few hundred meters.

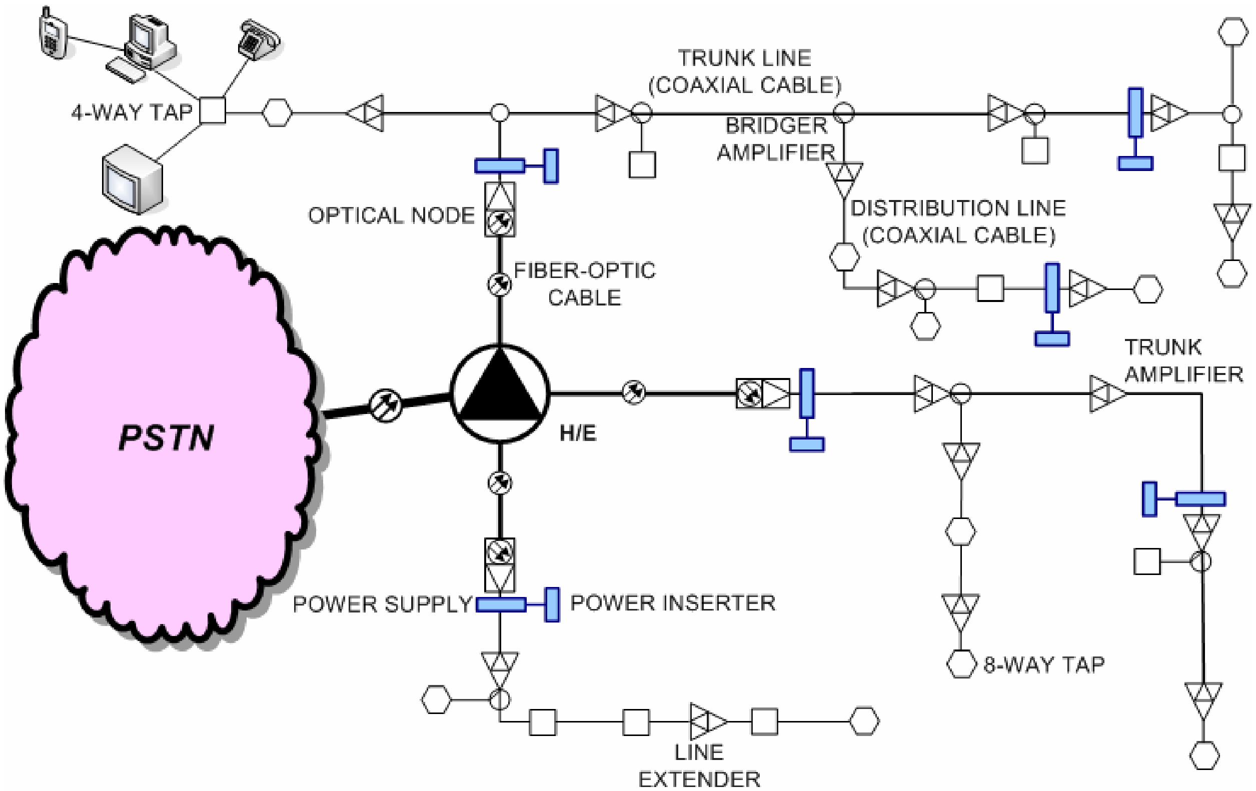

Fig. 2.12. CATV network schematic

The H/E, optical nodes and amplifiers require electrical energy to operate. Even though the H/E and the optical nodes require one power supply each, several amplifiers can be fed with one uninterruptible power supply (UPS). This is accomplished by injecting ac power into the coaxial cable, which is rectified for each amplifier. A UPS is a cascaded combination of a rectifier and an inverter with batteries connected at the rectifier output terminal to provide backup power for a few hours in case of an outage in the electrical supply. Usually, UPSs for individual amplifiers are placed in small cabinets mounted on poles, as shown in Fig. 2.13. Fig.

2.13 also displays the basic elements of a CATV network as well as broadcasting TV and radio stations.

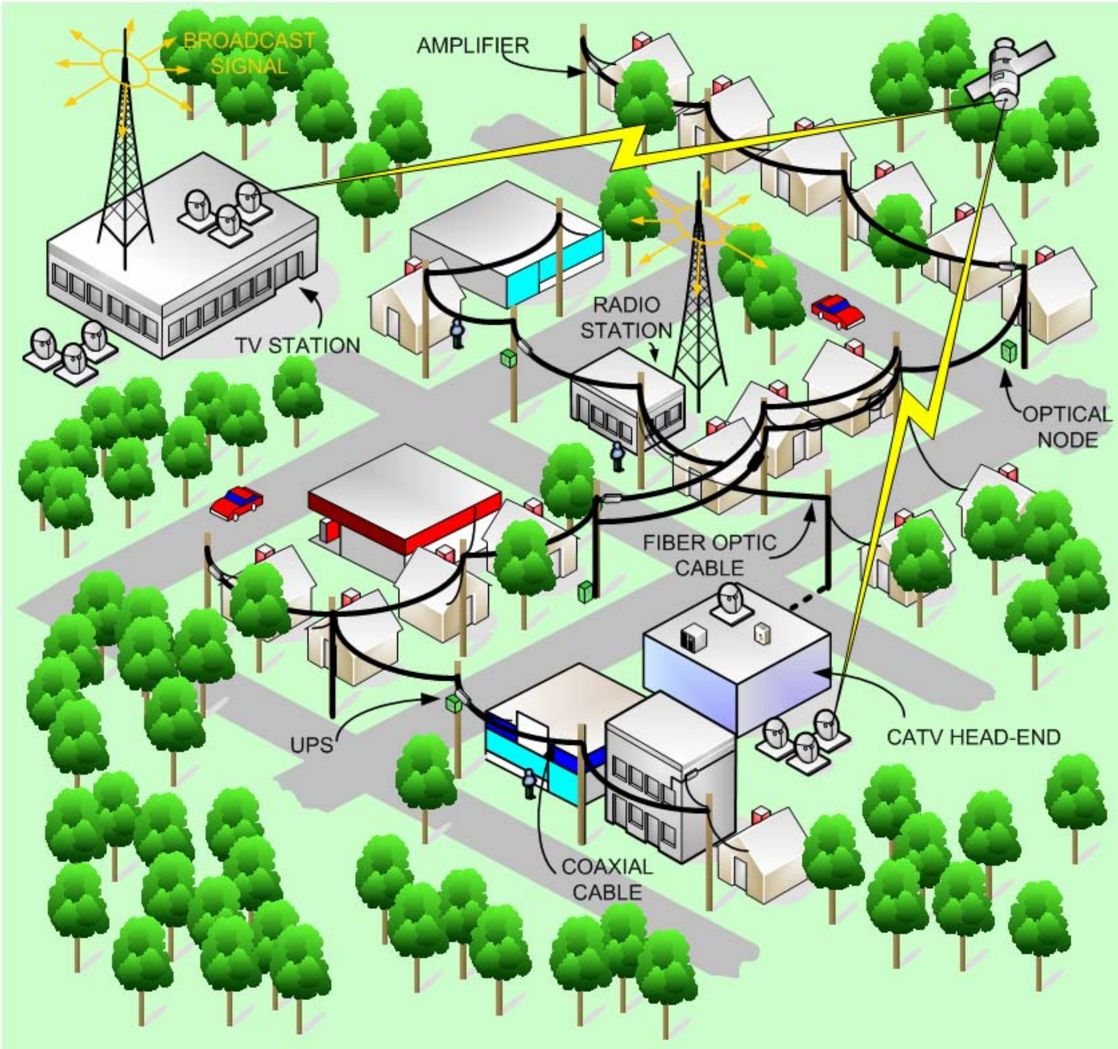

Fig. 2.13. TV and radio systems infrastructure elements

2.4 Electrical power systems

Fig. 2.14 presents a typical electrical power system with its main components. A power system has three main parts: generation, transmission and distribution. Electrical energy is generated in power plants and transmitted to substations close to the power consumption areas using high voltage (usually more than 110 kV) transmission lines. At the substation, the voltage is stepped down with transformers, and the electrical energy is distributed to individual consumers located close to the substation. The distribution involves at least one additional voltage transformation because the voltage output from a substation is usually 7.2 kV to 14.4 kV (medium-voltage) while the voltage at the ac mains drop of a typical small CO or cell site is 480 V, 230 V or 208 V (low-voltage). The medium-voltage conductors are called *primary* while the low-voltage wires are called *secondary*. The final voltage step down between primary and secondary conductors is performed in small pole-mounted distribution transformers with a power between 5 kVA and 200 kVA. Sometimes, the transformer can be located at ground level on a pad. In the case of large COs, the drop may carry voltages in the range of 1.2 kV to 4.2 kV. It is clear that most electrical systems include several transformation steps where the voltage is either increased or decreased.

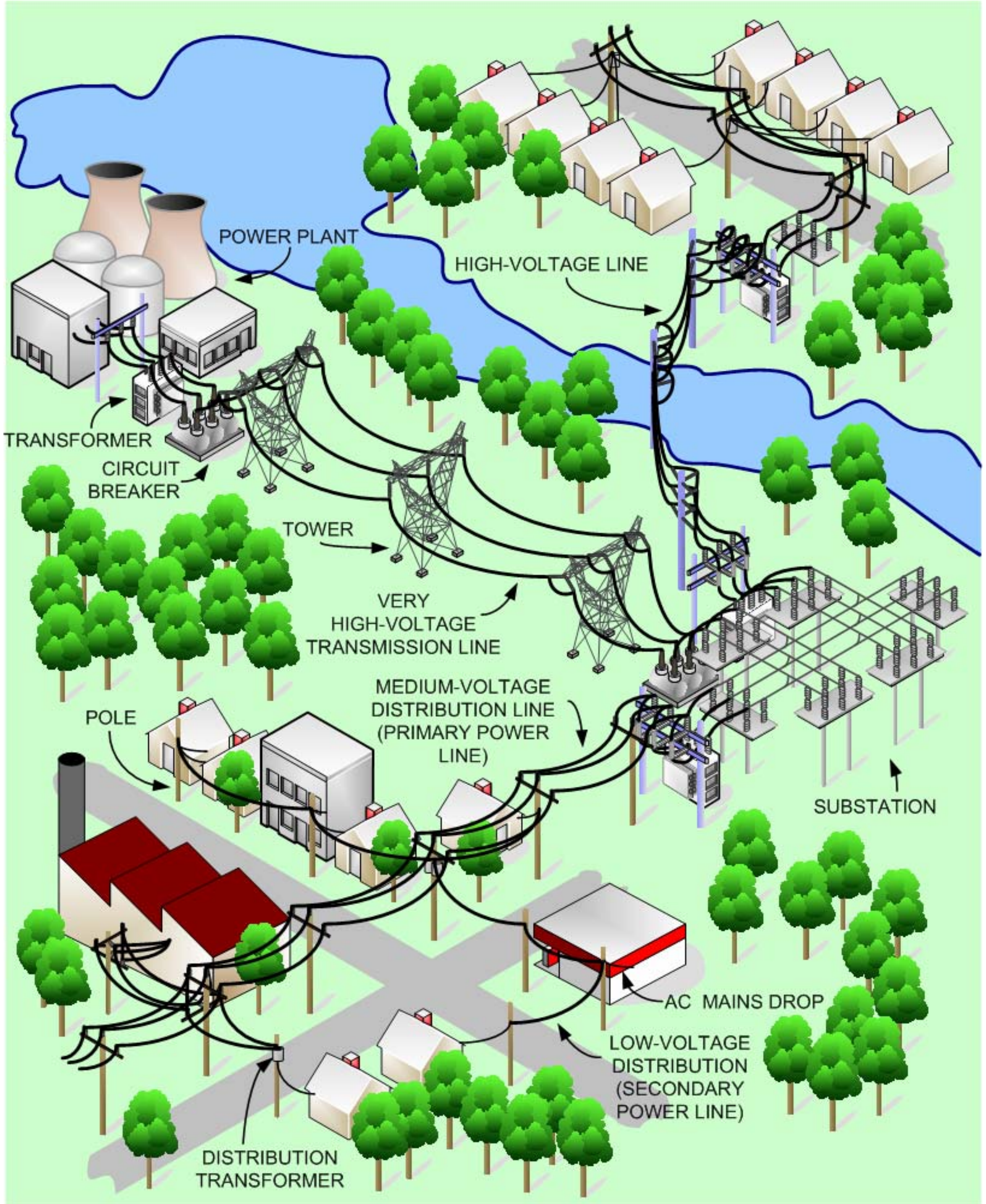

Fig. 2.14. Electrical power system components

2.5 *Electrical power system and communication network infrastructure*

The past sections have presented a short overview of existing communication networks and electrical power systems and provided a basic description of their infrastructure elements. Network infrastructure design is based on plans that foresee system requirements and parameters several years in advance. In the PSTN, the switch and transmission systems are designed for a 5-year future; the power plant and the outside plant, 10-year; and the CO building, at least 15 to 20 years in the future. Once the network is installed, it is extremely difficult and costly to rearrange all its elements. For example, relocating a CO building without disturbing service implies doubling the switching, transmission, and power capacity, as well as rerouting an important part of the feeder cables, the transmission links, the buried conduits and manholes. Thus, any analysis of the infrastructure needs to include a historical perspective using data from the geological, economical, social and political environment of that time. For example, barrier islands in the gulf and Louisiana's wetlands, which are natural defenses against hurricanes, have eroded significantly since the last network designs were completed in the mid 1990s,

As previously mentioned, communication networks have common connection points between each other and the electric grid. Moreover, it is accepted practice in the US to have common elements for different individual network infrastructures such as utility poles. As Fig. 2.15 shows, the poles are shared by the electric grid, the PSTN outside plant and the CATV network. Even though this practice reduces costs, it provides a common point of failure for all the networks that, in turn, decreases their reliability. The higher risk of failure is observed not only during a disaster but also in the aftermath during the reconstruction period when it is not unusual that a contractor fixing one network ends up damaging another network element sharing the same pole.

Fig. 2.16 represents typical hurricane damage. A hurricane has several ways of producing damage: heavy rain, high winds and storm surge. While the effect of high winds and heavy rain can be noticed several kilometers inland, the effect of the storm surge is limited to within a few kilometers from the coast. In all cases, the northeast quadrant of the hurricane experiences the most severe effects. Both the heavy rain and the storm surge may flood large areas from the coast and inland. Electric power outages can also be caused by high winds or storm surge causing poles to break or fall, or by trees pushing down lines. Houses lifted from foundations and floating around during the storm can end up damaging a pole by crashing onto it. As poles are usually shared by other networks, the loss of service may be extended into the local portion of the PSTN and CATV network. Moreover, sharing cables in the same infrastructure increases the weight load and the stress on the poles making them more susceptible to damage during a storm.

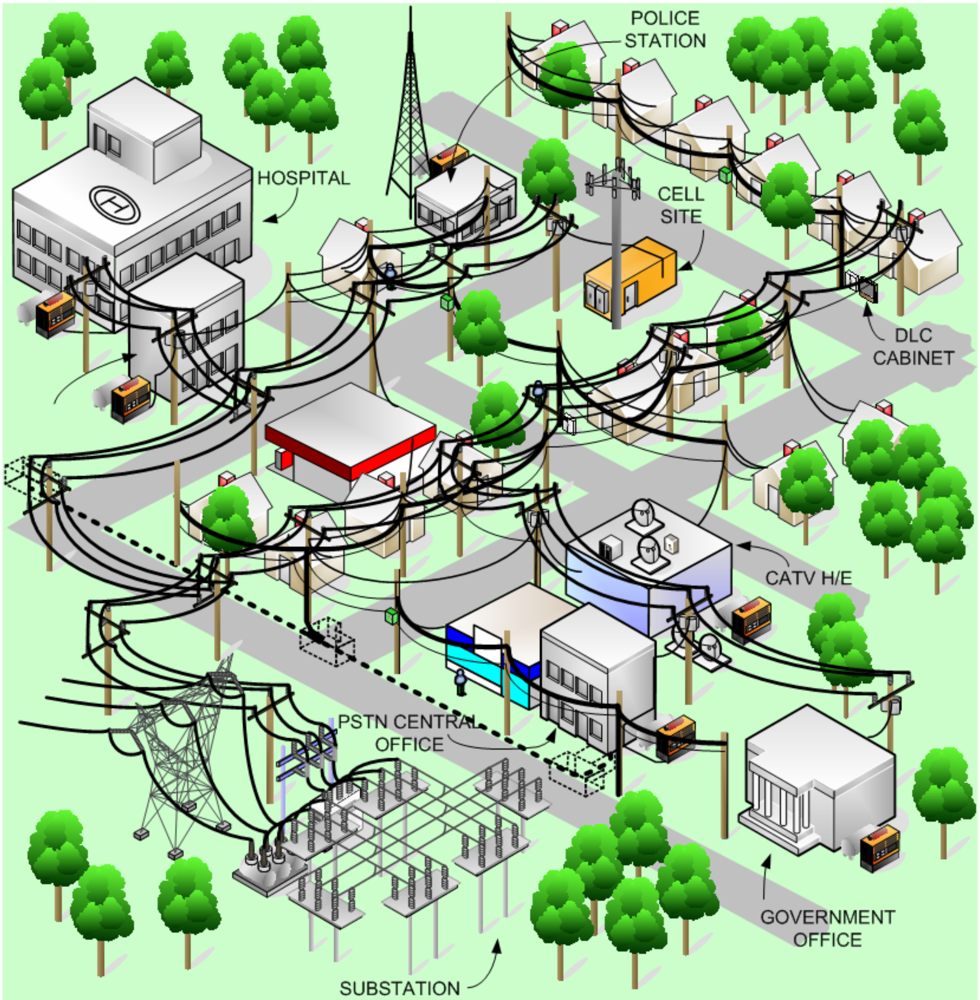

Fig. 2.15. Typical infrastructure in a US town

Floods can submerge manholes and the cables they contain, as shown in Fig. 2.16. Telecom copper cables can withstand submersions of short duration. Older cables are pressurized from the COs and newer cables are filled with gel that prevents water from entering the cable. However, when the pressurizing pump stops working due to lack of electric power or when the gel-filled cables are under water for a long time, the copper is corroded and the cable is destroyed. Thus, when COS are located in areas where flooding persists for several days, eventually all their feeder cables become permanently damaged and useless.

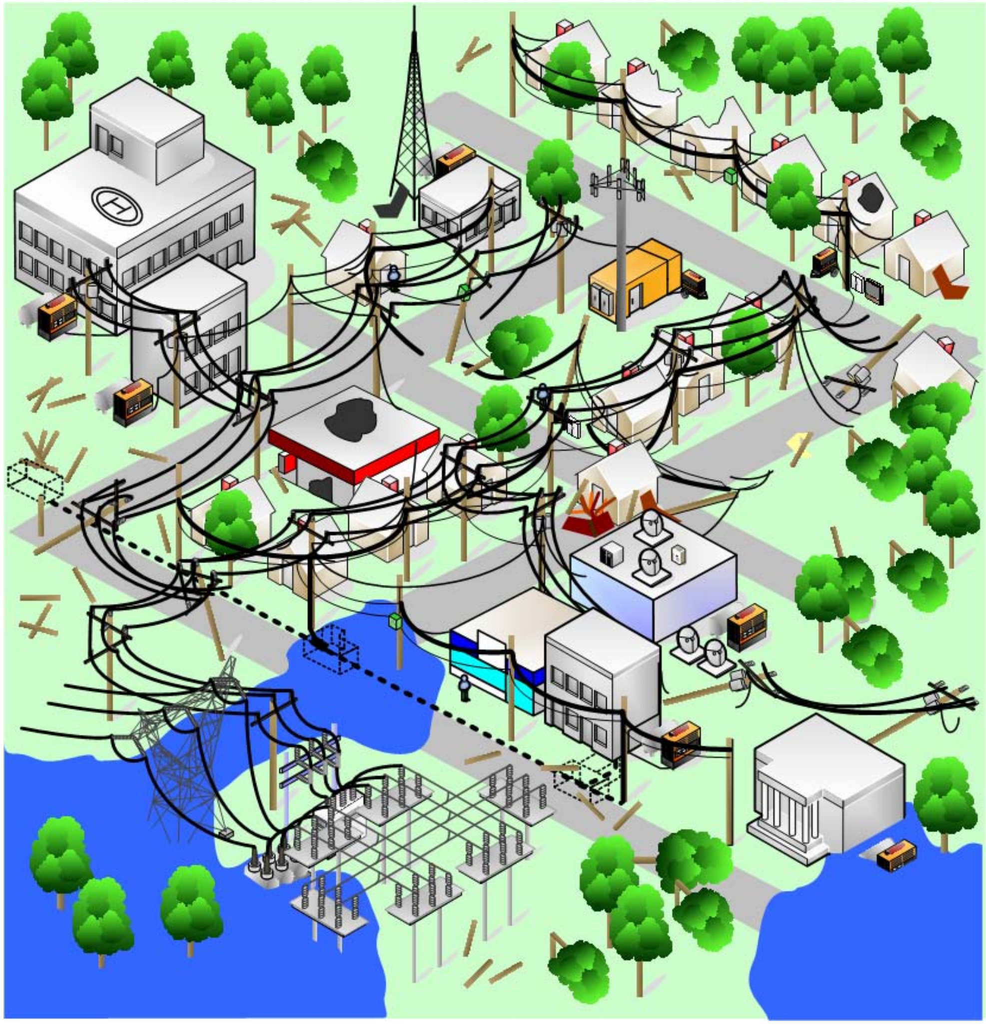

Fig. 2.16. Example of typical damage that a hurricane can cause in a town

Flooding and the storm surge can also affect the operation of backup gensets. All communication centers, government offices, hospitals, police stations and other buildings have permanent generator sets to provide electricity when there is a power outage. However, a storm may permanently damage the genset. The operation of gensets can also be indirectly affected by the presence of debris or flooding water in the streets that prevent reaching the site to refuel the generator. For example, in Fig. 2.16 the generators at the PSTN CO and the CATV H/E cannot be reached due to flooding and debris blocking all the roads. Not all the communication network elements, such as DLC cabinets and many cell sites, have permanent generators. During the initial hours of the electric grid outage, the DLC cabinets and cell sites without generators operate on batteries. When the storm passes, portable generators are taken to their locations, as is exemplified in Fig. 2.16. These generators also need to be refueled periodically, often daily.

2.6 Portable and backup power systems

Portable and backup power systems can utilize a variety of technologies such as combustion engines, fuel cells, turbines and solar, to name a few. While many types of power systems offer high efficiencies, they are usually less portable, have long setup times, can have poor electric transient response, and use nonstandard fuels. For these reasons the most common type of backup power system consists of a reciprocating engine and a genset. Some of the most important factors with genset usage in the context of disaster relief are capacity, transportation and fueling.

Typically, genset capacities can range from tens of kilowatts (Fig. 2.17) to megawatts (Fig. 2.18) and are transported as a single unit over road. Caterpillar,Inc., a major manufacturer of portable and backup power systems, deployed over 230 megawatts of power to the gulf region in the aftermath of Katrina [12]. As of February 28, 2006, approximately 10-20% of that capacity remained in the region. Most of the rest was in a standby application and called upon only when there were disruptions in the utility grid. However, there were still areas where reliable utility power was available and portable power the primary source.

Fig. 2.17. Trailer genset being transported

Transportation and deployment of such portable power to needed areas in the aftermath of a disaster is another hurdle. Roads, railways and waterways can be damaged and impassable. In cases like Katrina with urban unrest, security checkpoints can delay genset delivery. Fueling also is an issue. Once the genset is delivered and operational, fuel must be transported to the site throughout its operation. Fig. 2.19 shows the refueling of a genset providing power to a cell site in Biloxi, MS. During the on-site survey we spoke with the woman running the fueling operation. She stated that she picked up fuel in Birmingham, AL, and delivered it to cell sites all along the Mississippi coast every day. Gensets typically run on diesel fuel, however alternative units exist that run on natural gas only, gasoline only, dual natural gas – diesel, and bi-fuel.

Fig. 2.18. Caterpillar portable power trailer

Fig. 2.19. Refueling the genset that provides power to a Biloxi cell site

The key factor in preventing loss of service at COs is to keep the genset running. This makes the emergency generator the single most important component at a site after the storm. Unfortunately, gensets have an availability of 0.85 when run for 24 hours [13], meaning that a communication network availability is reduced from approximately 99.99% before the storm to 85% a day later. One alternative proposed by [14] in case of flooding is to have larger battery backup time. Besides the higher cost, more batteries presents disadvantages of significant battery weight and increased risk of fire, because higher energy storage can produce more intense short-circuit currents.

3 Damage Produced to Common Infrastructure of Communication and Electrical Networks

Electrical and communication networks use common elements in their distribution infrastructure. Figs. 3.1-3.22 show damage typical to the common infrastructure of electrical and communication networks observed during the site survey. Even though the damage to these elements was severe, it was usually limited to specific areas of the affected region. For example, Figs. 3.1 and 3.2 show extensive damage to both the residences and the entire infrastructure in Biloxi. The same destruction is depicted in Point A La Hache (Figs. 3.3 and 3.4) and Delacroix (Fig. 3.5). However, areas a few hundred meters away were not so heavily damaged, as Figs. 3.6-3.11 attest. Since the damage caused to the outside plant was limited to specific areas, it can not be explained how outages in communication networks were so widespread. In addition, although the damage in Figs. 3.1-3.6 is severe, it is relatively easy to fix, as shown in Fig. 3.12. Thus, long durations of service loss in many CO areas cannot be justified by this damage.

Fig. 3.1. Severe destruction in Biloxi, MS

Fig. 3.2. Total destruction in Biloxi, MS

Fig. 3.3. Severe structural damage to houses and a broken pole with distribution transformer and telecom outside plant cables in Point A La Hache, LA

Fig. 3.4. Total destruction on Highway 15, LA

Fig. 3.5. Fallen cables and destroyed houses in Delacroix, LA

Fig. 3.6. Severe damage to houses but light outside plant damage in Biloxi, MS

Fig. 3.7. Severe residential damage; none to electrical and PSTN distribution cables in Biloxi, MS

Fig. 3.8. Light damage to poles amid total destruction to buildings in Biloxi, MS

Fig. 3.9. Total destruction to houses but light damage to electrical infrastructure near Point A La Hache, LA

Fig. 3.10. Severe damage to construction but light damage to electrical and communication networks in Delacroix

Fig. 3.11. Severe damage to construction but light damage to electrical and communication networks in Delacroix, LA

Fig. 3.12. PSTN outside plant being repaired

In some areas, the infrastructure was damaged by houses, loosed from their foundations by the storm surge, floating until they hit a pole, as in Fig. 3.13. Yet, in similar cases, presented in Figs. 3.14-3.17, boats and houses that floated away did not damage the infrastructure.

Fig. 3.13. House crashed on a pole on Highway 15, LA

Fig. 3.14. Damaged pole and hanging wires on Highway 15, LA

Fig. 3.15. Crashed house on a pole on Highway 15, LA

Fig. 3.16. House lifted from foundation, boat, and undamaged poles in Slidell, LA

Fig. 3.17. Electrical and communication infrastructure in good condition
on Route 90 northeast of New Orleans

Scattered damage, as shown in Figs. 3.18-3.22, was encountered during the site survey in most of the area affected by Hurricane Katrina. Although this damage was not severe and was relatively simple to repair, being dispersed in a large area, it demanded considerable resources that, otherwise, may had been used to restore more seriously damaged zones. This damage affected only a small number of subscribers and was not the cause for the extended and severe loss of communication in the storm's aftermath. Critical outages were related to other causes including destruction of centralized communication nodes, such as COs, and electrical power failures. These will be discussed in the following sections.

Fig. 3.18. Damaged line on Route 11 south of Lake Pontchartrain, LA

Fig. 3.19. Broken pole and remains of telephone distribution cable in Slidell, LA

Fig. 3.20. Broken electrical pole in Biloxi, MS

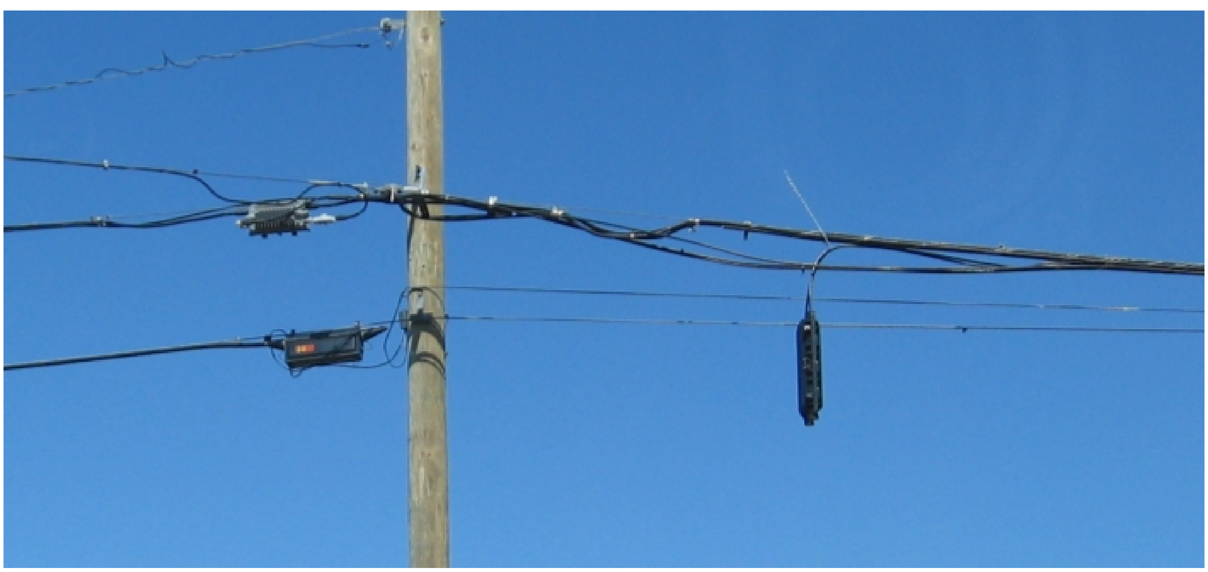

Fig. 3.21. Damaged CATV fiber-optic cable

Fig. 3.22. Hanging damaged PSTN outside plant distribution cable

4 General Damage to Communication Networks

A particular effect of Hurricane Katrina was its centralized nature, implying that communication interconnection points, such as COs, and electrical nodes, such as substations, suffered an unprecedented level of destruction. Damage to the cell sites, PSTN outside plants and electrical distribution grids was also severe but not significantly different from results of other strong hurricanes. Figs. 4.1-4.7 show typical damage caused by Hurricane Katrina in a communication center. As the figures indicate, the site was immersed in salty seawater that corroded all the equipment and destroyed the place. As will be discussed in following sections, such damage happened in several COs, long-distance switches, MTSOs, transmission sites and other communication nodes along the Mississippi coast, in New Orleans and Plaquemines Parish.

Fig. 4.1. Damaged switch (left). The rectifier bay is in the background, MDF on the left behind the switch. Notice the debris on the cable-racks.

Fig. 4.2. Inverter with mud

Fig. 4.3. Part of the switch on the left and two rectifier bays on the right

Fig. 4.4. Transmission-system power-distribution frame showing corrosion caused by immersion in sea water

Fig. 4.5. GPDF back side. Like the PDF in Fig. 4.4, it shows corrosion due to water immersion.

Fig. 4.6. Batteries on the left and rectifier bays on the right, both covered with mud

Fig. 4.7. Detail of two battery cells covered in mud. The green-colored interconnection bar is corroded copper.

5 Hurricane Katrina's Effects on the PSTN

BellSouth is the largest CLEC in the affected area, with a total of 4.9 million lines and thousands of kilometers in fiber-optic links. Thus, the focus of this report will concern Hurricane Katrina's effects on the BellSouth PSTN. Some analysis about transmission networks of other companies is included at the end of this section.

On August 30, 2005, the day after Katrina made landfall in Louisiana, 2.475 million BellSouth lines were out of service due to damage to the outside plant and outages in COs [15]. From the beginning of the storm, BellSouth lost service in 33 COs, 29 in the most severely impacted area of the Gulf Coast region shown in Figs. 5.1 and 5.2. Among the affected COs, nine were destroyed and two more severely damaged, an unprecedented level of destruction.

