A Reliability and Survivability Analysis of Local Telecommunication Switches Suffering Frequent Outages

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Abstract— **This paper presents a reliability analysis of local telecommunication switches experiencing frequent outages in the United States, based upon empirical data. Almost 13,000 switch outages are examined and over 2,500 are found to originate with just 156 switches experiencing eight or more outages each over a 14-year period. Telecommunication switch outage statistics are analyzed for this multiyear period, allowing examination into switch failure frequency, causes, trends, and impacts. Failure categories are created by reported outage cause codes, including human error, design error, hardware failure, and external factor causality categories. Principal findings are that there are significant differences in the switch and outage characteristics for switches experiencing more frequent outages/failures. Additionally, time series analysis indicates significant reliability/survivability deterioration in switches experiencing more frequent outages.**

Keywords- telecommunication; reliability; local switches; mobile switching centers; public switched telephone network; wireless systems.

I. INTRODUCTION

Historically, the Public Switched Telephone Network (PSTN) in the U.S. has been used predominantly for landline voice services. However, with the exponential growth of mobile voice services, the PSTN has been integrated with wireless systems. In fact, for calls outside of regional areas, wireless serves as radio interface technology, taking place of local loop connectivity. A call over hundreds or thousands of miles travels a very small percentage of the total distance over wireless infrastructure, as the wireless system connects to the PSTN for long haul transport. Both the PSTN and wireless systems use circuit switches manufactured by the same equipment suppliers. In fact, the switches are very similar. As such, we expect local PSTN telecommunication systems to be very reliable and survivable, as they are the access nodes to transport services in voice networks, for both landline and wireless calls. As there are many thousands of these switches in the PSTN, monitoring and improving local switch reliability is of great importance. Also, wireline switch outage characteristics serve as a good proxy for wireless mobile switching centers.

Continuous improvement of any communications device, such as local telecommunication switches, requires documenting today's performance, and measuring against that baseline. It is important to know reliability trends, not merely to predict, but to influence the future in a proactive way. The key to managing highly reliable systems is the recognition of an important precept – a reliability trend does not have to be accepted and actions may in fact be taken to alter the trend. However, all failures cannot be prevented, as products are put into environments with hazards of all types. But understanding failure modes and how to avoid certain failures is important. Additionally, management must endeavor to decrease the chance of human induced errors throughout he lifecycle. This can be done by training, tools, and other support, but management must make reliability a priority and fund reliability programs, effectively managing reliability engineering [1]. In order to change a trend, we look for approaches that will offer insights into why failures are occurring. Telecommunication switch reliability is determined by the complex interaction between software, hardware, operators, traffic load, and a variety of environmental factors. By knowing failure causes, designers (switch vendors) and operators of telecommunication switches (service providers) may take corrective action to alter future trends. Likewise, Barnard argues that modern reliability engineering must embrace the principal of continually improving products throughout the lifecycle, to include FRACAS (Failure Reporting, Analysis and Corrective Action System) before and during the operational phase of products [2].

There has been a paucity of published empirical research concerning the reliability of operational telecommunication switches in the US. Snow investigated local switch outage from 1992 through 1995, and documented reliability growth [3]. Later, Snow also noticed that some switches failed many times, while others failed infrequently [4]. This paper extends that early research over the years 1996 through 2009.

II. RESEARCH QUESTIONS

This Research will address the following questions regarding telecommunication local switch reliability and survivability over a 14 year period:

1. Are the characteristics of switches failing more frequently different from those that are not?
   a. Switch size (lines)
   b. Rural or Urban location
2. Are the event characteristics for switches failing more frequently different from those that are not?
   a. Causes
   b. Duration of outages and impact
   d. Time of day (TOD), Day of Week (DOW), and Month of Year (MOY)

 ISBN: 978-1-61208-245-5

3. Are the failure trends for switches experiencing failures more frequently different from those that are not? Has there been reliability/survivability:
   a. Growth,
   b. Constancy, or
   c. Deterioration?

