Effects of Notable Natural Disasters from 2005 to 2011 on Telecommunications Infrastructure:

Lessons from on-site Damage Assessments

Alexis Kwasinski
The University of Texas at Austin, USA
akwasins-at-mail.utexas.edu

***Abstract*— This paper discusses lessons from notable relatively recent disasters that had significant impact on communications infrastructure. The discussion will be based on field damage assessments and will be supported by extensive photographic evidence. In particular, the following disasters are discussed: from 2005, Hurricane Katrina; from 2008, hurricanes Gustav and Ike, from 2010 Chile's earthquake and tsunami, from 2011 New Zealand's earthquake in Christchurch, and the Great Earthquake and Tsunami in the Tohoku Region of Japan. This paper perspective focuses on basic questions addressed during field damage assessments that lead to identify potential ways for improving power supply availability during extreme events. Main failure modes are discussed, and similarities and differences observed from all these extreme events are commented. Predominant restoration strategies are also examined. Finally, this paper concludes with a summary of recommendations, including potential use of micro-grids as a powering option for communication sites in such extreme events.**

Keywords-Natural Disasters; Power Conversion; Power Availability; Hurricanes, Earthquakes; Failure Modes; Lifelines; Communications Power Plants.

I. Introduction

This paper discusses lessons from notable relatively recent disasters that had significant impact on communications infrastructure. In the past few years, several natural disasters have attracted significant public attention. Perhaps, the two most notable examples of such events are Hurricane Katrina in 2005 and the recent March 2011 M_w9.0 Great Tohoku Earthquake and Tsunami in Japan. In many of these disasters ,significant communication outages occurred. Then, understanding the reasons of these effects is important not only from the technical point of view of network operators but also from a societal view as a whole. Available communications are not only important when the disasters is happening and in its immediate aftermath. During the service restoration period after a disaster, communications are important for many other infrastructures that rely on public networks to coordinate their logistic operations. Furthermore, communication-supported services, such as the Internet, and financial and banking operations, are also important in order to support communities to recover. In the past, there has been very few works studying the effects of natural disasters on communication systems based on damage assessments. One of those is a comprehensive study of the effects of Hurricane Katrina [1]. Evidently, at the time of evaluating lessons from disasters it is important to consider which method is used in order to study the effects of such disaster and how those lessons were drawn. Any suitable method needs to be objective and, for this reason, scientific approaches are desirable. The most common of the scientific approaches is to rely on data from telecommunications network operators and/or regulatory government agencies. However, in most situations these data is incomplete and inexact because of normal confusions during such extreme events. One relatively uncommon approach in electrical engineering is to perform field damage assessments a short time after the disasters happens. Although this approach has been applied more widely in other engineering disciplines such as in Civil engineering studies of transportation infrastructure or building performance after earthquakes, performing such forensic studies after a disaster is uncommon in the electrical engineering field. This paper bases its discussion in this empirical approach of relying on field observations that is used to validate quantitative data from various sources. The discussion discusses the following events: from 2005 Hurricane Katrina; from 2008, hurricanes Gustav, and Ike; from 2010, Chile's Earthquake and Tsunami; from 2011 Christchurch, New Zealand Earthquake, and the Great Tohoku Region Japan Earthquake and Tsunami.

The discussion section following this Introduction is structured in the following way: first, the general approach for the analysis methodology is presented. Secondly, the aforementioned disasters are discussed within the context of methodology presented in the first part of Section II. This paper concludes with a summary of its main points.

II. Discussion

A. Analysis Methodology Approach

The analysis is based on field damage assessments. During these field reconnaissance trips data about communication network performance is collected and documented through photographic means. These data is also used to validate information obtained from network operators and government regulatory agencies. The goal is that the combination of both sources of information allow for an accurate description of the effects of the natural disaster under study. During the field damage assessment, the goal is to answer two sets of questions:

Material for this paper was obtained through support provided by a number of organizations including U.S. National Science Foundation, the ASCE, The Cockrell School of Engineering at The University of Texas at Austin, and the Center for Electric Machinery and Electromechanics at the University of Illinois at Urbana-Champaign.

978-1-4577-1250-0/11/$26.00 ©2011 IEEE

a) What infrastructure elements failed and what did not fail? Why?

b) In the cases when the infrastructure element under observation failed and/or was damaged, how was operation restored?

Answers to these questions can be translated in ways for improving power supply availability in communication sites subject to natural hazards. Consider that availability is

$$A = \frac{MUT}{MUT + MDT} \tag{1}$$

where MUT is the mean-up time and MDT is the mean-down time. The set #1 of questions aims at learning primarily how to achieve higher MUTs during extreme events, whereas the set #2 of questions targets at identifying ways used to reduce the MDT. The next portions of this paper answer questions a y b for notable recent disasters with a focus on communication infrastructure issues. Some other sources of failure in communication networks, such as network congestion due to increase traffic, are out of the scope of this work and, thus, are not discussed here. Hence, failure modes to be explored in this paper and that are related with communications infrastructure includes:

A) Lack of permanent onsite gensets and battery exhaustion (mostly occurring in cell sites and outside plant remote terminals).

