Regional Comparisons of Critical Telecommunication Infrastructure Resiliency Based on Outage Data

Andrew P. Snow, John C. Hoag
School of Information and Telecommunication Systems
Ohio University
Athens, Ohio USA
Email: snowa@ohio.edu; hoagj@ohio.edu

William A. Young
Department of Management and Strategic Leadership
Ohio University
Athens, Ohio USA
Email: youngw1@ohio.edu

Gary R. Weckman, Naga T. Gollamudi
Department of Industrial and Systems Engineering
Ohio University
Athens, Ohio USA
Email: weckmang@ohio.edu, ng746812@ohio.edu

***Abstract*— The resiliency of telecommunication infrastructure by US Federal Emergency Management Agency (FEMA) region, is presented, based on almost 9,000 telecommunication outages over a 14 year period. Executive policy organizations in the US have described a resilient infrastructure as one that can minimize the magnitude and/or duration of service disruptions. To that end an empirical assessment of resiliency is made by region using telecommunication outages, each of which has duration and magnitude (the number of users affected by the outage). Wireline central offices are essential to telecommunication infrastructure, as they house local switching, transmission, and user access infrastructure for both voice and data services, including the Public Switched Telephone System (PSTN), the Internet, mobile communications, and emergency communication. Central office resiliency is studied by proxy, examining local telephone switch outages in those offices over 14 years. Regional comparisons are first made using classic time-series-of-event reliability techniques, allowing reliability trend comparisons. Next, outage cause comparisons are made. Then, a resiliency metric is presented that allows a fair comparison between regions differing in population. Marked differences in resiliency trends are apparent in some FEMA regions.**

Keywords- Resiliency; FEMA; telecommunication outage; critical infrastructure.

I. INTRODUCTION

The resilience of telecommunication services and capabilities are important to any nation. In the US, the Department of Homeland Security (DHS) states, in reference to critical infrastructure of all types, that resilience is

> *"….the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies. Whether it is resilience towards acts of terrorism, cyber attacks, pandemics, and catastrophic natural disasters, our national preparedness is the shared responsibility of all levels of government, the private and nonprofit sectors, and individual citizens."* [1]

Additionally, The National Infrastructure Advisory Council (NIAC) was created as a Federal Advisory Committee to advise the President and the Secretary of Homeland Security on all areas of critical infrastructure. NAIC further refines the definition of effective infrastructure resilience to include measurable attributes:

> *"Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a … disruptive event."* [2]

This research presents a resilience metric that include not only the magnitude and duration (called "impact") of telecommunication outages, but also frequency of these outages, on a regional basis. The regional paradigm chosen for this research is defined by FEMA, who

> *"…coordinates the federal government's role in preparing for, preventing, mitigating …. responding to, and recovering from all domestic disasters, whether natural or man-made, including acts of terror."* [3]

In performance of this mission, FEMA has divided the US and its territories into ten regions, shown in Figure 1, which present a useful and practical way to study critical telecommunication infrastructure resiliency across the US.

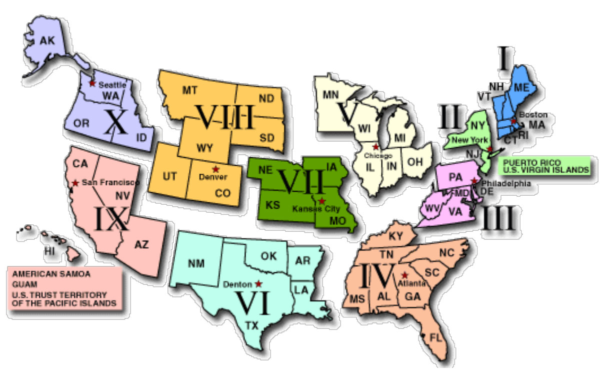

Figure 1. FEMA regions [4]

This paper addresses telecommunication infrastructure resiliency based on a 14 year record of U.S. PSTN local telecommunication switch outage data. In Section II Background, the role of local switches as service access points in the PSTN is covered. The importance of Central Offices where local switches, mobile switching, and internet access equipment is housed is discussed. Also, a description of the outage data is presented. In Section III, Methods and Results, regional differences in outage causality, reliability and resiliency methods and results are presented. Lastly, in Section IV Summary, major findings, research limitations, implications, and future research are discussed.