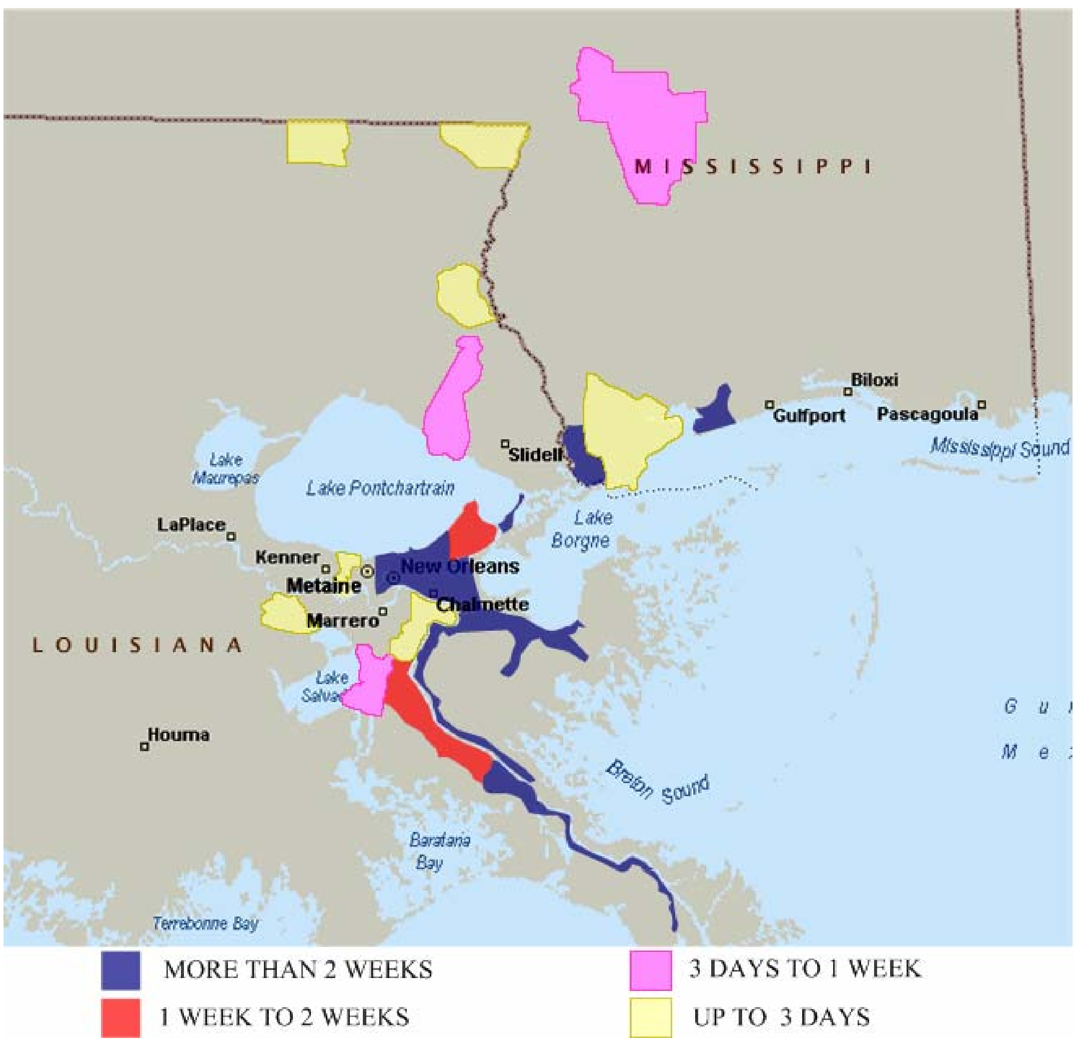

Fig. 5.1. Failed BellSouth CO regions and outage severity

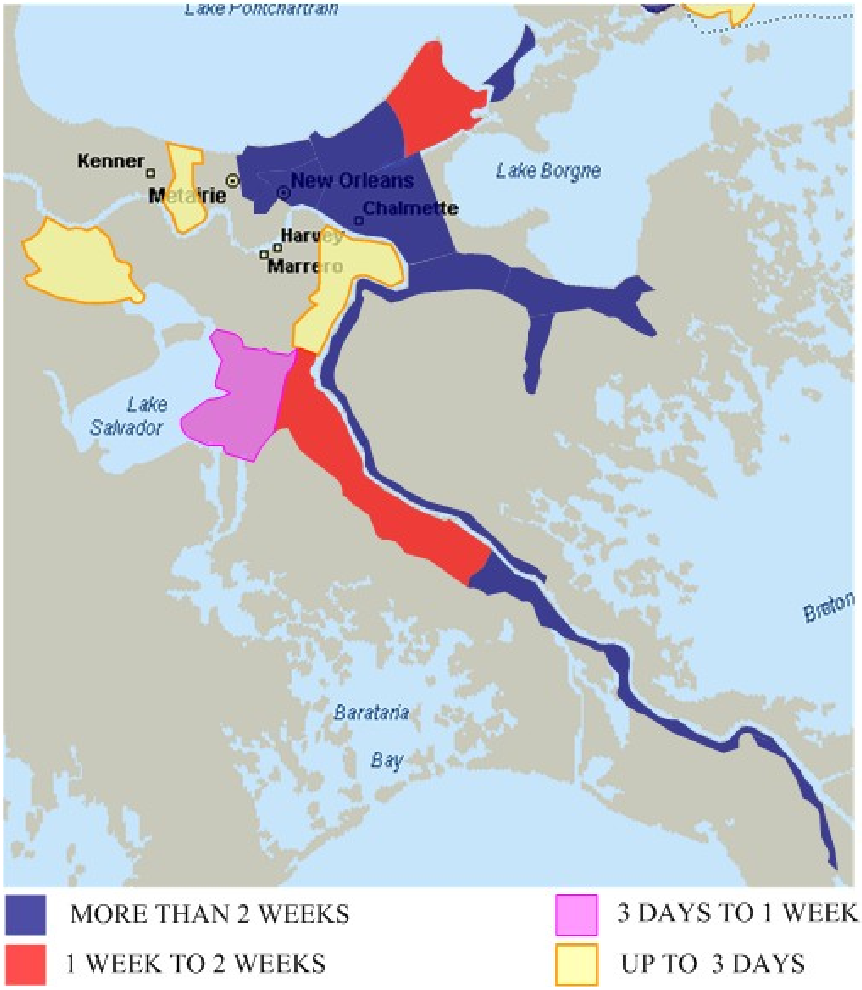

Fig. 5.2. Failed BellSouth CO regions in New Orleans and outage severity

Figs. 5.3 and 5.4 show causes for CO outages. Destroyed CO regions are shown in red. These are COs where all the equipment was ruined by the storm surge and, in many of cases, the building itself was destroyed. Blue areas indicate CO regions that failed due to water damage of the genset or lack of genset refueling but did not sustain equipment damage. The combined failure of a CO due to lack of electric power and partial equipment damage is indicated in yellow. Loss of service due to genset engine fuel starvation is shown in purple. In these cases, disruption of local diesel suppliers and obstruction of delivery capabilities due to impassable or damaged roads played a crucial role in many of the outages. Some of these COs also may have been subjected to flooding in buried fuel tanks but sustained no damage to the inside plant. It is also likely that damage in the outside plant may have accompanied the power-related outages. Damage to the outside plant may have directly affected a dedicated line or an important trunk, such as one connecting the PSTN to a mobile communication network element. Isolation of a remote switch from its host when the link between them was severed was another possible effect of outside plant damage.

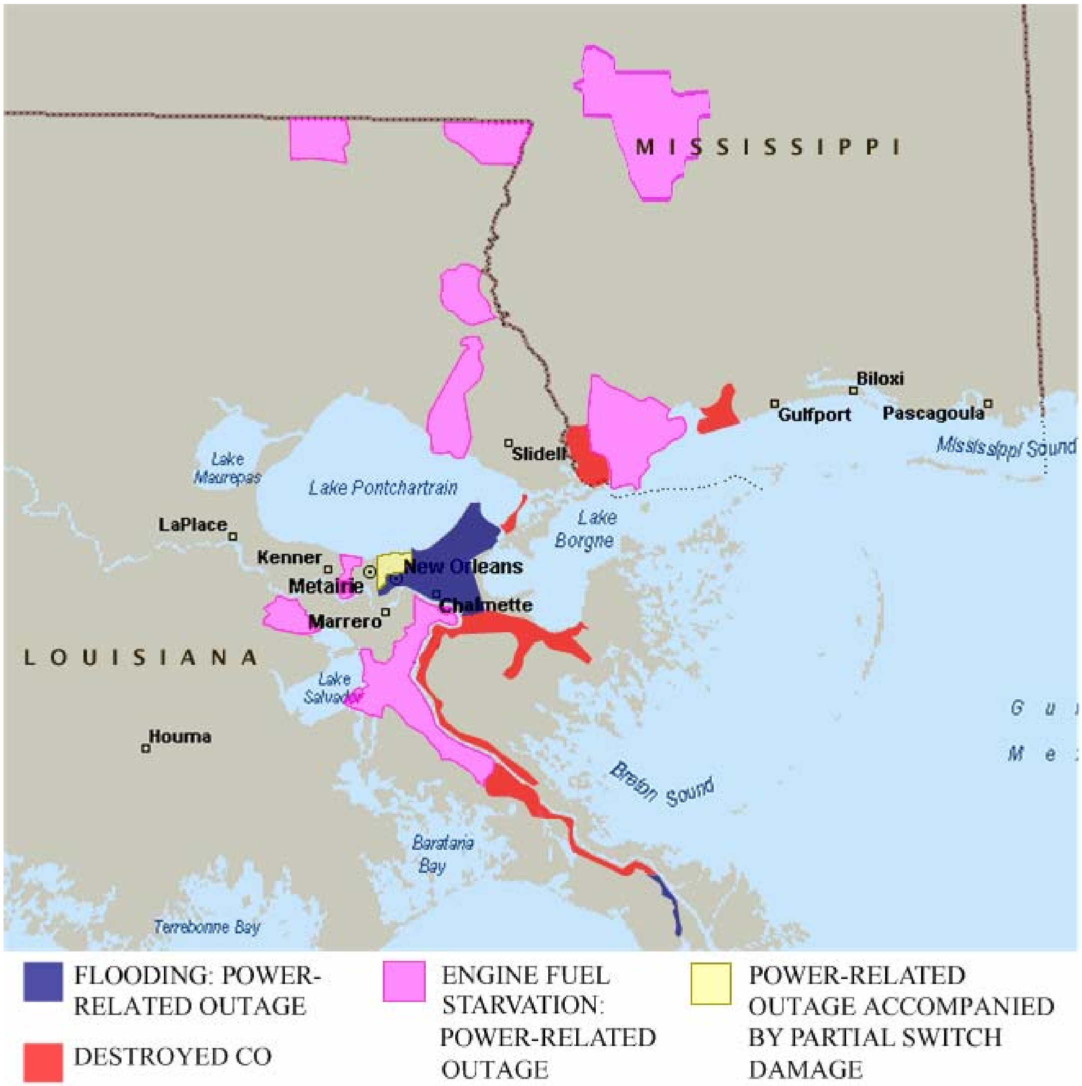

Fig. 5.3. BellSouth failed CO regions indicating the outage cause

Electric power outages influenced many more COs than those indicated in red in Figs. 5.3 and 5.4. Fig. 5.5 shows the status of the COs in the affected area on September 12, almost two weeks after the storm. Besides the existence of COs that were out of service due to power-related causes, Fig. 5.5 shows many more switches operating on emergency generators due to the lack of electric power.

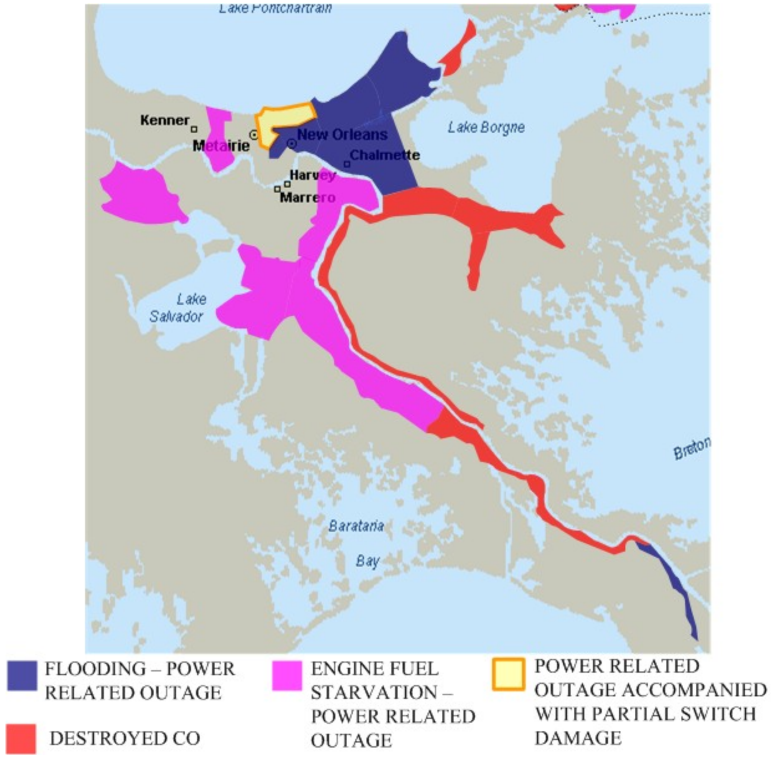

Fig. 5.4. BellSouth failed CO regions around New Orleans

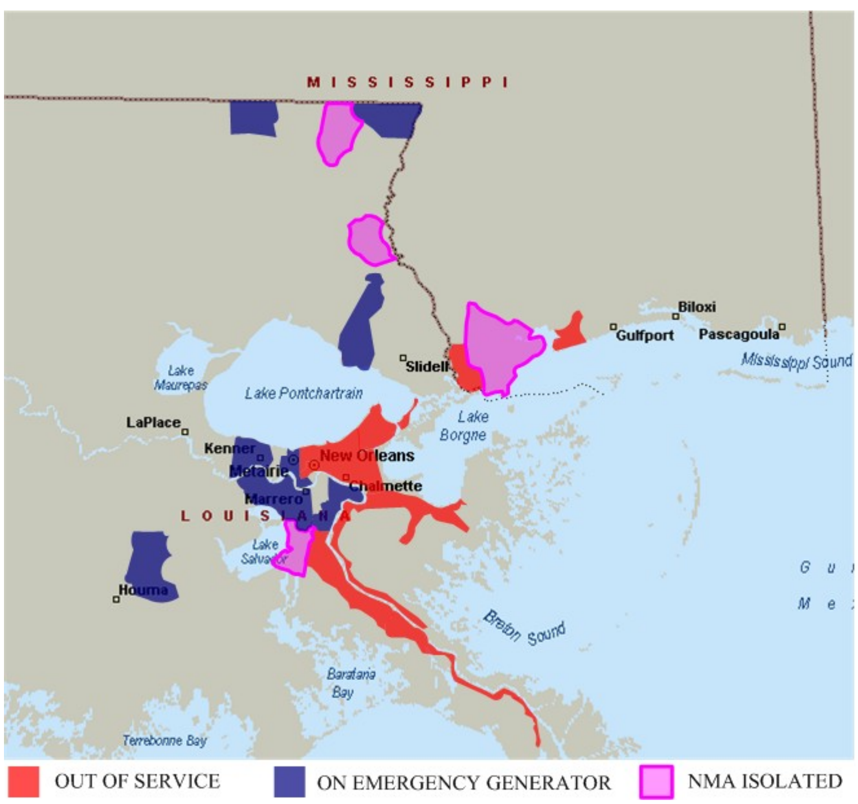

Fig. 5.5. CO status on September 12, 2005

E-911 centers were severely impacted by Hurricane Katrina both directly, when a PSAP or an E-911 was destroyed, and indirectly, when E-911 calls could not be routed due to PSTN failure. In Mississippi, service was affected in 43 out of 138 E-911 centers. All these 43 centers, many of which required re-routing of the traffic, were back in service by September 4th. In Louisiana, 35 of 91 E-911 centers failed. However, unlike Mississippi, service restoration took much longer due to the severity of the PSTN damage. By September 25th, almost one month after Hurricane Katrina landfall in Louisiana, 5 of the 35 E-911 centers in Louisiana, were still out of service.

Destroyed COs are always very difficult to replace. Fig. 5.6 shows two COs in normal operation while Fig. 5.7 exemplifies BellSouth's solution to replace destroyed COs. In Fig. 5.7 it is assumed that CO #1 has been destroyed while CO #2 still operates normally and has enough idle capacity to take over some of the CO #1 traffic. In order to provide service to CO #1 priority lines, a DLC system is placed beside the CO #1 building. Next, the DLC is connected to CO#2 using the existing fiber-optic cable link between CO #1 and CO#2 or by installing a new link. Finally, if the CO #1 feeder cables are in good condition, the DLC output copper pairs are spliced to feeder pairs. In this way, specifically selected CO #1 subscribers may receive normal service from CO #2. Fig. 5.8 displays the basic component of BellSouth's restoration tactic and telephone lines in the CO #1 area that may receive service through the DLC cabinets, including police stations, government buildings or emergency calling centers. Emergency calling centers (also called *phone banks*) seen during the site survey are shown in Fig. 5.9. The phone banks were used by evacuees to call the Federal Emergency Management Agency (FEMA) to obtain relief information. The fact that the output of the DLC is connected to feeder cables at the MDF or at the cable entrance facility is a clear indication that the outside plant is in fair enough condition to allow communication along part of the distribution cables and the feeders. One disadvantage of using DLC cabinets in a disaster aftermath is their batteries have a relatively short backup time. Hence, a portable genset is needed to provide an adequate service level.

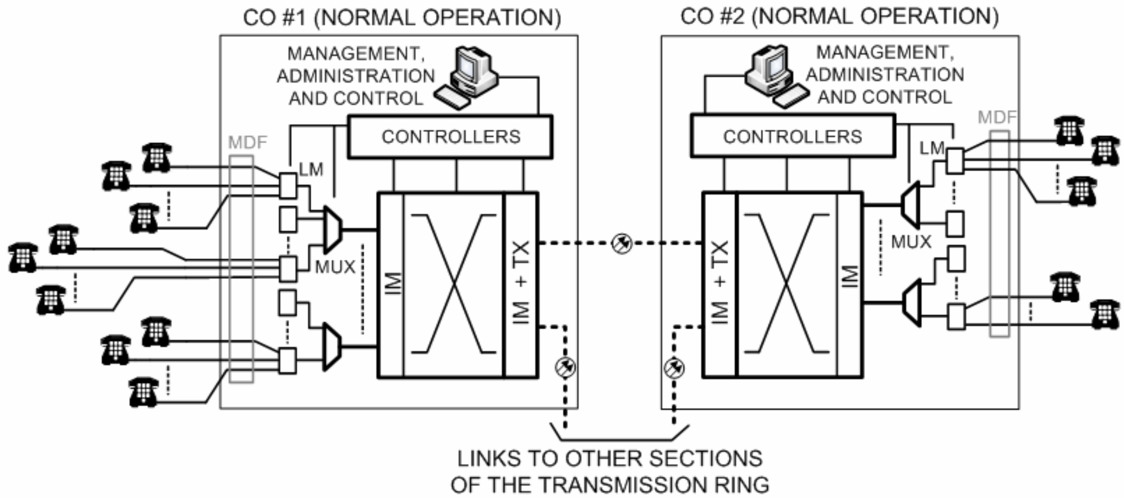

Fig. 5.6. Two COs in normal operation

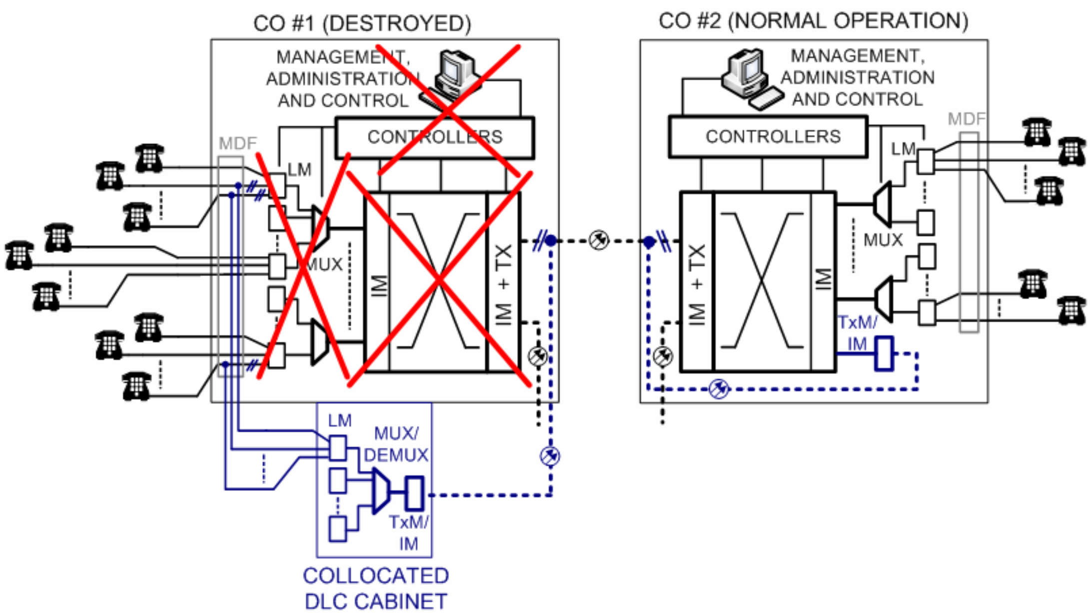

Fig. 5.7. Scheme showing BellSouth's solution to replace destroyed COs

A better alternative to DLC systems that was not used by BellSouth is to deploy a switch on wheels (SOW) to replace damaged COs. SOWs are truck-carried containers that house complete small switches, a power plant and transmission systems. These systems have already been used in rapid-deployed networks with new wireless networks and in countries with an extremely fast increase in POTS demand [16]. SOWs have two important advantages over DLC systems: they provide better functionality when connecting trunks, a requirement for cellular networks links, and they reduce potential congestion points by alleviating traffic of switches that otherwise will be hosting DLC systems. A disadvantage of SOWs is economic, as they are maintained idle for long periods without generating revenue. During this time, the SOW depreciates financially, while the batteries need to be maintained charged. Some authors [17] have suggested employing used parts to restore damaged COs. But they do not consider that legacy batteries are almost surely at the end of their life and cannot be used. Then the problem shifts into getting new batteries in a short time, which generally is not possible due to manufacturing constraints already cited.

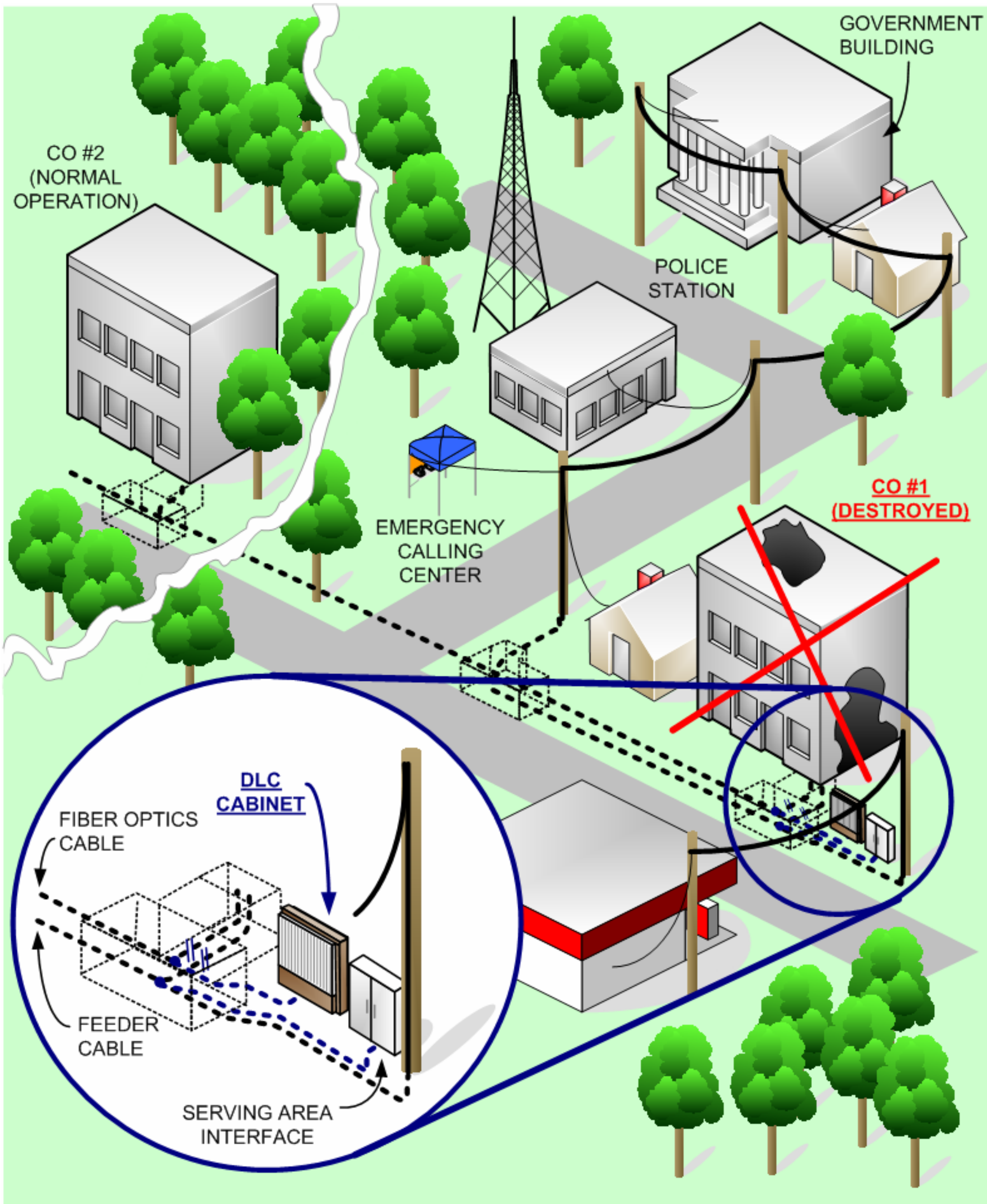

Fig. 5.8. Representation of the CO restoration tactic

Fig. 5.9. Phone banks

Restoration of the outside plant networks also involved using DLC systems. Water in manholes or along conduits from Hurricane Katrina flooding destroyed copper feeder cables in many COs. In case of very long immersion, fiber-optic cables also may have been slowly degraded until they were no longer operational. One important problem in planning outside plant restoration is that feeder cable capacity is calculated on, at least, a 5-year demand. However, mass evacuations and uncertainty about how and when the destroyed areas would be repopulated made it virtually impossible to calculate the demand and plan the installation of replacement feeder cables. While for a given copper, cable capacity is fixed and given by the number of pairs in that cable, for a given fiber-optic cable, capacity is not dependent on the cable itself but on the transmission equipment. Hence, from an outside plant-planning perspective, it makes more sense to replace the damaged copper feeders with fiber-optic cables connected to DLC cabinets, because the fiber-optic cables provide more flexibility to adapt to an uncertain demand. Fig. 5.10 shows an example of this method to replace damaged feeder cables implemented by BellSouth. The output of the DLC transmission equipment is connected to the feeder side of a serving-area interface that can be embedded in the DLC enclosure or located in a separate box beside the DLC cabinet. Within the service area, interface feeder pairs are connected with jumpers to distribution pairs, depending on where an existing or a new subscriber appears.

One important disadvantage of using fiber-optic cables and DLC cabinets to replace feeder cables is that DLC systems require local electric supply. Even though DLC cabinets have batteries which provide backup electricity for up to 4 hours, they need a portable genset to ensure there is no loss of service after that outage. Electric outages that last more than 4 hours are not uncommon, even with storms weaker than Katrina. Hence, deploying many DLC systems to replace damaged feeder cables creates logistical issues, since a portable genset needs to be deployed for each DLC cabinet. Moreover, for extended outages, the portable generators need to be refueled daily. Even worse, DLC enclosures are very vulnerable to flooding unless they are placed on top of poles. However, batteries placed on poles must be smaller than ground-mounted batteries thus reducing battery backup time to only a few minutes. So even though using DLC systems to replace feeder cables makes sense from a planning perspective, it has serious reliability issues.

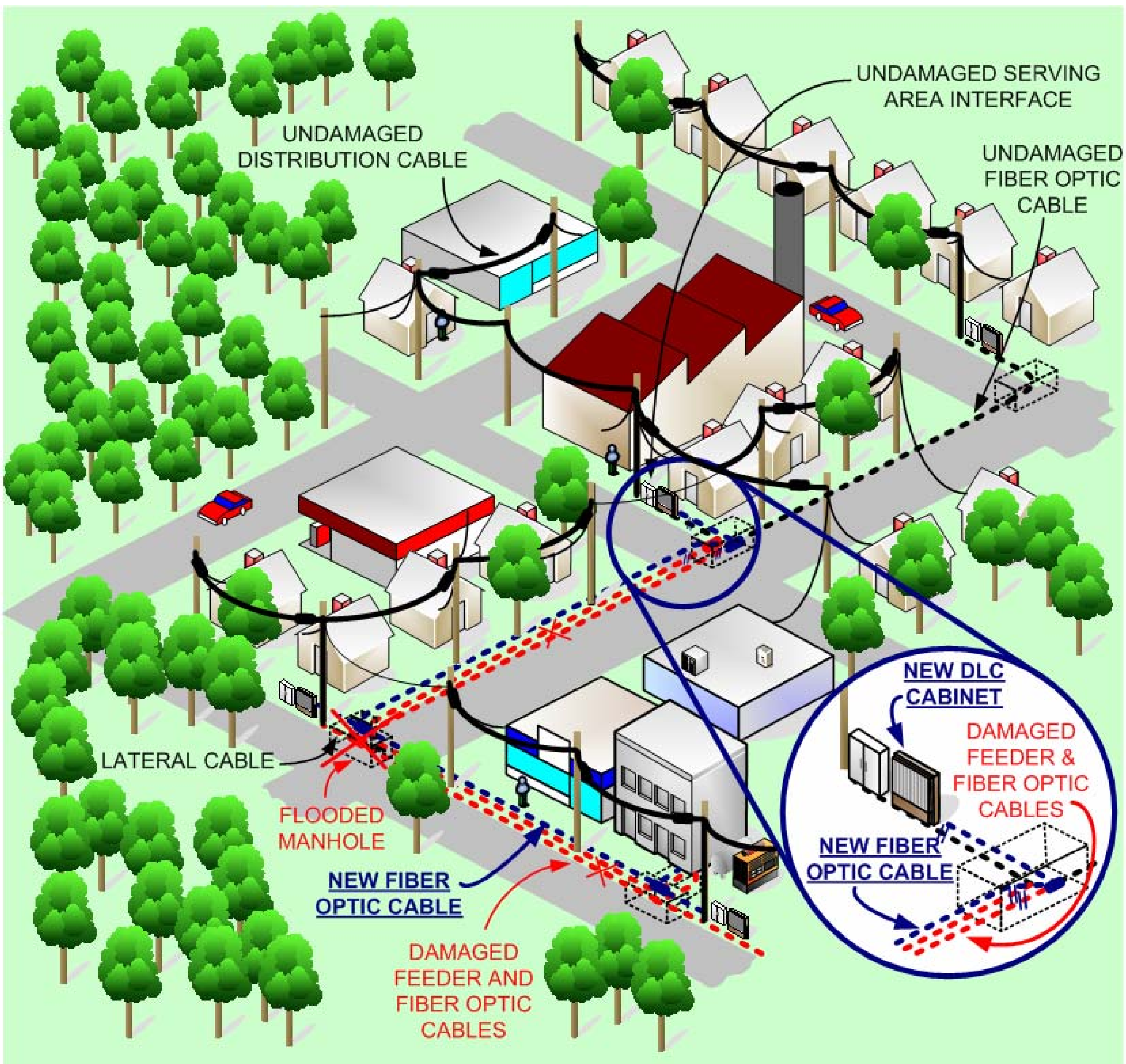

Fig. 5.10. BellSouth's solution to restore damaged feeders

5.1 COs that did not lose service

Even though a high number of COs lost service due to Hurricane Katrina, others maintained normal operations throughout the storm. Many of the surviving COs did not lose service thanks to remarkable efforts by BellSouth employees to keep gensets refueled and running. The New Orleans Main CO is a good example of a CO that survived unharmed both because of BellSouth employees and good fortune. The BellSouth Main CO entrance, shown in Fig. 5.11, is located on Poydras Street in New Orleans. This is the most important communications building in the affected region, because it houses several class 5 switches, a tandem switch, an AT&T long-distance switch and many important transmission terminals. Three factors affected operations in this CO during and after the storm: loss of electric power from the utility grid, flooding, and security issues related to public violence and looting. As Fig. 5.12 illustrates, the CO is situated in the heart of downtown New Orleans, halfway between the Convention Center and the Louisiana Superdome, an area that suffered extensive vandalism. Fig. 5.13 highlights the proximity to the Superdome, which explains why security was such an important factor in building operations.