Reliability is the probability a system will perform its intended function, in the intended environment and at a particular level of performance. Thresholds are very commonly used to declare a system as in either an "operational" or "degraded" mode [5]. Others define reliability as "conformance to specifications over time"[6].

If the system is in a degraded mode, there is a failure event. Survivability is "The capability of a system to fulfill its mission, in a timely manner, in the presence of attacks, failures, or accidents." and is also a resiliency characteristic [7]. Outage frequency and impact, resulting from failures and accidents, are survivability measures. Therefore, for this paper we will principally analyze failure events to assess reliability, and scheduled/unscheduled outages to assess survivability. The data consists of local switches experiencing outages 2 minutes or more in duration. If a switch experiences a failure, it results in an outage, which has an impact until the failure is mitigated and service restored.

III. CONTEXT AND IMPORTANCE

The PSTN is a complex, distributed system, and its functions are executed by the close cooperation between switching, signaling and transmission entities. These entities cooperate in order to provide circuit switching, or the establishment, maintenance and termination of temporary end-to-end connections between subscribers through a network, as shown in Figure 1. The switching entities are responsible for concatenating individual transmission links into an end-to-end circuit, while the signaling entities coordinate the establishment, maintenance and termination of the end-to-end circuit. Lastly, transmission entities provide links between switches. Local switches are defined as those having local loop access lines, including standalone, host, or remote local switches. Tandem switches that also have access lines, or access tandems, are also included in this study, but represent a small number of the total population. Tandem switch outages are beyond the scope of this research.

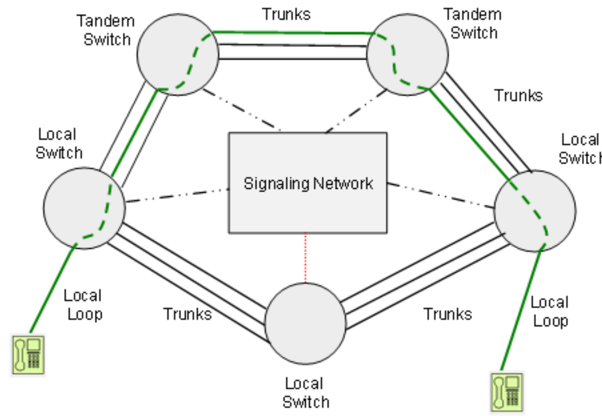

Figure 1. PSTN Infrastructure

Wireless voice infrastructure also includes switches, as seen in Figure 2. These switches, called Mobile Switching Centers (MSC) or Mobile Switching Telephone Office (MTSO) , are very similar to the wire line switches studied in this research:

> "The mobile telephone office (MTSO) is the switch that serves a cellular system. It is similar in function to a class 5 end office switch….Prominent makers of MTSOs include Northern Telcom, Ericsson, Motorola, DSC, and Lucent Technologies", the same manufacturers of local telecommunication switches."[8]

MSCs switch mobile calls in the wireless coverage area, and also interface to the PSTN if the call goes outside the wireless area being served.

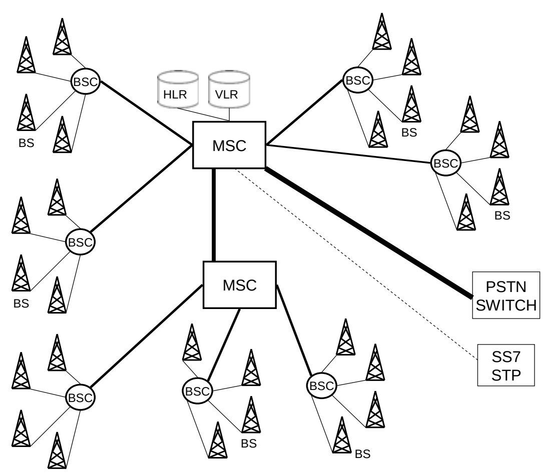

Figure 2. Wireless Infrastructure

In this work, the PSTN is viewed as a single system, made up of switching, signaling and transmission segments. The switching segment is made up of the tandem and local switch subsystems. The purpose of this paper is to investigate the reliability of the local exchange switching subsystem as a whole, by investigating the pooled failures of all individual local switches in the PSTN. There are a large number of different manufacturers and models of local switches in this infrastructure. Even the same model switch varies substantially from serial to serial because of differences in customers served and features offered. By pooling failures from different switches, we may assess the reliability of local switching as a whole, rather than the reliability of a single switch.