II. BACKGROUND

A. Central Office Buildings Serve More Than the PSTN

Central Offices house not only local voice telephone switches, but also other important network elements such as mobile communication backhaul and Internet access/transport equipment. For instance, it is not uncommon for a Mobile Switching Center (MSC) circuit switch to be located in a Central Office building. Alternately, the local exchange carrier often provide a wireless carrier Layer 1/2 connectivity between its Base Station Controllers (BSC) and its MSCs, which might be tens to hundreds of miles away. In these cases, the Central Office building is very important to wireless voice and data services.

Additionally, there are often optical SONET add/drop multiplexers in Central Offices that not only provide trunking between PSTN switches, but also digital internet trunks. At Layer 2/3, central offices involved in backhaul could be forwarding or aggregating Metro Ethernet virtual circuits per VLAN, interconnecting virtual circuits to Multiprotocol Label Switching (MPLS). Also, Central offices house important Internet assets such as routers and DSL internet access equipment. So, a range of services from Metropolitan Ethernet, MPLS, multiplexers and DSL can be adversely affected by the same factor that causes a local telecommunication switch in a Central Office to fail [5].

For these reasons, PSTN local switch outages that are caused by external circumstances, potentially affecting all electronics in a Central Office building, can be an indicator of PSTN, Mobile, and Internet telecommunication infrastructure resilience. Such local switch outage causes include those induced by external power outages, building damage, massive line cuts, and acts of god.

B. Local Telecommunication Switches

The PSTN is a complex system composed of a switching subsystem, a signaling subsystem, and a transmission subsystem. The switching subsystem routes voice calls throughout the PSTN network. The signaling subsystem coordinates call initiation, maintenance, and termination. The transmission subsystem provides physical links between switches so end-to-end voice circuit connections can be made. The signaling and transmission subsystems are not part of the research in this paper. The switching subsystem consists of local exchange switches (local switches), tandem switches, and international gateway access switches (see Figure 2). Only the local exchange switching subsystem is investigated in this study. There are three types of local switches: standalone, host, and remote. Less common are some tandem switches that also have access lines, but they are very small percentage of all switches in this study with outages. Importantly, best practices requires E911 call centers to connect to two tandems – however, as many centers are far away from tandems, some local switches are configured to act as tandems for E911 calls [6]. The importance of local switches using circuit switched technologies should not be underestimated. Even though the PSTN is migrating to voice over internet protocol (VoIP), the migration will take many years, and local switches will be in service for many years [7]. In 2011, although there were 32 million VoIP subscribers, there were 117 million subscribers connected over local loops to circuit switched local switches [8]. Also consider the work of Lyons, et al, where the economic impact of telecommunication outages were empirically assessed for local exchange outages. The economic loss estimates are based on actual business and residential demographics, including residential service and manufacturing. Economic loss estimates ranged from €370,000 to €1.1 million per day, for seven local exchange outages in Ireland [9].

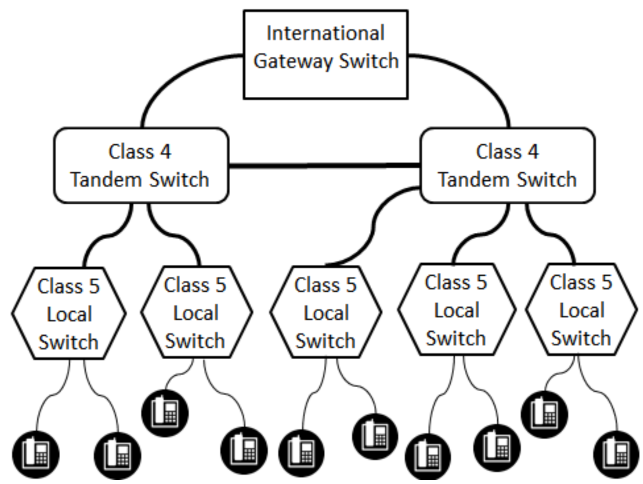

Figure 2. The PSTN switching subsystem.