B) Permanent onsite genset failure. Some potential causes include failure to start, fuel starvation, or other causes. In this case, overheating due to cooling failure is, typically, the next fault event to occur before batteries are discharged.

C) Power plant damage but communications equipment (e.g. switch fabric) undamaged. This failure mode is typically observed when part—e.g., batteries or diesel tank—or all of the power plant placed at ground level is affected by flood waters, storm surges, or tsunamis but the water level do not reach the communication equipment placed on higher floors

D) Communications site damage—i.e., power plant and communication equipment are damaged.

E) Other failures in communications infrastructure, such as severed cables or damage to transmission links.

B. 2005: Hurricane Katrina [1]

Hurricane Katrina made landfall on the morning of August 29 as a strong Category 3 hurricane near the town of Buras, in the state of Louisiana. Although Katrina's winds were strong, its most significant damage action was its storm surge which in some points in the Mississippi Gulf Coast reached almost 30 ft. high. This storm surge destroyed nine of Bellsouth's central offices (Fig. 1); five of them were restored with DLC systems with priority circuits hosted by a neighboring undamaged CO (Fig. 2). Six other central offices lost service when the levees that protected New Orleans failed and the city flooded. Additionally, eighteen central offices lost service due to engine fuel starvation or other type of genset failures. In total, about 2.5 million conventional PSTN lines lost service, representing about half of the total lines in the north Gulf coast area. Evidently, Hurricane Katrina affected Bellsouth's (now AT&T) centralized network elements more severely than other storms. These failures in the PSTN also led to loss of service in wireless networks because the latter often rely on former for call routing. A positive development was keeping New Orleans Main CO and tandem switch operational thanks a special delivery of diesel for the genset and water for the air conditioners with an armed-guarded convoy.

Distributed network elements, such as cell sites and digital loop carrier (DLC) remote terminals (RTs) were also certainly affected, but only 34—a relatively small number—of these distributed sites were damaged. Outages at most of these sites were also caused by power issues. In part, but particularly for DLC RTs, these power issues at distributed network elements were originated by lack of a permanent power onsite genset at the site. The solution implemented to power these sites was to deploy portable gensets. Yet, as it was found during the site survey, lack of coordination among different wireless network operators led to having at several cell sites multiple portable generators, each powering a different base station (Fig. 16.b in [1]). This lack of coordination in genset deployment led to ineffective resource management that translated into additional traffic in already congested roads during the immediate aftermath, and in extra logistical requirements. Another important issue observed during the damage assessment was lack of consistent construction practices for base stations, with sites having part of the infrastructure above the flood plane and part of the infrastructure below it. This is an important observation because most of the few damaged base stations among the 3,000 in the area affected by Hurricane Katrina, were located below the flood plane, and, thus, were damaged when flood waters reached the site. Also some towers at a few cell sites collapsed, but this was an occurrence affecting only a very small percentage of all wireless networks distributed locations. In order to restore service to damaged cell sites, network operators relied heavily on cell-on-wheels (COWs) or cells-on-light trucks (COLTs).

Other failure modes identified during the damage assessment was damage to outside plant copper infrastructure, and severed transmission links. Of these damage infrastructure, flood damaged copper cables were restored by replacing them

Fig. 1. Yscloskey CO after Hurricane Katrina.

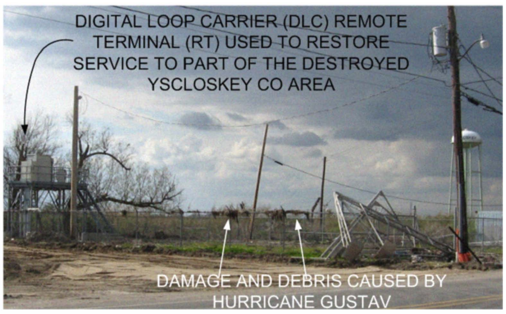

Fig. 2. The former location of Yscloskey CO after Hurricane Gustav.

by DLC systems, and severed transmission links were provisionally restored with emergency microwave links (Fig. 16.a in [1]). The damage assessment served to identify the storm surge as the most significant damaging action of Hurricane Katrina, followed by the related flooding. Hence, one of the damage assessment lessons was, wherever possible and in the area at risk of storm surge or flooding, to use pole mounted systems over ground mounted systems, because the field reconnaissance provided evidence of pole mounted systems surviving the action of Hurricane Katrina where ground located infrastructure was destroyed (Fig. 11 in [1]).