IV. EMPIRICAL DATA

Individual switch outage incidents of at least two minutes in duration have been reported to the Federal Communications Commission (FCC) by all price cap regulated local exchange carriers, accounting for over 90% of the wire line telephone access lines in the U.S. This data is part of the quality-of-service statistics required by the FCC's Automated Reporting and Management Information System (ARMIS) reports made to the FCC by the carriers. For each reported switch incident the date, time, duration, and outage cause are included, along with the number of access lines connected to the switch experiencing the outage. Very importantly, the reporting Carrier classifies each incident using one of fifteen different cause codes. This research presents a comprehensive reliability analysis of LEC local telecommunication switches in the United States using this public data over an extended period, January 1996 through December 2009 [9].

Local switches are repairable systems in that they are repaired by means other than replacing the entire unit. Renewal processes are often used for modeling such phenonoma, as it is hoped the system is made "good as new" through modular replacement. However, switches involve software, wherein some repairs result in a slightly different switch as the software changes. This means failures are not independent or identically distributed. This is the case of the non-homogeneous Poisson process (NHPP), the most common model used for repairable systems. For such systems the failure rate changes over time, and is nonstationary [10].The two-minute reporting threshold is recognized as a reliability threshold in this study. An outage is different from a failure event, as the outage also has a duration (how long the switch failed) and a size (how many subscriber lines connect to the switch). An impact metric, called "Lost Line Hours" or LLH is a survivability metric, and is used here to assess outage and reliability deficit impact. If a 10,000 line switch experiences a 2 hour outage, that is equivalent to a 20,000 line switch down for 1 hour, or 20,000 LLH. The results presented below make an important distinction between an outage and a failure event. Lastly, availability is another important aspect of switch quality-of-service too, but not in the scope of this study.

V. SUMMARY ANALYSIS

As mentioned, the reporting carrier attributes an individual switch outage incident to one of fifteen different cause codes, as required by the ARMIS reporting instructions. It is important to note that only total switch outages are reported. A partially failed switch is not a reportable outage, irrespective of the size of the partial switch outage. Neither are outages less than two minutes. An abbreviated definition for each cause code and the number of outages reported for each category is shown in Table 1. From here on, a distinction is made between a failure and an outage. Cause code one is recognized as a planned maintenance outage, while cause codes two through fifteen are treated as failures resulting in outages. From Table 1, note that the largest cause of outages was scheduled outages (about 30%) while the next largest was random hardware failure (about 23%), followed by roughly equal percentages of 8% for software design and acts of god.

A. *Causal Analysis*

Another way to summarize the failure data is to combine some of the codes into categories that might offer more insight into the reliability performance of local switches. The following categories are created by combining cause codes:

- Human error: Procedural errors made in installation, maintenance or other activities by Telco employees, contractors, switch vendors, or other vendors.
- Design error: Software or hardware design errors made by the switch vendor prior to installation.
- Hardware error: A random hardware failure, 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.

These categories, their composition, and the distribution of failures to each category are shown in Table 2, where scheduled outages are left out. Note that the largest categories causing failures in about equal proportions are hardware failure and external causes. The next largest is procedural error and design error, each with about half the failures as either hardware failures or external causes.

B. *Time Series Analysis of All Switch Outages*

A time series analysis of outages is shown in Figure 3. From this figure there appears to be a period of reliability growth followed by a period of reliability deterioration. However, during this study period, the number of local exchange switches decreased somewhat, as shown in Figure 4. From these results a time series of outage rate can be determined, as seen in Figure 5 (dividing the outage count per year by the number of switches per year). Here it is seen that the initial reliability growth is not as pronounced, and that the reliability deterioration is slightly more pronounced than that indicated by Figure 3.