C. Local Telecommunication Switch Outage Data

This study investigates 8,975 local telecommunication switch outages in the U.S. of at least 2 minutes in duration for a 14-year period (1996-2009) and considers only totally failed switches rather than partially failed switches (partially failed switches were not reported). Scheduled outages are not included because of their small duration – only the 8,875 outages caused by failures are studied here. Scheduled outages are not considered. This outage data was reported to the Federal Communications Commission (FCC) and obtained from [10]. Unfortunately, after 2009, the FCC stopped requiring carriers to report this data. Carriers classified each local switch outage incident using one of fifteen FCC defined cause codes. In this research, by combing

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similar cause codes reported to the FCC into categories, we reduced the fifteen causes reported to the FCC down to five causality categories, similar to what was previously done in [11]:

- Human Procedural Errors: Procedural errors made in installation, maintenance or other activities by Telco employees, contractors, or vendors.
- HW and SW Design errors: Software or hardware design errors made by the switch vendor prior to installation.
- Hardware Errors: A random hardware failures, which causes the switch to fail.
- External Circumstances: An event not directly associated with the switch, which causes it to fail or be isolated from the PSTN.
- Other/unknown: A failure for which the cause was not ascertained by the carrier.

As each reported switch outage includes date, time, duration, magnitude, and location, important reliability and resiliency analysis can be performed.

III. OUTAGE ANALYSIS METHODS AND RESULTS

A. Regional Local Switch Causality Differences

To see to what extent switch outage cause categories might differ across regions, histograms were created for major cause categories. Each histogram shows the percentage of outages due to a particular causal category across the ten regions, two of which are shown in Figure 3. These categories, their composition, and the distribution of failures to each category are shown in Table I.

Figure 3. Regional causal percentage histogram examples.

TABLE I. LOCAL SWITCH OUTAGE FREQUENCY BY CAUSE

OUTAGE CATEGORY	**Frequency**	**Percent**
Human Procedural Error	1,394	16%
HW or SW Design Error	1,214	14%
Random HW Failure	2,951	33%
External Circumstances	2,900	32%
Other/Unknown	516	6%
Total	8,975	100%

For each cause category, the question of interest is whether there is a statistical difference in causal category percentages across the regions. The following hypotheses were used to test this notion for each histogram:

H_0: Cause category percentages is uniformly distributed across the 10 regions

H_a: Cause category percentage is not uniformly distributed across the 10 regions

The method used to test the hypotheses is the Chi-squared test, where the expected values are the average percentage across the 10 regions for each cause category, and the observed values are the actual percentages across the regions in a histogram. The results are shown in Table II, where we accept differences across the regions in the "External Circumstances" and the "Other/Unknown" cause categories.

TABLE II. REGIONAL OUTAGE CAUSALITY DIFFERENCES

CAUSE CATEGORY	ACCEPT	P-VALUE	CONCLUSION
External Circumstances	Ha	0.0005	Different across regions
Random HW Failures	H_0	0.4599	No difference across regions
Human Procedure Errors	H_0	0.5655	No difference across regions
HW or SW Design Errors	H_0	0.2599	No difference across regions
Other/Unknown	Ha	0.0340	Different across regions

These results are useful, because they indicate that "External Circumstance" outages are not uniform across the regions. The makeup of external circumstances are the type of events that potentially affect all central office telecommunications equipment/services, rather than just the PSTN local telecommunication switch. For instance, the vast majority of external circumstance local switch outages are due to environmental reasons such as FCC cause codes described by "acts of god", "external power failure", "environmental" and "massive transmission facility loss". These type of outages are very likely to also affect all other communications services in the central office building such as mobile switches, transmission and internet equipment. Note that Regions 4 and 6 have the highest percentages of outages due to external circumstances

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B. *Regional Local Switch Reliability Differences*

Reliability is a study of times-to-failure (ttf), or said another way, the study of failure arrival process. If a failure rate is constant, the failure process is a stationary failure process, and Mean-Time-to-Failure (MTTF) can be calculated. If the times-to-failure are independent and exponentially distributed, the process is called a Homogeneous Poison Process (HPP). If the ttf's are not exponentially distributed, but still independent, the failure process is a renewal process (RP), and the distributions can be fitted to other distributions such as Weibull, Gamma, or other distributions.

