The Impact of Multi-Outage Episodes on Large-Scale Wireless Voice Networks

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Abstract— **Large wireless network infrastructures experience concurrent or overlapping service outages due to equipment and link failures. The frequency, duration, and impact of such episodes are of interest to users and network operators alike. Here, a research project which investigates through simulation the characteristics of concurrent network outages in large wireless network infrastructures is presented. The dependability attributes used to gain a perspective on this issue are network reliability, availability, maintainability and survivability. To assess these attributes in this setting, a new term, called an "impact epoch", is introduced. Epochs are defined as single, concurrent, or overlapping outages in time, consisting of *n* different outages. A wireless network is expanded in size and epochs observed as the network grows. The new proposed metrics offer valuable insights into the management of restoration resources. Simulations proved invaluable in identifying multi-outage epochs, as well as modeling their occurrence, frequency, duration, and size – results which are analytically intractable for assessing large networks.**

Keywords – RAMS; network outages; simulation; survivability; reliability; maintainability; wireless network infrastructure

I. INTRODUCTION

The larger the network, the greater the challenge for operators. Networks are critical telecommunication infrastructure, as millions of people depend on these networks for daily communication and commerce. As demand increases, so does network size, challenging engineers and operators to maintain—and not compromise—network dependability. As a network grows in size, the sheer number of components grows also, increasing failure hazard. With such an increase in hazard, the chance of concurrent, or overlapping, outages also can be expected to increase. Dealing with these concurrent outages is challenging because network operators have to judge priorities in allocating limited repair resources to outages spatially distributed. If the response is consistently substandard, the operator's ability to satisfy current customers—as well as accommodate new ones—could be adversely affected. Understanding the characteristics of concurrent outages as a function of network size, component failure, and repair rates offers network operators valuable information in developing outage recovery strategies. The number of customers that could be impacted by network failures is another important factor for network operators to consider. If the probability distribution of impacted customers is known, thresholds highlighting critical events can be established.

This paper investigates the characteristics of simultaneous network outages and attempts to identify the distribution of impacted customers through simulation. This phenomenon was first reported in [1], and this paper expands on and extends some of those preliminary findings. There is much interest in understanding the impact of outages. Hariri, et al [2] examined the impact of concurrent faults and attacks in large-scale networks, in particular the internet. However, the emphasis was on the effect of multiple transmission and switching outages to traffic, not predictions of the frequency of such phenomena. Alternately, Bassiri and Heydari [3] considered network survivability in the presence of regional outage scenarios. However, they concentrated on the effects of multiple switch and link outages in regional areas due to such phenomena as natural disasters, and also concentrates on traffic in internet environments. Recently, others invented an outage management portal to coordinate response to single outages [4]. However, no studies could be found that examined the probabilistic frequency and severity of concurrent outages. Prior published research has not considered how often multiple outage epochs occur in large-scale networks, how many simultaneous outage epochs can be expected, and how many users can be expected to be impacted for how long.

A. Dependability

Users count on networks. If a network is unreliable, hard to maintain, and has poor availability, it can hardly be deemed successful. Dependability has a number of different attributes. According to Avižienis, et al [5], the concept of dependability includes attributes like availability, reliability, maintainability, safety, confidentiality, and integrity. Others have included survivability as an additional network dependability attribute, since it is so important to measure the resiliency of the network to provide partial service to the population of users during network service disruptions [6].

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The higher the survivability, the better the chance a service provider has to satisfy customers in times of network stress due to component failures or traffic overloads. Integrity and confidentiality are not considered in the scope of this study. Rather, we consider RAMS attributes (reliability, availability, maintainability, and survivability) of dependability.

B. *Reliability*

Reliability is a function of how often we might expect failure. Conversely, the formal definition of network reliability is the probability that it will perform its required functions over a specific period of time [7]. The reliability for a network, a network service, or a network component is expressed as the probability that a network or component will not fail over some specified time period of interest, given by [5]:

$$R(t) = e^{-\lambda t} = e^{-1/MTTF} \tag{1}$$

Where λ is expected failure rate and MTTF (mean time to failure) is the average time between failures. If the time-period of interest is reasonably short, MTTF is assumed to be constant, meaning that an assumption of a Homogeneous Poisson Process (HPP) can be made.

C. *Maintainability*

Maintainability is a function of how fast we can expect to recover from a failure. Network maintainability is defined as the ability of a network to recover from failures [8]. Maintainability can be determined from the Mean Time to Restore (MTTR). Restore time is a random variable and typically consists of three parts – detection time, travel time to the outage location and the actual repair or replacement time. In this research, the lognormal distribution is used, as travel time plays an important role.

D. *Availability*

There are two forms of availability – instantaneous and average. Network instantaneous availability is defined as the probability that a network is ready for use when needed [8]. Average availability can be expressed as:

$$A = \frac{MTTF}{MTTF + MTTR} \tag{2}$$

Availability, being the fraction of time a network or network service is up, is a good metric to assess the state when the network is experiencing no problems due to failures.

E. *Survivability*

Availability is not always a good indicator of network dependability, as networks are very rarely “all-up” or “all-down”. Rather, networks are “mostly-up”—or said another way, “fractionally-up”. Survivability is a measure that can capture this phenomenon. Network survivability is defined as the ability of a network to provide services to most customers under partial failures. Snow [9] defined Prime Lost Line Hours (PLLH) as an impact measure for wire-line network outages that take into consideration usage levels at the time of the outage. PLLH is the product of the estimated number of customers impacted and the duration of an outage. Total Line Hours (TLH) is the product of the total number of customers served by the network and the total hours in the time-period of interest, resulting in a network survivability calculation in Equation (3).

$$NS = 1 - \frac{PLLH}{TLH} \tag{3}$$

The Telecommunication Committee T1, an ANSI-certified standards organization, developed the “outage index” as a survivability metric that includes consideration of the size and duration of the outage, in addition to the importance of the services affected by the outage. This metric uses weights for each of these three dimensions, and has been shown to be a questionable metric [10], [11], [12].

The organization of this paper follows. In Section II the concept of impact epochs is introduced, which represent multiple outages in time. In Section III, wireless voice infrastructure is introduced. Additionally, equipment and link reliability and maintenance are quantified. Then architectural scenarios investigated in this paper are presented. In Section IV the paper research questions are presented and discussed, while Section V introduces the simulation model used to address the research questions, and the assumptions and limitations of the model. Lastly, Sections V and VII present the results and conclusions, respectively.

II. IMPACT EPOCH

This research examines episodes where multiple outages overlap in time. Single outages impact some fraction of users. When they are coincident, the impact increases and challenges network operators. The focus of this research is on concurrent and time-overlapping component outages as the network size scales. In order to describe the characteristics of concurrent or overlapping outages from a network operator perspective, a new concept called *impact epoch* is introduced. An impact epoch starts when a network transfers from a state of no customers impacted to a state of having customers impacted. It continues until the network returns to the state of having no customers impacted. An impact epoch event includes single or multiple outages that overlap in time. The number of impacted customers during one impact epoch is not necessarily constant, since a single impact epoch may include more than one component outage due to nearly simultaneous failures in the network. An example of single

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impact epochs, consisting of two non-overlapping outages, is shown in Fig. 1 in the form of an epoch profile. Note that time is represented by the X-axis, and the Y-axis represents the percentage of customers served in the network. Each outage has a duration and a maximum impact.