 ISBN: 978-1-61208-245-5

TABLE I. LOCAL SWITCH OUTAGE AND OUTAGE CAUSE DISTRIBUTION

Code	Description	Number	%
1	Scheduled	3,885	30.2%
2	Procedural error (Telco install./maintenance)	446	3.5%
3	Procedural error (Telco non-install./maintain.)	376	2.9%
4	Procedural error (System vendor procedural error)	315	2.4%
5	Procedural error (Other vendor procedural error)	257	2.0%
6	Software design	1,078	8.4%
7	Hardware design	136	1.1%
8	Hardware failure	2,951	22.9%
9	Acts of god	935	7.3%
10	Traffic Overload	17	0.1%
11	Environmental	83	0.6%
12	External power failure	896	7.0%
13	Massive line outage, cable cut, other	660	5.1%
14	Remote - loss of facilities between host/remote	309	2.4%
15	Other/unknown	516	4.0%
	Total	12,860	100%

TABLE II. LOCAL SWITCH FAILURE CAUSE CATEGORY DISTRIBUTION

Codes	Failure Category	Numb.	%
2,3,4,5	Human Proc. Error	1,394	15.5%
6,7	Design Error	1,214	13.5%
8	Hardware Failure	2,951	32.9%
9 thru 14	External Circumstances	2,900	32.3%
15	Other/unknown	516	5.7%
2 thru 15	Total	8,975	100%

VI. SWITCHES WITH MORE FREQUENT OUTAGES/FAILURES

Do some switches experience more outages than others? The logarithmic plot in Figure 6 indicates this is in fact the case. Here we see that 156 unique switches experienced 8 or more outages during the study period, while 5,976 switches experienced 7 or less outages. The selection of 8 or more outages is somewhat arbitrary, but partly selected because the data points at 8 or more outages deviate from the smooth curve formed by the data points for 7 or less outages per switch.