C. *2008: Hurricane Gustav*

Hurricane Gustav made landfall 3 days after the third anniversary of Hurricane Katrina about 60 miles west of Katrina's point of contact with Louisiana's coast. Gustav's wind speeds where a little lower than Katrina's but still very similar [2]. The most significant difference between Gustav and Katrina was in the storm surge height. Gustav's storm surge was significant but less intense than that of Katrina and although some levees were just overtopped and a few breached, New Orleans did not flood. However, Gustav moved away from the coast much slower than Katrina originating some flooded areas and complicating restoration efforts due to persistent rain. Telephone outages affected close to 50,000 lines [3] in Louisiana with the peak occurring on September 4, 72 hours after Gustav made landfall. These data indicates that this delayed peak may have originated in power related outages in one or more central offices, because 72 hours is the typical storage time in central offices diesel tanks. Although there were no reports of such failure, damage assessments identified the central office (CO) in Fig. 3, where issues with its permanent genset are highly likely to have occurred as evidenced by a large portable genset and supplemental air conditioning system. The damage assessment was also able to identify fewer failures in fixed telephony outside plant distributed network elements than with Katrina. The reason for these fewer failures was that many DLC RTs were equipped with permanent natural gas gensets (Fig. 4). The damage assessment also identified that since Hurricane Katrina many of the DLC RTs located in areas vulnerable to storm surge and flooding had been placed on top of platforms (Fig. 5), thus, reducing the number of DLC RTs suffering direct damage from the storm. Avoiding such damage reduced the MDT even when in some of these sites, particularly those in the Mississippi River Delta where access is difficult and there is no natural gas distribution service, outages caused by lack of power occurred. Nevertheless, extensive deployment of portable generators prevented extensive outages in many other DLC RTs and wireless base stations not equipped with permanent gensets. However, power issues severely affected service of digital telephony provided by CATV operators, leading to ad-hoc solutions, such as the one in Fig. 8 in [2].

D. *2008: Hurricane Ike*

Hurricane Ike made landfall in Galveston Island, in the northeast Texas coast on September 13th. Although Ike was not an extremely intense hurricane in terms of wind speed, its storm surge was comparable to Katrina's reaching 20 ft at some points of the Bolivar Peninsula [4] versus maximum heights of 28 ft produced by Katrina in Mississippi [5]. Although the outages caused by Ike on communication networks were not as extensive as Katrina's they were nevertheless significant. The fixed telephony outages peaked at close to 340,000 [6]. AT&T lost service in 5 central offices with one of them, Sherwood (Fig. 1 in [2]), been destroyed. Although the damage assessment allowed to identify Sherwood CO's failure mode as communication site damage due to storm surge waters—all the equipment at the site was located no more than a meter above ground level—the failure mode of the other central offices was not completely clear. Although water marks in Fig. 6 suggests that Port Bolivar's CO may have been affected similarly than Sherwood CO by storm surge waters, it was possible to observe during the damage assessment that the onsite genset was operating. Moreover, unlike Sherwood CO where it was possible to observe "switch-on-wheels" (Fig. 7) used to restore service at the site, no equipment that could be used to potentially restore service was found outside Port Bolivar CO. The most likely failure mode in the other sites was a power related issue; perhaps diesel genset engine fuel starvation. These other central offices were likely small remote switches, like the one in Fig. 8 near Crystal Beach, which did not show any sign of damage observable during the field

Fig. 3. A large portable generator outside Goodwood central office in Baton Rouge, Louisiana, less than a week after Hurricane Gustav.

Fig. 4. A DLC RT with a natural gas genset located outside St. Bernard CO destroyed by Hurricane Katrina.

Fig. 5. A new DLC RT with a permanent genset installed on a platform after Hurricane Katrina next to another DLC RT installed on the ground before Hurricane Katrina.

reconnaissance. Another possible cause of failure was isolation due to a severed transmission link, as suggested by the emergency microwave transmission system in Fig. 4 in [2] and seen on the background in Fig. 8.

Power issues were one of the most important causes of outages affecting distributed network elements. In the area affected by Ike, AT&T lost service in 551 digital loop carrier (DLC) remote terminals (RTs) due to lack of power [6] but fewer than 3 % of all the DLC RTs were destroyed, like those in Figs. 2 and 3 in [2]. Some of these DLC RTs were damaged even when they were placed on platforms due to the significant storm surge height. A notable example of such occurrence can be found in the DLC RT in Fig. 10 in [2] used to restore service after Hurricane Rita destroyed Sabine Pass CO in 2005. Verizon outside plant infrastructure was affected in a similar way, with 321 RT affected, mostly from lack of power. Windstream lost service in 7 switching stations and 237 remote terminals due to lack of power [6]. More power originated outages were reported by Eastex, which lost service in 2 central offices due to failed gensets, and in 82 DLCs due to lack of power [6]. Although the effects of Hurricane Ike on Cameron Communications infrastructure are not known in detail, the damage assessment was able to identify some sites where damage likely occurred, such as the one in Fig. 5 in [2]. Damage to some of Cameron Communications DLC RTs may have been avoided by placing them on platforms (Fig. 10.a in [2]). Time Warner Cable had almost three-quarters of its network affected by lack of power [6], too. Service to DLC RTs affected by power outages was restored by deploying portable gensets (Fig. 6 in [7]), whereas service to some damage DLC RTs were restored with new cabinets on pallets (Fig. 8.b in [7]) or on wheels (Fig. 8.a in [7]). Although some cell sites were destroyed (Fig. 6 in [2]) or base station equipment were damaged, most of the loss of service in wireless networks was caused by lack of power in distributed network elements, particularly in sites without permanent gensets. Like with Katrina, cells on light trucks (COLTs) and cell on wheels (COWs) were extensively used to restore service to damaged cell sites (Fig. 7 in [2]).