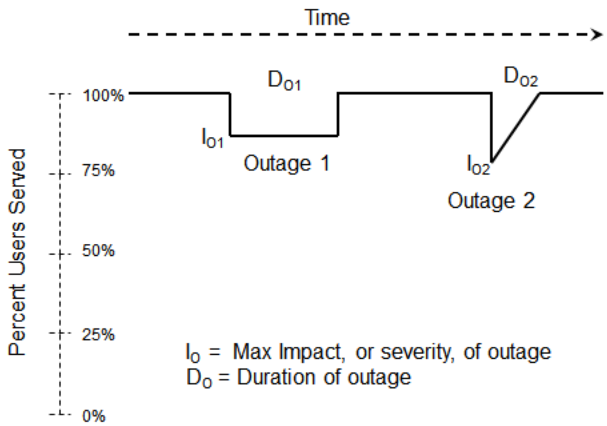

Figure 1. Non-Overlapping Outage Epochs

Next, refer to Fig. 2, which shows three different combinations of these two outages. Note how different these two events are, depending on degree of overlap. In the top profile, the two outages do not overlap and are separate epochs. In the middle profile, the outages combine into a single epoch with the same duration, but with a larger impact. Lastly, note the bottom profile, which has a different duration and impact.

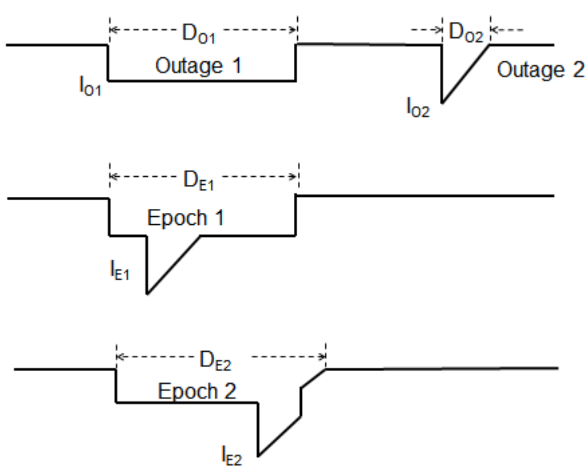

Figure 2. Different Perspectives of Two Overlapping Outages

Individual epochs are arrival events, and MTTE is defined as the mean time to impact epoch in a network. MTTE offers insights into the average interval before operators can expect disturbances that render the network incapable of satisfying all customers. Longer MTTE implies that the network has higher reliability, or the capacity and performance to lessen congestion events. Since epochs have duration, MTRE specifies the mean impact epoch restore time - a description of a network's maintenance response, or ability to recover gracefully from congestion.

Shorter MTRE implies that the network has better maintainability or recoverability. MTRE together with MTTE provides the average quiescent time (A_Q), or the fraction of time the network, on average, is not undergoing a disturbance that impacts customers. Quiescent availability can be determined by the following equation:

$$A_Q = \frac{MTTE}{MTTE + MTRE} \tag{4}$$

Equation 3 can still measure survivability from an epoch perspective. However, in an environment where there may be concurrent or overlapping outages, peak customers impacted (PCI) may be of interest. For instance, in Fig. 2, epoch 2 has a larger PCI than epoch 1.

The advantages of studying impact epochs instead of a single outage are that epochs:

- Provide a better-detailed description of the cumulative time-phased effect of network disturbances
- Offer a new way to evaluate network dependability, providing a different perspective important to network operators
- Provide insights into how characteristics such as frequency, duration, number of concurrent outages, and peak customers impacted might change as network size varies

Table 1 illustrates the mapping between wireless network dependability attributes and the metrics developed in this paper to assess them. In this wireless network example, a Wireless Traffic Profile (WTP) is developed using empirical wireless traffic data from the literature, allowing computation of PCI and WPLLH (Wireless Prime Lost Line Hours).

TABLE 1. New Network Dependability Metrics

Dependability	Network Attribute Name
Reliability	Network Mean Time To Epoch (MTTE)
Maintainability	Network Mean Time Restore Time (MTRE)
Availability	Network Quiescent Availability (A_Q)
Survivability	Peak Customer Impacted (PCI) Wireless Prime Lost Line Hours (WPLLH)

In this study, outages are due to component failures. In other words, this is a fault management, rather than a performance management, perspective -- operators are responding to outage events induced by component failures, and the need to restore or replace the faulty components. Therefore, this work presents conservative estimates of episodic occurrences.

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III. Wireless Networks

Like all telecommunications providers, wireless operators are reluctant to share statistics on service outages. Even so, extensive research has been conducted over many years regarding the traditional wire-line telephone network, also called the Public Switched Telephone Network (PSTN). These research efforts helped wire-line networks offer very dependable services with a common quality metric of Five 9's availability [13]. On the other hand, research in the world of wireless communication, especially in cell phone networks, is relatively new. Research into wireless telephone network reliability did not receive much attention until the late 1990s. Over the last 22 years, the wireless network has grown at an amazing rate. According to the Cellular Telecommunications Industry Association (CTIA) wireless Quick Fact Sheet [14], cellular subscribers in the US surpassed 5 million in 1990 and doubled in just two years. By 2012, cellular subscribers exceeded 300 million in the US and wireless penetration rate was over 65%. There were over 327 million customers in the US as of June, 2012.

In 1992, the FCC at first ruled that wire-line carriers had to report all outages that affected more than 50,000 customers for at least 30 minutes. This threshold was quickly lowered to 30,000 customers for 30 minutes in 1993 [10]. Thresholds for RAMS attributes have also been shown to be important in wireless networks [15]. Statistical failure data of wire-line local switches are publicly available from the FCC's Automatic Reporting and Management Information System (ARMIS) database. However, starting January 2, 2005, the FCC ruled that wireless carriers also had to report their network outages to the FCC [16]. Meanwhile, the FCC established a four-year rollout plan for E911 phase II, which began in October 2001. Phase II required wireless carriers to provide precise location information for wireless 911 calls, within 50 to 300 meters in most cases [17].

A. Wireless Network Infrastructure

Wireless networks consist of components, such as cable and equipment. Additionally, equipment consists of both hardware and software. The general structure of a wireless network with most of the required functional components is shown in Fig. 3. They include the network operation subsystem, base station subsystem, and network switching subsystem. Each subsystem includes a number of components that are studied in this research. This is a 2G+ architecture that has some similarity to 3G/4G architectures from hierarchical and topological perspectives. The Base Station Subsystem (BSS) is comprised of Base Stations (BS) and Base Station Controllers (BSC). A BS is essentially the radio station that broadcasts to and receives from the mobile station in a "cell". A BSC is the controlling node for one or more cells or BSs and manages voice or data traffic and signaling messages for all the cells under its control. The BSS provides the transmission path including traffic and signaling between mobiles and the Network Service Subsystem (NSS) [18].