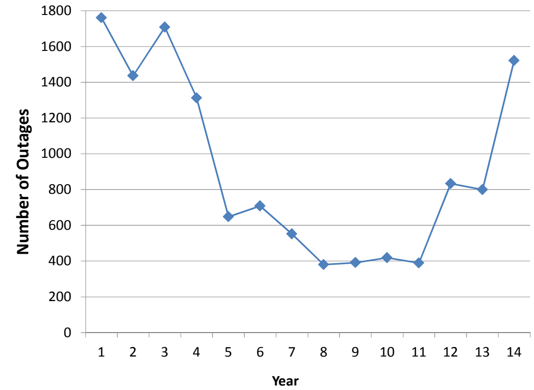

Figure 3. Time Series of Switch Outages Over the Study Period

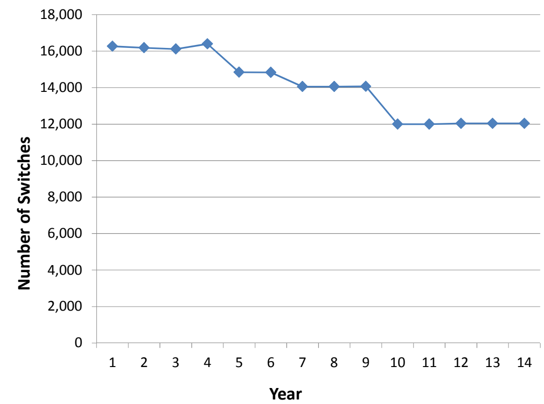

Figure 4. U.S. Local Switches Over the Study Period

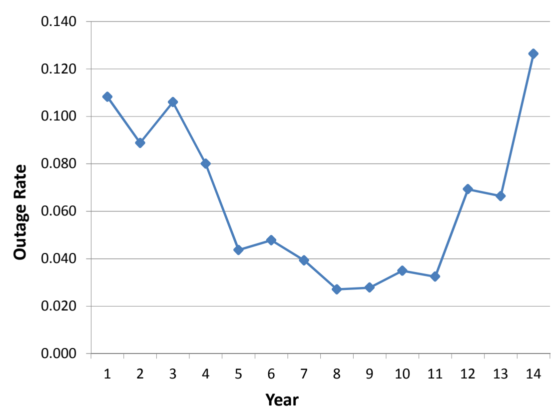

Figure 5. Switch Outage Rate Over the Study Period

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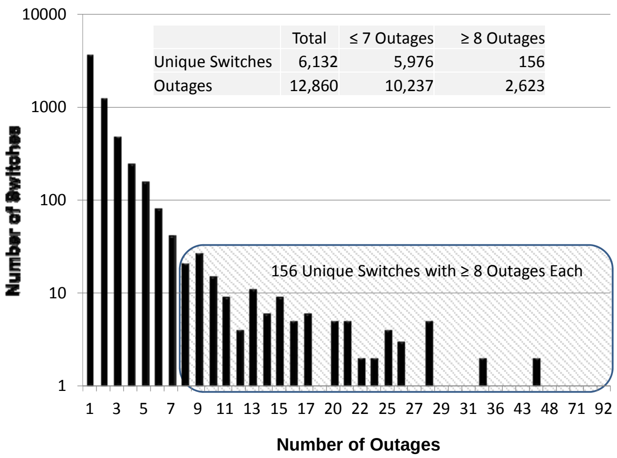

Figure 6. Number of Unique Switches One or More Outages

A. Causal Comparison of Switches with More Frequent Outages/Failures

The percentages of outages by cause code and category are shown in Tables 3 and 4, respectively. For a cause code comparison, note the following regarding switches with more failures compared to switches with less failures:

- One-half the percent of scheduled outages
- Double the percent for
  1. Acts of god,
  2. Line outage,
  3. Loss of connection to host switch, and
  4. Other/unknown

For major cause categories, note the following regarding switches with more failures compared to switches with less failures:

- One-third the human error
- Double external circumstances

B. Summary Analysis of Switches with Frequent Outages/Failures

A summary comparison of switches is shown in Table 5. First note that although less frequently failing switches account for but 3% of unique failed switches, they represent 25% of the switch failures. Also note that the less frequent failing total switch lines represent 10% of the total, they represent 22% of the total duration. On a better note, the more frequently failing switches represent only 7% of the survivability deficit due to the outages induced by these failures (lost line hours, or LLH). Note that the more frequently failed switches are about one-third the size of the less frequently failing switches. However, note little differences in the average duration of outages (4.61 versus 4.18 hours). Also note that the average LLH for the more frequently failed switches is about one-fourth of the less frequently failed switches. Also note that the median location for all failed switches is rural rather than urban (MSA stands for Metropolitan Statistical Area).

Lastly, refer to Tables 5 and 6 for the following temporal comparisons:

- Time of Day (TOD), where the day was divided into 6 timeslots
- Day of Week (DOW), where 1 is Monday
- Month of Year (MOY). Where 1 is January

Note that although the differences in average TOD and DOW week shown in Table 5 are small, Table 6 results indicates statistically significant differences. No differences are indicated for month of year.

TABLE III. COMPARISON OF CAUSE CODE DISTRIBUTION

Cause Code	≥ 8 Outages	≤ 7 Outages
1	15.7%	33.9%
2	1.9%	3.9%
3	0.5%	3.6%
4	0.5%	2.9%
5	1.1%	2.2%
6	10.8%	7.8%
7	0.7%	1.1%
8	27.4%	21.8%
9	14.0%	5.5%
10	0.2%	0.1%
11	0.5%	0.7%
12	8.5%	6.6%
13	8.2%	4.3%
14	4.0%	2.0%
15	5.9%	3.5%
Total	100.0%	100.0%

TABLE IV. COMPARISON OF CAUSE CATEGORY DISTRIBUTION

Cause Category	≥ 8 Outages	≤ 7 Outages
Scheduled (1)	15.7%	33.9%
Human Proced. Error (2-5)	4.0%	12.6%
Design Error (6-7)	11.6%	8.9%
Hardware (8)	27.4%	21.8%
External Circumst. (9-14)	35.4%	19.3%
Other/Unknown (15)	5.9%	3.5%
Total	100.0%	100.0%