Cumulative failure count versus time plots are often used to assess whether the arrival rate is constant, in that a straight line is apparent. However, if the plot is concave (bending down), reliability growth is indicated as the failures are decreasing over time. Conversely, if the plot is convex (bending up), reliability deterioration is indicated as the time between failures is decreasing. In these cases, the failure process is non-stationary and distributions cannot be used and MTTF cannot be calculated, as it is a function of time. However, if the bending is smooth and steady (monotonically increasing or decreasing), these processes can be modeled as Non-homogeneous Poison Processes (NHPP), also known as "doubly-stochastic processes" as the arrivals are random and the rate of arrivals is changing over time. If the changes are not smooth, these processes can often be analyzed in a piecewise fashion over time. The reliability from cumulative plots can easily be assessed visually, and if the changes appear subtle, analytical methods can be used to arrive at the degree of statistical significance of trends (using such tests as the Laplace trend, Lewis-Robinson, Mann, or the MIL-Handbook tests [12].

In this research, to compare the reliability of local switch outages by region, cumulative plots were made for each region and visually assessed for reliability growth, constancy, or deterioration. In no instances were the visual presentations subtle, so no formal statistical trend tests are necessary. An example of cumulative outage plots vs. years are shown in Figure 4. Note that the number of outages differs, however this is not important at this stage of the comparison, as we are looking for differences in trends for each region. A normalized resiliency comparison will be made later in the paper.

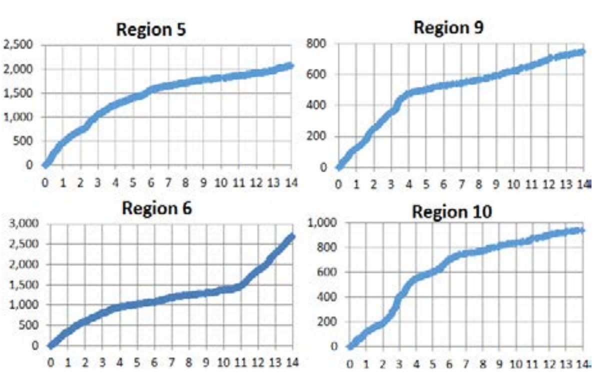

Figure 4. Regional switch cumulative failures vs. years

Region 5 exhibits classic reliability growth, which could by modeled by an NHPP. However, Region 6 exhibits two distinct piecewise regions – steady reliability growth over about 11 years, followed by reliability deterioration over the last 3 years. Region 9 also exhibits two distinct piecewise regions – fairly constant reliability for about 4 years followed by 10 years of fairly constant reliability at a much lower failure rate. Region 10 indicates reliability growth, but is not as smooth as smooth an improvement as Region 5. A summary of the visual assessments for each region is shown in Table III.

TABLE III. LOCAL SWITCH RELIABILITY TRENDS BY REGION

Reg.	Rel. Trend (Imp. - Improvement; Det. – Deterioration)
1	Monotonic Imp.
2	Monotonic Imp.
3	Monotonic Imp.
4	Monotonic Imp. for 13 years, steep Det. for last year
5	Monotonic Imp
6	Imp. for 11 years, steep Det. for last 3 years
7	Monotonic Imp.
8	Det. years 0-4, marked Imp. years 4-14
9	Constant years 0 to 4, marked Imp. years 4-14
10	Monotonic Imp.

At this point, it is useful to present the cumulative failure plot for all 8,975 switch failures in the U.S., as seen in Figure 5. Note that the overall trend is decreasing, as indicated by the Laplace Trend Test statistic U, where U is like a Z-score where at a value greater than +1.96, we accept the hypothesis of reliability growth at a critical value of 0.05. However, the trend is seen to be monotonically improving up to year 11, after which it starts to monotonically deteriorate. It appears that the reason for this deterioration is due to Regions 4 and 6. This observation is corroborated by the external circumstance frequencies for Regions 4 and 6, which is in Figure 3.

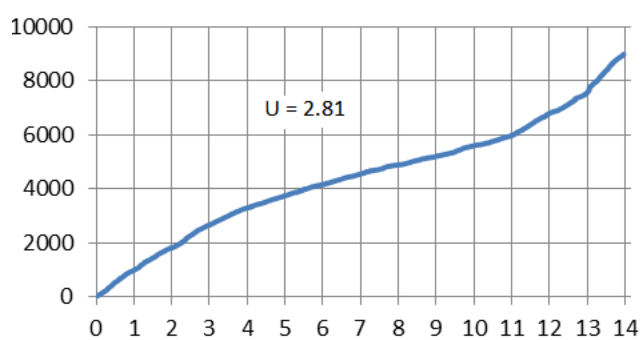

Figure 5. Local switch cumulative failure plot vs. years for the U.S.