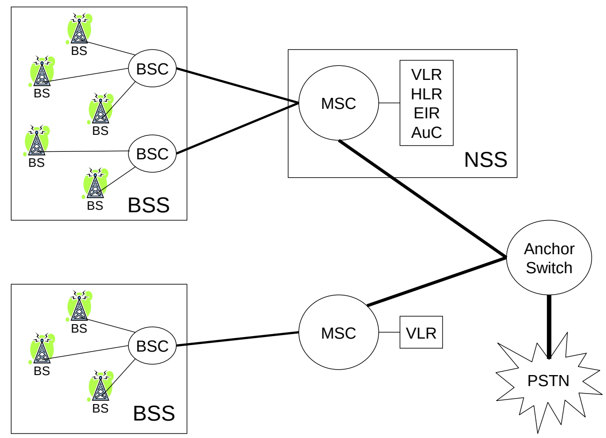

Figure 3. Wireless Network Infrastructure

The NSS is the switching and control portion of the entire wireless network. It is comprised of the Mobile Switching Center (MSC) and three intelligent network nodes known as the Home Location Register (HLR), Visitor Location Register (VLR), Equipment Identity Register (EIR), and the Authentication Center (AuC) [18]. The MSC is the central heart of a wireless network. The failure of a MSC typically results in communication loss of all users that the MSC controls, since calls cannot be originated or terminated. Carriers pay close attention to the status of a MSC since it supports billing functions such as collecting Call Detail Records (CDR). A typical MSC is engineered to be highly reliable. In A. Snow, [19], the authors introduced a wireless network infrastructure called the Wireless Infrastructure Block (WIB). The scope of the WIB is from the BS to the MSC, including the HLR/VLR database. They also discussed how MTTF and MTTR in a WIB might affect the network's dependability [19]. The topology used in a WIB is the star topology. Large wireless infrastructures consist of multiple WIBs.

B. Wireless Traffic

Wireless traffic, like all telecommunications traffic, varies widely over a single day. If equipment fails, or transmission links are severed, users are impacted. For faster restoration, providers use redundancy in equipment and links, and a topology that minimizes restoral times. Advantages of using the star topology include supporting modular expansion, as well as simplified monitoring and trouble-shooting. The largest disadvantage of star topology is the creation of a single point of failure, such as the MSC and database. Fortunately, these components are highly reliable. Table 2 indicates the number of components in a WIB along with the number of customers potentially impacted by each component. A WIB can serve up to

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100,000 customers. How many subscribers are actually impacted depends on utilization, which can be related historically to time of day and day of week. This can be represented by a time factor, which is really a time phased traffic profile that reflects percentage utilization at a point in time [20].

TABLE 2. No. of Components in One WIB and Maximum Failure Impact

Component	Number in One WIB	Number Customers Potentially Impacted
MSC	1	100,000
VLR/HLR DB	1	100,000
MSC-BSC link	5	20,000
BSC	5	20,000
BSC-BS link	50	2,000
BS	50	2,000
Anchor-MSC Link	1	100,000
Anchor Switch	*n*	*n* x 100,000
Anchor Link	*n*	*n* x 100,000

Note: *n* is the number of WIBs in the wireless infrastructure

The time factor accounts for time-of-day and day-of-week usage by customers. The goal of network engineering for carriers is to establish an infrastructure that satisfies peak hour traffic loading. Similar to traffic on a highway, voice traffic volume in networks varies over a day. According to historical statistics for wireline voice traffic [20], heavy traffic load in the wire-line network occurs between 9:00am and 4:00pm on weekdays. Taking traffic estimates into account, a network component failure occurring at different times may impact a different number of users. For example, a one-hour outage at 10:00am has much a larger impact than a one-hour failure at 3:00am in the morning. The time factor values, or utilization, for wire-line networks are summarized in Table 3 from [20].

TABLE 3. Time Factor for Wire-Line Network

Spanned	Time Period	Time Factor
Day	(8:00am to 4:59pm, Mon. ~ Fri.)	1.0
Evening	(5:00pm to 10:59pm, Mon. ~ Fri.)	0.3
Night	(11:00pm to 7:59am, Mon ~ Sun.)	0.1
Weekend	(8:00am to 10:59pm, Sat. & Sun.)	0.2

Say there is a failure of central office with 50,000 lines that lasts one hour. The number of affected customers is 1 x 50,000 = 50,000 if the outage started at 10:00am. However, if the outage started at 3:00am the number of affected customers is 0.1 x 50,000 = 5,000. The product of time factor and telecommunications capacity is the impact of the outage, in line hours. As the time factor are fractions of full utilization during the prime times of the day, this impact has been called prime lost line hours, or PLLH [9], [10], [11].

In this work, a new traffic profile for wireless networks is developed. This is because traffic patterns in wireless networks are different from that in PSTN. For instance, service charges in the PSTN are usually a flat monthly charge, while in a wireless networks there are more usage plans with differential charges based on the time of day a call is placed. For example, many cell phone plans offer free calls on weekends and after 9:00pm on weekdays. Some people could wait until 9:00pm to place calls and take advantage of this plan. Such phenomena results in different weekday and weekend traffic profiles in wireless networks. In Albaghdadi and Razvi [21], the authors studied an actual 1320 cell GSM network. In that research, the results reported in this GSM network were used to develop five-day weekday traffic and weekend traffic profiles as shown in Fig. 4 and 5 respectively. The data is from [21] while the solid lines are added for this research to create a wireless time factor. These wireless time factors were developed to create a wireless PLLH outage impact metric, called hereafter the WPLLH, where the W denotes wireless.