E. 2010: M_w8.8 Maule Region, Chile Earthquake and Tsunami

On February 27 the southern coast of Chile was shaken by a strong earthquake with epicenter located offshore about 105 km North-Northeast of Concepcion. Its offshore location caused an important tsunami that affected several hundred kilometers of the Chilean coast causing infrastructure damage. However, the most intense tsunami damage was confined to relatively small areas. Besides network congestion, the most significant cause of outage in Chile was lack of power, primarily in distributed network elements—wireless cell sites and outside plant DLC RTs—which in most cases were not equipped with permanent onsite generators. For example, one network operator had only a small percentage of its 1,000 cell sites and none of its 200 DLC RTs equipped with permanent gensets. Due to the difficulties in procuring portable gensets, network operators used the few portable gensets they already owned before the earthquake struck plus a few more they were able to add from different sources afterwards in order to restore service to their main sites. Once power from the grid was

Fig. 6. Port Bolivar CO.

Fig. 7. Emergency mobile switches outside Sherwood CO after Hurricane Ike.

Fig. 8. A small switch facility near Crystal Beach after Hurricane Ike.

restored to these sites, portable gensets were redeployed to other sites that did not receive gensets due to their lower importance. Nevertheless, service in some cell sites was only restored more than a week after the earthquake, when electricity from the power grid was once again available.

Another cause of failures in wireless cell sites—most of them located indoor, in shelters—was damage caused by the intense shacking due to improper anchoring of batteries, bended equipment frames, or some other type of vibration damage, such as the cell site in Fig. 9.a. Like in other disasters, service to damaged cell sites was restored with COWs, such as the one in Fig. 9.b. The damage assessment was also able to identify many sites where loss of service was caused by fallen or misaligned antennas. For one network operator about 50 % of its sites experienced this type of problems. Yet, cell tower damage was minor with only 2 of the towers of a major network operator collapsing. In one of these cases the failure was initiated by a fallen concrete water tank. The damage assessment was able to document a few cell sites where nearby walls collapsed on the base stations but none of these cases seemed to have led to site outages, corroborating information from network operators not including this failure mode as a cause for service interruptions. Nevertheless, some base stations located on building rooftops needed to be relocated

Fig. 9. a) Left: A damaged base station in Curico and b) Right: the COW likely used to restore service in its area. Notice the satellite link in the COW.

because of the severe damage suffered by the building where they were installed.

The damage assessment identified that infrastructure affected by fallen surrounding constructions was a cause of failure in conventional wireline telephony, especially with drops pulled down by fallen facades. However, many outages were avoided thanks to the use of concrete poles that withstand forces by fallen walls better than wooden poles used in many other countries. Still, lack of power was a failure mode that led to 150,000 wireline subscribers' loosing service; particularly in small remote switches with fewer than 5,000 subscribers because these sites did not have permanent generators. At least 3 larger COs lost service due to collapse walls or damage caused by tsunami waters. A few others sustained damaged, but this damage was not significant enough to prevent operation. At least another CO lost service due to high temperatures caused by air conditioner stopping to operate because the genset at this site failed, as verified by the provisional portable genset found during the damage assessment.

F. 2011: Feb. 22, Christchurch, New Zealand, Earthquake.

On February 22, 2011, Christchurch, New Zealand, was struck by a M_w 6.1 earthquake. Although the earthquake's moment magnitude may not seem as significant as other recent earthquakes, the shallow location of the hypocenter (5 km), soil and terrain characteristics, and the close location to the city, produced significant soil liquefaction areas and one of the most intense sackings ever recorded which in some points reached twice the acceleration of gravity. The earthquake occurred less than 6 months after another earthquake with a M_w of 7.1 affected the same area although with less significant effects. Despite the significant shacking and soil liquefaction observed in the Feb. 22 earthquake, besides network congestions, the most important communication networks failure mode for this disaster was lack of power affecting distributed network elements, particularly wireless communications base stations. Power outages originated in soil liquefaction caused extensive damage to buried cables of power utilities. In wireless networks these power problems were aggravated by extensive use of micro and mini-cells (Fig. 10) which are very rarely equipped with permanent gensets. Although the damage assessment allowed establishing that the area affected by the earthquake was small, the network architectures relying on many low capacity microcells implied both logistical issues and the impossibility of deploying portable gensets to all these sites. In order to prevent outages, important sites were originally designed with extended battery reserve time of up to 24 hours and at least 20 % of the base stations of each network operator received portable gensets immediately after the earthquake occurred. Yet, another potential problem of extensive use of microcells is that their outdoor cabinets are only generally cooled through heat exchangers leading, to more demanding environmental conditions that may affect battery lives and reduce their reserve time. Since the damage assessment was able to verify that outdoor cabinets are only cooled with heat exchangers (Fig. 10), reduced battery backup times is a possibility that may or may not be ruled out to have occurred in the aftermath of this earthquake, as it has been previously commented in earlier disasters, such as in [8]. Power outages not only affected distributed network elements of wireless communication networks but also of the public switched telephony network (PSTN). These PSTN distributed network elements were fiber to the node (FTTN) broadband cabinets. However, restoring power to these sites with portable gensets was in most cases not a primary concern because these cabinets provided data services to customers' computers that cannot operate without power.