C. *Regional Local Switch Resiliency Differences*

Earlier, we pointed out NAIC's interest to be minimizing the magnitude and/or the duration of impacts to critical infrastructure. So any resiliency measure must account for these factors. There has been past work using these two variables in assessing impact of telecommunication outages.

McDonald introduced the User Lost Erlang (ULE) as an impact metric for large-scale outages, given by:

$$ULE = log_{10}\ (Magnitude) \tag{1}$$

where magnitude is the subscribers impacted. So the impact of an outage affecting 100,000 lines would be 5 ULE. McDonald figured such a metric would be easy to use and be understandable by the public, similar to the logarithmic Richter scale for the intensity of earthquakes [13]. The disadvantage of the ULE is that only outage magnitude is taken into account -- duration is not. As outages have both size and duration, the ULE was not adopted or used, but did establish the need for an outage metric.

The FCC introduced use of the Lost Line Hour (LLH) metric, which is the product of the number of subscribers lost times the duration in hours, and also the lost line minute. For instance, a 100,000 line switch out for ½ hour represents 50,000 LLH. Although a straightforward metric incorporating both size and duration, the LLH does not include blocked calls. Also, the LLH is not logarithmic, a feature that nicely accommodates very long or large outages.

In the U.S., Committee T1, published an American National Standards Institute (ANSI) sponsored metric called the Outage Index (OI). This metric mapped duration and magnitude to weightings, which are logarithmic-like. The carrier industry adopted the OI metric. Analysis of the OI indicated a network administrator bias, as the index was sensitive to large size outages, but insensitive to long duration outages [14]. As an example, in [15] it was demonstrated that if a local switch with 10,000 lines experiences an outage of 24 hours duration the OI is 0.529, while an 8-day outage for the same switch is 0.532. The other disadvantage of OI is that the values are not intuitive, for example, what does an outage with an OI of 1.24 mean with respect to impact? Lastly, in [16], resiliency was more recently defined as the fraction of subscribers deriving successful service. Although an interesting metric, the number of users impacted is not apparent from say 0.99 resiliency factor.

Snow and Weckman recently introduced a novel resiliency metric for local switch outages in [17]. The metric is referred to as OI_{dbK}, includes both duration and magnitude (represented by LLH), is logarithmic, and intuitive as it is referenced to a baseline outage of 1000 LLH:

$$OI_{dbK} = 10log_{10}\left[\frac{LLH}{1000}\right] \tag{2}$$

Like the well-known *dbm*, a power referenced to 1 milliwatt in communications engineering, a doubling is about 3db while a halving is about -3db. Additionally, a tenfold increase is 10db and decrease by a tenth is -10db. Below are a few examples of OIdbK:

- OI_{dbK} = 0 corresponds to 1,000 LLH, as log of 1 is 0
- OI_{dbK} = -3 represents a halving, or 500 LLH
- OI_{dbK} = 20 corresponds to two orders of magnitude above 1,000 LHH, or 100,000 LLH
- OI_{dbK} = 23 is s a doubling above 20, or 200,000 LLH.

This new metric tames wide swings of LLH, and give an intuitive reference when doing time series plots and regression of outage resilience over time. Of course, if desirable, we can also have OI_{dbM}, which references the severity to one million LLH. Additionally, with outliers controlled, linear regression can be used to assess trends in resilience. An example of the utility of OIdbK is seen by referring to Figure 6 and Figure 7, where LLH and OIdbK for impact due to external circumstances are plotted The LLH plot appears unremarkable while the OIdbK plot indicates relative values of impact and a clear upward trend. In fact, statistically significant linear regression results for local switch external circumstance OIdbK indicate a 10.6 db increase per 10 years, which represents just over a 10 fold increase in LLH. [17].