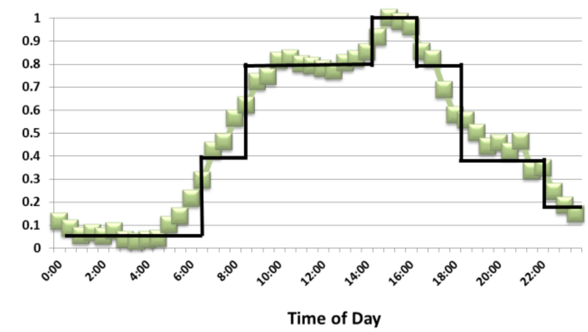

Figure 4. Wireless Weekday Time Factor

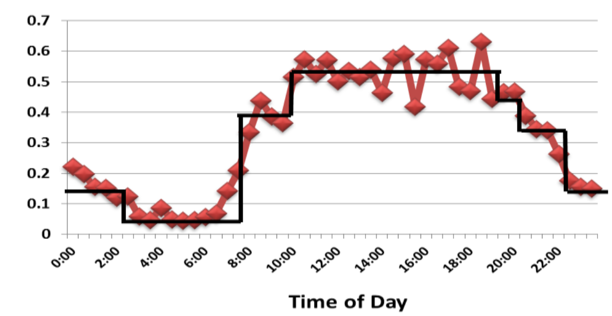

Figure 5. Wireless Weekend Day Time Factor

Because the interaction of reliability and maintainability attributes are expected to be complex when it comes to investigating multi-episodic events, three different scenarios are investigated as follows: nominal, degraded maintainability, and enhanced reliability and maintainability. The nominal scenario signifies that the network is operating within published reliability and maintainability norms, where regular maintenance schemes are used and reliability is stable. The degraded maintainability implies that the maintainability of the network is not as good as nominal, which signifies higher restore times from component

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failures. The enhanced reliability/maintainability scenario indicates that component reliability and maintainability are improved over nominal (with higher MTTFs and lower MTTRs).

C. Network Component MTTF and MTTR

Transmission links can be deployed with protection channels, wherein if the primary link is disrupted, the system switches to a protection channel**.** The more customers affected, the more likely there is a protection channel. Table 3 details a complete list of component MTTFs used in this study.

TABLE 3. Component MTTF and MTTRs Used in the Study

Component Name	Nominal MTTF (Years)	Enhanced MTTF (Years)	Degraded MTTR (Hours)	Nominal MTTR (Hours)	Enhanced MTTR (Hours)
Anchor Link	8.0	8.0	12.0	4.00	2.00
MSC/Anchor Link	8.0	8.0	12.0	4.00	2.00
MSC-BSC Link	2.7	4.0	12.0	6.00	3.00
BSC-BS Link	1.7	2.7	12.0	6.00	3.00
MSC/Anchor switch	7.5	7.5	0.51	0.17	0.12
VLR/HLR database	3.0	4.5	2.00	1.00	0.50
BSC	3.0	6.0	4.00	2.00	1.00
BS	2.0	4.0	4.00	2.00	1.00

The nominal MTTF for other components was taken from [19]. As the MSC has become a very stable control and switch system over many years' development and deployment, in this case, the nominal MTTF and enhanced MTTF of MSC are taken to be the same, which is 7.5 years based on the results derived from empirical local switch statistics in the Federal Communication Commission's ARMIS database.

Derivation of link MTTFs are also based upon empirical failure data for fiber optic links, and are derived here. As suspected, the MTTFs are greatly affected by power failures.

As seen in the multi-WIB architecture of Fig. 3, transmission systems include BS-BSC links, BSC-MSC links, MSC-Anchor links and the Anchor link to outside networks. Fiber cable is the transmission medium of choice for these link systems. Although microwave systems are sometimes used where fiber runs are not cost-effective, we assume the wireless infrastructure to be interconnected by fiber transmission capabilities. Fig. 6, 7 and 8 show the typical structure of link systems. Link systems can be generally classified as one of three cases:

- Case A is the single-fiber system with no backup (shown in Fig. 6).
- Case B has redundant fiber media backup. Redundant circuits are supposed to take different physical paths (shown in Fig. 7).
- Case C has fiber media, transceiver, and power backup, while transceivers are hot standby (shown in Fig. 8).

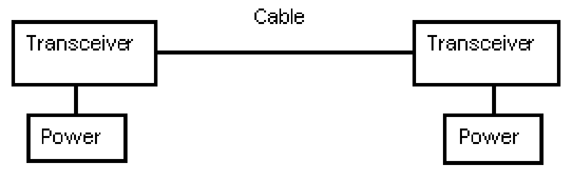

Figure 6. Unprotected Link

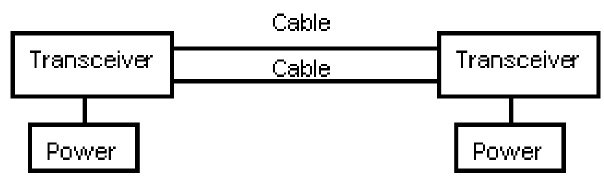

Figure 7. Partially Protected Link

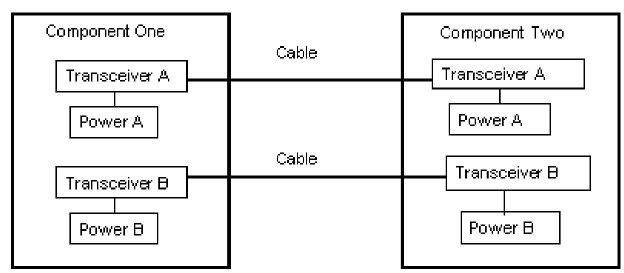

Figure 8. Fully Protected Link

From the multi-WIB infrastructure in Fig. 3, it is seen that although all links are important to a network's dependability, the reliability levels vary from one type link to the next. For example, the BS-BSC links are relatively less important than BSC-MSC links from the network operators' point of view. Similarly, BSC-MSC links are not as important as MSC-Anchor links. Each of the three link categories shown have different reliability or MTTF.

In Fawaz [22] fiber cable system reliability is discussed in detail. Statistics from Telecordia are referred to in that paper, where the authors came to three conclusions:

- The frequency of failure occurrence in optical network is not negligible.
- Cable cuts are the dominant failure scenario for long optical fiber networks.
- Power reliability is important in link reliability.

Table 4 shows their results. In this table, Failure In Time (FIT) is the average number of failures in 109 hours [22].

TABLE 4. Optical fiber and Transceiver Failure Rate [22]

Cable Cut rate FIT per 1000 miles	501142
Cable Cut rate per hour, 1000 miles	0.0005011
Cable Cut rate per year, 1000 miles	4.390
Cable Cut MTTF per 1000 miles (Yr)	0.228
Cable Cut MTTF per mile (Yr)	228
Transceiver Failure rate FIT	15178
Transceiver MTTF (Yr)	8.0
US Telecom Power failure rate per year	0.1252
Power MTTF (Yr)	8.0

The MTTF for links are different mainly because of the varying fiber length. If we assume that the hazard due to fiber cut will decrease linearly, the failure rate shown in Table 4 can be used in this work. For fiber links less than 10 miles, the transceiver and power systems become the dominant contribution to failure, rather than the fibers. This means that the total link system's MTTF is comparatively low for unprotected links. The MTTF of a parallel system with four components is about 1.6 times of the MTTF in the single system [9]. For instance, the MTTF of a 10-mile link without protection is given by:

$$MTTF_{10} = \frac{1}{\frac{2}{MTTF_{transceiver}} + \frac{1}{MTTF_{fiber}} + \frac{2}{MTTF_{power}}} \tag{5}$$

$$MTTF_{10} = \frac{1}{\frac{2}{8.0} + \frac{1}{22.78} + \frac{2}{8.0}} = 1.8 years \tag{6}$$

Likewise, the MTTF of a 10-mile, partially protected link is given:

$$MTTF_{10p} = \frac{1}{\frac{2}{MTTF_{transceiver}} + \frac{1}{1.6 * MTTF_{fiber}} + \frac{2}{MTTF_{power}}} \tag{7}$$

$$MTTF_{10p} = \frac{1}{\frac{2}{7.5} + \frac{1}{1.6 * 22.78} + \frac{2}{8.0}} = 1.9 years \tag{8}$$

Lastly a fully protected 10-mile link MTTF is given by:

$$MTTF_{10f} = 1.6 \times MTTF_{10} = 2.9 years \tag{9}$$

Table 5 shows MTTFs of fiber links under different protection schemes at different distances. From the calculation results, we can see that the MTTFs of fiber links at a distance between 10 to 20 miles are very similar.