Although shacking in this earthquake was extreme, important damage to infrastructure was limited to buried copper cables in areas where significant soil liquefaction occurred. Damage to base stations was very limited with less than a handful of them destroyed by nearby falling buildings or rocks, or because the building where they were located collapsed. Another small number of cell sites had leaning masts but no tower was found to have collapsed. Service to damaged cell sites was restored with COWs. A few COWs were also located at key sites, such as the Civil Defense Headquarters, in order to expand network capacity or to compensate lack of coverage from nearby cells that could not be accessed because, although they were not damaged, they were located on top of buildings at risk of collapse or were located inside the cordoned-out and powerless area of the Central Business District (CBD). Entrance and moving limitations in the CBD also affected operations in a key PSTN central office, which, although it was not damaged, its operation was limited by lack of power and water for its chillers. Although the damage assessment was able to establish some damage to COs, this damage was not critical. Power outages also affected COs, yet, the presence of onsite permanent diesel gensets.

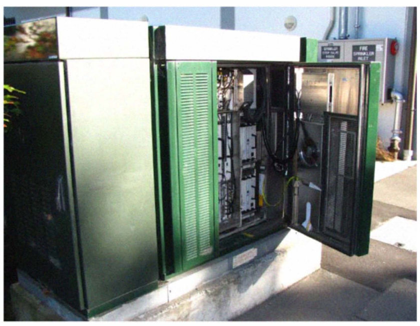

Fig. 10. A minicell base station cabinet showing the door heat exchanger.

G. 2011: Mw 9.0 Great Tohoku Region, Japan, Earthquake and Tsunami.

On March 11, a powerful earthquake struck about 120 km off Japan's Sanriku coast—this is Honshu's island northeastern coast, i.e. the eastern coast of the Tohoku region. Although shacking in most inland areas was not extremely intense, the earthquake location at a subduction zone offshore generated a massive tsunami that affected many coastal towns. In many of these cities, tsunami waves reaching in some places almost 40 m high, overtopped and destroyed seawalls protecting cities and towns. This huge tsunami led to destruction of towns and infrastructure along a several hundred km long stretch of coast. Fires that broke up in several coastal towns due to tsunami-induced damage, added to the destruction. Moreover, the tsunami damaged backup generators at the Fukushima Daiichi Nuclear Power Plant (FDNPP) which were essential to cool nuclear fuel rods when the power grid feed at the site failed. Without cooling, nuclear fuel overheating led to at least partial meltdown in three of the six reactors at the site and explosions at 3 and likely 4 of the reactors, leading to substantial radiation release to the atmosphere and the ocean. As a result of this nuclear accident, the Japanese government declared a 30 km evacuation zone around the FDNPP, of which, the 20 km inner area was eventually completed vacated of residents. In addition to having the FDNPP going offline during this accident, several other nuclear power plants in the area were stopped during the earthquake. Furthermore, some conventional coal-fired power plants were also damaged due to the tsunami. All this significant generation capacity brought offline by the earthquake and tsunami created peak power generation issues that will continue to impact communication networks for months and even years to come. In the immediate aftermath of the disaster, extensive power outages caused by damaged power infrastructure due to shacking (inland) and the tsunami (coast) created significant problems not only to communication sites but also to logistic operations when gasoline stations ceased to operate due to lack of power. Lack of refueling sites added to damaged roads to cause significantly difficult logistical problems that in some areas persisted for up to 3-weeks. Yet, even after roads were repaired and power was restored to gas stations, significant traffic increase in the entire eastern half of the Tohoku region led to road transportation delays up to double the normal time.