Fig. 5.11. New Orleans Main CO entrance

Fig. 5.12. Aerial view of downtown New Orleans [8]

Fig. 5.13. Louisiana Superdome and the New Orleans Main CO

The best explanation of how New Orleans Main CO maintained service in Katrina's aftermath can be found in the testimony of Bill Smith, BellSouth's Chief Technical Officer, before the Senate Committee on Commerce, Science, and Transportation [18]. In that hearing, he said:

> "Our experience in the New Orleans Main Central Office at 840 Poydras Street gives a sense of the situation on the ground. BellSouth employees began staffing an Emergency Operations Center (EOC) on the 12th Floor of the building on Sunday, August 28th. The office lost power and engaged generators when the storm hit on Monday, but occupants breathed a sigh of relief that there was no flooding. Then, the levee broke and conditions rapidly deteriorated on Tuesday. Technicians and engineers in the office were trying to re-establish service and maintain power by keeping the generators fueled and running. As the situation in New Orleans deteriorated with violence and looting, the New Orleans police and the Louisiana State Police told us to evacuate the building. There was gunfire in the area and we were told it was unsafe for our employees to remain. At 3:00 p.m. CST, the Louisiana State Police arrived and provided us with an armed escort so we could leave the building. We moved to Baton Rouge and, concerned for the security of the building, we arranged for FBI agents to take occupancy of the building at approximately 9:00 that evening. By Friday morning, the Louisiana State Police and the FBI occupied the building. At that time, we began armed and escorted caravans to the building to bring fuel for the generator, water for the chillers, BellSouth personnel, as well as personnel from other carriers (at BellSouth's open invitation). In spite of these harrowing facts, this key switch, which serves as a regional hub for multiple carriers, remained in operation."

This testimony highlights the critical importance of the power system operation and the logistic issues that appeared due to flooding and looting. However, good fortune played a role as well. As Figs. 5.14 and 5.15 attest, flooding reached within a few meters of the CO front door. If the flooding had been slightly worse due to a small change in the Hurricane path, strength or timing, the CO generator set would have been even harder to refuel and the switches may have lost service.

Overall network performance was degraded, even though both the tandem switch and AT&T's long-distance switch maintained full operation, because, due to the limited capacity of these switches, they could not take all the traffic rerouted from failed COs. Cut transmission links, both to the east and to the west, interrupted most of the traffic going in and out of the CO.

Thus, communication congestion appeared which restricted calls despite the fact that the electric power supply was maintained and service was never lost.

Fig. 5.14. Aerial view of New Orleans, August 31, 2005 [6]

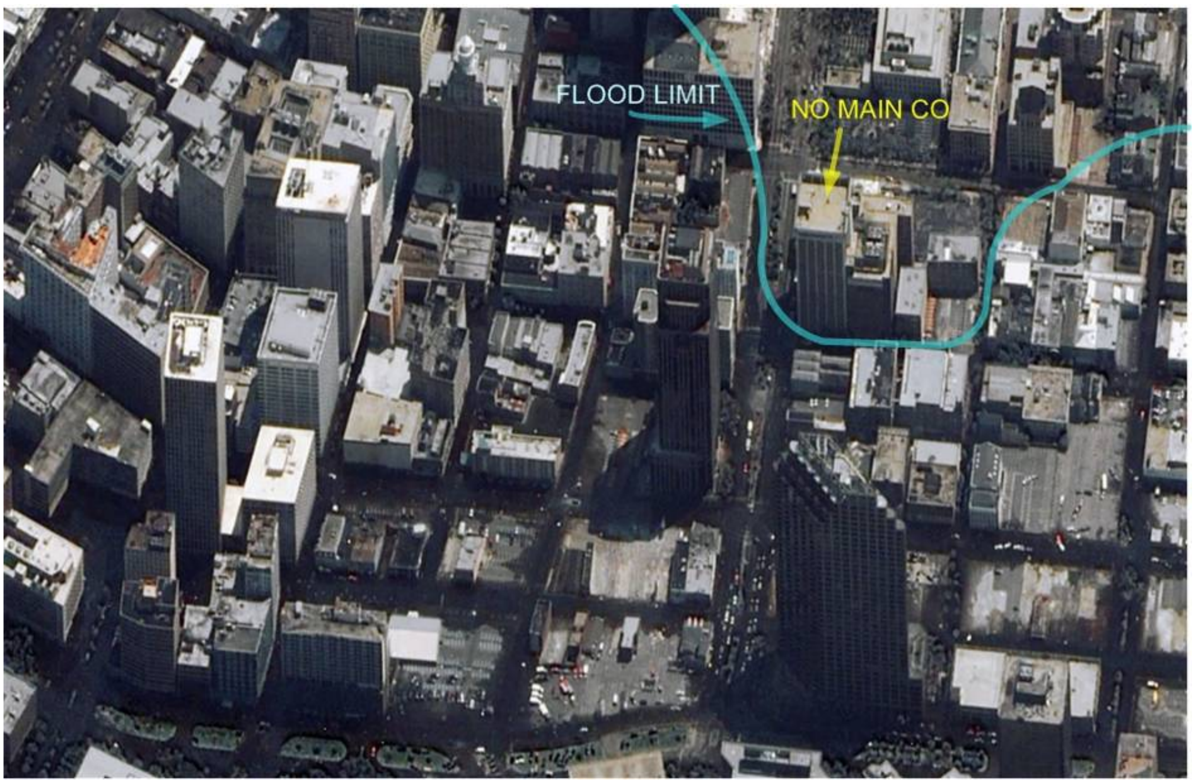

Fig. 5.15. New Orleans, August 31, 2005 [8]

Good fortune and efforts to keep gensets working played an important role in continuing service in other BellSouth COs. As Fig. 5.16 illustrates, many COs are located at sea level or below. Any small change in how Katrina impacted the coast may also have taken any of these COs out of service. Among these COs, Carrolton, shown in Fig. 5.17 is the one that was closest to being flooded with a few centimeters of water covering the streets all around. Even though the inside plant was not affected, many feeder cables were damaged and needed to be replaced by fiber-optic cables and DLC systems. In addition, floodwaters likely hampered the refueling of the emergency generator that provided electric power to the switch. Metairie and St. Charles (Fig. 5.18) are two other nearby COs that experienced flooding. The damage to their outside plants was less significant than in the case of Carrolton, but flooding may also have been an issue for refueling the gensets, especially for the St. Charles CO.

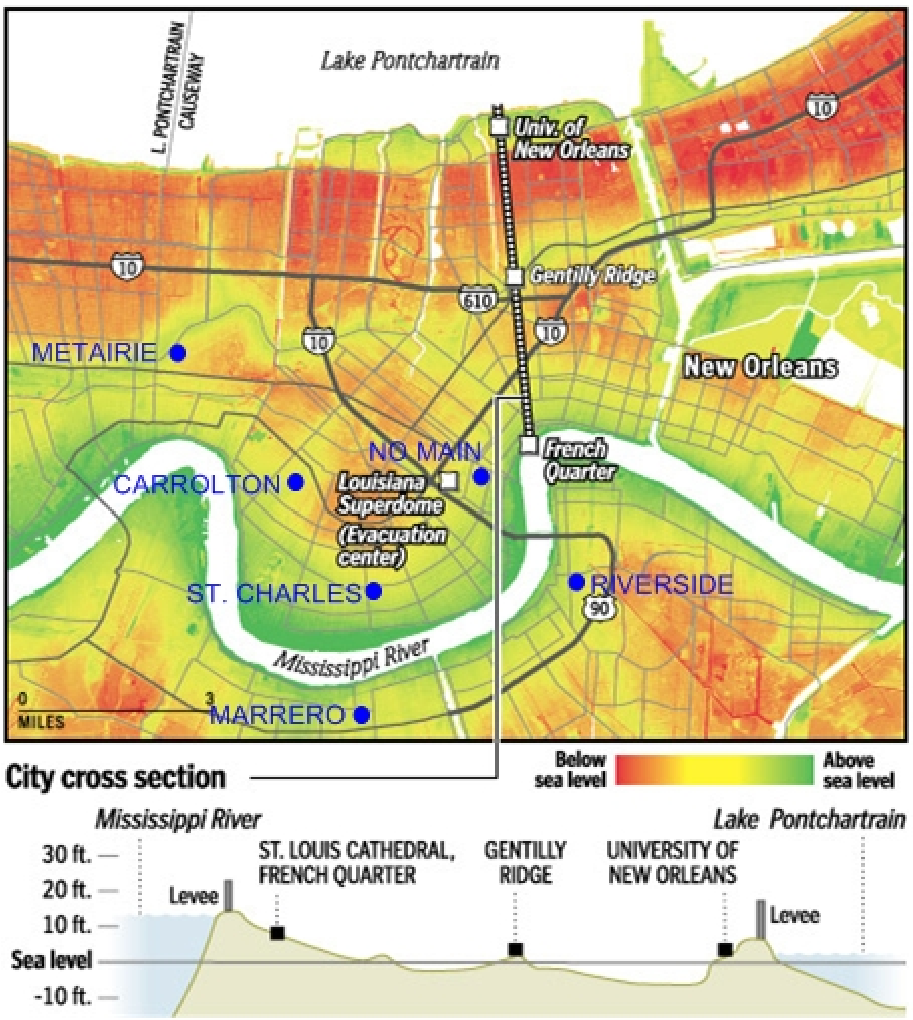

Fig. 5.16. COs that did not lose service and New Orleans area topographic map [19]

Fig. 5.17. Aerial view of Carrolton CO [10]

Fig. 5.18. Aerial view of St. Charles CO [6]

Slidell CO did not lose service even though it is adjacent to two COs that were destroyed, Lake Catherine and Pearlington. Nevertheless, Slidell CO (Fig. 5.19) did not avoid damage completely; some of the feeders needed to be replaced by DLC systems. Good fortune also helped to keep Slidell CO operational. During the on-site survey, we saw signs of flooding with water 20 cm high just 100 m south of the CO building. Although Slidell CO is not in a vulnerable location, it is only 7 km north of the Lake Pontchartrain shore with numerous waterways nearby, as seen in Fig. 5.20. As Fig. 5.19 shows, if the flooding had been worse because Hurricane Katrina has taken a westerly path, the genset fuel tank may have been damaged because it was placed almost at ground level. Most access to Slidell is from the north. Routes 11, I-10, I-59 and I-12 were not blocked or damaged, which surely helped keep the CO genset refueled.

Fig. 5.19. Slidell CO

Fig. 5.20. Aerial view of Slidell CO [10]

COs along the Mississippi Coast were also saved from losing service by efforts of BellSouth employees to maintain operation of the genset. The most remarkable example is Gulfport CO, shown in Fig. 5.21. This is a relatively important CO, since its switch is host to other regional remote switches. Bill Smith's testimony to the Senate [18] highlights the critical importance given to the electric power and how the hard work of BellSouth employees maintained the switch.

> "On September 3rd, a brick wall protecting the main generator keeping the central office alive started to give way. Nine workers from that central office ran from the basement, where they had been working while riding out the storm, to the rooftop room and fortified the walls with whatever they could find – plastic tarps, plywood and even the cardboard from a science project of one worker's son. The main wall in the office collapsed, yet their efforts to protect the switch were successful."

Fig. 5.21. BellSouth Gulfport CO

During the on-site survey to Gulfport on October 22nd, we were unable to identify damage to the wall of the Gulfport CO, probably because it had been repaired. Collapsed walls are not evident in either Fig. 5.22 or 5.23, although some likely spots of damage are suggested in Fig. 5.23. Fig. 5.23 also indicates the storm surge inflow and the railroad tracks, which protected the CO from serious damage. As seen in Fig. 5.22, the railroad tracks pass 1 meter above the street level forming a levee that stopped most of the storm surge.

Fig. 5.22. Gulfport CO on August 31 or September 1, 2005 [7]

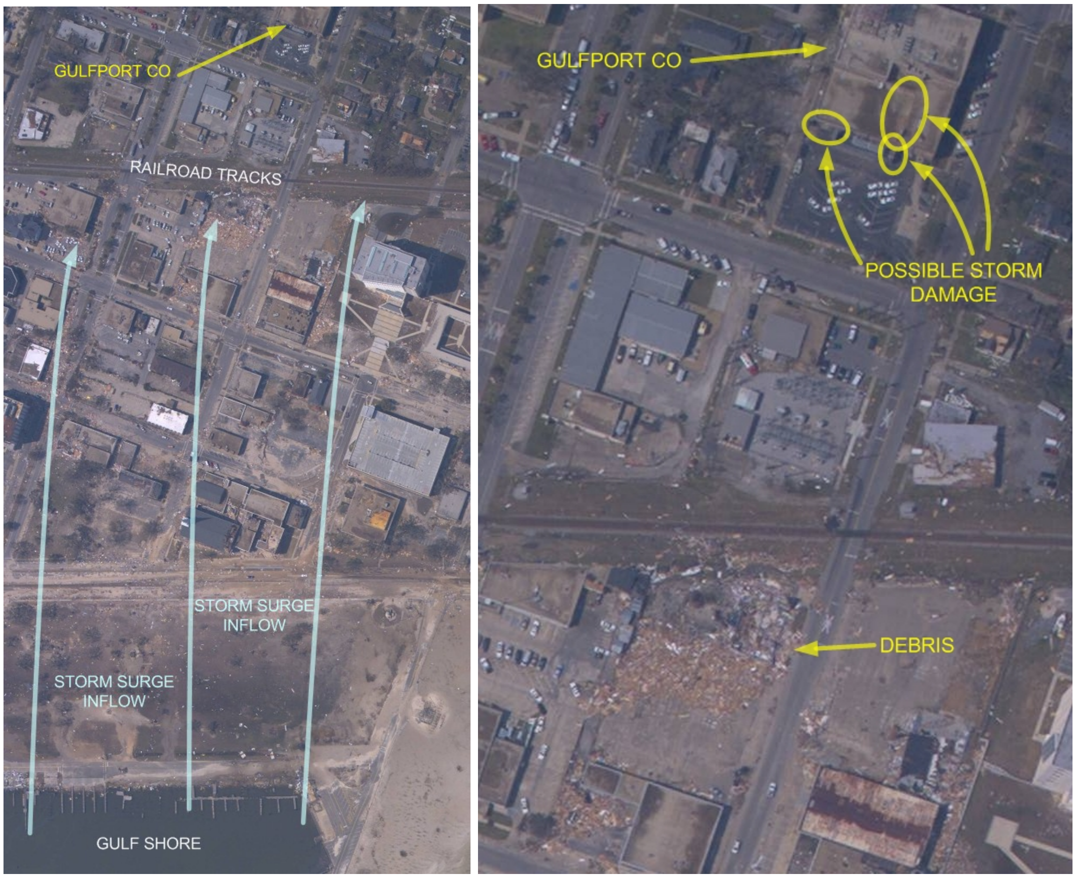

Fig. 5.23. Aerial view of Gulfport CO, August 30, 2005 [6]

Like the Gulfport CO, the Biloxi CO (Fig. 5.24) did not lose service even though it is located south of the railroad tracks. Good fortune played a role in averting an outage at this site, because the CO was built at an elevation high enough to avoid the storm surge (Figs. 5.25 and

5.26). Had Katrina taken a course a few miles more to the east, the Biloxi CO almost certainly would have suffered catastrophic damage. The unblocked access to I-110 (Fig. 5.27) may have also kept the genset refueled and operating.

Fig. 5.24. Biloxi CO

Fig. 5.25. Biloxi CO, August 31 or September 1, 2005 [7]

Fig. 5.26. Aerial view of Biloxi CO, August 30, 2005 [6]

Fig. 5.27. Aerial view of downtown Biloxi and CO [6]

Other COs in the Mississippi Gulf Coast, such as Edgewater, Gautier, Ocean Springs and Pascagoula, escaped damage and never lost service. With no outages in Gulfport and Biloxi, the service restoration time was shorter than in Louisiana. Nevertheless, Mississippi did have COs destroyed.

5.2 Destroyed COs

Fig. 5.28 shows the nine COs destroyed by Katrina, all by the storm surge. The presence or lack of electric power was not an issue when evaluating the cause of failure.

Fig. 5.28. Destroyed COs

Two of the destroyed COs were in Mississippi: Pass Christian and Pearlington. The Pass Christian CO is shown in Fig. 5.29. Storm surge damage is clearly visible. The reason Pass Christian CO was destroyed can be understood by looking at Figs. 5.30 and 5.31. The building was just 300 meters from the shore, an extremely vulnerable location. Strangely, the building was not constructed on pilings although it was located so close to the shore, meaning that even a small storm surge would have destroyed the switch. The emergency DLC system to replace the

CO was hosted by the Gulfport CO. Fig. 5.29 shows that the outside plant was in relatively good condition, which made possible the use of DLC systems. As was mentioned previously, using a DLC system to replace destroyed COs hints that the outside plant was not as seriously damaged as the CO itself. At the time of the on-site survey on October 17th, the DLC system had no genset to provide extended backup power in case of an electric grid outage, a common event during recovery operations.

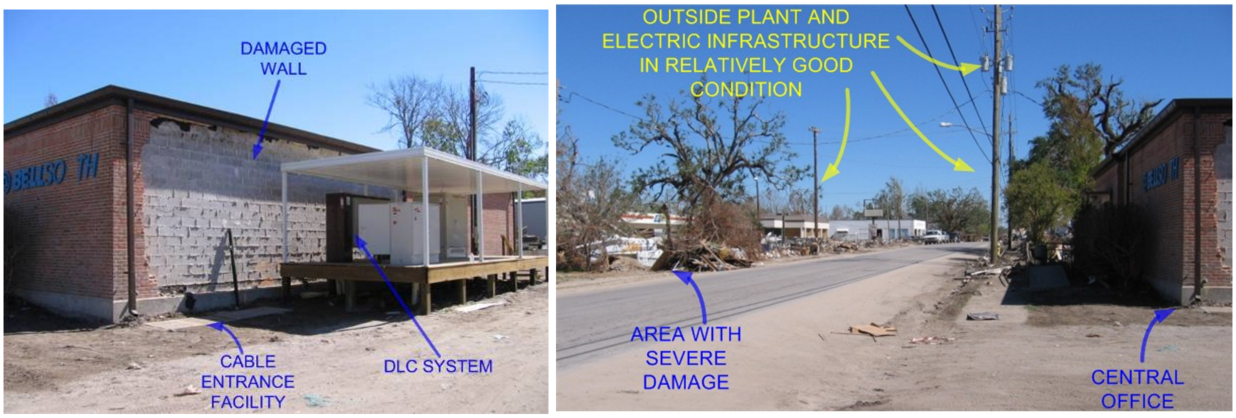

Fig. 5.29. Pass Christian CO

Fig. 5.30. Pass Christian MS, August 31 or September 1, 2005 [7]

Fig. 5.31. Aerial view showing vulnerable location of Pass Christian CO, August 30, 2005 [6]

The other destroyed CO in Pearlington, Mississippi, unlike Pass Christian, was located 8 km inland, not a vulnerable position. However, the CO, shown in Figs. 5.32 and 5.33, was destroyed when it was covered by more than 2 m of water from the storm surge. None of the pictures indicates a genset. As with the Pass Christian CO, the DLC that replaced the switch had no generator to extend the battery backup, which may have negatively affected PSTN reliability in that area. In addition, like the Pass Christian CO, the Pearlington DLC was hosted by the Gulfport CO. During the on-site survey on October 20th, work was being done on the outside plant, probably to connect the output of the DLC. This implies that the area recovered POTS service around that date.

Fig. 5.32. Pearlington CO

Fig. 5.33. Aerial view of Pearlington CO, September 2, 2005 [6]

The northernmost destroyed CO in Louisiana, Lake Catherine, was located 17 km to the southwest of Pearlington. However, Hurricane Katrina's effects on the Lake Catherine CO were more severe than in Pearlington, or any other CO. As Fig. 5.34 shows, the Lake Catherine CO was obliterated; only the building's supporting pilings survived.

Fig. 5.34. Remains of Lake Catherine CO [20]

The rest of the destroyed COs are located in Plaquemines Parish and south St. Bernard Parish. Two, Yscloskey (Figs. 5.35 and 5.36), and Delacroix (Figs. 5.37 and 5.38), were small remote switches constructed on pilings. Fig. 5.39 indicates that both buildings were better built than the surrounding houses with the objective of withstanding hurricanes. Unfortunately, they did not seem to have been designed for a hurricane as strong as Katrina. The photos in Fig. 5.40 show that the gensets of both COs were located outside at the same level as the switch. At the time of the on-site survey on October 18th, both COs had been abandoned with no DLC system because their operational areas were unpopulated. On November 7th the emergency DLC replacement systems hosted by the Chalmette CO were put into service in both Delacroix and Yscloskey COs.

Fig. 5.35. Delacroix CO

Fig. 5.36. Delacroix CO

Fig. 5.37. Yscloskey CO

Fig. 5.38. Yscloskey CO

Fig. 5.39. Aerial view of Delacroix and Yscloskey CO, September 7, 2005 [6]

Fig. 5.40. Gensets: Left – Delacroix, Right – Yscloskey

South of Delacroix and Yscloskey is the Point A La Hache CO which was also destroyed by Hurricane Katrina. While the area suffered severe damage, the building, (Fig. 5.41) showed no significant structural damage. However, the switch and all other equipment inside the CO were destroyed when a storm surge of approximately 2.5 m overtook the site. Some of the resulting flooding is shown in Figs. 5.42 and 5.43. The height of the storm surge was verified by the debris seen in Fig. 5.44. As in many other COs, the genset fuel tank was located in a vulnerable spot at ground level. Thus, even if the storm surge had not reached the level of the CO floor, the switch still would have gone out of service because the fuel tank would have been flooded. At the time of the on-site survey, there was no electricity in the entire area and no sign of people returning to their homes. There were also no indications of DLC enclosures to provide emergency telephone service to the area while the switch was not working. However, BellSouth's notices of network changes announced that a DLC system hosted by the Marrero CO was to be installed at the site by November 7th [21].

Fig. 5.41. Point A La Hache CO, October 18, 2005

Fig. 5.42. Aerial view of Point A La Hache CO [20]

Fig. 5.43. Aerial view of Point A La Hache, September 3, 2005 [6]

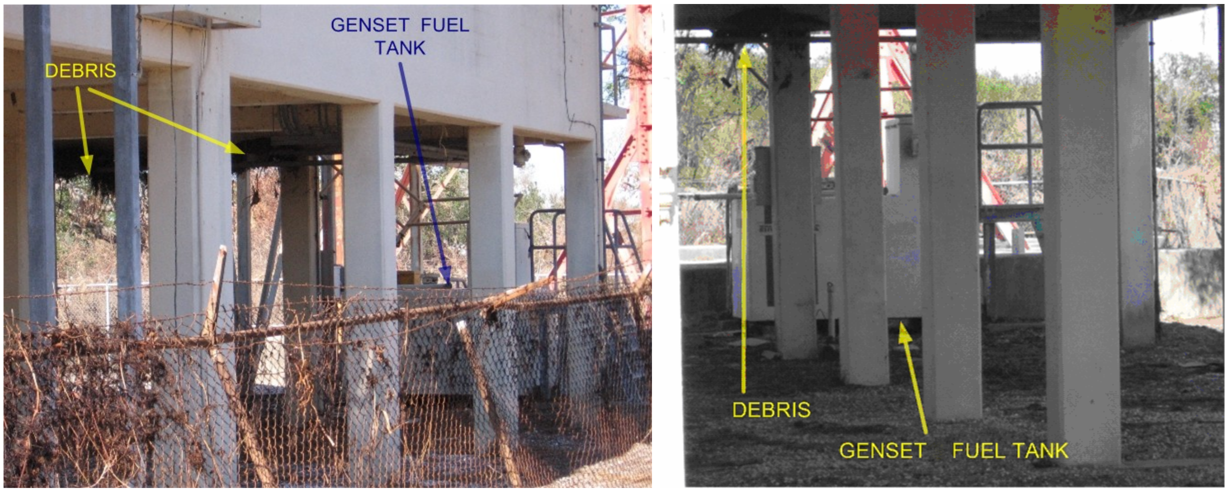

Fig. 5.44. Point A La Hache CO genset fuel tank.

The same issue encountered with the Point A La Hache CO genset fuel tank was also seen in the St. Bernard office located about 30 km to the north. The St. Bernard CO construction implies an even riskier condition because, as shown in Fig. 5.45, the building was not constructed on pilings, even though the area was at risk of flooding. Even a small amount of flooding, as indicated in Fig. 5.46, could cause serious damage and take the switch out of service. A similar problem was also noted in the Pass Christian CO, but in this site the building was not destroyed. At the time of the visit on October 22nd, contractors were finishing cleaning the interior from mold and mud. As in other sites, there was no indication of a DLC system, but there were also plans to install one, hosted by the Marrero CO, by November 7th.

Replacing destroyed COs with DLC cabinets leaves the PSTN in a very vulnerable condition if a strong hurricane hits the area again during the 2006 hurricane season. All of the last four analyzed COs were replaced by DLC systems hosted by the Marrero CO, one of the COs located at sea level shown in Fig. 5.16. Even worse, Marrero is a remote switch hosted by the Schrewsbury CO, located below sea level, which failed during Katrina. Hence, the Marrero-Schrewsbury link constitutes a single common point of failure for a very large area.

Fig. 5.45. St. Bernard CO

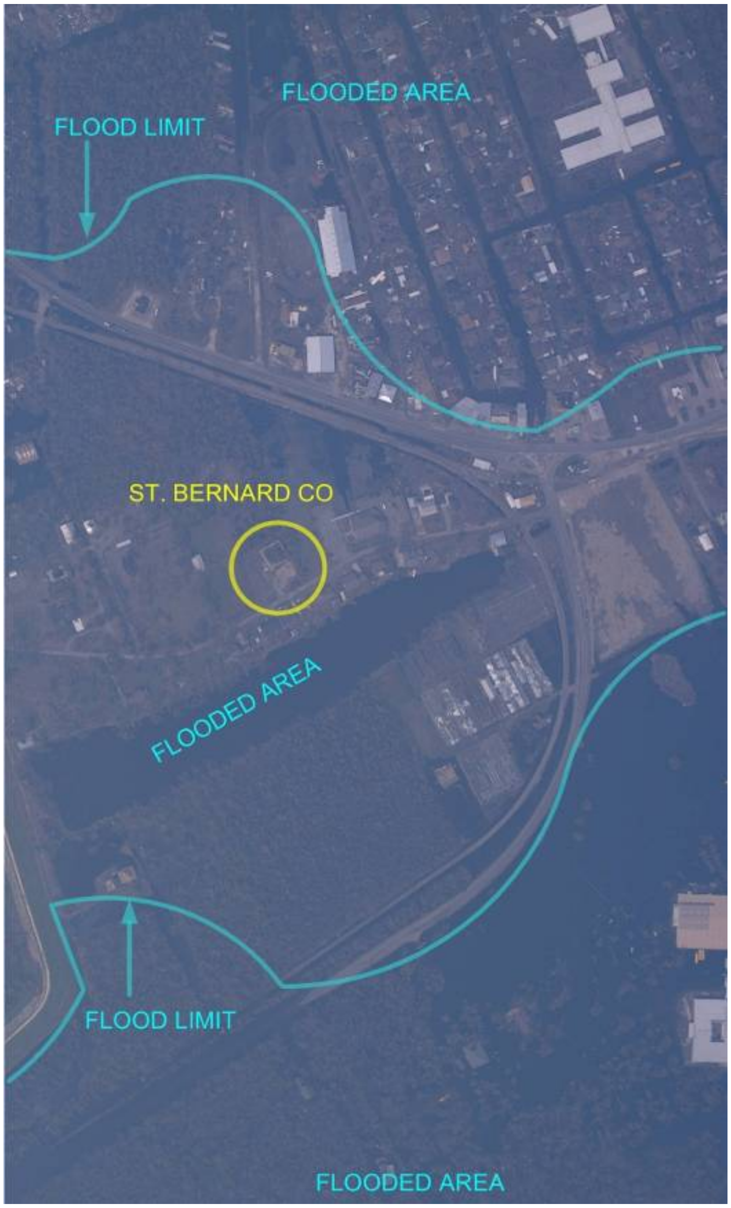

Fig. 5.46. Aerial view of St. Bernard, September 3, 2005 [6]

The remaining two destroyed COs are Buras (Fig. 5.47), and Port Sulphur (Fig. 5.48). Both COs were built similarly to Point A La Hache and experienced similar damage from the storm surge. Like Point A La Hache, the Buras genset or its fuel tank seems to have been located at ground level. Also, like Point A La Hache, the area around the COs experienced catastrophic damage, some of which can be seen in Figs. 5.49 and 5.50. Both switches were replaced on November 7th with DLC systems hosted by the Aurora CO. In addition, all the feeders were destroyed and replaced by DLC enclosures during the first quarter of 2006.

Fig. 5.47. Aerial view of Buras CO [20]

Fig. 5.48. Aerial view of Port Sulphur CO [20]

Fig. 5.49. Aerial view of Buras CO, September 3, 2005 [6]

Fig. 5.50. Aerial view of Port Sulphur CO, September 3, 2005 [6]

5.3 COs that failed due to lack of electric power caused by flooding

The most common outcome of any hurricane is the loss of electric power in a large region lasting days and, in some cases, weeks. Hurricane Katrina was no exception; all the affected area shown in Fig. 5.3 lost power. However, an electric power outage does not necessarily imply that a CO will lose service. Given periodic refueling, the on-site backup genset can maintain the switch for extended periods. The main difference between Katrina and other hurricanes is that the densely populated area depicted in Fig. 5.51 was flooded when the levees failed. Even though this is a small area, it contains several of the largest switches. Thus, a major percentage of the lines that went out of service belong to this area.

The flood created three problems:

1) Direct water damage to power plants, gensets or fuel tanks but not to most of the communication equipment
2) Loss of service from lack of refueling a CO genset because the water depth made reaching the site impossible
3) Loss of service from lack of refueling a CO genset because of civil unrest, looting or curfew

These problems caused CO outages due to lack of electric power. Six of the seven COs with these power-related outages are displayed in Fig. 5.52. Two, Lake and Mid City, suffered partial damage of communication equipment, including the switch. Mid City also had damage in the power plant located in the basement. As Bill Smith commented in [22]:

> "…In New Orleans, we've had water into some of the power facilities and power rooms but to the best of our knowledge, in the survey process, the majority of equipment has remained dry. We expect our challenge there will be to restore the power equipment with batteries and generators. … The switch was positioned on upper floors of the CO building precisely to avoid flood waters."

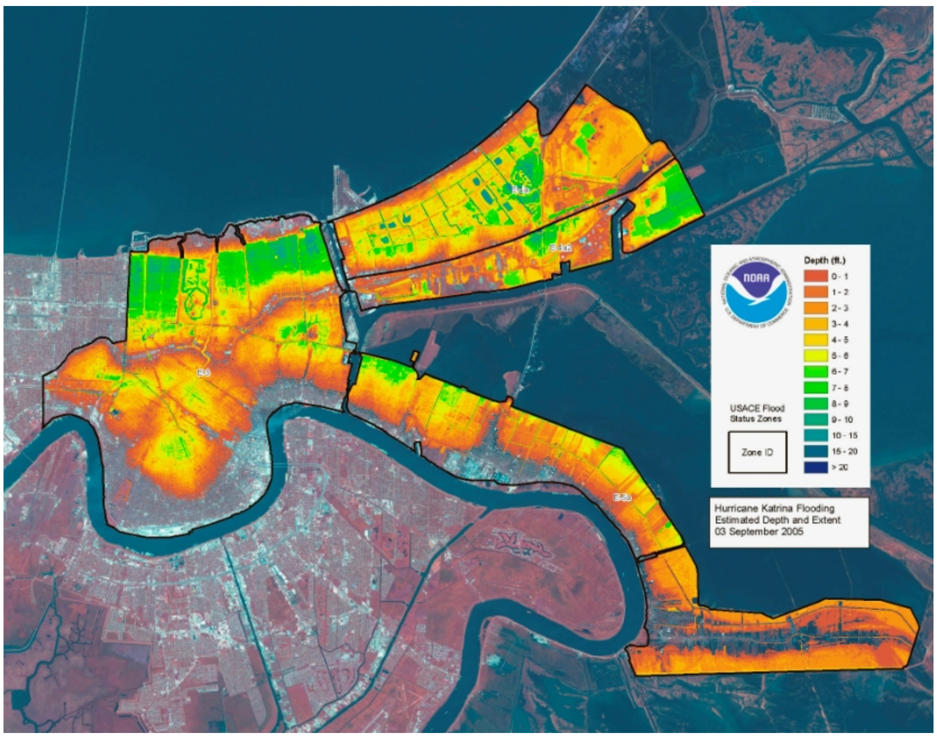

Fig. 5.51. New Orleans flooded areas with the estimated water depth [NOAA]

Bill Smith's comments show the importance of protecting the power plant in the same way that the switch is protected, by locating it on floors above sea level. They also explain why flooding and power-related outages are considered as the same failure cause. As Fig. 5.53 indicates, five of the COs shown in Fig. 5.52 are located below sea level in locations that were prone to flooding. Most of these COs were built some decades ago when design methodologies were not as comprehensive with respect to hurricanes. However, modern design guidelines place all CO critical systems, including the entire power plant, above sea level.