TABLE 5. Optical Fiber Link MTTF

Link Length (Miles)	Optical Fiber MTTF (Years)	Unprotected MTTF (Years)	Partial Protect MTTF (Years)	Fully Protect. MTTF (Years)
1	222.79	3.9	3.8	6.3
5	45.56	1.9	2.0	3.1
10	22.78	1.8	1.9	2.9
20	11.39	1.7	1.8	2.7

According to the statistic data from US Census Bureau [23], the number of persons per square mile ranges from several hundred to over a thousand in metropolises such as Los Angeles, New York, Atlanta, and Phoenix. In this study, the following assumptions on fiber length and protection lead to the following MTTFs for links:

- Fiber link of BS-BSC is at 20 miles.
- Fiber link of BSC-MSC is at 5 miles level.
- Fiber link of MSC-Anchor switch is very short, less than 1 mile.
- Fiber link of Anchor switch-PSTN is very short, less than 1 mile.

A component's maintainability is represented by its MTTR. In order to understand the role that MTTR plays in dependability, three MTTR scenarios are used in the simulation: nominal, degraded, and enhanced. Nominal MTTR was obtained from [19]. The degraded MTTR was taken as three times the nominal MTTRs, excepting switches. Table 3 also lists the component MTTRs used. The repair distributions are modeled based on a lognormal distribution, which is commonly used for long-tailed distributions when travel time is involved. To summarize:

- The nominal case uses reliability and maintainability levels from literature and empirical data
- The enhanced case uses improved reliability and maintenance levels
- The degraded case uses lower maintainability levels

IV. RESEARCH QUESTIONS

In this section, four major research questions are presented and discussed. Additionally, the assumptions made in addressing the research questions are listed.

Research Question 1: How will the number of impact epochs and their composition (number of concurrent component outages making up epochs) change as the network size, component reliability, and component maintainability change?

As customer demand increases in an area, the network size increases, and more components (equipment and links) are used. We expect that more component outages will occur as the network grows. The wireless infrastructure studied in this research, as shown in Fig. 3, indicates that the total

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number of components failing is expected to scale with network size. We also expect impact epochs to grow along with network size—however, what is the relationship between the number of epochs and the network size? Will this number linearly scale as the network grows? Notice that impact epochs include both single and concurrent outage epochs, and as we count overlapping outages as one epoch, we expect the total number of impact epochs to grow nonlinearly.

Over time, how many impact epochs consist of more than one outage? The answer depends on several factors. First, more components mean more possible failures. So as the network grows bigger, the probability of simultaneous outages increases. This probability increases nonlinearly as the network size increases. The second factor is component MTTF. As component MTTF decreases, more component outages occur over a period of time. We expect multi-outage impact epochs to increase in a network as component MTTFs decrease. The third factor is component MTTR. If the repair time for a single outage increases, the probability for other outages happening during this repair interval increases. Thus we expect multi-outage impact epochs will increase as the component MTTRs increase. Network size, reliability, and maintainability interact in ways that make it difficult to predict either linear or non-linear behavior with regard to the number of impact epochs. This research investigates the relationship based on network size, reliability, and maintainability scenarios.

Research Question 2: What fraction of time is the network in a non-episodic state as network size, reliability, and maintainability change?

The percentage of time in one year that a network is in the quiescent state and non-quiescent state is insightful. The average quiescent availability is an important issue to network operators. The total non-episodic time is the sum of time that a network is in quiescent state over one year. It is expected that as the network size increases, the total time the network will be in a non-episodic state will decrease.

This question deals with how network size, component reliability, and component maintainability affect the total non-episodic time in a wireless network. More frequent failures and increasing repair times should decrease quiescent time. However, overlapping outages could increase quiescent time. How these factors combine to effect total quiescent time is not obvious.

Research Question 3: How will the dependability characteristics of impact epoch change with the network size, component reliability, and component maintainability?

Impact epochs have a number of characteristics such as MTTE, MTRE, and the peak number of impacted customers. As a system, a wireless network's MTTF is dependent upon all of its component's MTTFs. As the network size increases, the network component outages increase linearly.

MTTE is the mean time to epochs, instead of component failures within a wireless infrastructure. Because each epoch may be a single- or multi-component failure, the probability that an epoch includes more than one failure nonlinearly increases as the network size becomes bigger. So for MTTE, we expect it to decrease in a nonlinear fashion as the network expands.

The second attribute of impact epochs that is investigated in this work is MTRE. Due to increases in simultaneous component outages, MTRE increases as a network grows. How long MTRE lasts depends on how many impact epochs are multi-outage epochs. The higher the percentage of multi-outage epochs, the longer the MTRE will be. We expect a nonlinear growth on MTRE as the network becomes bigger.

The third impact attribute investigated in the research is Peak Customers Impacted (PCI). This factor shows how serious an impact epoch could be in the dimension of impact size. If we can find the distribution of PCI, we may be able to provide network operators the probability of an impact epoch impacting more than a set number of customers over a period of time. For example, we may calculate the probability of PCI exceeds 8000 customers. This could be valuable information to network operators.

Research Question 4: How will different thresholds help network operators filter impact epochs in a network?

Peak customers impacted (PCI) provides information of an epoch in only one dimension. Another perspective is one that considers size and duration of an epoch. In this research, the two-dimensional metric called WPLLH, discussed earlier, is also used to measure impact epoch. The WPLLH uses the wireless traffic profile developed earlier, rather than wire-line PLLH usage time factor.

Thresholds are powerful tools in network management because network operators usually prioritize their activities to respond to more important events in their networks. In this thesis, three different thresholds are investigated—5000 WPLLH, 10,000 WPLLH, and 15,000 WPLLH. The number of impact epochs over these thresholds is expected to grow as network size increases, or component reliability or component maintainability decreases. The number of epochs exceeding a threshold will change from one threshold to another. For example, the number over 15K WPLLH threshold may not change as fast as the number of epochs over a 5K WPLLH threshold. This is because epochs over 15K WPLLH rarely occur in smaller networks. This applies to different scenarios. For example, the number of epochs over 15K WPLLH is certainly less than that in a degraded reliability and maintainability scenario.