Earthquake and tsunami impact on all communication networks in the affected area was significant. However, since NTT occupies a highly dominant market position in both the fixed and wireless communication markets, most of the description that follows next applies to NTT. Maintaining communication services during earthquakes is extremely important in Japan, not only because of well known reasons mentioned in Section I, but also because Japan has implemented an earthquake warning system that gives people a few life-saving seconds notice of a soon to happened earthquake. After an earthquake, maintaining service operation is important in order to send warning messages when strong aftershocks happen. In total, almost 1.5 million PSTN lines lost service during this disaster with the peak outage occurring on March 13th. By March 28th 90 % of these outage lines were restored. Initially, approximately 1,000 of NTT's 1,800 buildings in the region were affected in different ways by the earthquake; most of them affected by power outages. Initial issues affecting most of these approximately 1,000 buildings were soon addressed. However, on March 28th 55 buildings were still presenting issues. Sixteen of these 55 buildings were having minor damage, but the site was not under normal operation due to damage to the power plant but not to the switch fabric, or due to some other unknown reason. Two of these sites with potential power plant issues identified during the damage assessment include the COs at Miyako (Fig. 11) and at Ofunato (Fig. 12). Presence of mobile gensets despite the fact that the site has a permanent genset seem to indicate that the most likely failure mode at Ofunato was failure mode C, although some communication equipment was also affected. Having this failure mode in earthquake and tsunami areas is not uncommon because heavy batteries loading force building designers to place the power plant at low levels in the building in order to prevent structural issues. In Miyako the most likely failure mode was A. Service restoration at these sites involved deploying mobile generators, such as those described in [9] and shown in Figs. 11 and 12. In these cases, transportation infrastructure performance played an important role because of the need for rapid deployment of mobile gensets before batteries are discharged. In other sites, like in Otsuchi, or Yamada (Fig. 13), power was restored with more conventional portable gensets. In both of these sites, the field reconnaissance was able to identify good building construction practices because of the reduced damage received by the switching equipment despite the extreme damage observed around the COs. The damage assessment also documented the presence of water tight doors in the CO of Kamaishi (Fig. 14.a). These doors likely prevented further damage and reduced the MDT at this site, yet power issues, such as those in Miyako may have still occurred in this site. Likewise, watertight doors may not seem to have completely prevented damage to the power plant and communication equipment at Ofunato (Fig. 12). A potential way of further reducing buildings vulnerabilities to tsunamis is to extend water tight closings to windows or to eliminate completely all windows at COs. Still, the cable entrance facility (Fig. 14.b) may be a vulnerable point for water to flood a site. Another vulnerability when implementing this approach is the presence of conventional commercial offices at ground level, that would difficult sealing the building completely to external water actions. Although most of these 16 buildings are located in coastal areas affected by the tsunami, 5 of them are located a few kilometers inland, northwest of the severely affected town of Ofunato and the completely destroyed town of Rikuzentakata. In these 5 COs the failure mode is not clear because they were not directly affected by the tsunami. However, their most likely failure cause was power related. In general, power-related issues was an important failure mode as evidenced by the fact that the initial number of failed lines was a third of those observed at the peak which occurred between 24 and 48 hours later. This is an expected outcome because, as described in [9], many of the low capacity sites do not have permanent gensets and rely on deployment of mobile or portable gensets before batteries are discharged in order to avoid loosing service.

Although power issues were an important source of outages in the PSTN, direct damage caused by the tsunami also contributed to many line failures. Of the 55 buildings with

Fig. 11. Miyako CO powered by a mobile generator.

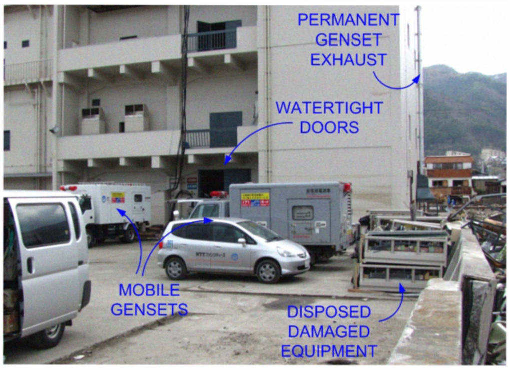

Fig. 12.Ofunato CO powered by mobile and portable gensets.

Fig. 13. Yamada CO powered by portable gnsets.

Fig. 14. a) Left: A water tight door in Kamaishi CO. b) Right: Cable entrance facility in Nobiru CO (as seen from the top).

Fig. 15. Onagawa CO with a house on its roof.

Fig. 16. Rikuzentakata.

issues on March 28^{th}, 26 of them had been destroyed by the tsunami or all of their equipment had been rendered useless by the tsunami. In some of these sites, including Onagawa (Fig. 15), Rikuzentakata (Fig. 16), and Shizugawa, the COs are one of the few remaining standing buildings in the town, which suggest an adequate CO building performance considering the tremendous magnitude of the tsunami—notice that the CO building in Onagawa has the remains of a home on its roof. Such adequate performance will certainly contribute to reduce the MDT. Service restoration in the areas served by some of these COs, such as Onagawa, were similar to those implemented after Hurricane Katrina, i.e., use DLC systems to provide circuits to government facilities and emergency response sites. In other sites, such as in Rikuzentakata, service was partially restored by hosting most of its switching services in a neighboring undamaged CO.

Other failure modes for PSTN COs include isolation due to severed transmission links. These links were interrupted when fiber optic links were damaged by the tsunami, usually by destroying bridges where the fiber optic cable had been installed. Of the originally 90 fiber optic links damaged, on March 28^{th} there were still 4 COs with this problem. Service restoration involved repairing these fiber optic links. Of course, another source of PSTN failure was extensive damage to the outside plant in areas affected by the tsunami. Finally, of the 55 buildings still experiencing issues on March 28^{th}, 9 of them were located in the forced evacuation area around the FDNPP where access was prohibited due to health issues associated to radiation exposure.