Fig. 5.52. New Orleans flooding with related failed COs in yellow and levee breaches indicated in light blue. Background satellite picture from [23]

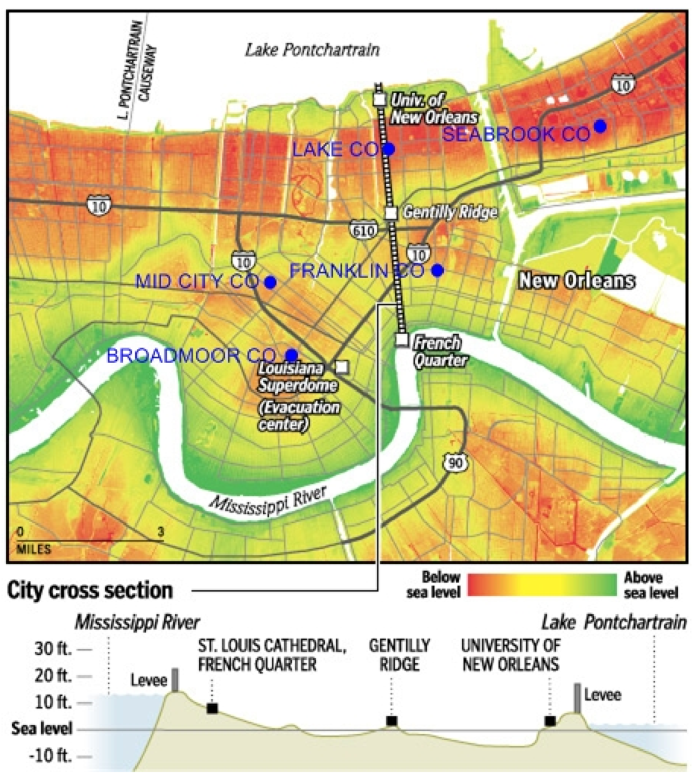

Fig. 5.53. New Orleans topographic map [19] with power-related CO outages.

Among the eight COs with power-related outages, Lake suffered the highest floodwaters. As Fig. 5.54 shows, the floodwaters reached a depth of more than 3 m. Besides being in one of the lowest points in the city, Fig. 5.55 shows that the building is located 300 m from the London

St. Canal levee, which breached 800 m southwest of the CO. The high floodwaters caused the destruction of the oldest switch in the building [24]. A newer switch was undamaged and used to restore service to subscribers of the older switch. Although the damaged switch was not replaced by a DLC system, several DLC enclosures were used to replace the entire destroyed feeder facility.

Fig. 5.54. Aerial view of Lake CO [20]

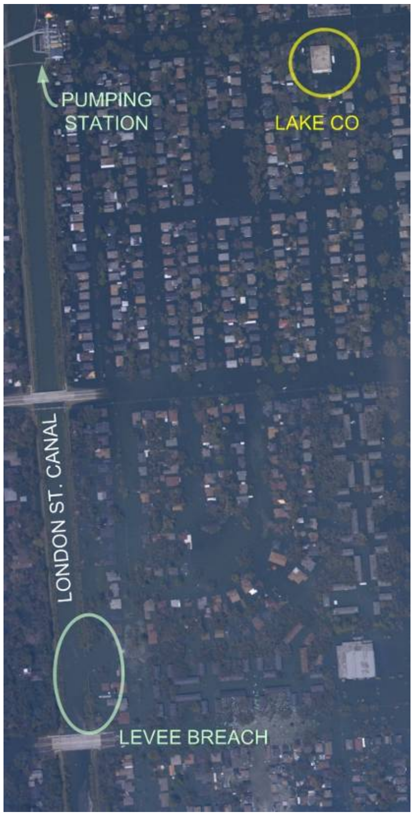

Fig. 5.55. Aerial view of Lake CO, August 31, 2005 [6]

Mid City is another of the COs that suffered damage to its switch. Fig. 5.56 shows that flooding was not as severe as in Lake; likely the switch was located at ground level. It is unclear how much damage the switch received, but probably it was not totally destroyed. The fact that it was an old switch may have contributed in the decision to replace it with a new one [25]. However, the power plant located in the basement was destroyed. Fig. 5.57 depicts the flooding around the CO. Even though the building was less than 500 m away from an exit on I-10, the flooding was significant enough to prevent reaching the site. Like the Lake CO, all copper feeders facilities were destroyed and will be replaced by fiber-optic and DLC systems.

Fig. 5.56. Aerial view of Mid City CO [20]

Fig. 5.57. Aerial view of Mid City CO, August 31, 2005 [6]

Broadmoor is another CO that suffered damage in the feeders and lost service due to lack of electric power (Fig. 5.58). During the on-site survey, on October 21st, the genset at the back of the CO was running, indicating that the electric utility grid was not providing power. This hints that the power plant was not damaged. Fig. 5.58 indicates that the flooding at this site was not severe and that there is a chance that the genset and other equipment located at ground level may have narrowly avoided damage. It is certain that the switch in this site was not damaged. However, part of the copper feeder facility was destroyed and needed replacement by DLC cabinets and fiber-optic cables. Fig. 5.59 reveals that the CO is located very close to I-10, but flooding may have prevented refueling the genset, inducing a switch outage.

Fig. 5.58. Broadmoor CO, Left: Front, Right: Back

Fig. 5.59. Aerial view of Broadmoor CO, August 31, 2005 [6]

Not all the COs that suffered severe flooding were damaged. Venice CO, shown in Fig. 5.60, is the most remarkable example. This is Louisiana's southernmost CO, located near the mouth of the Mississippi River and about 15 km west from where Hurricane Katrina made landfall on August 29th. Despite its extremely vulnerable location and that the area surrounding the CO was catastrophically destroyed by the storm surge, as depicted in Fig. 5.61, there were no reports of damage in the CO except the genset. The only road access to Venice is Highway 23 from the north. It passes through one of the most severely affected areas by the storm, which surely prevented any genset refueling efforts by land. The building houses a remote switch hosted, before the storm, by the Buras CO. Since the Buras CO was destroyed, Venice is now hosted by the Jesuit Bend CO. There are no current reports of feeder damage.

Fig. 5.60. Aerial view of Venice CO [20]

Fig. 5.61. Aerial view of Venice CO, September 3, 2005 [6]

Seabrook, shown in Fig. 5.62, is another CO that experienced severe flooding but no damage to the CO or feeder cables. Fig. 5.62 indicates the CO was without a power supply. The genset may have been damaged and its fuel tank flooded. Even if the genset had not been damaged, it could not have been refueled since, as depicted in Fig. 5.63, this site had no direct access to dry land. Thus, the CO went out of service due to lack of electric supply. Fig. 5.63 suggests that one alternative to refuel the genset could have been to use boats like those employed in rescue missions.

Fig. 5.62. Aerial view of Seabrook CO [20]

Fig. 5.63. Aerial view of Seabrook CO, August 31, 2005 [6]

Franklin CO, depicted in Fig. 5.64, was another of the COs in New Orleans that lost service due to lack of electric power because refueling was impossible. Hence, although there was no damage to the power plant or any other equipment, the genset could not be refueled. Thus the switch lost service due to lack of power. In addition, there are no reports of extensive damage in the feeders. Since Franklin acts as an important center for routing E-911 communication, the outage in this CO had a severe impact on emergency calls. BellSouth’s solution was to reroute E-911 calls to Carrolton until Franklin regained full service.

Fig. 5.64. Aerial view of Franklin CO [20]

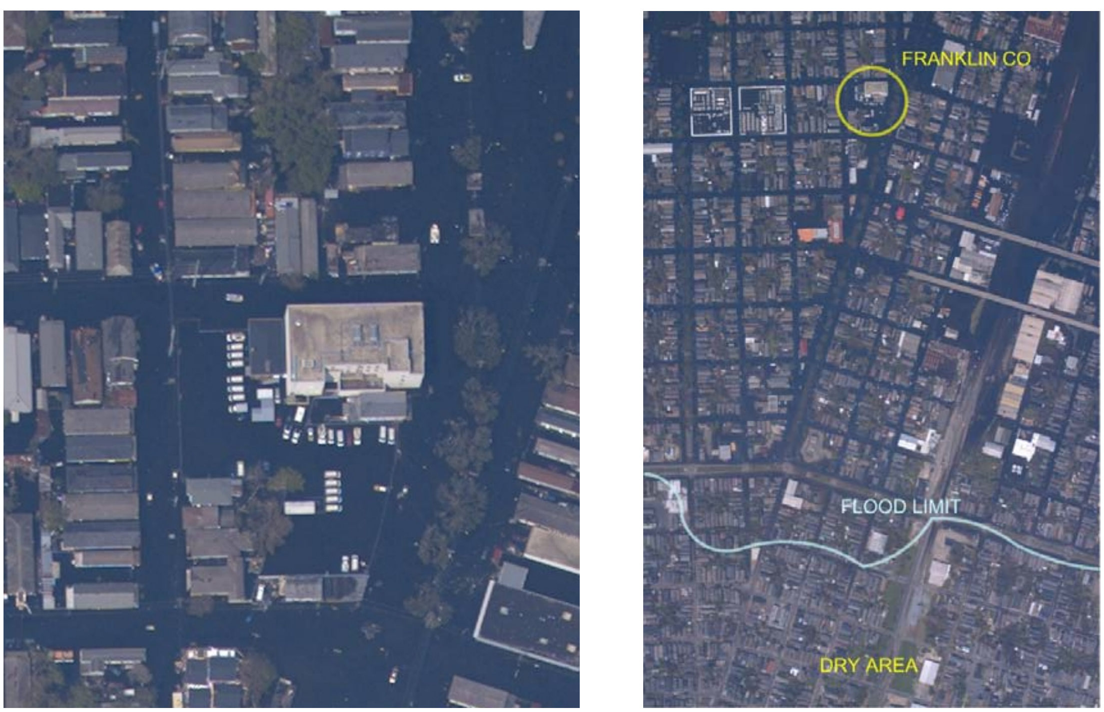

Fig. 5.65. Aerial views of Franklin CO, August 31, 2005 [6]

The Lower 9th Ward was one of the New Orleans' most severely flooded neighborhoods. Chalmette CO is located 7 km southwest of the Industrial Canal levee breaches that inundated that area of the city. Fortunately, the CO, shown in Fig. 5.66, was located on slightly elevated terrain and received only 1 m of water. During the on-site survey, on October 18th, we were informed at the site that no equipment was damaged but that the utility grid electric power had been out since the storm. They were expecting to have electric power restored from the grid before the end of October, as the work shown in Fig. 5.67 attests. By the time of the visit, they had no refueling problems. However, as Fig. 5.68 reveals, while the flood persisted, the CO was surrounded by high water that isolated the site and negated any refueling possibilities. Security issues may have also played an important role. During the on-site survey, we observed a sign on the front door by the police guard post reading, *BellSouth Fort Apache*. Hence, because of flood and security issues, the switch failed when it was impossible to deliver fuel to the genset.

Fig. 5.66. Aerial view of Chalmette CO [20]

Fig. 5.67. Chalmette electric drop being repaired

Fig. 5.68. Aerial view of Chalmette CO, August 31, 2005 [8]

Michoud CO experienced the same conditions as Chalmette: There was no damage to the equipment but flooding prevented fuel delivery to the genset. During the on-site survey on October 17th, local employees confirmed to us that there had been no damage to the equipment but that they suffered a long outage from the electric utility grid. Like Chalmette, the building is constructed on terrain slightly higher than its surroundings, as shown in Fig. 5.69. Additionally, the lowest floor is approximately half a meter above ground. These two factors may have assisted in avoiding equipment damage. However, the building was isolated when all the access routes became impassable due to the flood.

Fig. 5.69. Aerial view of Michoud CO, September 3, 2005 [6]

5.4 COs that lost service due to genset engine fuel starvation

Disrupted local diesel supply and obstructed roads are two possible primary causes for all the remaining CO failures. Contrary to previous cases, in these COs the flood waters receded quickly. Three COs that fall into this category, Bush, Lumberton and Bay St. Louis, may have also experienced damage to the outside plant that isolated them from the rest of the network, as Fig. 5.5 seems to indicate.

The Bay St. Louis CO is the most interesting of these three. As shown in Fig. 5.70, this CO area is on the coast, between two destroyed COs, Pearlington and Pass Christian. The CO contains a remote switch hosted by Gulfport CO and linked by a fiber-optic cable running along the coast and passing through Pass Christian CO. Other possible links connect Bay St. Louis CO with Pearlington to the west and Bayou Laterra to the north. The Bay St. Louis main link to Gulfport was interrupted when the bridges on Bay St. Louis were destroyed by the storm. Alternative links may have been interrupted due to storm surge damage in the town of Bay St. Louis and along Highway 603. The Bay St. Louis CO outside plant also received considerable damage, and plans to replace most of the feeders by fiber-optic cables and DLC cabinets were carried out at the end of 2005. As Fig. 5.71 shows, there is no indication of damage or flooding in the CO itself. However, the destroyed bridge on Route 90, flooding in a section of Highway 603, and catastrophic damage west of Bay St. Louis in Waveland likely delayed any effort to refuel the genset. As a result, the remaining fuel was consumed and the genset ceased operating.

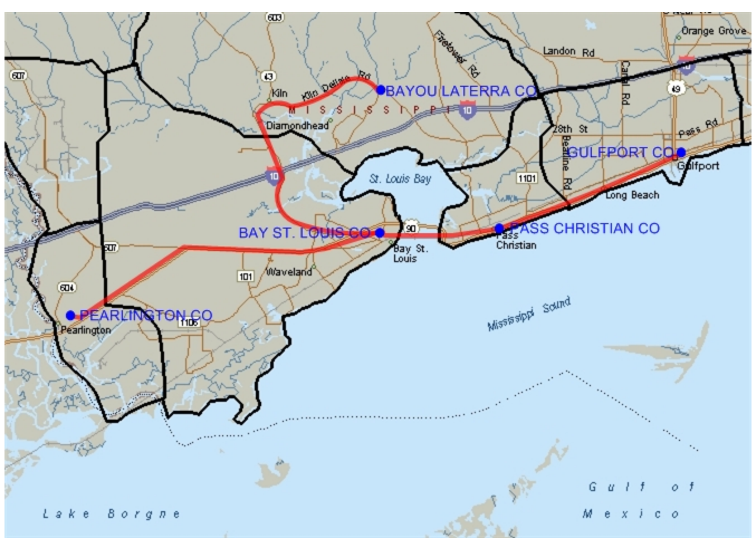

Fig. 5.70. Map of Bay St. Louis area with likely transmission paths indicated in red

The rest of the COs that lost service from fuel starvation are Mount Hermon, Angie, Lacombe, Schrewsbury, Harahan, Aurora, Luling / Boutte, Jesuit Bend and Laffite. Disruption of the local diesel supply may have caused lack of fuel for the gensets at Mt. Hermon and Angie. These COs are located almost 100 km north of New Orleans, where extensive damage and flooding was unlikely. Among the nine remaining COs, the most interesting are Schrewsbury and Aurora.

Fig. 5.71. Aerial view of Bay St. Louis CO, August 31, 2005 [6]

As Fig. 5.72 indicates, Schrewsbury CO is a host switch situated below sea level. Moreover, Fig. 5.73 shows that there is a canal less than 200 m north of the building. Thus, Schrewsbury CO is located in an area that may be easily flooded during storms. The genset or its fuel tank possible location, as pointed out in Fig. 5.73, is at ground level, which implies that it may be damaged even in light flooding. Schrewsbury CO is an extremely vulnerable node in the PSTN network because, as was mentioned earlier, it hosts Marrero, a CO that, in turn, hosts DLC systems that replaced destroyed COs in St. Bernard Parish. The low-lying terrain where Schrewsbury CO was built is at risk of flooding from levee breaches in the canals around Metairie and Kenner west of the Lake Pontchartrain causeway. If this disaster occurs, the PSTN outage area may be more extensive than that created by Katrina.

As Fig. 5.74 shows, the Aurora CO is similar to Schrewsbury; it is built below sea level near canals. In fact, Aurora's location is even more vulnerable than Schrewsbury, being so close to Norman Canal, as shown in Fig. 5.75. This figure displays more signs of flooding than

Schrewsbury and also reveals that the genset and its fuel tank are probably at ground level, an extremely exposed spot when flooding occurs. If the area is hit by a hurricane similar to Katrina, the Aurora CO is very likely to fail again. However, since it is now hosting the DLC systems that replaced the destroyed COs of Buras and Port Sulphur, the affected zone will be larger.

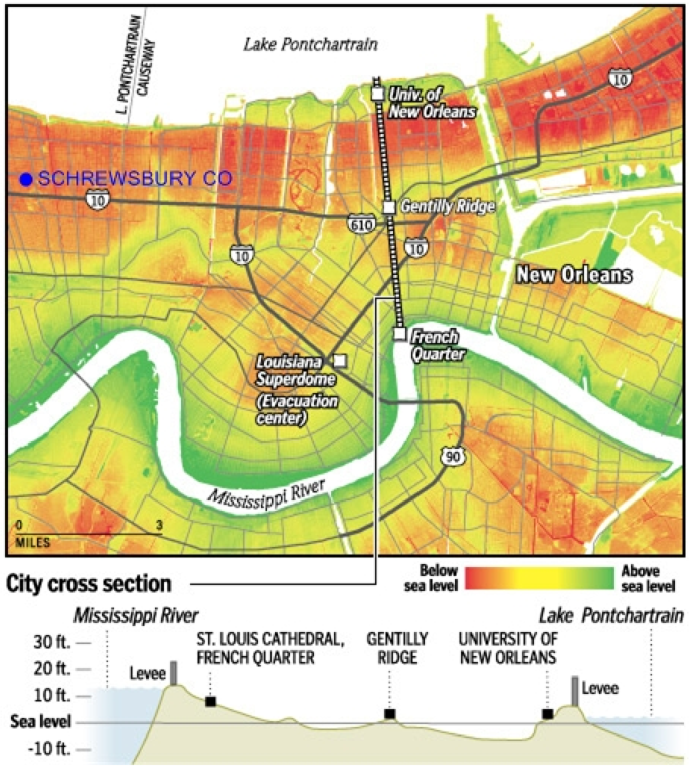

Fig. 5.72. New Orleans topographical map [19]with Schrewsbury CO location

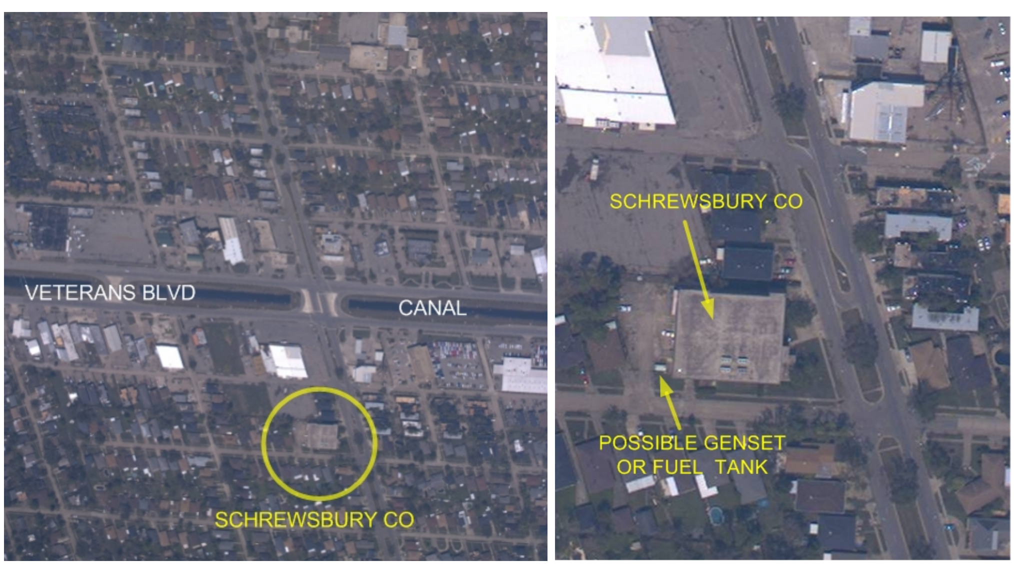

Fig. 5.73. Aerial views of Schrewsbury CO, August 31, 2005 [6]

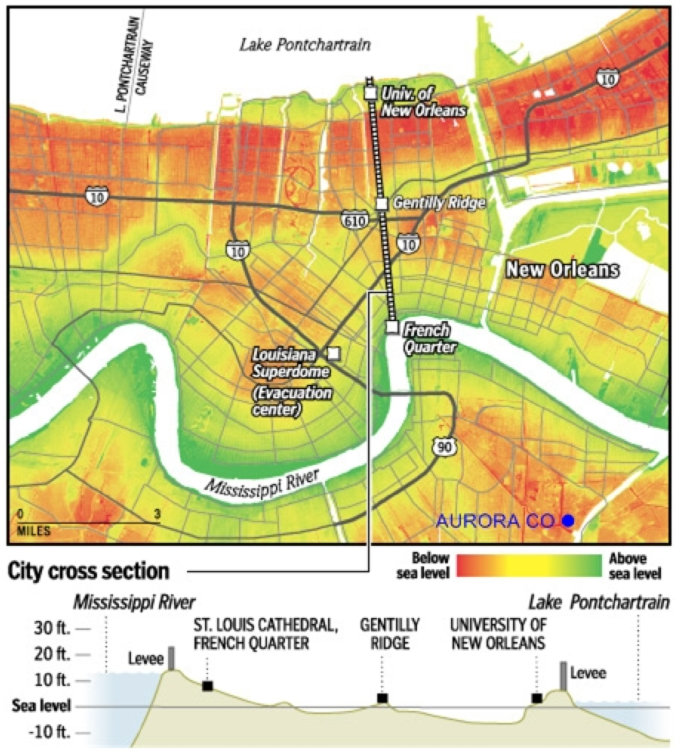

Fig. 5.74. Aurora CO location and New Orleans topographical map [19]

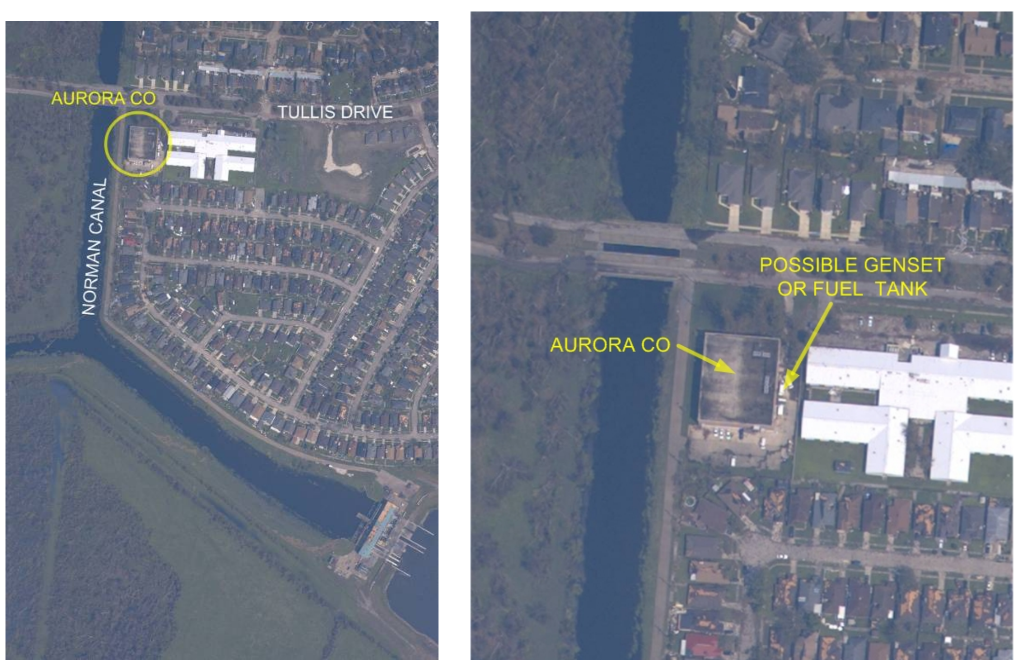

Fig. 5.75. Aerial views of Aurora CO, September 5, 2005 [6]

Natural gas provides a means to alleviate the genset engine fuel demand in some of these sites. In many disasters, utility gas outages are not usually as widespread as electric grid failures.

For example, during Katrina the city of Mobile lost most of the electrical supply but natural gas provision was not affected [26]. In hurricanes, natural gas supply is not generally interrupted inland, allowing the opportunity to reduce fuel delivery constraints by using natural gas or dual natural gas/diesel genset engines instead of the more common diesel ones. Natural gas engines have the additional advantage of not requiring a fuel tank that can be flooded during intense storms. The most reliable option is to use dual natural gas/diesel engines, since it will always leave open the possibility of using truck-delivered diesel in case the natural gas supply is interrupted. Logistical efforts can be eased when COs located further inland, not necessarily exposed to hurricanes, are equipped with natural gas genset engines; they release resources (trucks, gallons of diesel oil, people) to take care of the most compromised COs.

Larger and less exposed fuel tanks are other solutions to ease logistics requirements and reduce the risk of outage due to engine fuel starvation. As Fig. 5.76 indicates, other CLECs in the Gulf Region with capacity similar to those of Bellsouth seem to have larger fuel tanks for COs. For example, while Ybor City CO has an 8000 gallon fuel tank, Slidell CO has only 3000, as shown in Fig. 5.19. Hence, observations around the Gulf Coast seem to indicate that Bellsouth design practices require less genset autonomy than others CLECs in equally hurricane-exposed areas. Bigger fuel tanks have the additional advantage of higher access points, which makes them less prone to damage due to flood waters.

Fig. 5.76. Verizon CO fuel tanks on the Gulf Coast, Left: Sarasota, Florida,
Right: 8000 gallon tank of Ybor city CO, Tampa, Florida

5.5 Communication transmission networks

Sprint was the long-distance carrier suffering the most severe damage in its network, including the total loss of two key facilities – a switch in New Orleans and a POP in Biloxi [27]. When these two facilities failed, all the sites between them along the coast were cut off, affecting not only the transmission network but also the links between mobile communication cell sites. New Orleans' failed long-distance switch is shown in Figs. 5.77 [28] and 5.78. As the figures show, severe flooding damaged the equipment inside the building, thus causing the outage. In this case, availability of electric power had no relevance, because the primary cause of failure was equipment damage.

Fig. 5.77. Aerial view of New Orleans Sprint long-distance switch taken on September 1, 2005 [28]

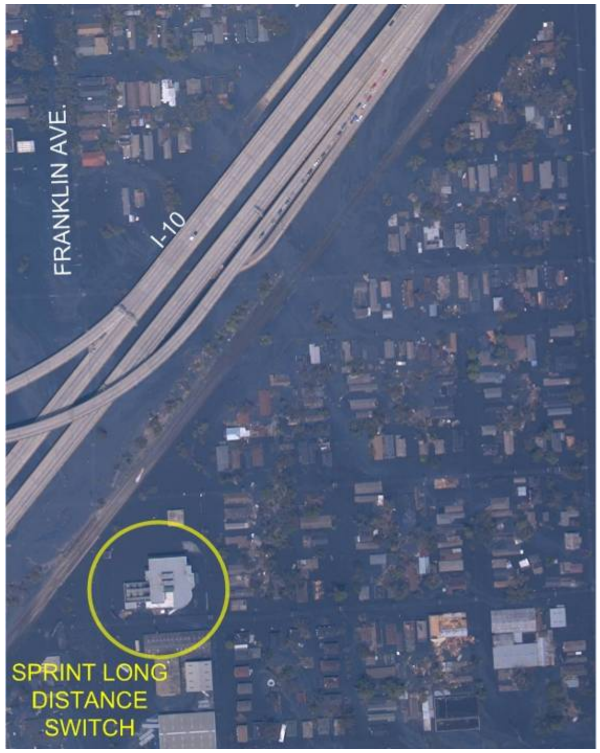

Fig. 5.78. Aerial view of Sprint switch in New Orleans, August 31, 2005 [6]

Neither did loss of electric power play a role in the single outage reported by AT&T, a flooded regeneration hut near New Orleans. The damaged hut reduced AT&T transmission network capacity by 5%. Lost capacity was restored by redirecting traffic using software that automatically reconfigured transmission equipment and by installing a new fiber-optic cable. The deployment of portable gensets to sites that did not have fixed emergency generators and keeping the main AT&T switch in New Orleans working were key factors in maintaining most of the AT&T traffic. As was mentioned, the AT&T switch in New Orleans is collocated with the BellSouth New Orleans Main and Tandem switches at 840 Poydras Street and was kept operating mainly due to employee effort and good fortune. Still, many calls were blocked due to congestion caused by other network failures.

Fig. 5.79 depicts another AT&T regeneration site, this one in Gulfport, MS. The figure shows that while the building is elevated 50 cm, the genset is located at ground level. During Hurricane Katrina, this facility did not fail. It was not flooded (Fig. 5.80) as it is located 2 km inland. However, a stronger hurricane passing closer to Gulfport could create flooding significant enough to damage its genset.

Fig. 5.79. AT&T regeneration site in Gulfport, Mississippi

Fig. 5.80. Aerial view of AT&T site, September 4, 2005 [6]

Level3 Communications has a transmission network that acts as the Internet backbone. One of Level3's regeneration sites along Route 90, south of Pearlington, Mississippi, was visited during the on-site survey. The site is depicted in Fig. 5.81 on October 17th. There were two gensets. However, Fig. 5.82 shows no generators at this site four days after Katrina made landfall in Louisiana. Although there are no reports of outages in Level3 networks, lack of gensets in an area where utility-grid power was out for several weeks after the storm is a strong indication that the site shown in Fig. 5.81 lost service due to power-related causes. Other outage causes such as equipment damage or severed fiber-optic links are highly unlikely because, as Fig. 5.83 depicts, the site was built on a slightly elevated terrain. This protected it from flooding and there were no signs that the fiber-optic cable was affected.

Fig. 5.81. Level3 Communications transmission site south of Pearlington, Mississippi

Fig. 5.82. Aerial view of Level3 transmission site, September 2, 2005 [6]

Fig. 5.83. Level3 transmission site showing its location on elevated terrain

MCI, another long-distance carrier with light damage to its network, reported loss of capacity due to some "water issues" in regeneration sites and a severed fiber-optic cable east of New Orleans [29], probably running along the I-10 bridge over Lake Pontchartrain. No power-related outages were reported by MCI.

5.6 DLC applications in outside plant

DLC cabinets existing when Hurricane Katrina struck the Gulf Coast created a logistical challenge in the aftermath, because the enclosures required extended backup to avoid running out of power. The DLC cabinets have local embedded batteries that provide power backup for only a few hours. Therefore, BellSouth had to deploy one portable genset for each DLC enclosure, as shown in Figs 5.84 and 5.85. Most of the DLC systems observed during the on-site survey belonged to the Bay St. Louis CO and Bayou Laterra CO. All of the portable generators at these sites were still working at the time of the visit. As mentioned, new DLC systems are being installed to replace destroyed copper feeder facilities. Most have been added to COs where, previously, there were no DLC systems, thus dispersing into a much wider area the sites that will require the deployment of portable gensets after a hurricane. It is clear that adding DLC systems to replace feeders will further complicate the logistical efforts in future hurricanes and reduce overall network reliability.