TABLE V. RELIABILITY AND SURVIVABILITY COMPARISON

Cause Codes 2-15	Outages	≥8 Outages	≤7 Outages	% ≥8	% ≤7
Number Outages	8,975	2,210	6,765	25%	75%
No. of Switches	4,517	154	4,363	3%	97%
Total Lines	65.6 M	6.6 M	59.0 M	10%	90%
Total Dur. (Hrs)	41.3 K	9.2 K	32.1 K	22%	78%
Total LLH	307.8 M	20.5 M	287.3 M	7%	93%
Avg Sw. Lines	7,313	3,000	8,723		
Avg Dur. (Hours)	4.61	4.18	4.75		
Average LLH	34,295	9,257	42,475		
Median TOD	10:57 AM	12:00 PM	10:34 AM		
Mean TOD	11:02 AM	11:54 AM	10:45 AM		
Median DOW	4.09	4.29	4.06		
Mean DOW	4.22	4.32	4.19		
Median MOY	6.89	7.08	6.82		
Mean MOY	6.87	6.90	6.86		
Median MSA	Rural	Rural	Rural		

VII. TIME SERIES ANALYSIS OF SWITCHES WITH FREQUENT OUTAGES

Here the outage data is investigated for trends and arrival process assessment. The perspective is that the PSTN is viewed as a single repairable system, and that we are investigating the local switch subsystem as a whole. The first method in assessing a trend is visual, using the cumulative failures versus time plot. A linear plot means constant arrival process. This is a homogeneous-Poisson-process (HPP) if the time-to-failures are i.i.d. and exponentially distributed. If the events are i.i.d. and the distribution is other than exponential, then we may classify the process as renewal [10]. However, if the cumulative plot bends downward or upward, the failures are not from a common distribution, and we have either reliability growth or reliability deterioration, respectively. In this instance, the most common classification is expected to be the nonhomogeneous Poisson process (NHPP), where subsequent failures come from a different distribution [10]. This should be expected, as switches commonly receive new software versions and feature upgrades.

The Cox-Lewis trend test (Laplace test) can be used to tease out whether subtle upward or downward bending of cumulative outage/failure plots are statistically significant cases of reliability deterioration or growth, respectively. The Laplace test looks for trends where the homogeneous Poisson process (HPP) is the null hypotheses. The resulting test statistic rapidly converges to a normal score with very few data points [10]. However, the sample results presented here are visually convincing, with no need for formal trend testing to detect periods of reliability growth, constancy, and deterioration.

TABLE VI. TEMPORAL COMPARISON FOR OUTAGES AND FAILURES

T-TEST (Results Summary)	≥ 8 Outages	≤ 7 Outages	Result
TOD (All Cause Codes)	11:41:23 AM	10:43:48 AM	Difference
TOD (Cause Code 1)	10:32:08 AM	10:39:36 AM	No Difference
TOD (Cause Codes 2-15)	11:54:19 AM	10:45:57 AM	Difference
DOW (All Cause Codes)	4.37	4.25	Difference
DOW (Cause Code 1)	4.68	4.36	Difference
DOW (Cause Codes 2-15)	4.32	4.19	Difference
MOY (All Cause Codes)	6.90	6.93	No Difference
MOY (Cause Code 1)	6.89	7.06	No Difference
MOY (Cause Codes 2-15)	6.90	6.86	No Difference

Reliability growth, constancy, and deterioration can be examined through cumulative outage plots. A cumulative plot of all outages reported during the study period is seen on Figure 7. Note three general regions of the curve :

- Region I: Reliability constancy – outage rate constant for years 1 to 4
- Region II: Slight reliability growth for years 4 to 11
- Region III: Slight reliability deterioration for years 11 to 14

Region I constant outage rate is about 1500 outages per year, indicating process stability. For Region II, the outage rate is demonstrably lower than Region I, and slowly decreases nonlinearly over years 4 to 12. The average outage rate in Region II is about 540 per year. Reliability growth is indicated from Region I to II. However, the reliability starts to deteriorate again in Region III, albeit not as bad as Region I reliability, with an average rate of about 1000 per year. Overall however, the Laplace trend test indicates very strong evidence of reliability growth over the entire 14 year period.