Wireless communication networks were also severely affected by the disaster. Although an appreciable number of base stations were destroyed by the tsunami, since most base stations lack a permanent genset, grid power outages were the origin of most base station failures. Once again, lack of power as a main cause of outages can be verified by the fact that on March 11^{th}, 2,200 base stations were down, whereas 24 hours later, out of service base stations peaked at 6,720. Power issues affecting base stations could be examined based the on significant reduced network coverage inland, where the effects of the tsunami were not felt and where shacking was relatively minor. For example, on March 13^{th}, NTT DOCOMO network coverage in Iwate prefecture was 50 % of normal levels inland and there was no network coverage on the coast. The same day, network coverage in Miyagi prefecture was almost non-existent except for the city of Sendai which was mostly covered. In Fukushima Prefecture and on this same day, network coverage on the coast was 0 %, and was about 10 % in the eastern half of the prefecture terrain, and 100% of nominal levels on the western half of the inland area. By March 22nd, service at all but 788 base stations had been restored either because grid power was once again available at the site or because a portable genset had been deployed to restore power. By March 28th, 307 base station had its service disrupted. Of them, 224 had issues with severed transmission links, 62 had been destroyed by the tsunami and 21 still needed to be inspected. By late April 59 base stations were still experiencing outages. It is also important to point out that 68 service affected base stations in the area around the FDNPP need to be added to the figures of March 22nd, March 28th and late April. Of the damaged base stations, the field reconnaissance documented cases of collapsed towers (Fig. 17), destroyed base stations after having been hit or carried away by the tsunami and debris (Fig. 18), and/or fires (Fig. 19). Notice in all these cases the vulnerable location of base stations at ground level. By finding collocated wireless network switching equipment and PSTN equipment, the damage assessment was also able to identify that another problem that affected wireless networks operation, particularly during the first days, was outages affecting PSTN exchanges. Service restoration to damaged base station involved some limited use of COWs (Fig. 20.b) , micro-cells (Fig. 20.b), equipment repair, or shifted coverage to neighboring cell sites with increased capacity and that were undamaged by the tsunami because they were on hill tops. Severed links were restored through repairing them or by installing temporary microwave links (Fig. 21) or satellite links (Fig. 20.b). Up to 870 satellite phone terminals were also used to restore wireless services in some key locations. Satellite phones were also used to support utilities restoration efforts in the aforementioned disasters, although in the case of Hurricane Katrina, their use was affected for a period of a few days when an intense solar storm interrupted satellite communications.

One final note of relevance is to mention the satisfactory performance of the microgrid site in Sendai that was presented in INTELEC in earlier years [10]. Thanks to the reinforced design of the natural gas feed for the generators and the agreement in place with the natural gas distribution company, natural gas to the microgrid was not interrupted, even when the rest of the city had its natural gas service stopped for several days. Although the generators went offline for a few hours onsite batteries kept the load at the high-power quality circuits powered. After the issue with the generators was addressed, they remained powering the high-power quality levels loads continuously. As expected, power to the standard-quality levels loads was off until power from the grid was restored.

III. ADDITIONAL OBSERVATIONS AND RECOMMENDATIONS

Consider once again the set of questions that are the target of the damage assessment studies and that were introduced in Section II.A. The set of questions #1 refer mostly to design and operational issues. For both failure modes A and B, one alternative approach is to utilize novel communication power plants based on micro-grids [11], such as the one tested by NTT in the city of Sendai. One of the advantages of micro-grids is enabling a more reliable power supply through functional diversity [11]. Moreover, they allow integration of renewable sources such as photovoltaics which do not depend on lifelines. As such, micro-grids become true sustainable power systems in the sense that they sustain operation amid extreme conditions. Furthermore, use of combined heat and power generation address issues due to air conditioners low power supply availability [12]. Other design approaches imply the use of extended local energy storage through fuel cells (Fig. 22) or alternative local power standby systems [7]. The set of questions #2 allow to address the aforementioned failure modes, too. In this case, in addition to design and operation issues, the MDT is also related with maintenance policies and logistical operations. For example, as already discussed, failure modes A and B are typically addressed through the deployment of portable generators. Failure mode C can be addressed by deploying mobile power plants. Unfortunately, in some severe events, Failure Mode D is inevitable (Figs. 15). In these cases, some of the discussed solutions include deploying digital loop carrier systems (Fig. 4) or containerized solutions (Fig. 23) or switch-on-wheels to restore a damaged central office (Fig. 7), or cell-on-wheels to restore service to damaged base stations (Figs. 20.a).