V. SIMULATION MODEL

Fig. 9 displays the input and output process of the simulation and the derived results, while Fig. 10 shows the

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architecture simulated. Inputs for the simulation include all component MTTRs and MTTFs, wireless traffic profile, the network size, and an operational time of one year.

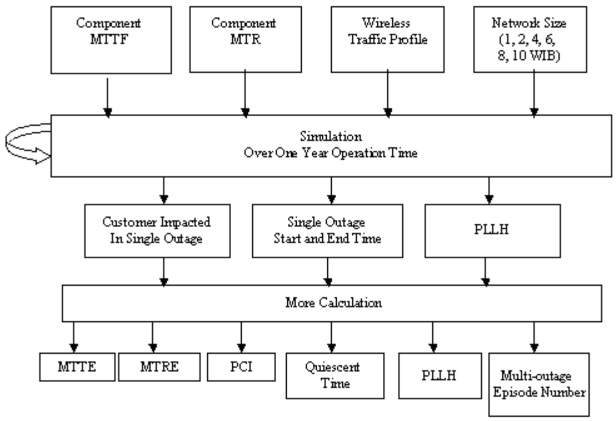

Figure 9. Process of Simulation and Results

Outputs from the program are network survivability as well as detailed outage information including start time, stop time, the number of customers impacted, and the WPLLH for each outage. Other results like MTTE, MTRE, PCI, and quiescent availability are derived from these simulation outputs using MS Excel^{TM}.

To fully investigate effects of different levels of reliability and maintainability for different size networks (size determined by the number of WIBs), we investigate three scenarios: nominal, degraded maintainability as well as enhanced reliability and maintainability. The maximum deviation in the nominal scenario between the simulation output and the analytical result was 0.85% for 8 WIB's, which was acceptable. This verified the simulation. Direct simulation program outputs include outage numbers, start time, end time, impacted customers, WPLLH, and duration of each component outage. An example of a simulation output is revealed in Table 6, showing four component outages, starting at 308.465 days into the year.

TABLE 6. Simulation Output Example for A 10 WIB Network

Failure Start Time (Days into Year)	Failed Component	WIB Number	Duration (Hours)
308.465	Base Station 32	6	6.55
308.694	Base Station 15	5	1.50
308.698	Base Station 5	4	2.90
309.292	BSC-BC-Link 41	10	6.52

Fig. 11 illustrates the impact epoch over the simulation time. The Quiescent Time can be derived from direct outputs of the simulation program and is calculated as:

$$Q_t = \sum_{i=1}^{n} TTE_i = TotalSimulationTime - \sum_{i=1}^{n} TRE_i \quad (10)$$

where n is the number of quiescent periods. The sum of all TTEs and all TREs should equal the total simulation time, as shown in Fig. 11.

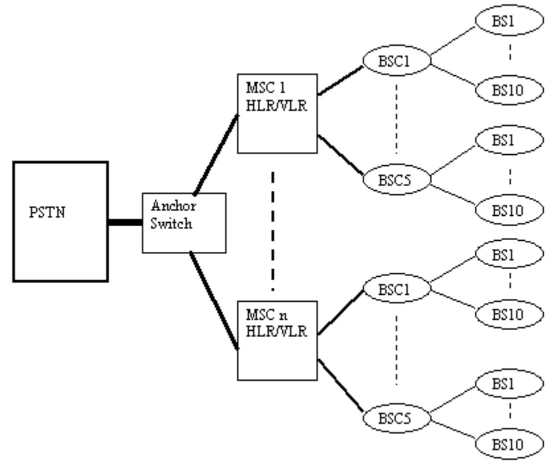

Figure 10. Scalable Network Size

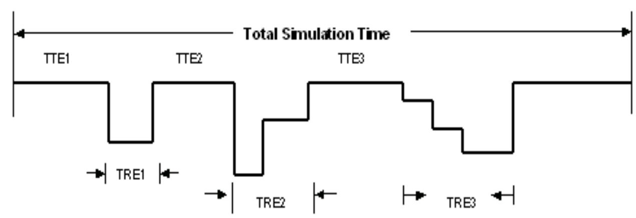

Figure 11. Relationship of TTE, TRE and Simulation Time

Likewise, we expect the MTTE (mean of all times to epochs TTE), MTTR (mean of all times to restore epochs TRE) and total simulation time to be:

$$MTTE = \frac{\sum_{i=1}^{n} TTE_i}{n} \quad (11)$$

$$MTRE = \frac{\sum_{i=1}^{n} TRE_i}{n} \quad (12)$$

$$Total\_Simulaiton\_Time = (MTTE + MTRE) \times n \quad (13)$$

A. Further Model Verification

The discrete time event simulation model was written in VC++. All components/links in the WIB(s) are in service simultaneously. Component times to fail are exponential, while repairs times are lognormal. Simulated failure counts were exhaustively compared to expected component failure counts, while simulated repair times were compared to fitted lognormal repair distributions. The null hypotheses of "no difference" were accepted at high degrees of inference, using chi-squared test statistics.

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Next, network survivability was checked for consistency against the three different scenarios investigated, and compared to analytic calculations. As explained earlier, survivability is defined as the fraction of WPLLH offered over a one year operation:

$$\text{Network Survivability} = 1 - \frac{WPLLH}{n \times TLH} \quad (14)$$

$$= 1 - \frac{WPLLH_A + WPLLH_{AL} + \sum_{m=1}^{n} (\sum_i WPLLH_i)}{n \times TLH} \quad (15)$$

where:

- *TLH* is Total Line Hour for one WIB (365×24× 100,000);
- *WPLLH* is Wireless Prime Lost Line Hour;
- *i* is the number of outages in the network;
- *n* is the number of WIB in the wireless infrastructure;
- $WPLLH_A$ is the prime lost line hours because of the anchor switch outage;
- $WPLLH_{AL}$ is the prime lost line hours because of the anchor link outage; and
- $WPLLH_i$ is the prime lost line hours for the i^{th} WIB in the network.

Based on the infrastructure used in this research, each WIB has the same structure, reliability, and maintainability levels, meaning that same-type component MTTF and MTTR are the same for each WIB in the architecture. So we may expect that each WIB will generate similar numbers of outages, outage repair times, and WPLLH. From the above equation, we can see that factors affecting network survivability are $WPLLH_A$ and $WPLLH_{AL}$. As any failure of the anchor link or anchor switch will impact the entire network no matter how many WIBs are in the infrastructure, we expect that the network survivability will stay relatively constant in each scenario, as survivability is the fraction of user hours available over a time period. However, nominal, degraded maintainability—as well as enhanced reliability and maintainability scenarios—will exhibit different network survivability levels. We expect that enhanced scenario to have the highest survivability because we expect the least outages. In contrast, the degraded maintainability scenario should have the lowest survivability because we expect the most outages.