Fig. 5.84. SLC-96 DLC systems in Bay St. Louis and Bayou Laterra

Fig. 5.85. Two views of a DLC system in Waveland, Bay St. Louis CO

6 Hurricane Katrina's Effect on Mobile Communication Networks

Over 3000 cell sites in the area were affected by Hurricane Katrina. Half of them are located in the hardest hit areas of the Mississippi coast, New Orleans and Plaquemines Parish, shown in Fig. 6.1. The extent of Katrina's effect on mobile communication networks varies with geographic area and company. The three main reasons for cell site outages are:

1) Damage due to high winds

2) Damage due to storm surge or flood

3) Failure due to loss of power

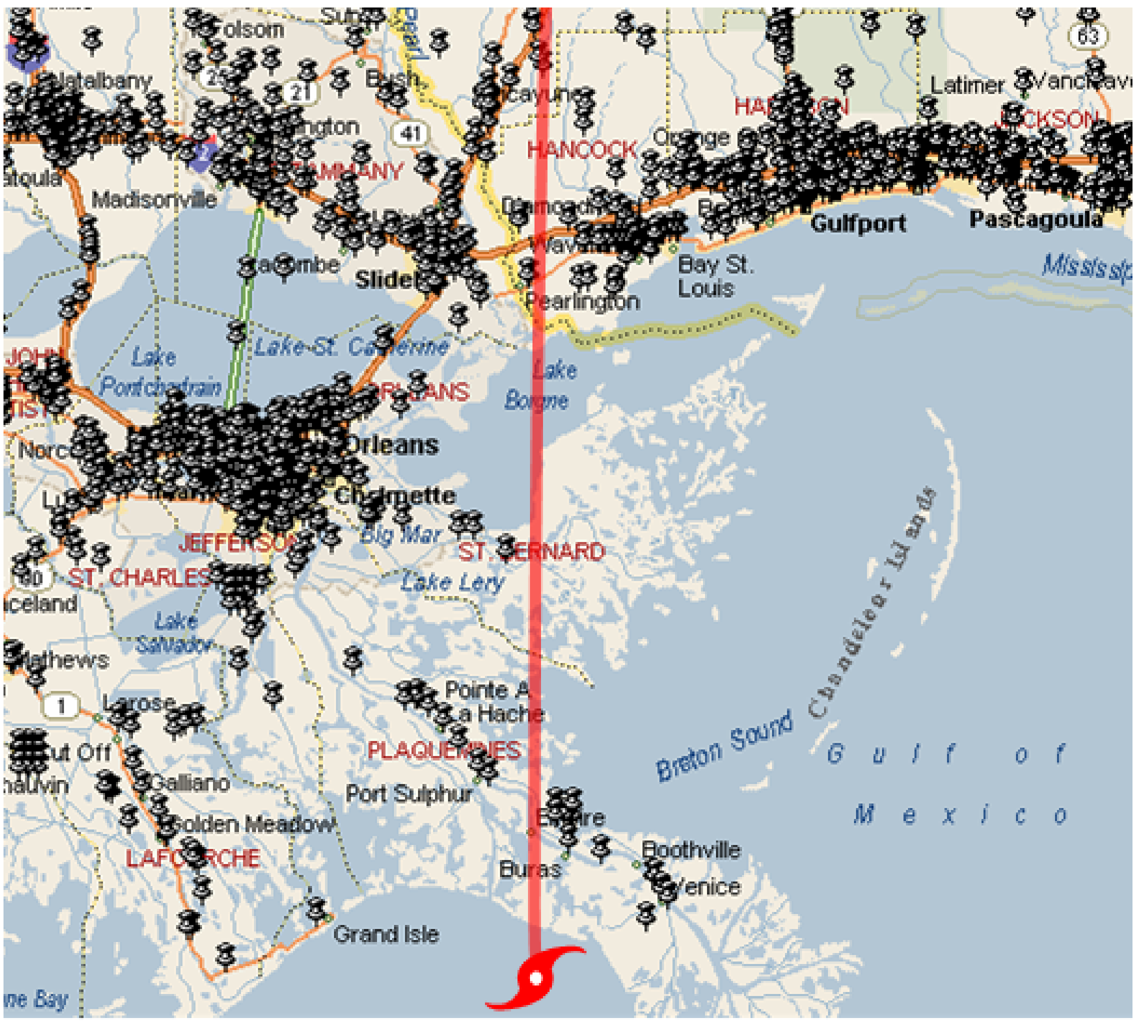

Fig. 6.1. Cell sites located in the affected area and path of Hurricane Katrina

Causes 1 and 2 concern failure due to critical damage in all or part of the communication-related components, including the antenna and base-station communication cabinets. For these causes, it is more useful to identify failure severity than failure origin. Power-related outages occurred when the power plant or the genset failed due to flooding, damage or lack of refueling.

Another possible indirect cause of failure is cell site isolation due to a PSTN failure. It occurs when a fiber-optics cable is damaged or a CO in the transmission path is destroyed. When the PSTN fails, the links between cells sites and remote switches with their host MTSO cease to operate. This failure cause is only relevant for sites where none of the other failure causes occurs. Unfortunately, identifying which cells failed for this reason requires highly detailed, proprietary network architecture information not typically provided by the service providers. Hence, it was only possible to mark the possible failure area.

Fig. 6.2 shows the most common solutions implemented by the mobile communication providers to restore their networks. Cell sites without electric power and no permanent genset were equipped with portable gensets, as in cell site # 11 of Fig. 6.2. All fixed and portable gensets require constant refueling, usually once a day, which presents important logistics issues. Hence, in preparation for the storm, portable generators need to be staged in places where they are not at risk from the storm but are close enough to their assigned sites so that they can be quickly deployed after the storm. Taking the genset to a site is usually complicated, because roads may be damaged or filled with debris and bridges may have been washed away. Security checkpoints and areas closed during rescue activities add more complications to portable power distribution. The same logistic issues usually persist during the refueling period that may take from a few days up to several weeks. Another problem after the storm is to replace destroyed cell sites. Cell site #8 in Fig. 6.2 exemplifies how damaged cell sites can be replaced by cells-on-wheels (COWs), base stations mounted inside a truck or a trailer. In some cell sites with platform-mounted outdoor cabinets, the site functions were entirely replaced by COWs. When possible, interrupted transmission paths were reestablished by using MW links, as shown with cell sites #9 and #10 in Fig. 6.2. Another alternative to restore transmission links was to reroute the path, shown with the PSTN link in Fig. 6.2. When an MTSO is damaged, its functions and subscriber database are transferred to another MTSO, although higher traffic in the backup switch may limit the number of calls in the damaged MSC area.

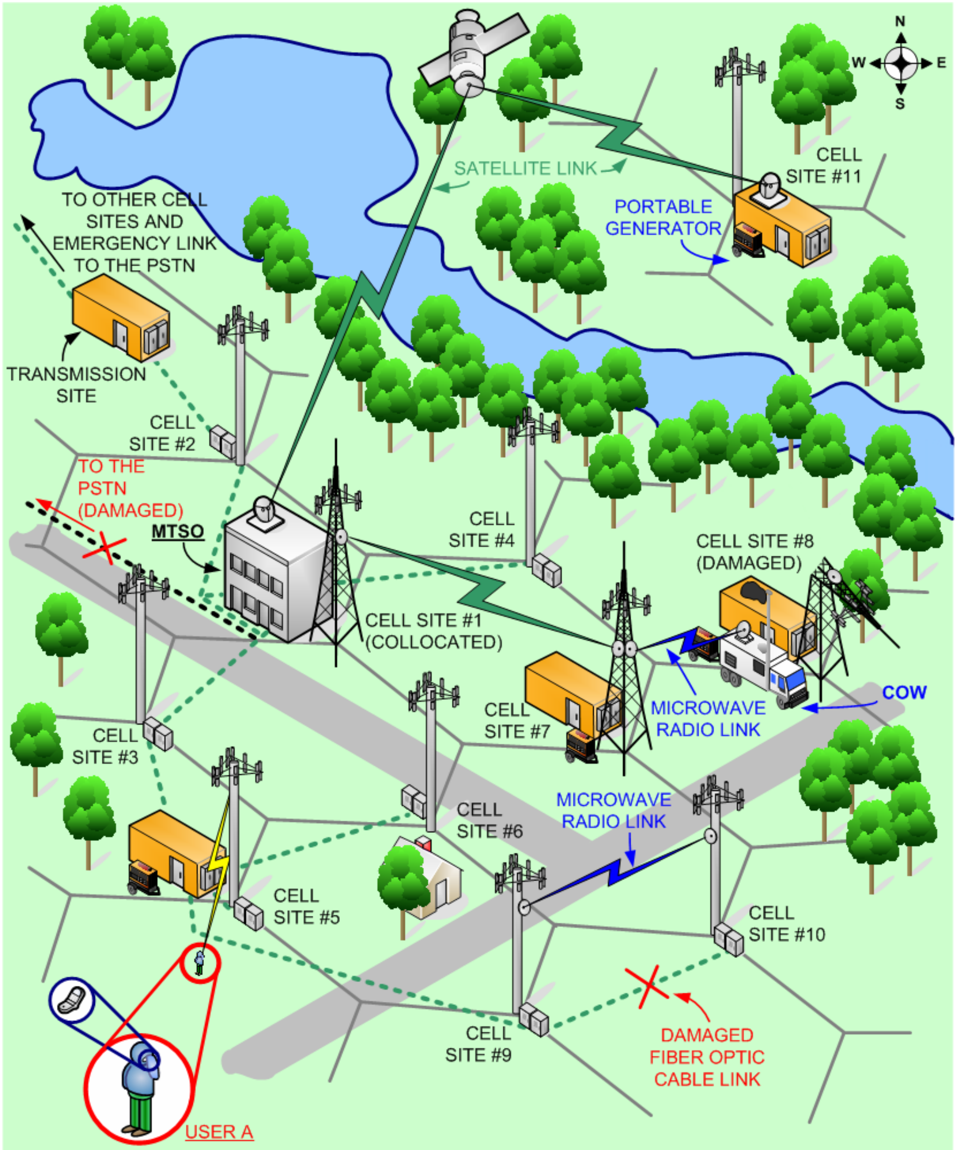

Fig. 6.2. Scheme of the mobile communication network restoration solutions

Cellular telephony companies made extensive use of these solutions in Hurricane Katrina's aftermath. Cingular deployed approximately 500 portable gensets and 30 COWs [30]. Verizon, Sprint-Nextel, Cellular South and T-Mobile also stated they used hundreds of gensets and dozens of COWs. Since MTSOs do not need to be as close to the demand center as PSTN switches, not many MSCs were damaged. Cingular lost of one its two switches in New Orleans due to flooding [30] and, as was discussed previously, Sprint-Nextel operations were affected by flooding in the long-distance switch [27]. The T-Mobile switch in New Orleans never lost service [31] due to employee efforts to refuel the switch genset and good fortune. Verizon switches did not need good fortune to maintain full operation during the storm, since they were located further inland in Baton Rouge, LA and Covington, LA[32]. All mobile communication providers lost connection to the PSTN due to flooding in New Orleans and severed fiber-optic cables, one of which is located on the I-10 bridge over Lake Pontchartrain [33].

Because of efforts of all mobile companies during the restoration process, a week after Katrina hit the coast cellular telephony networks were almost fully operational along the Gulf Coast and partially operational in New Orleans and Plaquemines Parish. The mobile communication network proved to be more flexible and resilient to natural catastrophes because of its modular architecture and the lack of fixed connection to the subscribers. Wire-line networks were more complicated to restore than wireless networks because of the PSTN fixed outside plant and, especially, the lack of flexibility introduced by the MDF in the CO. Another advantage of cellular telephony networks over fixed telephony networks is that COs do not need to be close to the demand center. Thus they can be located further inland in less vulnerable locations, as proved by Verizon.

A small sample of cell sites was surveyed in order to map the effect of Hurricane Katrina on mobile communication networks. These sample sites and failure causes are shown in Fig. 6.3. The red zone represents an area where a majority of the cell sites experienced equipment destruction due to wind, flood or storm surge. Yellow indicates partial equipment damage due to wind, flood or storm surge. Blue shows that the majority experienced power-related failures. Green and white striped zones represent areas where some cell sites may have been isolated from their MTSOs due to PSTN failure. The green area indicates regions where a large percentage did not fail. Circles mark the position of cell sites with a confirmed known condition after the storm. Cell site locations indicated with squares imply that the condition after the storm is estimated with a high degree of confidence. COWs are marked by truck icons, while sites where the genset was operating at the time of the site survey are showed with flags.

The blue area (where cell sites failed due to power-related causes) is the smallest, but it includes approximately half of all the affected cell sites. A map detailing these New Orleans cell sites is displayed in Fig. 6.4 with the analyzed sites marked on Fig. 6.5. Another area where cell sites are more concentrated is around Gulfport and Biloxi, Mississippi. Fig. 6.6 shows a detail of the all cell sites in this region and Fig. 6.7 displays the cell sites studied.

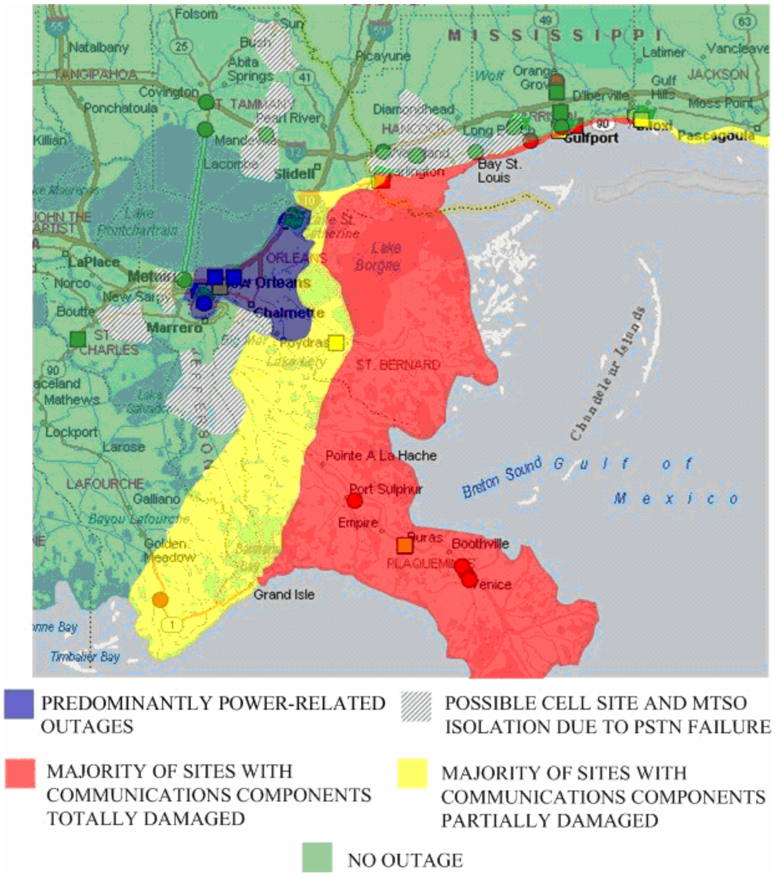

Fig. 6.3. Analyzed cell-site locations with predominant cause of failure

Fig. 6.4. Cell sites in New Orleans

Fig. 6.5. Analyzed cells in New Orleans.

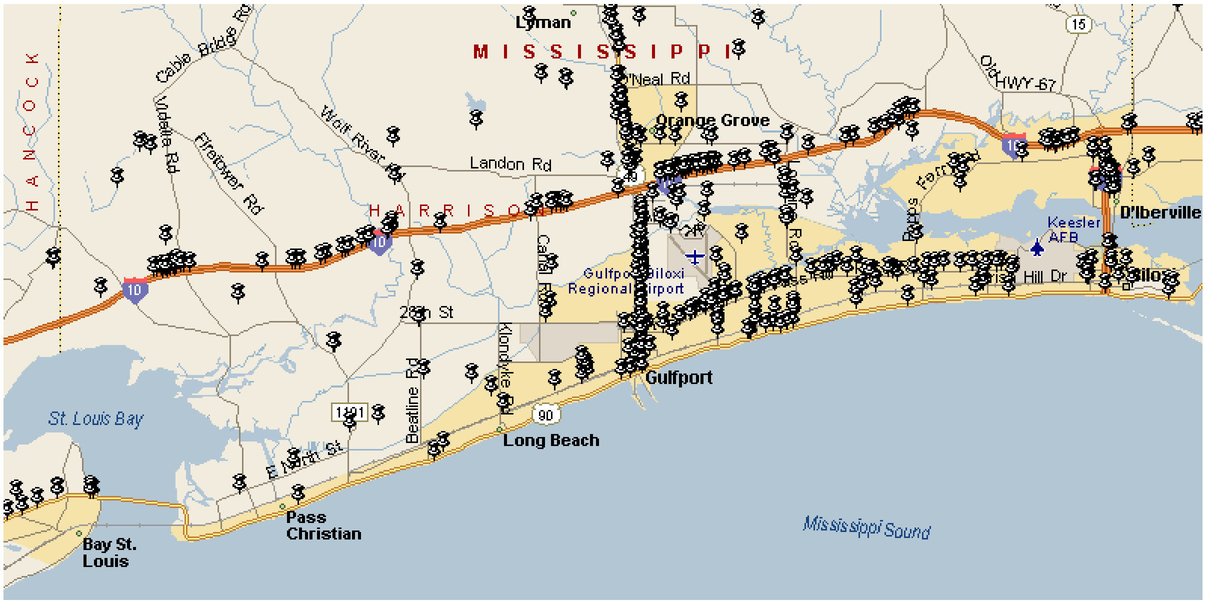

Fig. 6.6. Cell sites around Gulfport and Biloxi, MS

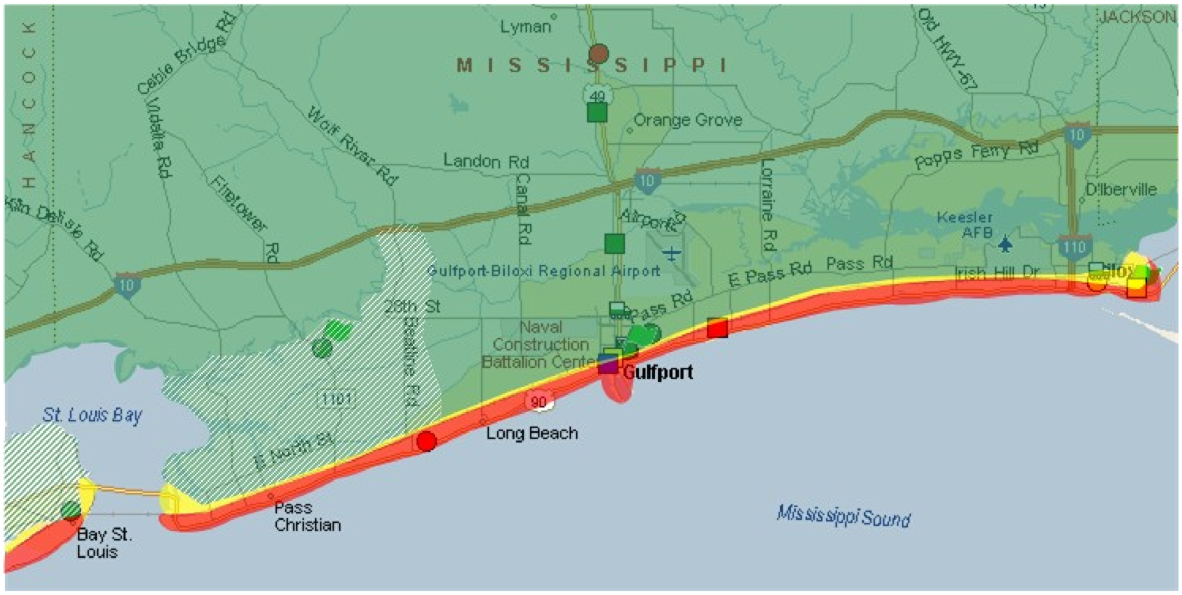

Fig. 6.7. Surveyed cell sites around Gulfport and Biloxi, MS

This work continues with an analysis of each of the sample cell sites along with a discussion of failure cause for each of the zones shown in Figs. 6.3 and 6.7.

6.1 "Red Zones": Areas where a majority of cell sites experienced total equipment destruction due to wind, flood or storm surge

Most of the cell sites in these areas were destroyed by Hurricane Katrina. Fig. 6.3 shows that this zone corresponds to the path of Katrina's eye and around 50 km to the east. It includes Plaquemines Parish and the eastern half of St. Bernard Parish, as well as a 1 km wide strip of the Mississippi Gulf Coast between the border of Louisiana and Mississippi and Biloxi Bay. Even though this zone covers a large region, it includes less than 1% of all the cell sites in the affected region.

Figs. 6.8 and 6.9 show two cells destroyed when different ships carried inland by the storm surge crashed on to the antennas. Fig. 6.9 shows that the two sites are close together in the southernmost populated area of Venice located on the Mississippi River Delta. Neither cell site appears to be adequately constructed for such an extremely vulnerable location; the shelters sit on low platforms in an exposed and unprotected position.

Fig. 6.8. Aerial view of destroyed cell sites in Venice, LA [34]

Fig. 6.9. Aerial view of destroyed cell sites in Venice, LA [6]

Figs. 6.10 and 6.11 show more destroyed cell sites in Venice, LA. The cell site in Fig. 6.10 is located 2 km north of the cells in Fig. 6.9; those in Fig. 6.10 are close to the BellSouth CO. These three cell sites suffered damage from wind and the storm surge. Their towers fell to the northwest, an indication that they may have fallen before Katrina made landfall. The aerial picture in Fig. 6.11, taken on September 3, 2005, clearly shows that water level was over the cell site platforms, with the storm-surge maximum level reaching even higher. It is unclear whether or not there were design guidelines for the platforms. However, it is certain that they were not designed for such a strong hurricane, either in terms of wind intensity or storm surge levels. In none of the three sites did electrical power supply play a role in their failure.

Fig. 6.10. Aerial views of destroyed cell site in Venice, LA [34]

Fig. 6.11. Aerial views of destroyed cell site in Venice, LA [6]

Figs. 6.12 and 6.13 show another destroyed cell site located in Port Sulphur, LA. As in previously analyzed sites, this one was destroyed by strong winds bringing down the tower and the storm surge flooding the entire site. The aerial picture displayed in Fig. 6.13 shows that the site is near the Mississippi River, as were the other cell sites discussed. However, the shelter and outside cabinet platform are located almost at ground level, implying a lack of uniform design guidelines in cell-site infrastructure design. As shown in the Venice site (Fig. 6.8), the fixed generator was also destroyed because of its vulnerable location.

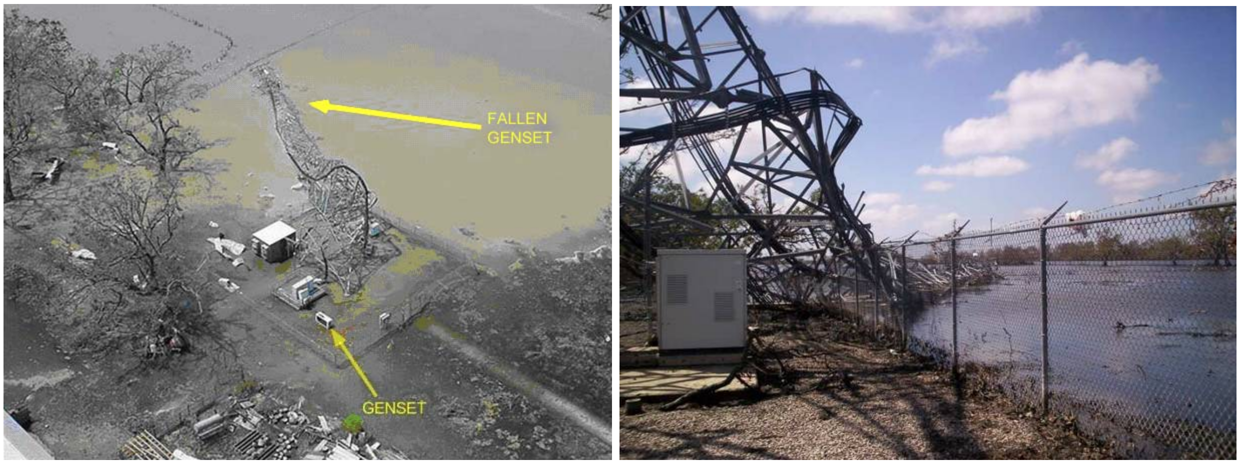

Fig. 6.12. Destroyed cell site in Port Sulphur, LA Left: [34]Right: [35]

Fig. 6.13. Aerial view of destroyed cell site in Port Sulphur, LA September 3, 2005 [6]

The lack of uniform cell-site design guidelines was verified by inspecting the sites displayed in Figs. 6.14-6.16. These are located in Buras, Louisiana, where Hurricane Katrina's eye made landfall. Even through the hurricane's strongest winds, their towers did not fall. It should be noted that the cell site west of the BellSouth CO is located on higher ground with all the base station shelter and cabinets on high platforms. It failed due to lack of power. However, it is difficult to evaluate how much damage this site received, though it may have been less than other sites. It is also unclear how much damage the cell site collocated with the BellSouth switch received (Fig. 6.16). Even though the BellSouth Buras CO was flooded by the storm surge, the cell-site platforms are higher than the CO floor. Thus these cell sites may have suffered only partial damage. However, since the storm surge reached higher levels than those indicated in the pictures, it is still possible that the storm surge may have damaged all three sites.

Fig. 6.14. BellSouth Buras CO showing the collocated cell site [20]

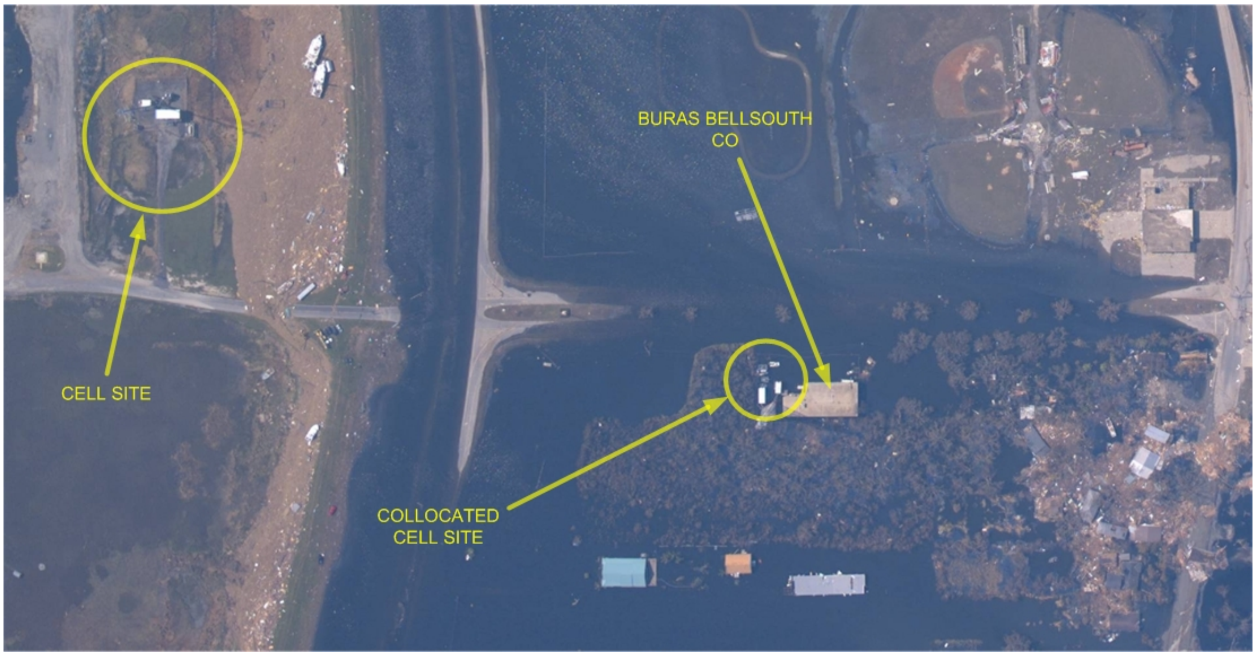

Fig. 6.15. Aerial view of the area around the BellSouth Buras CO, September 3, 2005 [6]

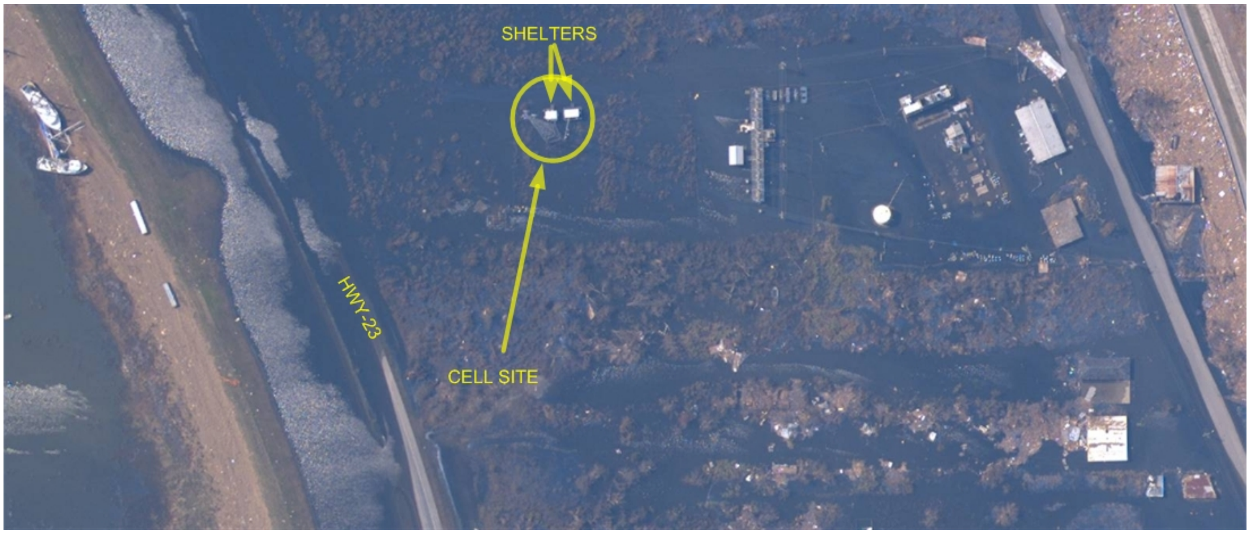

Fig. 6.16. Aerial view of the area around the BellSouth Buras CO, September 3, 2005 [6]

Cell-site destruction due to the storm surge also occurred on the Mississippi Gulf Coast. Figs. 6.17-6.19 show a base station in Long Beach destroyed by the storm surge. Only the tower remains standing. The aerial pictures presented in Figs. 6.18 and 6.19 indicate that the cell site was located in an extremely vulnerable spot. As Fig. 6.19 shows, the railroad tracks prevented the storm surge from further progress inland and thus protected the area to the north from catastrophic damage. Hence, the railroad tracks mark the northern limit of the zone where the majority of the cell sites were destroyed. Needless to say, the site failure was not power-related.

Fig. 6.17. Remains of a cell site in Long Beach, MS [36]

Fig. 6.18. Aerial picture showing the destruction of a cell site in Long Beach, MS [7]

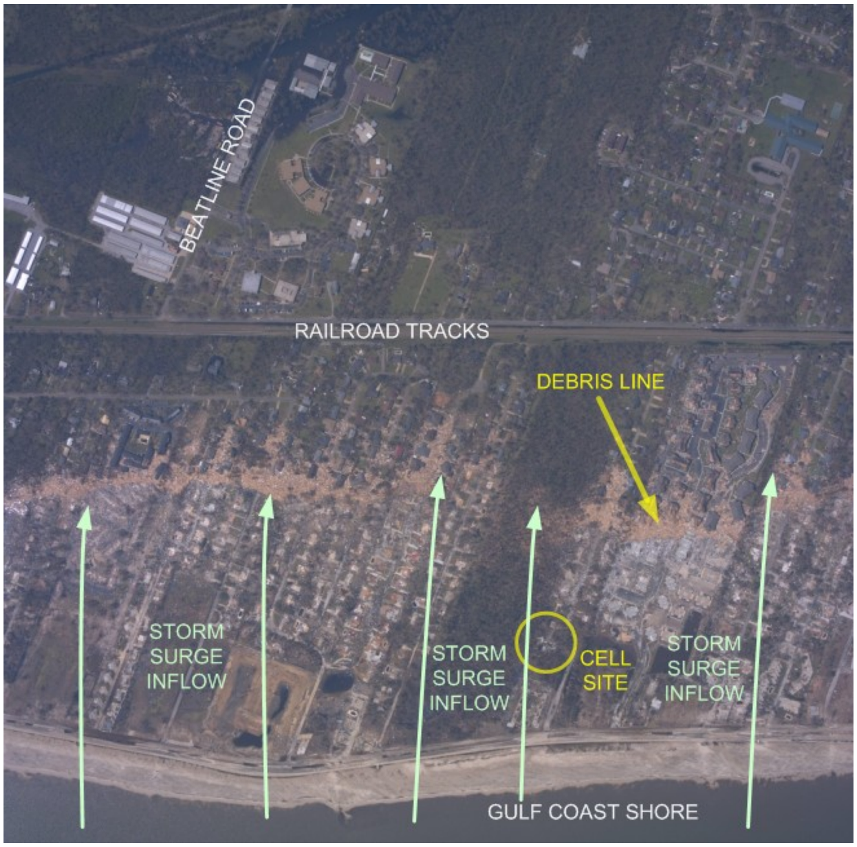

Fig. 6.19. Aerial view of the area around the cell site in Long Beach, MS [6]

In some cell sites, water towers are used instead of standard structures. Fig. 6.20 shows one cell site located east of Gulfport, MS, where the antenna is mounted on the water tower. Unfortunately, like the site in Fig. 6.17, this site was located just south of the railroad tracks and was probably destroyed by the storm surge. Figs. 6.20-6.22 display significant difference in the amount of damage north and south of the railroad tracks and show the role that the railroad tracks played in preventing serious damage to the north.