 ISBN: 978-1-61208-245-5

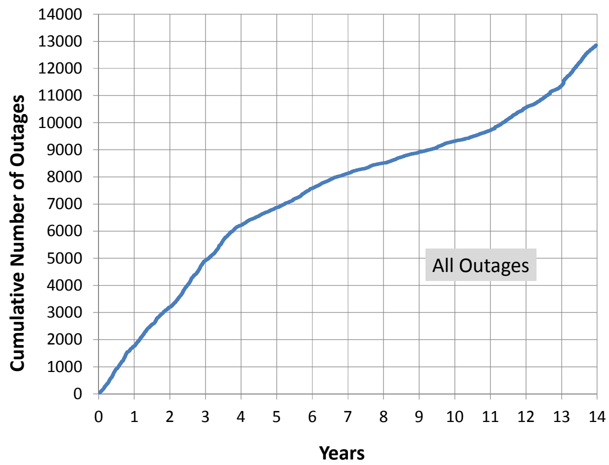

Figure 7. Cumulative Outage Plot: All Outages

To compare switches with more frequent outages to those with less, refer to Figures 8 and 9. The switches with less outages exhibit a very strong reliability growth, with improvement starting about year 4. If we linearize into two regions, we see very significant reliability growth about 1400 outages per year (years 1 to 4 years) to about 460 per year (years 4 to 14). There is a slight tailing up of outages in year 14. However, for the switches with more frequent outages, from Figure 9 we see that there are three well defined regions of constancy, reliability growth, followed by a very strong region of reliability deterioration.

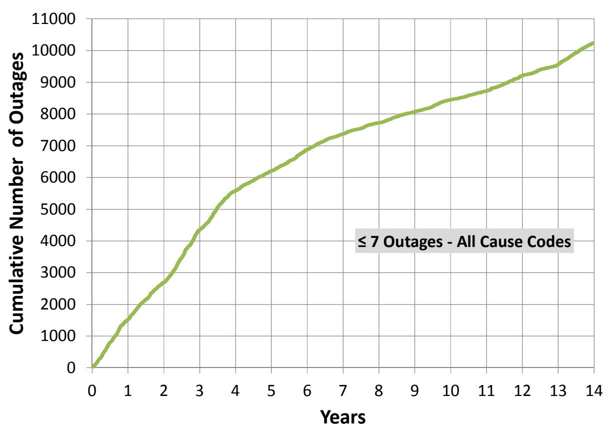

Figure 8. Cumulative Outage Plot: All Outages (Seven or Less per Switch)

Further insights into the switches with more frequent outages are shown in Figures 10 and 11. First, note very significant decreases in scheduled outages (Figure 10), and a very rapid increase in outages due to unplanned failures during the last three years of the study period (Figure 11). In Figure 11 the failure rate the first 11 years is about 55 per year, while for the last three years it is about 530. This is a tenfold increase and represents very severe reliability deterioration.

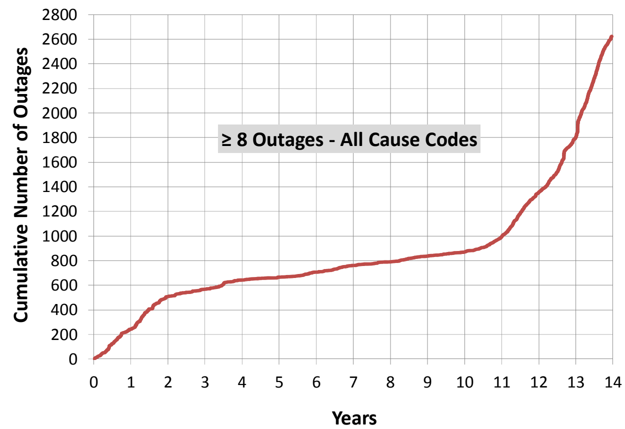

Figure 9. Cumulative Outage Plot: Outages (Eight or More per Switch)