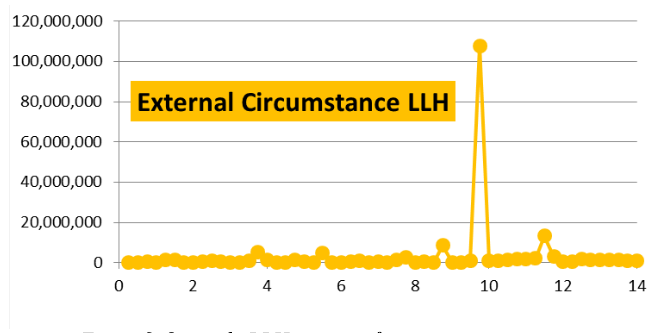

Figure 6. Quarterly LLH vs. years for ext. circumstance outages

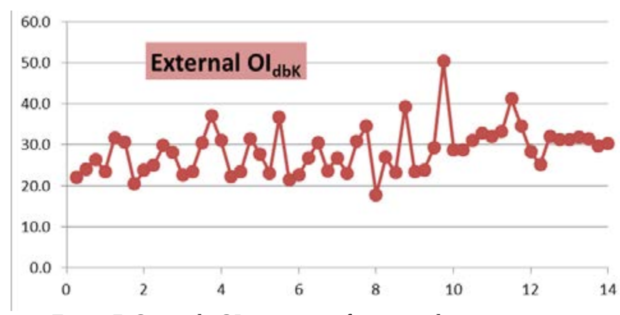

Figure 7. Quarterly OI_{dbk} vs. years for external circumstance outages

FEMA regions are different in a number of geographical factors, such as climate, area, and population. Where there are more people, there are more switches, so we expect more failures and more impact on resilience due to switch outages. There is a large range in population over the regions, as seen in Table IV.

TABLE IV: REGIONAL POPULATION AND OUTAGES

Region	Population (Millions)	Outages
1	19.0	139
2	31.6	301
3	28.3	519
4	55.3	2,300
5	50.7	1,299
6	34.4	2,139
7	13.1	1,065
8	9.7	246
9	44.0	488
10	11.6	479

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For a fair comparison of regional resilience, in this research we modify the OIdbK by weighting LLH by population in millions, and reference the value to 1000 LLH per 1 Million people:

$$OI_{dbK/M} = 10log_{10}\left[\frac{LLH}{Pop\_Mill}\Big/\frac{1000LLH}{1\ Mill}\right] \quad (3)$$

where Pop_Mill is average regional population (in Millions, e.g., 19.0 for Region 1) over the study period. The average population was used because there was little percentage change in regional population over the study period. This new metric has all the advantages of OI_{dbK} in addition to being scaled to the number of people in the region.

Comparative regional resilience examples are shown in Figure 8 and Figure 9, due to all outages. In Figure 8, upward impact over time indicates resiliency deterioration in both Regions 4 and 6. The deterioration in these regions are very similar, however note the large outliers in years 6 and 10 for Region 6. Examples of resiliency growth and constancy are shown in Figure 9. In Region 1, relatively constant resiliency is indicated, while in Region 1 strong resiliency growth is seen by the dramatic downward trend in outage impact.

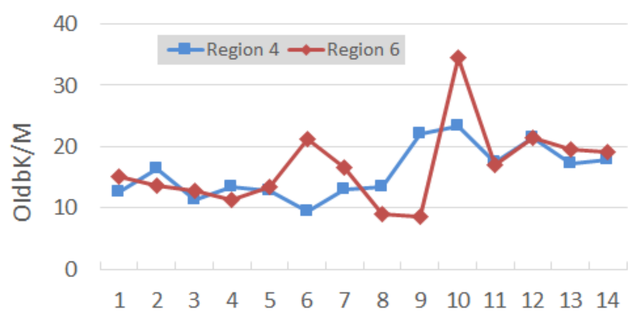

Figure 8. Yearly outage impact for regions 4 and 6

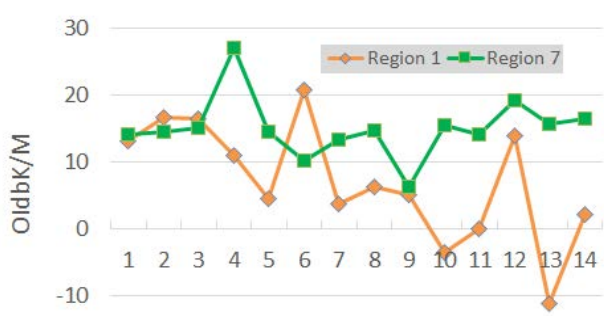

Figure 9. Yearly outage impact for regions 1 and 7

Although there is not room in this paper to show all ten regional impact plots, a qualitative description of FEMA regional resilience is given in Table V. In this table, regional resiliency is described as either improving, constant or deteriorating. Trend descriptions are based on regression lines for each regions outage impact plot.