Fig. 6.20. Cell site located east of Gulfport that uses a water tank as tower [7]

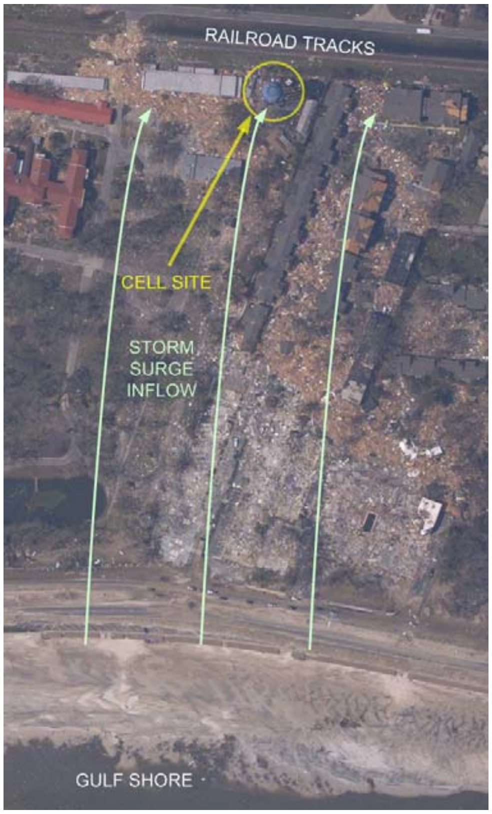

Fig. 6.21 Aerial picture showing the storm surge inflow near the cell site at the water tower [6]

Fig. 6.22. Damage next to water tower cell site [9]

Near the Mississippi/Louisiana border, the storm surge moved further inland, reaching up to 1.8 m in the town of Pearlington. Figs. 23-6.25 show two cell sites in the southern outskirts of this town: Fig. 6.23 toward the north, Fig. 6.24 to the east. Even though the cell sites are only 500 m apart, their construction is different. While the northern one has an elevated platform and shelter, the eastern one has a shelter at ground level. Fig. 6.24 shows a COW deployed at this site. The communication equipment was probably destroyed as equipment was at ground level and the storm surge reached at least 1.5. This site was without commercial electrical supply for about 3 weeks after the storm had passed.

Fig. 6.23 shows a common occurrence in many visited cell sites: the deployment of more than one portable genset to a single site. Usually, each cellular network operator deployed its own generator and refueling to each site. Thus, a significant number of cell sites received multiple gensets. It is clear that logistical burdens may have been eased if companies had coordinated their efforts so that only one genset was deployed to each site to power all the base stations located there. In fact, the site in Fig. 6.23 had three generators at the time of the visit on October 17, 2005 – two operating portable ones and one fixed unit not in service. Several factors indicate that the equipment on this platform was damaged including remains of equipment packaging, debris in the surrounding fence, a fixed generator replaced by a portable one and the fact that the storm surge height in Pearlington exceeded the platform height. However, since the portable generator feeding the shelter was working and the shelter floor was higher than the metallic platform, it is reasonable to assume that the equipment inside the shelter was not damaged. Thus, this cell site may have suffered only partial damage. Fig. 6.23 shows that portable gensets were deployed after September 2nd. Likewise, Fig. 6.24 shows that the COW was also taken to the assigned site after September 2nd. These figures set a time frame for network recovery in this area and confirm the estimated one-week recovery time.

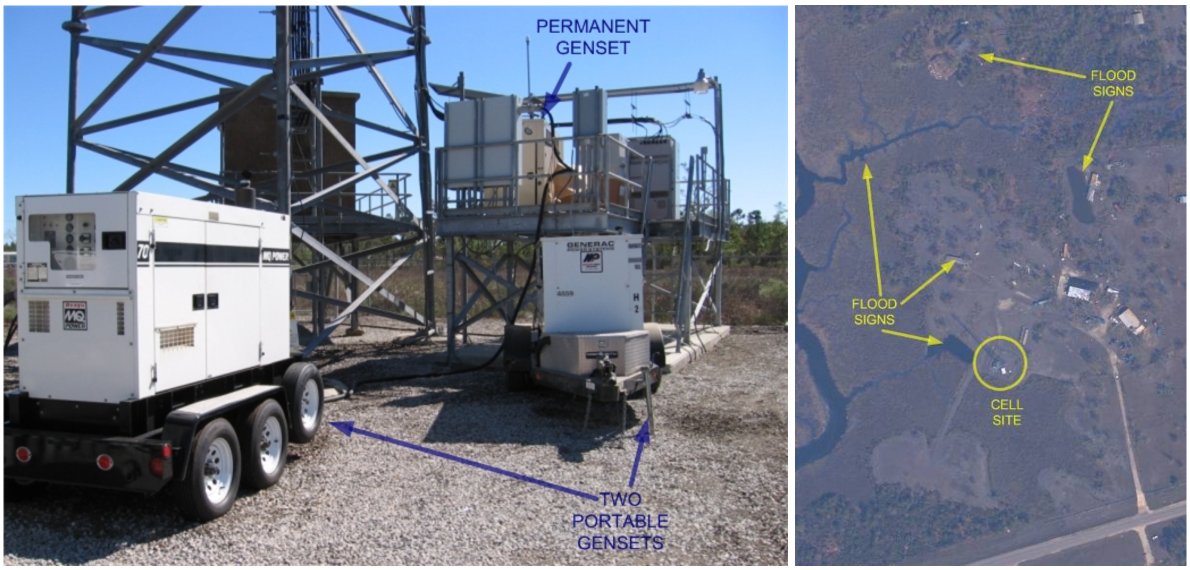

Fig. 6.23. Cell site located north of Pearlington, MS, September 2, 2005, Right: [6]

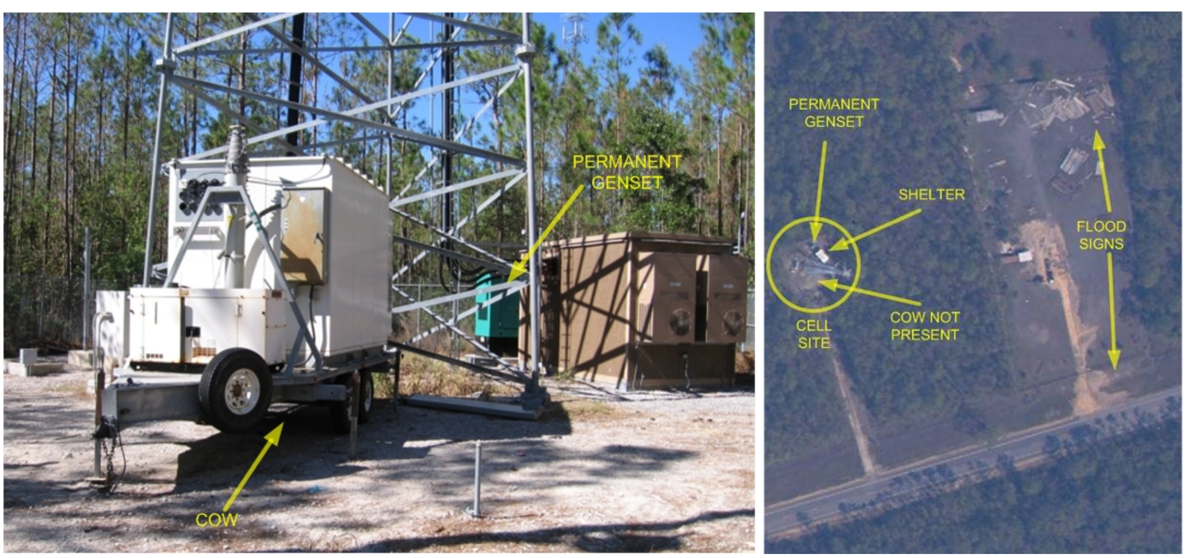

Fig. 6.24. Cell site located south of Pearlington, MS, September 2, 2005, Right [6]

Fig. 6.25. Aerial pictures of cell sites located around Pearlington, MS, September 2, 2005 [6]

6.2 "Yellow Zones": Areas where a majority of cell sites suffered partial damage due to wind, flood or storm surge

In these areas some of the cell components may have been damaged. In cases where there was more than one base station, not all were damaged. Fig. 6.3 shows that the largest yellow zone covers the south part of Jefferson Parish, the northern portion of Plaquemines Parish, a small strip of St. Bernard Parish east of Chalmette, and the southern coast of Slidell. Another small area includes a 200 m strip located approximately 500 m inland from the Gulf Coast. A 500 m strip of the Mississippi Gulf Coast, east of Biloxi Bay and extending to the border with Alabama, is also considered a yellow zone. Figs. 6.2 and 6.3 show that less than half of one percent of the total number of cell sites in the area affected by Hurricane Katrina fall into yellow zones.

Figs. 6.26-6.29 show examples of cell sites with partial and likely unseen damage. The site in Fig. 6.26 is located in Biloxi and operated by several mobile communication companies. Fig. 6.28 shows that this cell site is situated in a very vulnerable location, as it received storm surge inflow from two directions. Even though the site itself presented clear damage only to the perimeter fence, the surrounding area suffered catastrophic damage. Hence, it is almost certain there was some damage. This site also had remains of equipment packaging, which further supports the idea of some site damage and repair. Based on observations and storm-surge data, it was concluded that this site might have received partial damage to the platforms with the outdoor base station cabinets but not to the shelter in the back. A significant observation for Figs. 6.27 and 6.27 is the five generators (shown with red and white arrows) deployed after the storm, one of which is not portable. None of these generators was present when the picture in Fig. 6.29 was taken on August 31, 2005. However, a truck with equipment is seen in Fig. 6.28 parked in front of the cell. Both of these pictures suggest that the networks were operational again within approximately one week after the storm.

Fig. 6.26. Cell site in Biloxi, MS

Fig. 6.27. Cell site in Biloxi, MS

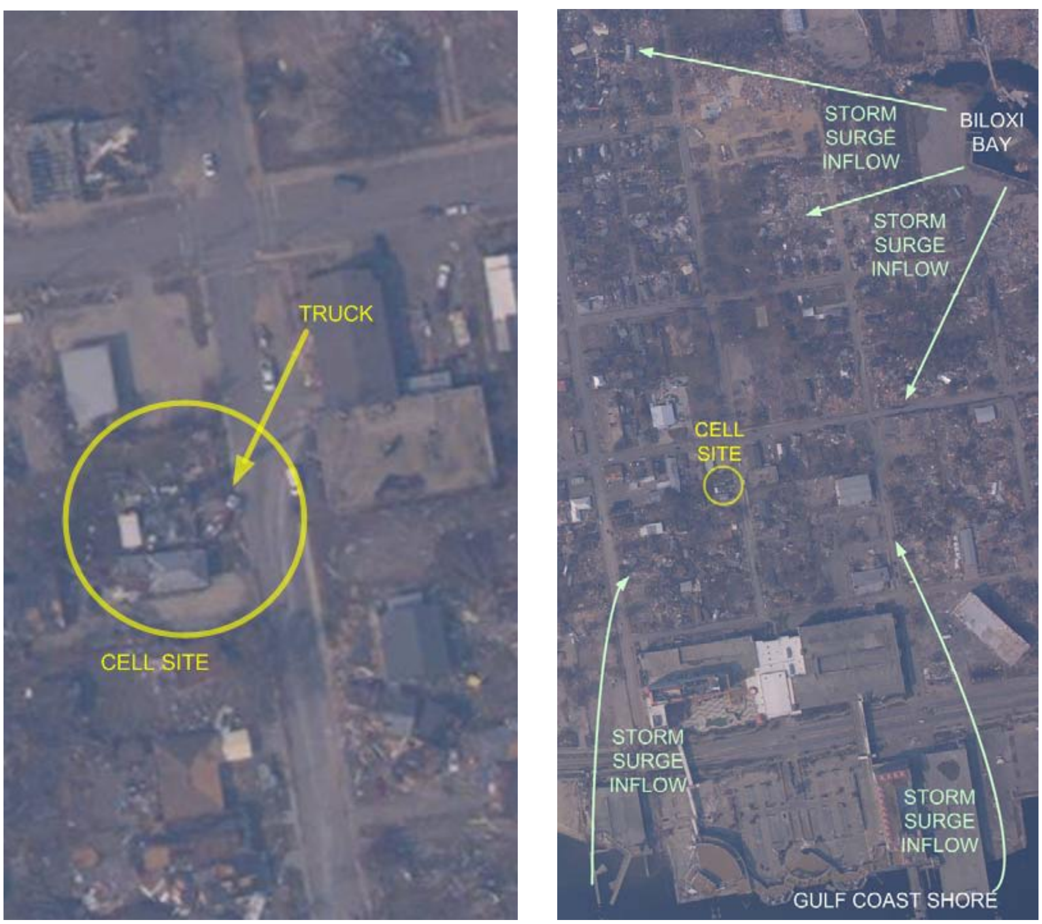

Fig. 6.28. Aerial picture of the cell site in Biloxi, MS. Note the parked truck. [6]

Fig. 6.29. Aerial picture of the cell site in Biloxi, MS, August 31, 2005 [8]

Biloxi had another cell site that experienced only partial damage. Figs. 6.30 and 6.31 show this cell site, which is situated approximately 400 m from the coast. Fig. 6.30 shows a general view of the cell site with a fixed genset that was not operating on October 17th, since the electric supply to this location had already been restored. An Alltel COW was also at the site, very likely to replace damaged equipment in a small shelter that was already removed by the time of the site survey. The small shelter, shown in Fig. 6.31, can be observed in a picture taken the day after Katrina made landfall. The COW was powered by a 45 KVA portable genset that was refueled every day. There were no indications of further damage in the cell site, and local residents informed us that the storm surge barely reached the cell site. Thus, this site received only partial damage to the (removed) small shelter.

Fig. 6.30. Cell site in Biloxi showing a COW and a missing small shelter

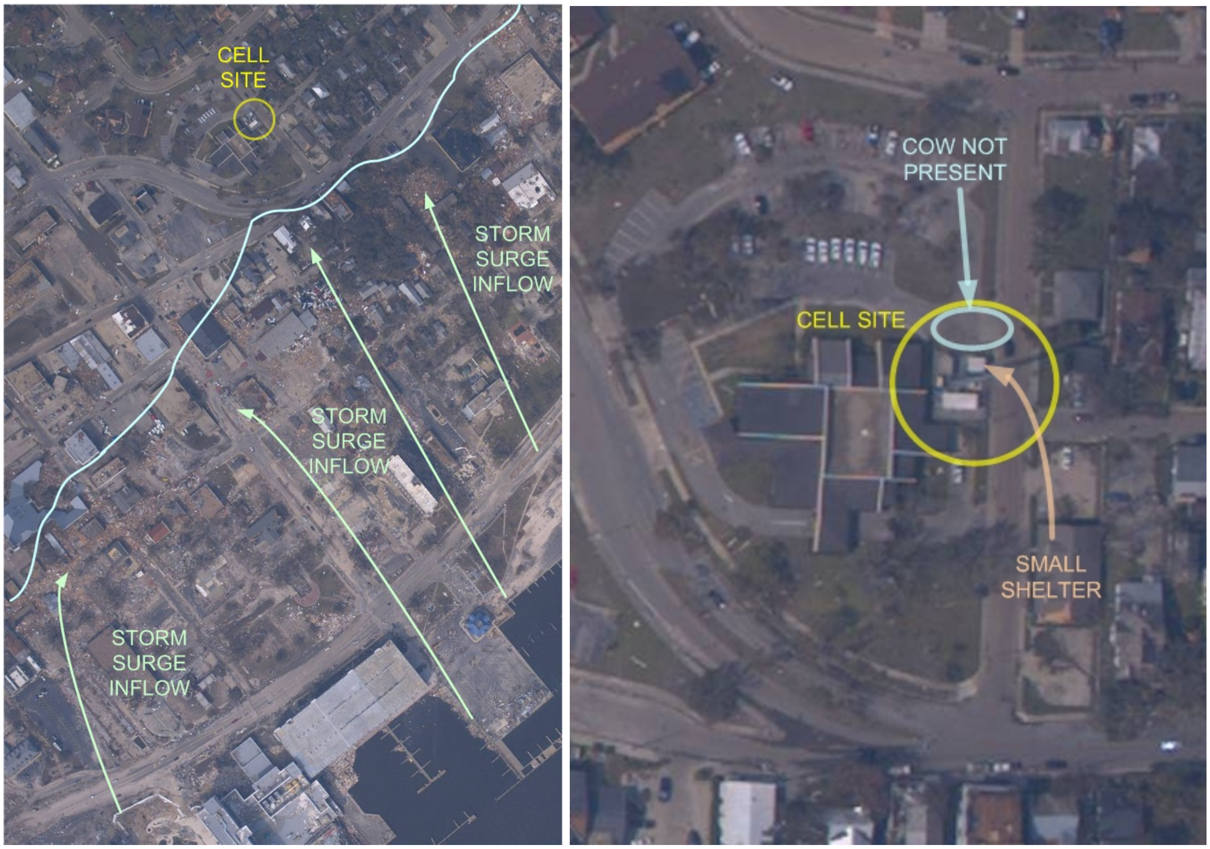

Fig. 6.31. Aerial pictures of cell site in Biloxi, August 30, 2005 [6]

Figs. 6.32 and 6.33 depict a cell site located 3.5 km north of Yscloskey in St. Bernard Parish that potentially suffered partial damage. During the survey, this is the only area in which there was no signal on our cell phones. Fig. 6.32 shows a platform with debris on top from the storm surge and a portable generator. An aerial picture taken on September 7, 2005 shows no sign of this portable genset. However, it does display a fixed yellow genset on the platform that was missing at the time of the survey. Fig. 6.32 also indicates the conduits used to pass the cables from the fixed genset into the shelter, with part of them left on the ground after the generator was removed. Fig. 6.33 (b) shows the destruction caused by the storm surge around the cell site. In this location, the storm surge was approximately 2 m deep. All these facts point to the possibility that the fixed genset was removed because it was damaged. This also implies that additional base-station components inside the shelter may have been damaged. Hence, it is more likely that this site failed from partial damage to its base station components than from a power-related cause.

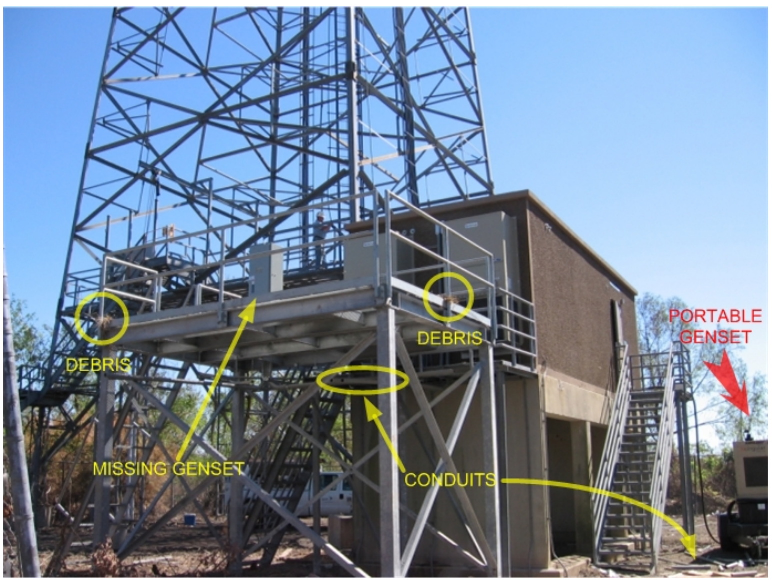

Fig. 6.32. Cell site on highway 46, St. Bernard parish

Fig. 6.34 shows a cell site in Gulfport which failed due either to power-related causes or to partial damage in its communication components. Interestingly, the picture shows two shelters and two gas tanks but only one genset, implying that another genset was missing. The aerial picture in Fig. 6.35, taken on August 30th, shows no sign of another genset, which means that the site had only one during the storm. Hence, if it was not damaged, one of the shelters may have failed due to lack of electric power. As Fig. 6.36 indicates, the cell may have received strong storm-surge inflow. If that was the case, part of the base station equipment may have been damaged because both shelters are at ground level. Remains of equipment packaging seem to support this possibility. Their vulnerable locations and shelter elevation show, once again, a lack of uniformity in cellular infrastructure design.

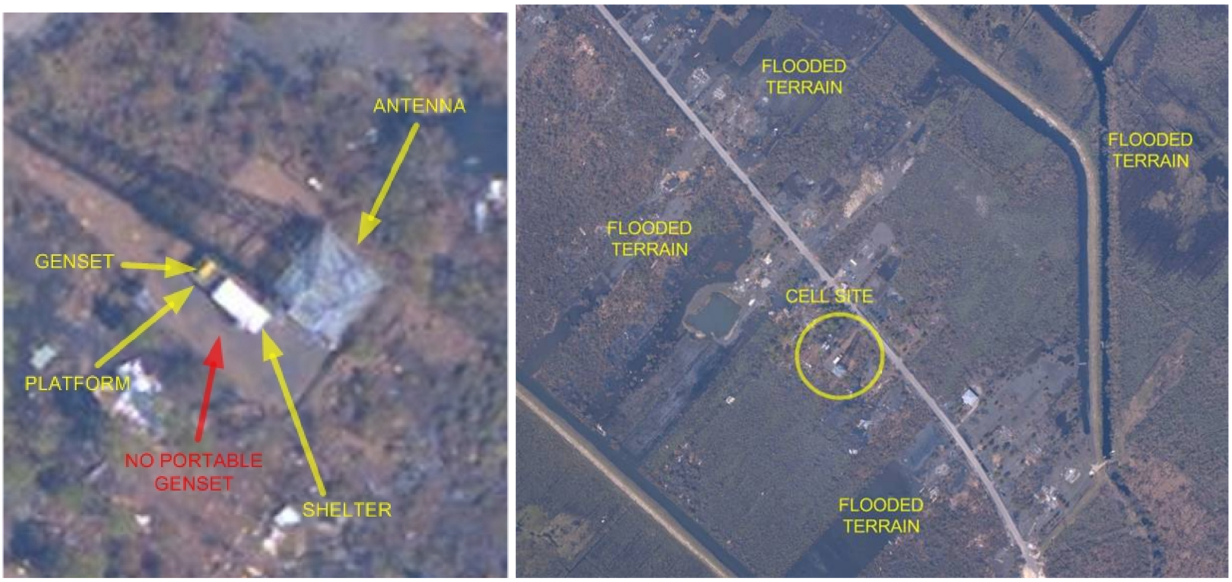

Fig. 6.33. Aerial pictures of cell site on Highway 46, St. Bernard parish [6]

Fig. 6.34. Cell site in Gulfport

Fig. 6.35. Aerial view of cell site in Gulfport [6]

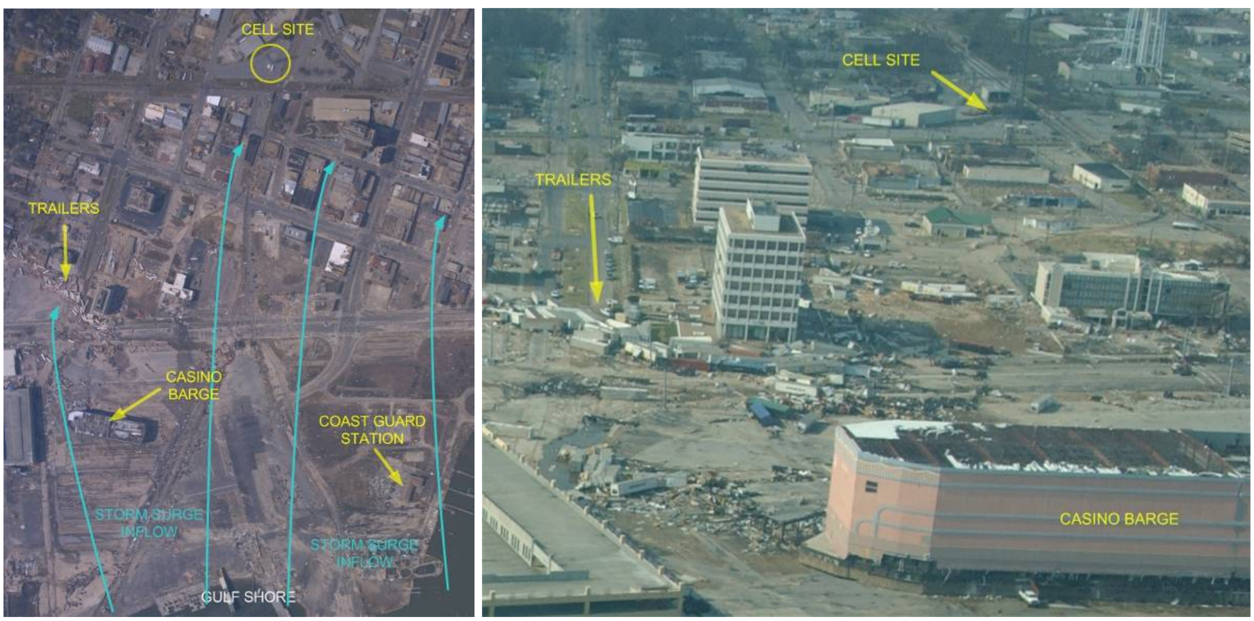

Fig. 6.36. Views of the destruction of Gulfport, Left: [6] Right: [7]

Figs. 6.37 and 6.38 show an exception to the type of damage in yellow zones. The cell site in these figures, located on the southern edge of Leeville, Louisiana, suffered catastrophic damage from the storm. The site tower fell, even though Leeville is east of the hurricane path where winds were less intense. Some towers nearby suffered no damage, which seems to indicate that the fallen tower may have had structural issues before the hurricane brought it down.

Fig. 6.37. Fallen Tower in Leeville, LA [36]

Fig. 6.38. Aerial view of the cell site with the fallen tower in Leeville, LA [10]

6.3 "Blue Zones": Areas where a majority of cell sites experienced power-related failures

In these areas, most of the cell sites were isolated by the flood. They could not receive portable gensets or existing gensets could not be refueled. In some cases, the base station power plant may also have suffered damage, but the communication portion of the equipment was not affected. Fig. 6.3 shows that this zone corresponds to the portion of New Orleans east of the 17th Street Canal and the neighboring northern portion of St. Bernard Parish. Nearly 50 % of all the sites affected by Hurricane Katrina are in this zone.

Figs. 6.39 and 6.40 present a cell site located on the Irish Bayou. As seen in Fig. 6.39 (b) there were multiple generators present: 3 portable gensets and 1 permanent one. All four gensets were operating at the time of the survey on October 21st. The site construction also indicates a lack of common design guidelines. Figs. 6.39 and 6.40 show that this cell site had the equipment placed over 3 m high, which prevented damage. Even though there was considerable damage in the surrounding area, the site only lost some side panels of the shelter platform. Fig. 6.41 displays an aerial picture taken on August 31, 2005, with this site being identified as the south cell site. It is clear that this area was severely flooded, with the storm surge reaching 2 m high, as indicated by the missing side panels of the shelter platform marked with yellow arrows in Fig. 6.40 (b). The flood prevented deployment of portable generators and refueling of any existing genset. Thus, when the electric power went out at this site, the base station was operated from batteries. When the batteries were exhausted, the cell site ceased operation.

Fig. 6.42 shows the north cell site indicated in Fig. 6.41. The shelter of this cell site is slighter lower than in the cell site in Fig. 6.39, approximately 2.5 m high, proving once again the use of different design guidelines from site to site. Yet, the shelter height was enough to prevent damage to the base station components. Fig. 6.42 also shows the deployment of multiple portable gensets in each cell site. In this case, there were two portable generators, indicated by yellow arrows in Fig. 6.42 (b). As with the south cell site, all the gensets were running during the site survey, indicating that this site also failed due to lack of electric power. Flooding prevented transporting portable gensets to the site.

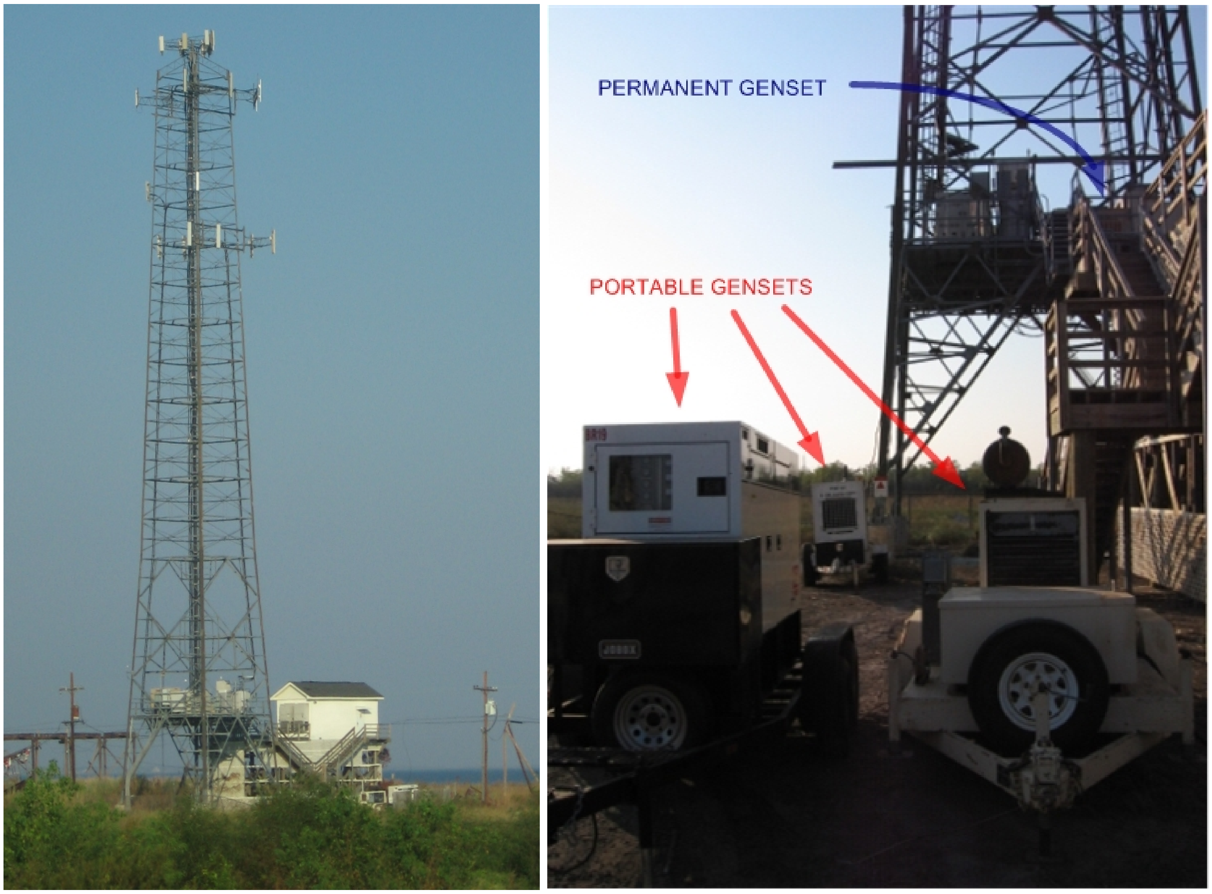

Fig. 6.39. Cell site in Irish Bayou

Fig. 6.40. (a) North side of cell site in Irish Bayou, (b) South side of the same site with arrows indicating the maximum height reached by the storm surge

Fig. 6.41. Aerial view of cell sites in Irish Bayou taken on August 31st [6]

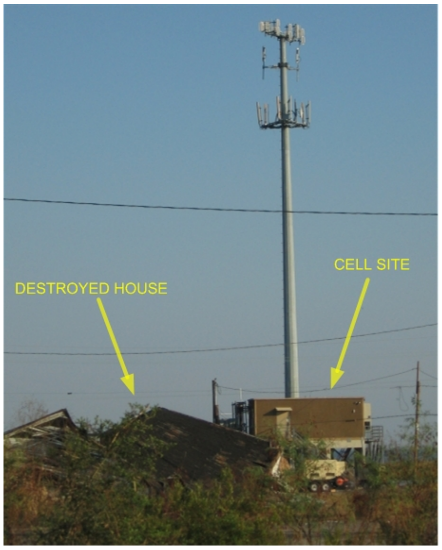

Fig. 6.42. (a) General view of the north cell site in Irish Bayou, (b) Closer view of the same site with two portable generators indicated by yellow arrows

Fig. 6.43 presents a cell site in a flooded area of New Orleans, as shown in the aerial view displayed in Fig. 6.44. Even though the site was flooded, there was no damage to the base station communication equipment inside the shelter, as the flood level never reached the shelter floor shown in Fig. 6.43. The site survey on October 21, 2005, revealed that the generator was new and had not yet been connected. Since Fig. 6.44 clearly shows that a generator set was present during the flood, it can be concluded that the original genset was damaged during the hurricane and needed to be replaced. In addition to this damage, flooding and security issues prevented the network operation personnel from reaching the site to keep the electric power on. Hence, this site clearly failed due to power-related causes.