The network survivability simulation results for each of the three scenarios is seen in Fig. 12. As expected, the enhanced network has the highest survivability and the degraded network the lowest. Also, for each scenario the network survivability remains constant for different network sizes, as expected. It also indicates that the simulation is verified with the new wireless traffic profile. In addition, the survivability by scenario and size were compared to analytic predictions and compared by chi-squared statistics.

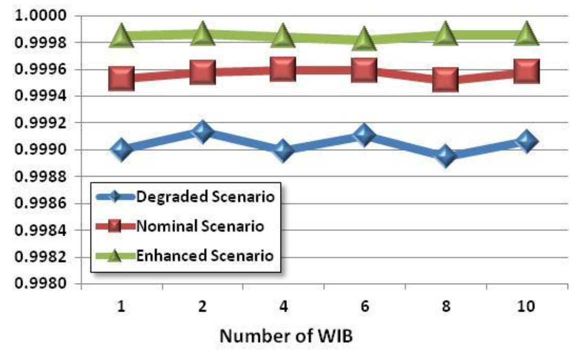

Figure 12. Network Survivability by Scenario

B. Assumptions and Limitations

The model is subject to the following assumptions and limitations:

- This work considers outages due to equipment and link failures (“components”), and does not focus on network disturbances due to traffic congestion.
- The wireless network under study is an infrastructure with an anchor switch as the gateway connecting to outside networks, such as the PSTN or other wireless networks. The anchor switch acts as the only interface to the outside world. All MSCs in this network will route their traffic with outside destinations to the anchor switch for further routing.
- An anchor switch is assumed to have the same dependability features as any other MSC in the network. The MSC has become very stable and reliable over many years of development.
- The network topology is a star topology, which is very popular in practice. The star topology distributes network functionalities geographically. It is assumed that there are no mesh topologies in the network.
- Structure and scale of all WIBs within the wireless infrastructure are the same.
- Nominal component MTTFs and MTTRs are based on published literature [10] and are not based on empirical data collected for this research.
- Component MTTF and MTTR are invariant over a one-year period. TTFs are exponentially distributed, consistent with a homogeneous Poisson process. TRs are lognormally distributed, consistent with long tail distributions to account for travel time.
- The impact on network dependability caused by anomalous propagation is not in the scope of this research as it relates to single outage.
- Fractional component failures are not considered in the research.
- Inter-WIB traffic is not modeled; however, impact

epochs in the research do include both incoming and outgoing communication loss.

- Optimal reliability and maintenance strategies are not addressed, as cost is not part of this research.

VI. RESULTS

Research Question 1: How will the number of impact epochs and their composition (number of concurrent component outages making up epochs) change as the network size, component reliability, and component maintainability change?

The number of impact epochs increases as the network expands in all three scenarios, since newly added WIBs in a wireless infrastructure will contribute more component outages. Fig. 13 illustrates the relationship between the total numbers of impact epochs at a different network size for each scenario over a one-year interval.

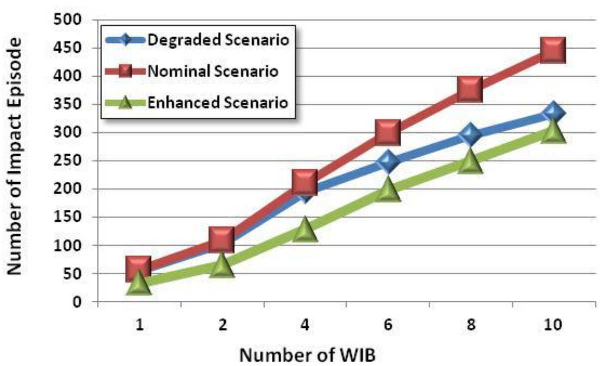

Figure 13. Total Number of Impact Epochs

Remember, this also includes single-outage epochs. The nominal and degraded scenarios both use nominal MTTF; therefore the expected number of single component failures in these two scenarios should be at the same level when the network size is small (such as 1 or 2 WIBs), since the number of impact epochs is approximately the same. As the network size increases, the nominal scenario has more impact epochs as compared to the degraded maintenance scenario, since longer repair times mean that fewer components online at any instant can fail. As it turns out, the degraded case has less epochs, but more multi-outage epochs. Remember – a 1-WIB network serves 100,000 customers, while a 10-WIB network serves 1,000,000.

For larger networks that do not have enhancements in component reliability and maintainability, expanding a network presents challenges for network operators who must cope with impact epochs consisting of multiple outages that overlap in time. Repairing simultaneous outages is challenging in large networks especially because of geographic dispersion, which requires more maintenance staff, equipment, and vehicles. Component maintainability must be achieved even though there are simultaneous outages in the network. See Tables 7, 8, and 9 to see how the frequency of multi-outage epochs decreases as reliability and maintainability improve.

TABLE 7. Frequency of Multi-Outage Epochs: Degraded Scenario

No. Outages in Epoch	Number of WIB				
	2	**4**	**6**	**8**	**10**
1	65	125	189	234	281
2	1	4	9	15	20
3	0	0	0	1	1
4	0	0	0	0	0

TABLE 8. Frequency of Multi-Outage Epochs: Nominal Scenario

No. Outages in Epoch	**Number of WIB**				
	2	**4**	**6**	**8**	**10**
1	105	1	105	1	105
2	4	2	4	2	4
3	0	3	0	3	0
4	0	4	0	4	0
5	0	0	0	0	1
6	0	0	0	0	0
7	0	0	0	0	0

TABLE 9. Frequency of Multi-Outage Epochs: Enhanced Scenario

No. Outages in Epoch	**Number of WIB**				
	2	**4**	**6**	**8**	**10**
1	94	154	183	198	205
2	9	31	49	62	70
3	1	8	12	23	30
4	0	1	5	9	17
5	0	0	1	4	7
6	0	0	0	2	4
7	0	0	0	1	2
8	0	0	0	0	0

Research Question 2: What fraction of time is the network in a non-episodic state as network size, reliability, and maintainability change?

The simulated number of multi-outage epochs for each network size and scenario is displayed in Fig. 14. The curve increases almost linearly for networks in the degraded and nominal scenarios after network size exceeds 2 WIBs. The rate of growth slows down significantly in the enhanced scenario. Table 10 indicates that nearly 40% of the total impact epochs are multi-outage epochs in a 10-WIB network with the degraded scenario. This situation improves in the enhanced scenario, where less than 8% of total impact epochs include more than one outage.