Table V. REGIONAL RESILIENCY TRENDS

Reg.	Resiliency	Description based on Regression
1	Improving	Starting at 16db, and dropping to 0db over 14-years (from 40K to 1K LLH per mill pop.)
2	Improving	Starting at 16db, and dropping to 6db over 14 years (from 40K to 4K LLH per mill pop.)
3	Deteriorating	Starting at 10db, and increasing to 16db over 14-years (from 10K to 40K LLH per mill pop)
4	Deteriorating	Constant first 8-years at 13db, up to 19db over 6-years (from 20K to 80K LLH per mill pop.)
5	Constant	Constant at about 10db, or about 10K LLH per mill in pop.; some large variances
6	Deteriorating	Starting at 13db, and increasing to 18db over 14-years (from 20K to 80K LLH per mill pop.)
7	Constant	Constant at about 15db, or about 40K LLH per mill in pop.
8	Improving	Starting at 10db, and dropping 10db over 14 years, a drop of 10,000 LLH per mill pop.
9	Constant	Constant at about 10db, or about 10K LLH per mill in pop.; some large variances
10	Constant	Constant at about 10db, or about 10K LLH per mill in pop.; some large variances

IV. Summary

A. *Major Findings*

The major findings of this research on FEMA regional local telecommunication switch outages from 1996 to 2009 are:

- From a causality perspective, there are statistically significant differences in external circumstance outages across the regions. Additionally, histograms indicate the largest differences are due to Regions 4 and 5. External circumstance local switch outages are also likely to affect other telecommunication sector capabilities such as mobile and internet.
- Over a 14-year period, the arrival process of outages in each region are non-stationary processes for which time-to-failure distributions and MTTF metrics are not feasible. However, there are clear instances for some regions where there are different processes over the entire period, which can be segmented and analyzed separately. In some instances they are piecewise linear (constant reliability) where MTTF can be calculated.
- Most regions experienced dramatic reliability growth in local switch reliability over the 14-year period, although two regions (Regions 4 and 5) experienced initial reliability growth for most of the time period but severe reliability deterioration towards the latter part of the 14 years.

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- From a resiliency perspective a recently introduced resiliency metric was successfully modified to weight impact by regional population, offering a fairer way to compare geographically different regions. The metric also conforms to NAIC desires, as it accounts for both magnitude and duration.
- These results indicate that empirical methods and metrics are very useful in understanding the impact of outages to critical infrastructure, and that resilience is best understood when coupled with reliability, or the arrival rate of outages, which are in fact resiliency deficits.

B. Research Limitations

As the quantitative research presented here is based on data reported by carriers, it is not known how consistent the reporting was over a 14-year period by each carrier, and how similar the capabilities of carriers to capture outages, and accurately report the size, duration, and cause of outages. Additionally, only complete switch failures are reported and partial switch outages were excluded from reporting requirements. Also, this research was limited to using lost line hours in its resiliency metrics, as no reporting of blocked calls was required of carriers. Lastly, actual impact of local switch external circumstances outages on mobile communication and Internet services/infrastructure in the same Central Office buildings cannot be quantified by these results.

C. Future Work and Policy Implications

More research is required to develop better resilience measures across all sectors of the telecommunication industry, in addition to metrics that can be linked or include economic impact. Additionally, the results in this paper indicate that local switch outages might serve as a “canary in the mine shaft” with respect to telecommunication infrastructure resiliency, due to the plethora of other telecommunication service sector equipment residing in PSTN Central Office buildings. In retrospect, these results indicate that the FCC’s discontinuance of local switch outage reporting after 2009 might be unfortunate, as an insightful reliability and resiliency bellwether seems to have been lost.

V. ACKNOWLEDGEMENT

This work is based on an unpublished paper presented at the 13th Annual Conference on Telecommunications and Information Technology, ITERA 2015 [18]. The original work has been corrected, refined and augmented here.

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