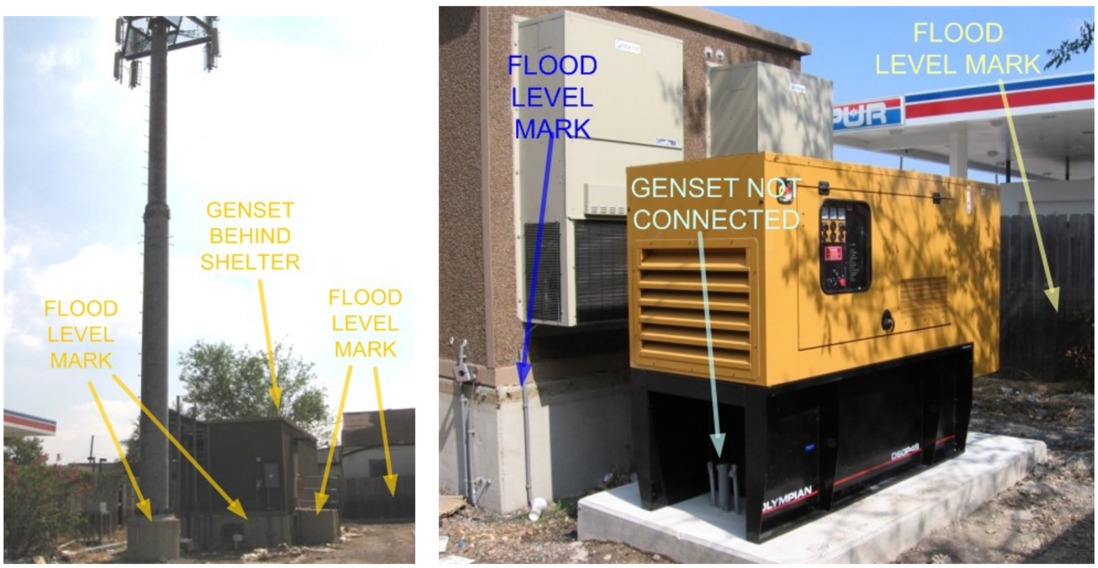

Fig. 6.43. Cell site with permanent genset in Broadmoor district

Many times cell sites in cities are placed on rooftops. For example, the base station in Fig. 6.45 was installed on a building located on I-10 and Chef Menteur Highway in Orleans Parish. Gensets are not usually placed on the rooftop because they are difficult to refuel and leaking fluids may damage the building. Using natural gas instead of diesel as the genset engine fuel reduces this problem. However, it is more expensive and seldom used. Instead, gensets for rooftop sites are usually placed on the ground by the building, making them vulnerable in case of flooding. This site did not seem to have a fixed genset, rather it had a portable generator connected to the base station with cables running outside the building, as shown in Fig. 6.45. The picture in 6.46, taken on August 31st, shows no portable genset outside the building and no evidence of flooding in the area around the building. However, the site was isolated by flooding in surrounding areas. This flooding may have prevented reaching the site to install a portable genset to power the base station until the water receded. Hence, the most probable cause of failure in this cell site is lack of electric power.

Fig. 6.44. Aerial picture of the cell site in Broadmoor district showing flooding in the area [6]

Fig. 6.45. Cell site located on the rooftop in Orleans Parish

6.46. Aerial picture taken on August 31st showing the building location of the cell site in Orleans Parish [6]

Fig. 6.47 shows a standard cell site installation located by I-10 south of Louisiana State Charity Cemetery. The aerial picture of the cell site in Fig. 6.48 shows that the area was flooded. However, the water-level marks in the picture in Fig. 6.47 indicate that the base station equipment was mounted high enough on a platform inside a shelter to avoid flooding. Hence, the base station was probably not damaged but failed due to lack of power.

Fig. 6.47. Cell site in New Orleans, northwest of downtown

Fig. 6.48. Aerial picture of a site northeast of downtown New Orleans

Some cell sites in New Orleans were collocated with BellSouth COs that failed. Fig. 6.49 shows one where the antenna can be seen on the rooftop of the Lake CO. Whether or not the base station equipment was damaged depends on the floor where those systems were located. The only certain cause of failure is the lack of power caused by the flooding. Another example of a collocated cell site is at the Broadmoor CO shown in Fig. 6.50. In this case, it is clear from the marks in the figure that the water did not reach the base station cabinets. However, the flooding shown in Fig. 5.59 prevented delivery of fuel for the cell site genset, causing a failure due to lack of electric power.

Fig. 6.49. Collocated cell site inside BellSouth Lake CO [20]

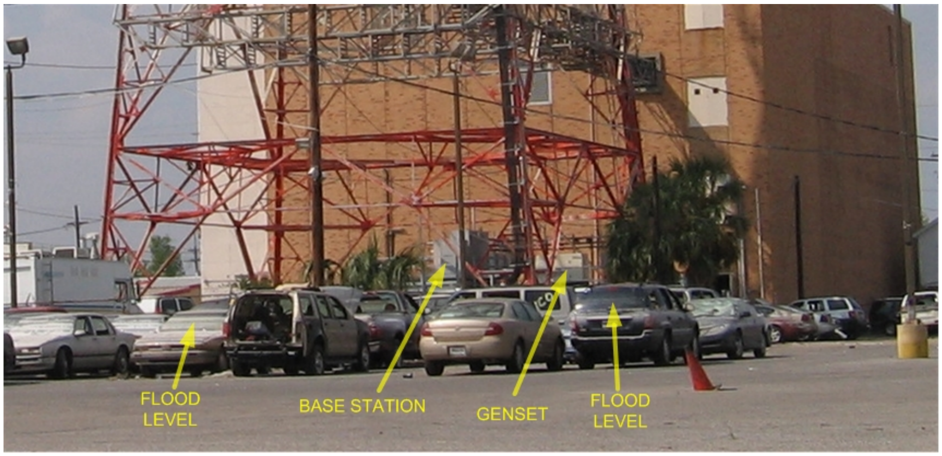

Fig. 6.50. Collocated cell site on a platform outside BellSouth Broadmoor CO

Fig. 6.51 shows a cell site that may have experienced partial damage to the equipment located inside one of the shelters. This site is situated 500 m south of the damaged Sprint long-distance switch of Fig. 5.77, near the intersection of I-10 and I-610 northeast of downtown New Orleans. As the aerial picture in Fig. 6.52 indicates, water covered the wooden fence in front of the site but did not reach the floor of the north shelter. Hence, the base station in this shelter probably lost electric power. However, inconsistent design guidelines led to an almost certain flooding of the south shelter and the outdoor platforms; their floors were not as high as the north shelter. As a result, all the base stations except the one inside the north shelter likely were damaged. The possibility of damaged equipment at these parts of the site is supported by the existence of a cardboard box by the north shelter stairs, probably containing replacement equipment for the damaged base stations. Thus, even though this site is in a blue zone, it is considered to have failed due to damage in one of the base-station communication components.

Fig. 6.51. Cell site northeast of downtown New Orleans

Fig. 6.52. Aerial picture of cell site northeast of downtown New Orleans, August 31, 2005 [6]

6.4 "Green Zones": Areas where the majority of cells sites stayed in service after the storm

The green zones cover the areas affected by Hurricane Katrina that were not included in the other regions. In a green zone most of the cells sites operated after the storm without major problems, implying that portable gensets could be delivered to the site and that repaired and portable gensets were regularly refueled. However, some of the cell sites in these zones may have been isolated by a PSTN failure.

Fig. 6.53 shows a cell site in Bay St. Louis spared from damage because it was located north of the railroad tracks, which provided a storm-surge break. The site had a permanent genset with no need of a portable one. As Fig. 6.7 indicates, the only reason this site might have failed was by being isolated by a PSTN outage.

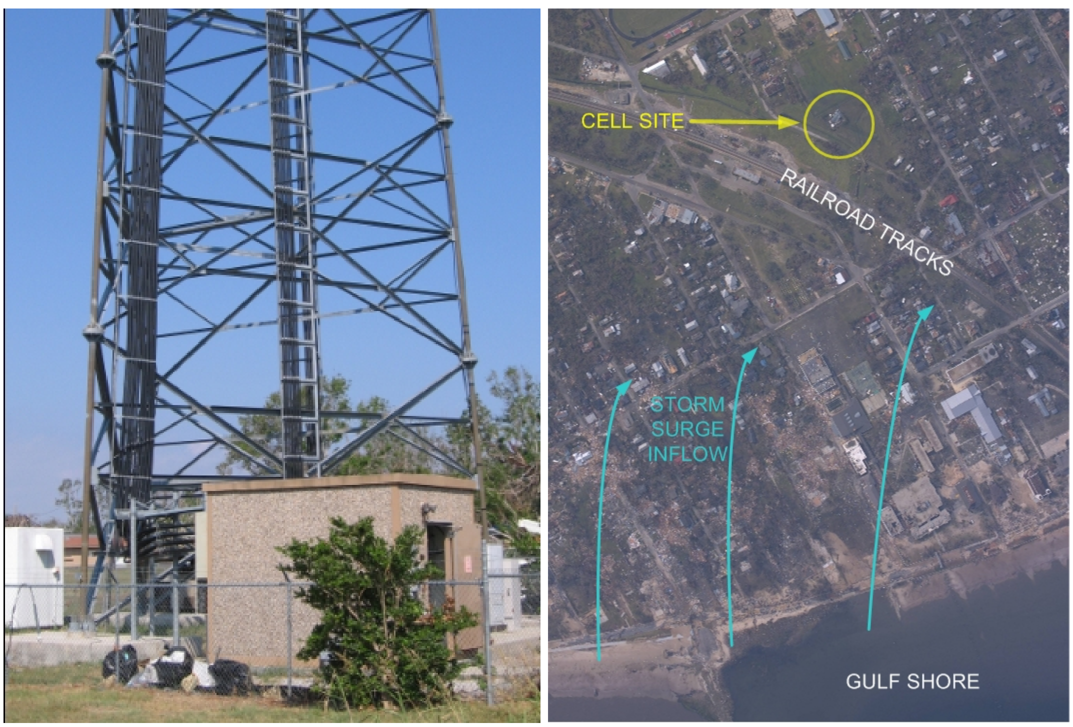

Fig. 6.53. Views of cell site in Bay St. Louis. Aerial picture taken on August 30th [6]

Fig. 6.54 shows a cell site located on Route 607, approximately 500 m south of I-10. Fig. 6.54 (a) shows two of the three fixed gensets marked with yellow arrows. These gensets were not operating at the time of the site survey on October 17th, indicating that electricity was already restored. Fig. 6.54 (b) shows that this site is next to two substations and that the site and surroundings suffered no damage. Thus, we surmise that this site did not fail.

Fig. 6.54. Cell site on Route 607, off I-10 showing two of the three gensets with yellow arrows. Aerial view [6]

There were other cell sites in a similar situation. Figs. 6.55 and 6.56 show two cell sites located side by side at the intersection of Routes 90 and 607. The electric power was on at both sites. However, at the site shown in Fig. 6.55, the remains of a power cable indicates that by the time of the site survey on October 17th, a portable genset had already been removed. The portable generator can be observed in the aerial picture taken on September 3rd and displayed in Fig. 6.56 (b). As with the cell site in Fig. 6.54, there were no indications of damage or failure of any kind. The dissimilar design criteria previously observed in other cell sites is also noticeable in the cell site of Fig. 6.55 in which some of the equipment was placed on a platform 2 m above ground and the rest was installed inside a shelter at ground level.

Fig. 6.55. Cell site located at the intersection of Routes 90 and 607

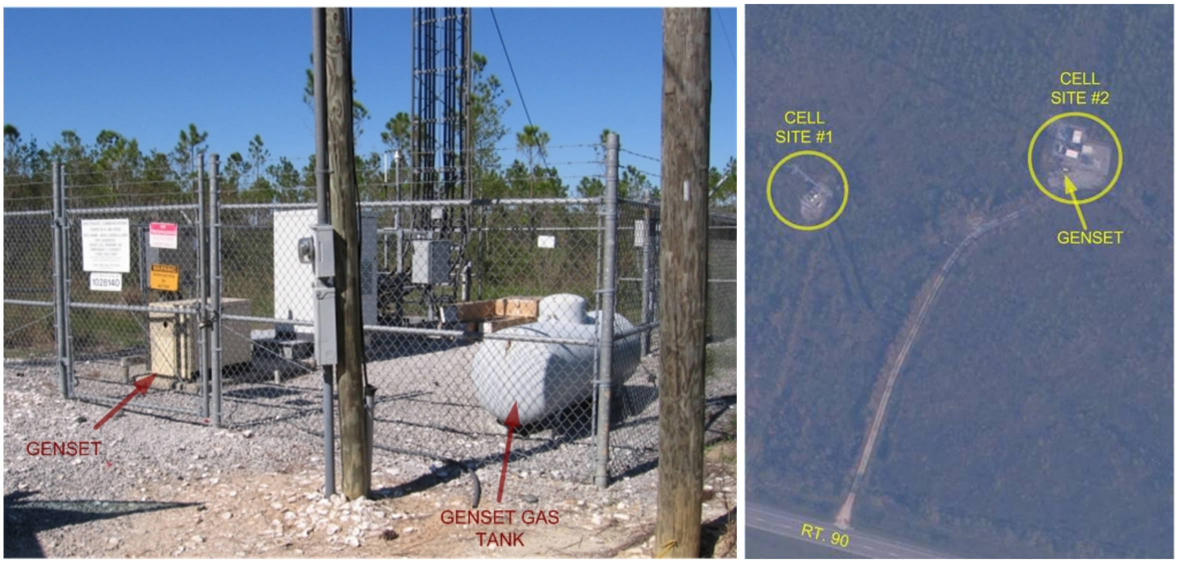

Fig. 6.56. (a) Left: Cell site located 100 m west of the one shown in Fig. 6.55, (b) Right: Aerial view of the cell sites in Fig. 6.55 (cell site #2) and in Fig. 6.56 (a) (cell site #1) [6]

Figs. 6.57 and 6.58 show an interesting cell site located northeast of Gulfport harbor. It has a permanent satellite link to its network, even though there are fiber-optic cables terminated at the site. The reason for this configuration is unknown. This was located at a safe distance from the shore site and showed no damage. However, one shelter was removed between the time the picture in Fig. 6.58 was taken and October 22nd. This cell site had three fixed gensets, which is enough to power the entire location. Since there was no sign of damage or information to the contrary, it is reasonable to assume that neither of the base stations lost service. The electric power had been restored by the date of the site survey.

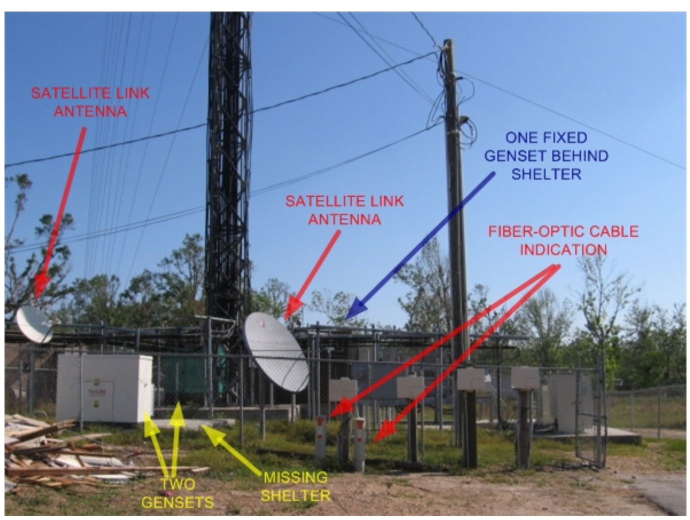

Fig. 6.57. Cell site in Gulfport with satellite-link antennas

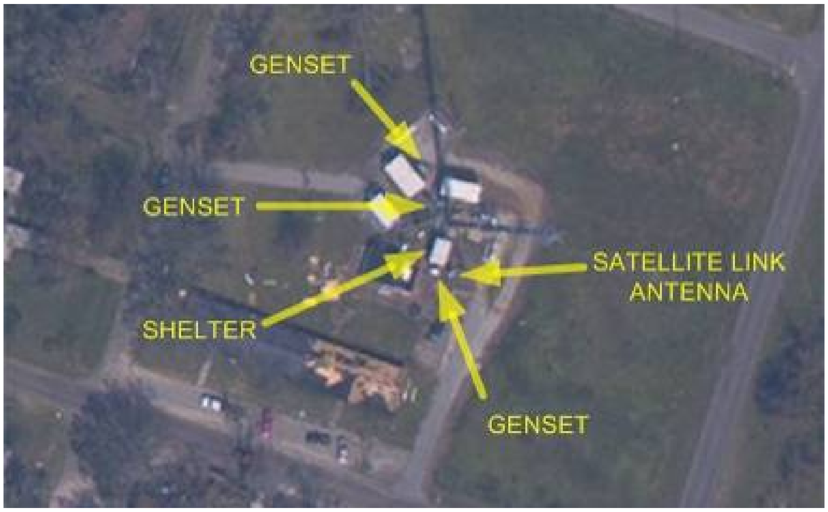

Fig. 6.58. Aerial view of cell site in Gulfport, August 30, 2005 [6]

Fig. 6.59 shows a cell site, located by a Lake Pontchartrain Causeway tollbooth, which had no damage and likely never lost service. This is an important cell because it covers a vital segment of the causeway, one of the few remaining points of access to New Orleans after the storm.

Fig. 6.59. Cell site next to Lake Pontchartrain Causeway Toll

Another site situated in an important location was the T-Mobile New Orleans MTSO and its collocated cell site. Fig. 6.60 (a) shows a picture of the MTSO obtained during the on-site survey. This place was very important during the rescue and relief operations because it was located by a main staging area west of New Orleans. Figs. 6.60 (b) and 6.61(a) show the helicopters and ambulances used to evacuate people after the storm. The location also helped T-

Mobile to coordinate with local law enforcement and genset refueling personnel. The T-Mobile MTSO avoided damage by good fortune. The blue dot Fig. 6.61 (b) indicates the MSC is located below sea level and 3 Km west of the 17th Street Canal. If the 17th Street Canal levees had breached to the west instead of to the east, the T-Mobile MTSO would have been flooded and destroyed, as happened to one of the two Cingular MSCs in New Orleans. Thanks to good luck the MTSO operated normally throughout and after the storm.

Fig. 6.60. (a) Left: T-Mobile MTSO picture obtained during the site survey,
(b) Right: Picture from FEMA showing the staging area next to the T-Mobile MSC, indicated in the background with a red arrow [37]

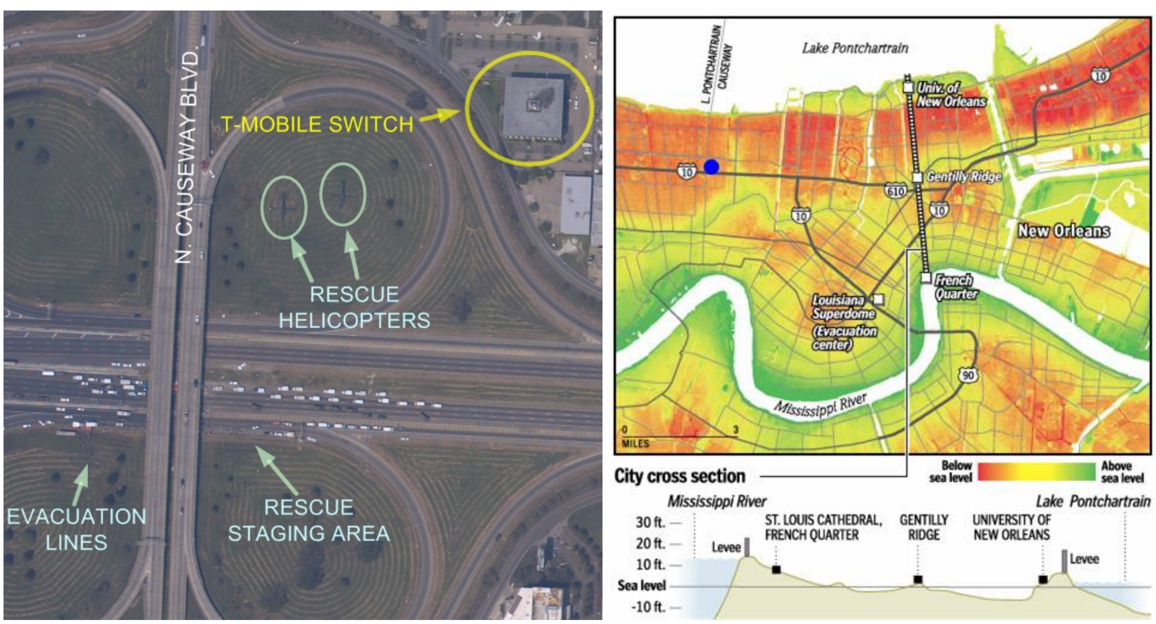

Fig. 6.61. (a) Left Aerial picture taken on August 31st showing the T-Mobile MTSO and rescue staging area [6], (b) Right: New Orleans topographic map [19].
The T-Mobile MTSO is marked with a blue dot.

Fig. 6.62 shows a cell site located north of Pass Christian that may have failed due to lack of electric power. As Fig. 6.62 (b) indicates, the site did not have a genset by September 4th. During the on-site survey on October 17th the portable generator deployed there was operating, indicating that the electric power from the grid was still off. The cell site showed no sign of damage and for that reason we considered it likely did not fail.

Fig. 6.62. (a) Left: Cell site located north of Pass Christian, (b) Right: Aerial picture of the cell site in Fig. 6.62 (a) taken on September 4th [6]

During the site survey, many COWs were found in Gulfport. The most interesting is shown in Figs. 6.63 and 6.64. This COW belonged to Sprint Nextel and was installed next to an AT&T transmission site on Highway 49 and 30th Street, north of Gulfport. The site is interesting because of a microwave transmission repeater that was installed next to the COW. As was mentioned previously, the Sprint-Nextel transmission network was interrupted when the Sprint long-distance switch in New Orleans, along with the POP in Biloxi, were destroyed. Likely, the site in Fig. 6.63 acted as part of a temporary link that replaced the severed transmission path between New Orleans and Biloxi. The aerial picture in Fig. 6.64 was taken during the site installation and shows the raising of the tower for the northeast link. Hence, Fig. 6.64 sets a period for the Sprint-Nextel network restoration. The picture was taken on September 4th. Therefore, it is safe to assume that it was roughly one week after the storm before the network was restored.

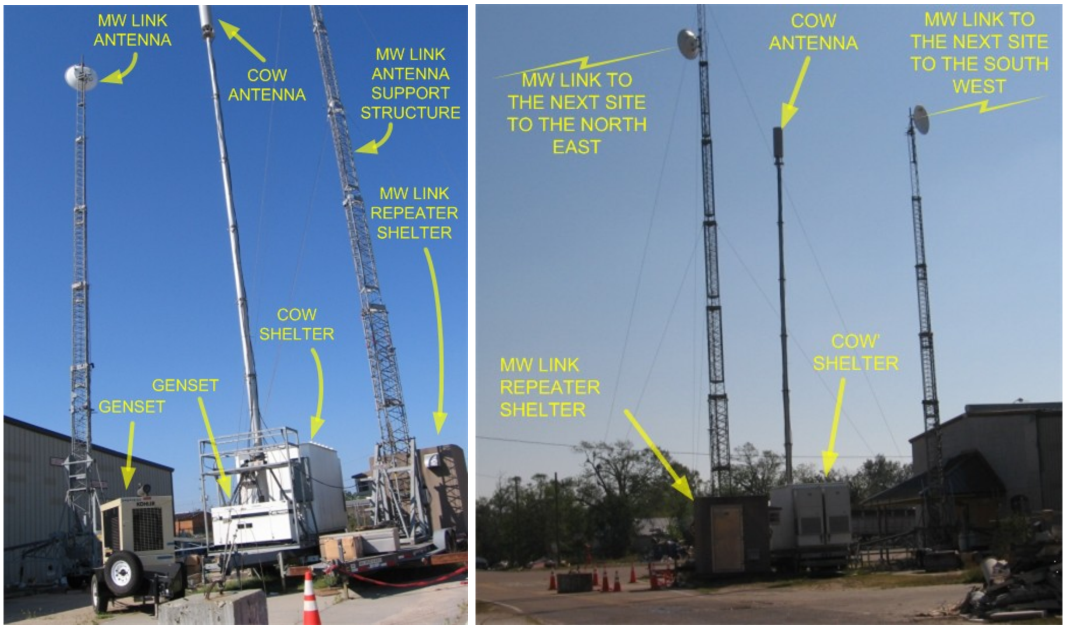

Fig. 6.63. (a) Right and (b) Left: Sprint Nextel COW and emergency transmission repeater

Fig. 6.64. Aerial shot of Sprint Nextel COW and emergency transmission repeater, September 4th [6]

Fig. 6.65 shows another COW found one block northwest of BellSouth CO in Gulfport. The picture on the left was taken during the site survey on October 22nd while the aerial picture on the right was taken on August 30th. The latter shows that the COW was not installed at that time, the day after Katrina made landfall.

Fig. 6.65. (a) Left: COW in Gulfport, (b) Aerial picture taken on August 30th of the area where the same COW was installed [6]

Fig. 6.66 shows a COW mounted on a truck in Gulfport. This COW was set up in an alley next to a BellSouth CO. The cables that connect the base station with the PSTN are visible in the picture. The genset that powers the COW is located behind the truck.

Fig. 6.66. COW behind BellSouth Gulfport CO

Figs. 6.67 and 6.68 show two damaged cell sites within the green zone. Fig. 6.67 shows a broken tower at a cell site located on the Jackson State University campus in Jackson, Mississippi. The tower may have had structural damage before Hurricane Katrina, since the winds in Jackson were not strong enough to topple the tower. The tower broke at a reinforced section, which is usually added when more antennas are included on a tower. So it is possible that the structural damaged was caused during the retrofitting process or because of the addition of the reinforced sections. Fig. 6.68 shows an aerial picture taken on September 4th of another cell site with a fallen tower. In this case the cell site was located about 15 km north of Gulfport, on Route 49. Like the tower in Jackson, there must had been preexisting structural damage before Katrina, because many other cell sites closer to the coast and on the same route did not suffer such catastrophic damage.

Fig. 6.67. Broken cell-site tower on the Jackson State University campus [38]

Fig. 6.68. Aerial picture of a fallen monopole tower north of Gulfport, MS [6]

7 Damage to Radio & TV

Even though radio and TV allow for communication in only one direction, they help during disasters by providing rescue and relief-related information. A radio is always recommended as an item for storm kits. Radio and TV studios and transmitters experienced damage similar to the mobile telecommunication networks.

Most of the transmitters close to the Mississippi Coast and in the southwestern half of Plaquemines Parish and St. Bernard Parish were destroyed. Fig. 7.1 shows one located in Delacroix, Louisiana. The storm surge destroyed the transmitter although the antenna remained standing. Even though the genset was located on a high platform (Fig. 7.2), it was damaged. Other site antenna towers were toppled by the wind. Such was the case with WLOX-TV in Biloxi, as shown in Fig. 7.3. Fig. 7.4 shows that while the railroad tracks may have protected the station from the storm surge, high winds brought the tower down.

Fig. 7.1. KQLD-FM Radio transmitter and tower in Delacroix, LA

Fig. 7.2. KQLD-FM radio transmitter genset

Fig. 7.3. WLOX-TV antenna tower [36]

Fig. 7.4. Aerial view of WLOX location in Biloxi [6]

Other sites in New Orleans were destroyed by flooding. One of those was WVUE-TV. As Fig. 7.5 shows, the channel was knocked off the air by severe flooding of the transmitter located next to the studio. Other TV stations that suffered transmitter flooding were WDSU and WGNO located in Chalmette. Figs. 7.6 and 7.7 show these two transmitters suffered extensive flooding. The studios of WDSU in downtown New Orleans were not flooded, as Figs. 7.8 and 7.9 show, but the building was evacuated and the transmission moved to Florida. The WGNO approach to regain service was different from WDSU. WGNO restored service in its transmission site by replacing the damaged equipment with truck-mounted equipment. Other transmitters damaged were WYES and WVUE TV.

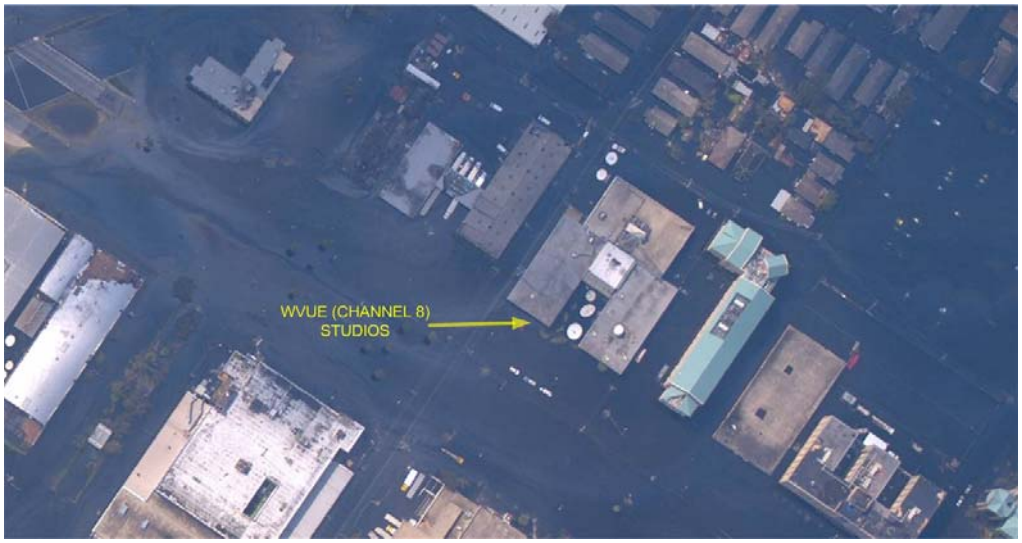

Fig. 7.5. Aerial picture of WVUE-TV studios in New Orleans, August 31st [6]

Fig. 7.6. Aerial view of WDSU transmitter, September 3rd

Some destroyed transmitters were replaced by a new site located in downtown New Orleans owned by the American Tower Company. This transmitter was the new home of WPL, WUL-DT, WHNO, WQUE, WYLD, WEZB, WTKL, WLMG, and WWNO. It also transmitted the signals of several government agencies, including the US Coast Guard, the FBI, the IRS, and the DEA. Clear Channel Communications, owner of some of the radio companies using the site, refueled the genset from Orlando and later from a FEMA deposit in Baton Rouge.

Fig. 7.7. Aerial view of WGNO transmitter taken on September 3rd. Other towers correspond to WYES and WVUE TV and some FM radio stations [6].