In all these recent disasters it was possible to find one or more COs that loose service. This outcome seems to exceed the effects of disasters of a decade or more ago. The question that remains to be answered is whether this difference is caused by new observations enabled by the damage assessments, or whether the failures of COs in recent disasters are originated in new communication technologies that make COs more vulnerable to natural disasters. Similar questions can be raised regarding entire networks. Have new technologies made them more vulnerable? One of such newer technological approaches already discussed in [7] is the increased use of locally powered distributed network elements, such as DLC RTs. For these network elements, wherever possible it is advisable to use central power from the CO using a split phase ±190V power distribution system using existing copper infrastructure. In some other few cases, use of renewable energy sources may reduce logistical needs even when it may not be possible to power the entire load. However, as pointed out in [7], it is still difficult to find a general solution for all cases.

IV. CONCLUSIONS

This paper has shown the value of conducting damage assessments after natural disasters as an extreme empirical approach to support learning about communication infrastructure availability, both in normal conditions and during extreme events. The damage assessments attempt to answer two set of questions through field collected data and information. The discussion is supported by describing relevant observations gathered from damage assessments conducted after recent disasters around the world. Common failure modes and practices both to reduce the mean down time and to increase the mean up time are discussed with the end goal of improving communications availability.

Fig. 17. A destroyed cell site near Rikuzentata.


Fig. 18. A destroyed cell site in Ishinomaki.

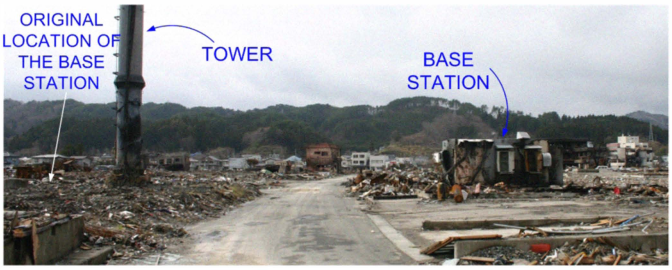

Fig. 19 A destroyed cell site by the tsunami and fire in Yamada.

REFERENCES

[1] A. Kwasinski, W. Weaver, P. Chapman, and P. T. Krein, "Telecommunications power plant damage assessment caused by Hurricane Katrina - Site survey and follow-up results," *IEEE Systems Journal*, vol. 3, no. 3, pp. 277-287, Sept. 2009.

[2] A. Kwasinski, "Telecom Power Planning for Natural Disasters: Technology Implications and Alternatives to U.S. Federal Communications Commission's "Katrina Order" in View of the Effects of 2008 Atlantic Hurricane Season," in *Proc. INTELEC 2009*, 7 pages.

[3] Louisiana Public Service Commission public records.

[4] R. Berg, "Tropical cyclone Report, Hurricane Ike (AL092008), 1 - 14 September 2008." National Hurricane Center Report, 23 Jan. 2009.

[5] R. D. Knabb, J. R. Rhome, and D. P. Brown, "Tropical cyclone Report, Hurricane Katrina, 23-30 August 2005." National Hurricane Center Report, Dec. 2005 – Updated Aug. 2006.

[6] Texas Public Utility Commission, public records.

[7] A. Kwasinski, "Telecommunications Outside Plant Power Infrastructure: Past Performance and Technological Alternatives for Improved Resilience to Hurricanes," in *Proc. INTELEC 2009*, 8 pages

[8] R. Ireland, "Learnings and challenges of the Northern California earthquake," in *Rec. INTELEC 1990*, p. 1.

[9] S. Iwai, et. al., "Use of mobile engine generators as source of back-up power," in *Proc. INTELEC 2009*, 6 pages.

[10] K. Hirose, T. Takeda, and S. Muroyama, "Study on Field Demonstration of Multiple Power Quality Levels System in Sendai," in *Proc. INTELEC, 2006*, pp. 256-261.


Fig. 20. a) Left: A COW in the town of Osawa. b) Right: A micro-cell used to restore service to the cell site in Fig. 17.

Fig. 21. An Emergency microwave transmission site in Otsuchi.

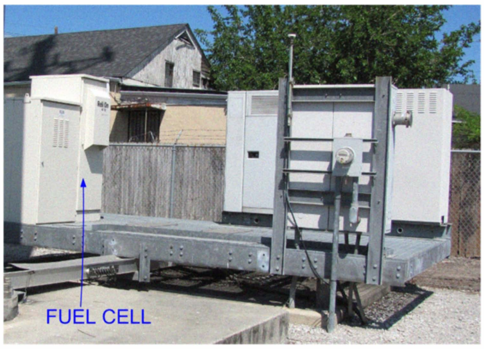

Fig. 22. A back up fuel cell for a base station in New Orleans.


Fig. 23. Shelters with switching equipment used to restore service to Shichigahama CO. Its original building was displaced 500 m by the tsunami.

[11] A. Kwasinski and P.T. Krein, "Optimal configuration analysis of a microgrid-based telecom power system," in *Proc.INTELEC 2006,* Sept. 2006, pp. 602 - 609.

[12] A. Kwasinski, "Analysis of Electric Power Architectures to Improve Availability and Efficiency of Air Conditioning Systems," in *Rec. INTELEC 2008*, 10-2 pp. 1-8.