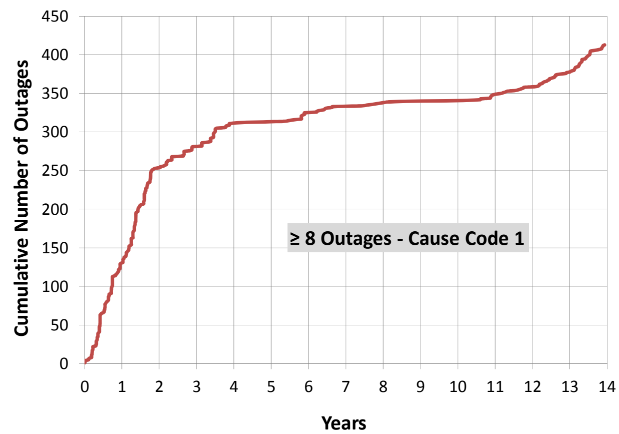

Figure 10. Cumulative Outage Plot: Scheduled Outages (Eight or More per Switch)

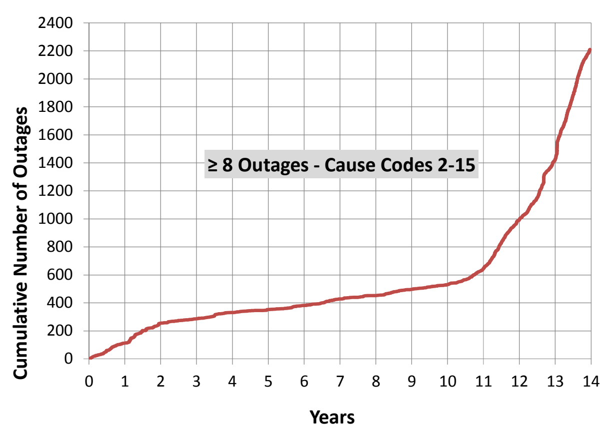

Figure 11. Cumulative Outage Plot: Outages Due to Failures (Eight or More per Switch)

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VIII. SUMMARY OF FINDINGS AND CONCLUSIONS

Over the study period there was significant reliability growth for all local switches. However, the outage rate (number of switches with outages divided by number of switches) accelerated over the last four years of the study period.

A summary of the more interesting and significant findings for switches that experience more frequent outages are:

- There is very severe reliability deterioration in switches that go down more frequently while there is good reliability growth for switches that fail less frequently.
- Switches that go down more frequently are decidedly smaller, more rural, and receive much less scheduled maintenance than those failing less frequently.
- Human error induced failures are much less of a problem for the more frequently out switches. Perhaps this is due to their rural nature, where there are less visits by technicians. Or perhaps the rural switches are hosted to larger switches more often, and require less visits by technicians.
- Scheduled outages occur less frequently for the more frequently out switches, perhaps indicating less frequency preventive maintenance. On the other hand, this could be an artifact of smaller switches hosted to large switches.
- Acts of god, massive line outage, loss of connection to host switch, and other/unknown causes are much more of a problem for switches with more frequent outages. This could be suggestive of weaknesses in host-remote switch architectures and/or susceptibility of physical plant to natural disasters.
- There are significant differences in the times-of-day and days-of-week between the more and less frequently out switches. This suggests a different maintenance/disaster-recovery approaches for large vs. small and/or rural vs. urban switches.
- The more frequently out switches represent 2.5% of the switches with outages, but account for 7% of the lost line hours. This means that frequently out switches are about three times less survivable than switches that are out less frequently.

In conclusion, there are demonstrable differences in (1) the causality of outages and (2) the characteristics of switches suffering outages, and (3) switch resiliency when it comes to switches out more and less frequently. Also, there is a slight uptrend in outages in the last several years of the 14 year study period. Unfortunately, the FCC stopped collecting this data from carriers in 2009, masking the trends since then and in the future. This research demonstrates that very pronounced reliability and survivability trends are identifiable, some of which are troublesome. This is a good example of retrospective quantitative research analysis, yielding important trends that can be investigated further and corrective action taken.

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