In none of the previous sample sites was the primary failure cause power-related. However, power-related outages did occur in other sites. The transmitter for WWL radio is located in Estelle, south of Marrero. This area was not flooded and suffered no significant damage. The transmitter had a 12000-gallon fuel tank for the genset, more than enough to sustain operations for several days. However, the WWL radio signal went off the air when the transmitter genset had a failure and provided only half of its rated power. As a result, the WWL radio broadcast was moved to the WWL-TV transmitter located in Gretna.

Fig. 7.8. Aerial view of WDSU studios in New Orleans taken on August 31st [6]

Fig. 7.9. Oblique aerial view of WDSU studios taken on August 31st [8]

WWL-TV transmits from a hurricane-hardened building equipped with a 1 MW generator and up to 11500 gallons of fuel stored in two tanks. Nevertheless, the WWL-TV staff was moved to Baton Rouge, and the WWL-TV signal was never lost. Refueling the genset was a complicated operation that required a delivery escorted by security guards armed with semi-automatic weapons.

Cable TV companies faced additional problems because the CATV outside plant is more vulnerable. Yet, during the site survey, we did not observe more significant damage than what was seen in the PSTN outside plant. Although serious damage occurred, especially in the coastal areas of Mississippi, most pole-mounted UPSs, such as those showed in Fig. 7.10, seemed to have been undamaged. These UPSs were able to operate for a few hours until the batteries were exhausted. After that, service was only recovered when the electric grid was restored.

Fig. 7.10. Pole-mounted CATV UPS

During the on-site survey, we also noticed that pedestal-mounted UPSs seemed to have received more damage than pole-mounted units. Pedestal UPSs are located at ground level, a vulnerable configuration. Fig. 7.11 shows a case of two UPSs, one pole-mounted and the other pedestal-mounted. The pole-mounted unit seems to be undamaged, while the pedestal UPS was destroyed.

Fig. 7.11. Pole-mounted and pedestal-mounted CATV UPSs.

8 Damage to Electrical Networks

This project is primarily focused on issues in telecom-related infrastructure. However, since the terrestrial electric grid is the primary power source of most telecom equipment, a brief overview with observations on the electric grid is presented here. Additional information can be found in studies and reports focused more on the grid [39-42].

8.1 Generation and transmission

In the transmission network, the physical infrastructure is large, relatively sturdy, and configured in direct point-to-point fashion. While there are disastrous failure modes – conductor failures have toppled miles of towers in previous cases, dead-end towers and sturdy foundations help keep damage local. Repair is relatively straightforward since right-of-way access is usually part of the initial design.

Like all damage from Katrina, high winds and flooding were the root cause of most electrical outages. Mississippi Power is the primary utility for the Mississippi gulf coast region. The Watson Electric Generating Plant, shown in Fig. 8.1, is a critical generation plant for the Mississippi coast. As Fig. 8.2 attests, the power plant suffered minor damage during the storm.

Fig. 8.1. Mississippi Power, Watson Electric Generating Plant

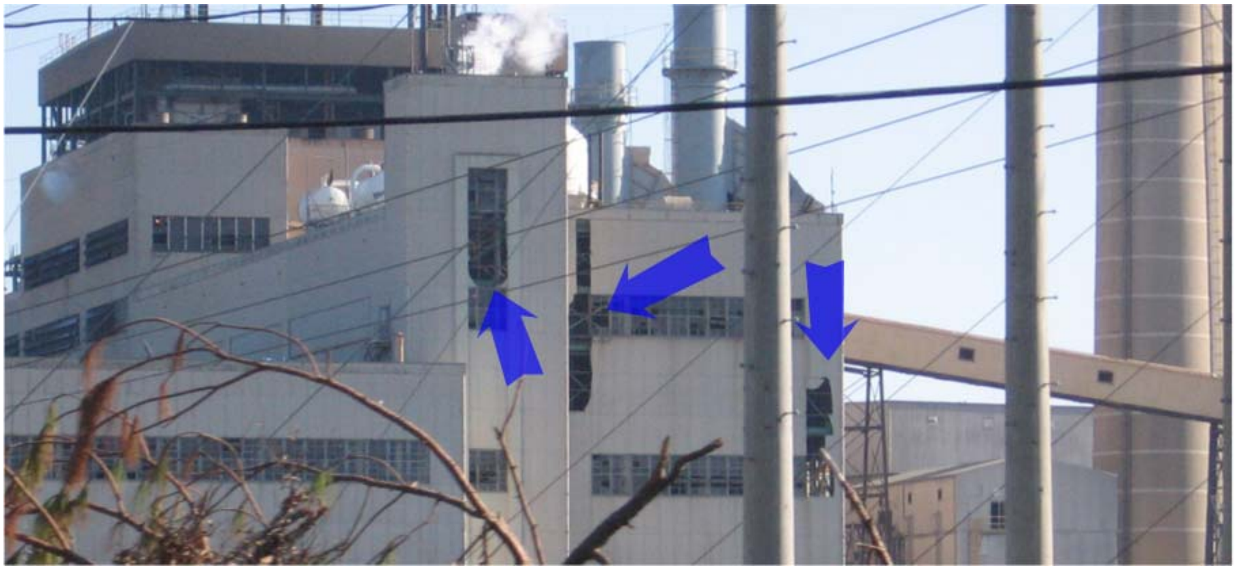

Fig. 8.2. Blue arrows indicating damage to the Mississippi Power Watson Electric Generating Plant

After Katrina, all 195,000 Mississippi Power customers lost power, nearly two-thirds of the transmission and distribution system was damaged or destroyed, and all but three of the company's 122 transmission lines were out of service. More than 300 transmission towers were damaged, 47 of them metal towers in the 230-kV bulk power system. In the distribution system, about 65 percent of the facilities were damaged; 9,000 poles and 2,300 transformers were lost; and 23,500 spans of conductor were down [43]. Louisiana suffered similar damage. Even though only the eastern half of the state was affected, 63 percent of the customers (678,850) remained without power as of September 3rd (Fig. 8.3).

8.2 Substations

Substations are a localized point of failure in the electric power grid. In the areas affected by Katrina, substations were most damaged by flooding and debris. The concentration of live, exposed conductors in a substation made outage from storm waters and debris a high likelihood. However, because of the low-wind profile of most substation equipment, wind damage is not often significant. For example, the substation in Fig. 8.4, off Louisiana Highway 39 near Belair and adjacent to a levee of the Mississippi River, sustained substantial flooding and debris damage from the storm including a control structure with the foundation indicated in Fig. 8.4. Figs. 8.5 and 8.6 depict other substations that were also damaged by the storm surge. Flooding took most of the New Orleans substations out of service. Two of those are shown in Figs. 8.7 and

8.8. At the time of the on-site survey, most observed substations were cleared of water and debris and were operational. An exception is the Biloxi substation, full of debris, with broken conductors and control panel doors hanging open, shown in Fig. 8.9. However, if we consider that most customers were incapable of receiving service at this time, it is reasonable that Mississippi Power had allocated resources to more critical areas.

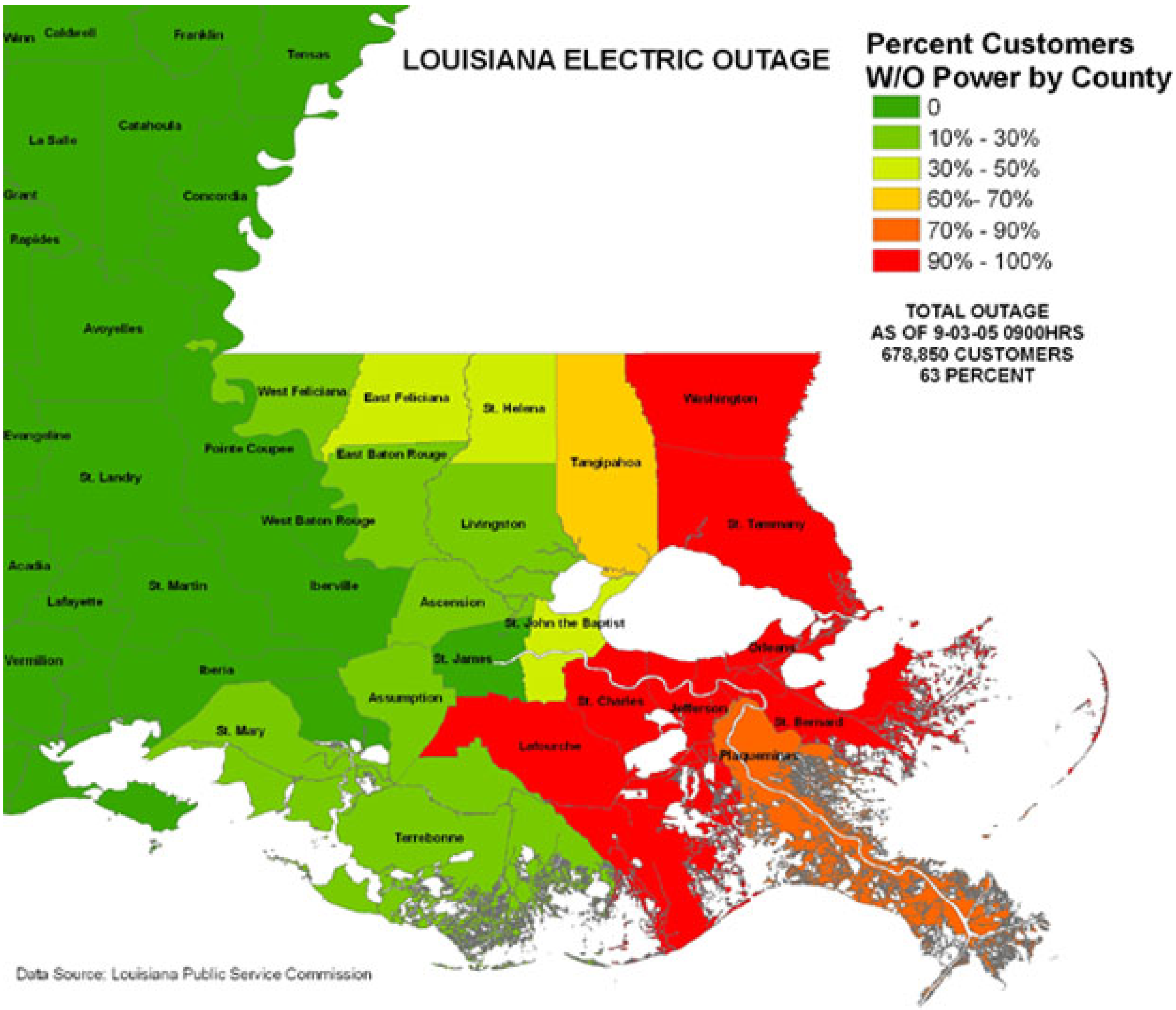

Fig. 8.3. Electric-outage severity map in Louisiana as of September 3, 2005 [44]

Fig. 8.4. Entergy 66MVA Substation near Belair, LA

Fig. 8.5. Damaged substation on Route 603, northwest of Waveland, MS

Fig. 8.6. Substation in Waveland, MS

Fig. 8.7. Debirgny Substation near Louisiana Superdome in New Orleans

Fig. 8.8. Substation northwest of downtown New Orleans. Aerial view on the right taken on August 31, 2005 [5]

Fig. 8.9. Mississippi Power substation in Biloxi, MS

8.3 Distribution

In the distribution network, the physical infrastructure is vast, and the sheer number of connections makes restoration a long and labor-intensive effort. In a situation like Katrina where a substantial fraction of structures sustained heavy damage, power restoration is coupled to structure restoration and the process can take months to years. Costs are likely to be high since heavy damage may require near-complete rebuilding of the distribution infrastructure in the hardest-hit areas.

Figs. 8.10 and 8.11 show damaged distribution infrastructure including lines and poles. The broken pole shown in Fig. 8.10 highlights the susceptibility of multiple networks succumbing at a single point of failure. This pole supported a common distribution transformer and power lines as well as telephone and cable television lines. The picture in Fig. 8.11 shows a repaired distribution line near Pearlington, LA with damaged and discarded equipment on the ground. The photograph in Fig. 8.12 shows an example of a staging area for replacement distribution transformers at a substation. These substation staging areas were often observed throughout the affected areas during the on-site survey and are examples of effective distribution of resources by the power companies.

The restoration strategy of a distribution system needs to take into account the customer base in an affected area. For example, a large area may be without service, but if most customers within the area were evacuated or incapable of receiving electric service due to site damage, then restoration resources would be best served in a smaller, but still populated area. However, priority should be given to service restoration in areas that contain key telecommunication sites, such as PSTN COs, transmission sites, and large cellular sites.

Fig. 8.10. Damaged pole

Fig. 8.11. Damaged lines in Pearlington, MS

Fig. 8.12. Staged distribution transformers

9 Additional Electric Power Issues

Hurricane Katrina also affected operation of security and health centers. Many were destroyed when Katrina made landfall, while others suffered electrical outages and failure of the PSTN. These effects are described in sections 9.1 and 9.2 to convey a sense of the importance of electrical supply to the operations of vital human services. Finally, a short analysis of alternative methods to solve the problems caused by lack of electric power in a disaster aftermath is given in section 9.3. Although such methods of producing electrical energy could improve electric supply, the site survey did not reveal their extensive use in the aftermath of Hurricane Katrina.

9.1 Electric power backup in police stations and other security offices

Communication networks for security forces failed because of damage produced by Katrina at the communication centers and by failure in the PSTN. Direct damage produced by the storm occurred in most of the stations located on the Mississippi Gulf Coast and in the City of New Orleans. In New Orleans, two primary tower sites were lost while police and fire centers had to be evacuated due to flooding. Fig. 9.1 shows one of the fallen antennas in Gretna, south of downtown New Orleans. Direct damage to the US Coast Guard (USCG) station in Gulfport, MS is obvious in Figs. 9.2 and 9.3. Lack of power was not the main cause of failure in these sites. Other centers destroyed by the storm were the Bay St. Louis Police Department, the Hancock County Emergency Operations Center, the Jackson County Sheriff's Department PSAP and several other PSAPs along the Jackson County Coast. During the site survey, we visited the Jackson County Emergency Operation Center in Pascagoula where additional gensets and communication systems had been installed (Fig. 9.4). An added genset was also installed at a public safety building in Biloxi, MS, shown in Fig. 9.5. Provisional communication services were restored by September 1st, using equipment provided by the Florida Department of Law Enforcement and a military communication unit with a satellite link. In Hancock County, E-911 service over the PSTN was finally restored by September 19th. Harrison County experienced only the destruction of the Pass Christian PSAP. However, most of the PSAPs along the coast lost service when the PSTN failed.

Fig. 9.1. Fallen antenna in Jefferson Parish sheriff office building [45]

Fig. 9.2. USCG station in Gulfport, MS [7]

Fig. 9.3. USCG station in Gulfport, MS [9]

Fig. 9.4. Jackson County Emergency Operation Center in Pascagoula, MS

Fig. 9.5. Public safety building in Biloxi, MS

9.2 Electric power backup in hospitals and other health centers

Hospitals and other health center operations were affected similarly to security offices and police stations. According to [46], in New Orleans, the Chalmette Medical Center, Charity Hospital, the Children’s Hospital, Lindy Boggs Medical Center, Memorial Medical Center and St. Charles Specialty Hospital suffered damage from flooding and were evacuated shortly after the storm. However, West Jefferson Medical Center and East Jefferson General Hospital were not damaged and their gensets worked without problems allowing these hospitals to maintain relatively normal operations throughout the storm and its aftermath. Health Centers close to the Mississippi Gulf shore suffered extensive damage. Figs. 9.6 and 9.7 show a nursing home in Pass Christian, MS that was destroyed by the storm surge. As Fig. 9.7 attests, the genset in this site was destroyed as well.

Fig. 9.6. Destroyed nursing home in Pass Christian, MS

Fig. 9.7. Destroyed genset at nursing home in Pass Christian, MS

9.3 Alternative sources of energy

Although alternative sources of energy may facilitate restoration efforts by reducing site logistical requirements, the site survey revealed that they were rarely used. AT&T was the only communication company that reported using backup systems other than gensets. In [47] AT&T said they used fuel cells in a few sites to generate electricity for extended periods. There was no further comment about use of fuel-cell technologies. However, unless a fuel cell includes a natural gas reforming unit, there would be no reduction in site refueling needs. Even with a reforming unit, a fuel-cell system needs to be installed where gas utility service has not been lost, unless the fuel cell is refueled regularly using portable containers.

Diversified fuel sources and use of local generation to construct a microgrid may provide a better long-term solution. Use of distributed generation resources such as reciprocating engines, microturbines and solar panels may be more reliable than traditional power plants [48]. Fuel cells with hydrogen sources could be used and be more convenient than traditional gensets. Microgrid-based telecom power plants would also reduce energy storage requirements using alternative energy storage devices such as fly-wheels and ultracapacitors, which are lighter than batteries.

Some distributed generation solutions, such as solar panels used as a microsource, can be implemented short term. Solar-powered systems reduce logistical requirements by decreasing the load on a site genset, thus cutting fuel consumption. During the night, power may be provided by a battery bank or a genset. Even though deploying solar-powered systems in communication sites is potentially advantageous, there are no reports that any communication company used solar-powered systems in Katrina's aftermath. However, during the site survey, we found a solar-powered portable water purification unit, shown in Fig. 9.8. Similar units can be adapted for use in communication sites and deployed after a storm to cell sites, MTSOs and COs to reduce genset fuel consumption. In the case of COs, having a solar energy source allows the use of the site genset with an extended autonomy without modifying the size of the genset fuel tank. In this way, network operators have more time to deliver fuel to the site, thereby lowering the risk of an outage due to genset fuel starvation. If solar-powered units are permanently installed in communication sites equipped with larger battery strings, the number of portable gensets needed to be deployed after a storm can be reduced significantly. In addition, utilizing solar power in cell sites throughout the year can significantly reduce expenses owed to an electric utility company, because less electric power will be consumed from the electric grid.

Fig. 9.8. Portable solar-powered water purification unit

9.4 Power of Last Resort

Solar-powered units offer an alternative for battery charging in CO locations. Communication failures following Katrina were extreme, however, and first responders may need a functional backup that operates even when extensive infrastructure damage occurs. One possibility is a network of low-power low-capacity radio repeaters, designed to support several channels of mobile communication. If a network of this type could be overlaid on the existing infrastructure, it could provide basic radio communications for first responders even in the midst of a storm. The intent is a low-power backup system – up to only a few watts per location – that functions entirely on its own without other external energy.

"Power of last resort" arrayed in this manner would have to be implemented as a maintenance-free standalone unit rugged enough to survive almost any disaster. Individual units would have to be adaptable for installation on buildings, power poles, highway structures, cell towers, or other structures likely to survive a storm. Such a network offers a possible alternative to satellite-based communications and could be suitable for use by local responders during a crisis. A set of projects initiated by the U.S. military [49] is seeking to develop battery-free, maintenance-free power devices for communications energy. The outcomes have potential impact as a worst-case communications alternative.

10 Conclusions

10.1 Causes of communications failure

Why did communication networks fail in such a severe way from Hurricane Katrina? As with any disaster there is no single explanation. One important reason was Hurricane Katrina's unusual strength made evident by the height and extent of the storm surge. Even though the winds were strong, Katrina made landfall only as a category 3 hurricane on the Saffir-Simpson scale. Given that a category 3 hurricane can produce severe damage, there have been many category 3 hurricanes that hit the continental US without producing catastrophic damage. Hence, response planning based on the Saffir-Simpson category may yield misleading results.

Although the storm surge was the most important destruction factor affecting, primarily, sites in Plaquemines Parish, the eastern half of St. Bernard Parish and a 1 km strip of the Mississippi Gulf Coast between the Louisiana border and Pascagoula, flooding due to broken levees in New Orleans affected more sites and originated many failures from lack of electric power. Katrina's effect was more centralized than distributed. Several substations were severely damaged, while not many high-voltage transmission lines were affected. Eleven switches were destroyed but, even though in some areas the outside plant suffered significant damage, only a few cell sites were destroyed. This destruction pattern was more favorable for mobile communication networks than for the PSTN.

Another important reason that explains the severe communication network outage in the aftermath of Hurricane Katrina is the existence of three common points of failure: in many areas the PSTN acted as a single transmission backbone for most of the networks, shared infrastructure (poles), and the telecommunication sites' power feed. The BellSouth network not only transmitted POTS but also interconnected many cell sites and remote MSCs with their respective MTSOs. Moreover, the entire E-911 system is based on the PSTN network. Thus, when the PSTN COs lost service, the transmission links and access points passing through failed COs were interrupted. In the cases where the switch could be maintained, as in the New Orleans Main Tandem switch, rerouted traffic from failed COs was higher than the available capacity, creating congestion points that reduced the network functionality. Thus, the PSTN failure was a major contributor to the breakdown of the entire system.

An unavoidable common point between communication and electrical networks is the power feed. Besides the direct destruction of sites caused by the storm surge, the main reason for CO and cell site failure that accounts for the majority of outages was loss of electric power. In some COs in New Orleans, the primary failure cause of the power-related outages was flooding that prevented deploying portable gensets or did not allow refueling. Disruption of the local diesel supply and the impossibility of delivering fuel due to damaged roads also played an important role in areas where COs lost service even though the initial flooding subsided in a few days. In some COs, flooding damaged fuel tanks buried below ground level while the rest of the equipment was unaffected. Even though the area affected by flood-related power outages was relatively small, it held the highest density of communication systems.

The fact that many outages were caused by lack of electric power highlights the importance of securing communication sites' electric supply during and after storms. It also emphasizes how dependent telecom networks are on electric power and, especially, on continuous genset operation after a storm. The site survey revealed that all networks relied almost entirely on gensets to provide extended backup power. However, generators are relatively inefficient when required to operate for more than few hours. This suggests that from a reliability standpoint, the connection between the electric grid and communication networks is a weakness.

Vulnerable construction practices may have been a factor in the failure of some sites. We observed many examples that attest to this. For example, the Pass Christian CO, located a few hundred meters from the coast, was built at ground level. Sometimes the existence of a vulnerable construction is seen as a lack of uniform design guidelines, such as having the same cell site base stations on platforms of different heights. Reasons for these contradictory designs are unknown. But they should be analyzed with a historical perspective, since many of the infrastructures were constructed several years ago. As with numerous issues related to infrastructure design, solutions may also take many years.

Having analyzed the reasons why the communication networks failed in such an unprecedented way with Hurricane Katrina, one can ask the question, "What factors prevented the outcome being worse?" Certainly, good fortune played a crucial role in some cases. And hurricane preparedness was adequate based on pre-Katrina criteria. The single most important factor that prevented further damage was the remarkable effort, amid extremely difficult conditions, of communication and electrical company employees. Flexibility to adapt to the new conditions and ease of implementing alternative, on-the-spot solutions to clear outages showed extraordinary experience levels from these employees.

10.2 Proposed solutions

A first lesson that can be learned from Katrina is that communication companies must base their hurricane-restoration plan not only on the wind-speed forecast, but also on other hurricane parameters such as the forecasted storm-surge height and extension. Future research on the effects of strong storm surges versus extremely intense winds on telecommunication infrastructure is needed to support contingency plans. Hurricanes where wind speed is more important than storm-surge strength may produce more distributed damage instead of affecting centralized elements of the communication network.

Common points of failure among the networks can be addressed in a variety of ways. One approach for decreasing the risk of a major system break-down due to PSTN failure is to increase mobile communication transmission capacities and provide architectures with more network diversity. These include increasing direct connections between wireless communication networks. A short-term, relatively inexpensive solution is to create microwave links between cells and MSCs currently connected to its network through the PSTN. On the PSTN side, destroyed switches could be replaced by SOWs instead of DLC cabinets. SOWs are more expensive than DLC enclosures, but they are more reliable, provide better functionality for trunks, and reduce congestion nodes by allowing better distribution of traffic. Yet, the majority of the damaged PSTN COs were replaced by DLC systems, which were mostly hosted by the Schrewsbury and Aurora COs. These COs were built on terrain located below sea level and close to canals. Thus, they and the PSTN network in New Orleans were at a high risk of failure. Another factor that added to the higher PSTN failure probability, even with moderate strength storms, was the replacement of damaged feeder facilities by DLC cabinets.

A shared infrastructure is both less costly when built and less reliable in a disaster. While sharing poles is accepted in the United States, in many countries it is an exceptional case or prohibited. Even in countries where all the networks belong to the State, higher reliability and improved safety receive priority over lower costs, leading to separate infrastructures. Hence, it is advisable that to increase network diversity and improve overall reliability, infrastructure should not be shared among different networks.

A third point of failure, the connection between the electric grid and a communication network, is a weak point in the infrastructure. Site failure from lack of power can be reduced if the communication network dependency on the electric grid is minimized by providing local sources of energy with improved reliability. Gensets, the widespread solution in Katrina's aftermath, have a relatively low availability when used for more than a day. Genset reliability can be improved if logistics and fuel delivery are enhanced in two ways: first – diversify the fuel supply by using dual natural-gas or diesel gensets for COs close to the shore, and second – reduce fuel distribution by using natural-gas engines at inland sites. A direct method is to increase the electric energy stored at each site, i.e., increase the number or capacity of battery strings. Another way is to employ alternative sources of energy, especially solar power to provide electricity to the communication system during the day. Solar-assisted power plants can be installed in a relatively short time, easing genset fuel demand. Distributed generation resources, such as reciprocating engines, microturbines and fuel cells may provide a long-term increase in availability by making the site independent of the electric utility grid.

Power-related outages could also be reduced by revising and improving restoration plans based on several different disaster scenarios. Plans need to consider three equally important factors: resource availability after the storm, resource deployment, and response timing. The objective of the plan should focus on the common good with an emphasis on avoiding outages. Commercial competition between companies should be set aside. As a first milestone, resources need to survive the storm. Then steady distribution needs to be ensured after the storm and during restoration. Inland staging areas with good access to the coast have to be identified and prepared before the hurricane season begins. Emergency diesel fuel and portable gensets can be stored there. Living arrangements for personnel working on restoration should also be made in advance. Plans should be coordinated with local law enforcement officials to ensure access to the affected area after the storm without interfering with rescue operations. After the storm, fuel should be delivered in a timely fashion through routes previously agreed upon by security officials. Plans should consider alternative routes to the main sites and alternative means of fuel transportation, including helicopter and boat.

A recovery operation group should be defined before the hurricane season starts. The group should use personnel within the affected area and have a well-defined structure including a liaison with other communication companies, the FCC and law enforcement officials. Plans of BellSouth and other companies that provided for housing and relief of the affected employees and their families were extremely useful and productive because they improved an otherwise extraordinarily difficult working environment. Resources need to be administrated wisely. The logistical effort of deploying and refueling generators can be reduced if all operators of a same cell site agree on one genset supplier for that location instead of each providing its own genset. This alternative way of delivering gensets can be implemented in a very short time well before the start of the hurricane season. Mobile communication networks were restored much faster than the PSTN. However, the restoration time could have been even shorter if there had been coordination to provide just one genset per site. The impact of this recommendation may extend beyond the communication industry; fewer deployed gensets implies fewer trucks on the road, which will reduce traffic and support rescue and relief efforts. Finally, the plan should include a clear restoration order, giving the highest priority to E-911 centers and law enforcement and emergency response offices with lower priority to communication network connection points.

Vulnerable construction can be avoided at the network design stage. In the communication industry there are design guidelines for areas at high risk of earthquakes. Similarly, communication companies might agree on common design guidelines in coastal areas at high risk of hurricanes. These guidelines should include a unified code for infrastructure design and construction. They could be extended to add improvements in network architecture and interconnections. For example, the guidelines should define not only the recommended height at which communication systems are constructed, based on their geographical location and topographical data, but also the required structural strength depending on proximity to the shore. Topographical characteristics of the coast should also be taken into consideration. In addition, the design guidelines should be coordinated with city planner decisions. For example, levee strength and network survivability objectives may influence new CO construction. Plans to reinforce CO buildings should include expected flooding. Better ways of sealing the interior of a CO from flooding waters should be developed. Doors can be strengthened to keep water from entering the building. Conduit seals that prevent water from easily inundating manholes and cable entrance facilities already exist on the market, implying that this solution can be rapidly implemented. Power-plant components should be given the same importance as any other element of the communication network, such as the switch. Gensets located outside, in sites close to the coast, should be considered destroyed after even moderate hurricanes. Emergency generators, engine fuel tanks, pumps and other ancillary components also should be placed inside at an adequate height with respect to sea level. Having larger fuel tanks to provide extended autonomy may be an adequate solution for sites where alternative energy solutions cannot be implemented.

10.3 Follow-up commentary

One team member, P. Krein, visited New Orleans in July 2006 and observed evidence of the reconstruction process. He toured a residential area near the 17th Street Canal levee breach where there had been nearly three meters of flooding for more than two weeks after Katrina. While most residents evacuated, some took refuge in attics. There were fatalities. Today the neighborhood is a disquieting mix of abandoned churches and homes, un-repaired houses for sale, structures being readied for demolition, houses in early stages of heavy restoration work, and a very few fully recovered houses. As a rough estimate, about 10 per cent of the houses have been recovered. A higher percentage does not appear to have been touched since the storm.

The electrical and communications infrastructure is generally restored. Cell telephone service is normal. Even at this late date, most of the houses have not been sufficiently repaired to permit grid reconnection and thus do not have electrical or telephone service. Fig. 10.1 illustrates part of this issue. It shows damage in a residential area and abandoned cable infrastructure in the vicinity of the 17th Street Canal in July 2006. Fig. 10.2 shows a nearby house with a large tree yet to be removed. Fig. 10.3 shows an apparently abandoned home in this formerly affluent neighborhood. The visible high-water line in the image is about 1.9 m above grade. Neighbors reported that the water level reached about 2.4 m, and traces are more evident in the interior of many structures. In these areas, many distribution network repairs seem to be temporary or incomplete, but this is probably justifiable since the load is only a small percentage of pre-storm demand.

Fig. 10.1 Abandoned cable run and residence damage in an alley a few blocks east of the 17th Street Canal, Orleans Parish, July 2006. Photo courtesy of D. Dickey.

Fig. 10.2 Residence that still shows heavy storm damage from Katrina, July 2006. Photo courtesy of D. Dickey.

Fig. 10.3 Abandoned home east of 17th Street Canal, July 2006. Photo courtesy of D. Dickey.

To the west, in Jefferson Parish (this canal breach was on the east side, toward Orleans Parish) recovery appears to be essentially complete. To the south, along Canal Street toward the central city areas, there are long stretches where businesses and other facilities remain closed. Outside plant infrastructure seems to be complete, but damage to structures obviously has overwhelmed the ability to carry out repairs. Farther south, near downtown areas, most businesses seem to have re-opened and recovery is progressing. While a few buildings downtown are still under repair, most seem to be in normal operation. Downtown and in the French Quarter, most of the people on the streets and customers in businesses appear to be out-of-town work teams from churches and various charitable groups.

New Orleans and other sections along the Gulf Coast continue a long recovery process from Hurricane Katrina (in some areas exacerbated by later effects of Hurricane Rita). While most of the power and communications infrastructure has recovered and is in operation, some of the repairs used temporary fixes and will need to be addressed again as restoration continues. Neighborhoods subjected to extensive flooding will not recover fully for many years.

10.4 Afterword

Communication companies should not be blamed for the extensive outage that followed Hurricane Katrina's landfall. They implemented plans based on hurricanes such as Camille, Hugo and Andrew which were more intense than Katrina; some of these past storms also flooded New Orleans. On the night of August 28, one could ask the question, "If the PSTN has survived so many hurricanes in the past, why should Katrina be different?" If events are analyzed with a historical perspective, the answer to this question is, "Nothing should have been different." A possible mistake among communication planners was a failure to recognize the evolving nature of land, communications and electrical networks. Some of these changes have been relatively recent, so they were difficult to identify in a timely manner. One example is the high dependency on a PSTN that was designed a decade or more ago, before the installation of mobile communication networks. In addition, various published scenarios suggested that a hurricane with the strength of Camille with an unfavorable landfall point would cause extensive flooding as actually occurred from Katrina. Soil erosion along the Louisiana coast in recent years has weakened natural barriers to strong hurricanes, and other known effects have altered the potential impact of large storms in this region.

We now know that a series of incidents caused the unprecedented outage in communication after Hurricane Katrina. Now is the time to act to prevent such a disaster from reoccurring. Some of the strategies discussed in Section 10.2 and elsewhere in this report can be implemented in the short term. These will alleviate certain effects a future hurricane similar to Katrina might produce. Other strategies will require planning, financing, and more time, even years, as for any major infrastructure change. Until long-term changes are carried out, military-type communication systems or last-resort repeater networks need to be ready to support rescue and relief efforts after a disaster like Katrina.

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