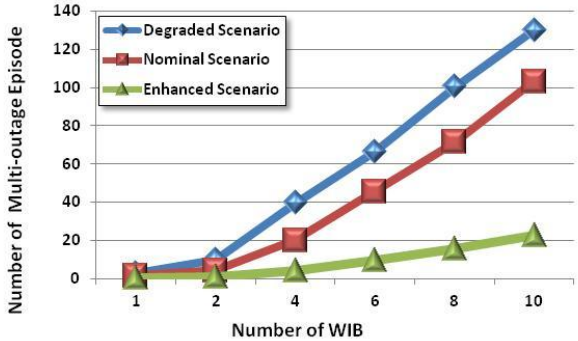

Figure 14. Multi-Outage Epoch Number

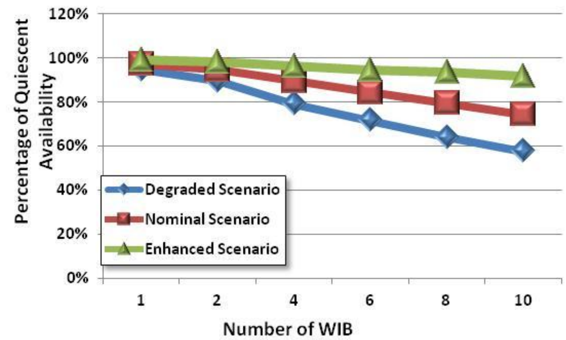

Figure 15. Percentage of Quiescent Availability

TABLE 10. Multi-Outage Impact Epoch Composition

# WIB	≥ 2 concurrent outages			≥ 3 concurrent outages		
	Degraded	Nominal	Enhanced	Degraded	Nominal	Enhanced
2	9.8%	4.6%	1.6%	1.1%	0.3%	0
4	20.1%	9.5%	3.3%	4.6%	1%	0
8	33.5%	18.3%	6.3%	12.7%	4.2%	0
10	39.5%	23.2%	7.7%	17.9%	6.5%	< 0.9%

The difference between the degraded and enhanced scenarios is significant. The percentage of network epochs in the degraded scenario increases from 4.6% to 17.9% as it expands from 1 to 10 WIBs. The range is from 0.3% to 6.5% for networks in nominal scenarios. While in an enhanced scenario network, the 3-or-more outage epoch virtually disappears. Notable differences occur among three scenarios involving the multi-outage epochs. In the enhanced scenario, impact epochs consisting of more than 2 concurrent outages rarely happen, even when a network expands to serve 1 million customers. However, in the degraded scenario, when the network has 6 WIBs, the composition of impact epochs consisting of more than 2 concurrent outages is 7%. When the network has 10 WIBs, the number is 18%. Concurrent outages become a huge challenge for network operators in the degraded scenario, especially when network size grows.

The results of the network quiescent days for each scenario are shown in Fig. 15. As the network expands, its quiescent availability decreases, almost linearly. In the degraded scenario, the total non-episodic time of a WIB network is 345 days over a one-year operation time. By contrast, for a 10-WIB network, the number is only 213 days, which demonstrates that the network is in an episodic state 42% of the time. In the nominal scenario, which has the same reliability as the degraded scenario, the total non-episodic time of a 1-WIB network is 355 days, and 272 days for a 10-WIB network. This implies that 25% of the time the nominal network is in an episodic state for a 10-WIB network, which is approximately a 30% improvement over the degraded scenario.

Research Question 3: How will the dependability characteristics of impact epochs change with the network size, component reliability, and component maintainability?

The nominal and degraded scenarios use the same component reliability or MTTF. The difference is the component maintainability. Meanwhile, the nominal scenario is different from the enhanced scenario for both the component reliability and the maintainability. Fig. 15 shows the quiescent availability of a network in different scenarios. The nominal curve lies between the enhanced and degraded curves. Thus, the component maintainability, rather than reliability, is more decisive to the network quiescent availability. Efficient management of maintenance resources seems to have a positive impact on sustaining a network and avoiding an episodic status.

There are four important attributes of an impact epoch: MTTE, MTRE, PCI, and WPLLH. MTTE is the average time between two impact epochs, which is used to model the network's reliability. MTRE is the average time to repair an impact outage in the network, and is a measure of the network's maintainability. PCI and PLLH are subsequently used to model the wireless network's survivability.

A. Mean Time to Epoch and Mean Time to Restore Epoch

Results demonstrate that MTTE decreases nonlinearly, as expected, as the network size increases for each scenario. In all three scenarios, MTTE decreases quickly as the network grows from 1 to 3 WIBs, and the rate of decrease slows after 3 WIBs. The MTTE in degraded and nominal scenarios are very similar, as they have the same reliability. This is because single component outages are still dominant when the network is less than 3 WIBs. After that, as the network size increases, the overlapping phenomenon begins to play an important role in determining the total number of impact epochs.

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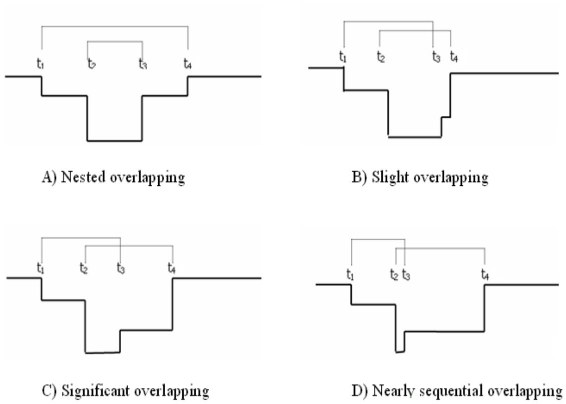

Figure 16. Different Overlapping Patterns

MTRE is expected to increase as outage overlapping occurs. How much overlapping affects MTRE depends upon the pattern of the overlapping. There are several different overlapping patterns that could occur, shown in Fig. 16 A, B, C, D. Among these four patterns, pattern "A" does not increase TRE, since repair time of the second outage completely occurred within the repair time of the first outage (TRE in pattern "A" equals the MTTR of component one). Pattern "B" has a small degree of overlap and effect on TRE while pattern "C" has a moderate impact on TRE. Pattern "D" overlap is nearly sequential, having the largest impact on TRE. All these types of overlapping patterns may impact MTRE. Fig. 17 illustrates the simulation output of the MTRE changes due to network size.

As expected, MTRE in the degraded maintainability scenario increased nonlinearly as the network expanded, due to overlapping outages. As the network grows, more overlapping instances occurred and the chance of overlapping pattern "A" increased, thereby decreasing MTRE. The component maintainability in the degraded scenario is lower than that in the nominal and enhanced scenarios. The MTRE of a 10-WIB network in the degraded scenario increased by approximately 28% (about 144 minutes) from the 1-WIB network, while a 10-WIB network in the enhanced scenario increased by only 5.4 minutes longer than the 1-WIB network.

B. Peak Customers Impacted

A question that a network operator may ask is, "What is the chance an impact epoch affecting more than 10,000 customers will occur in the next 30 days?" Understanding the distribution of peak customers impacted can provide insights into such questions. The PCI for each simulation run was collected and the data was fitted to an Exponential Distribution [24] with a high degree of significance (p value less than 0.0001). This allowed easy calculation of probabilities of peak outages. Table 11 shows the exponential PCI means.

Table 12 displays the probability of a PCI greater than or equal to 10,000 customers in 30 days for different scenarios and network sizes, along with the same results for a PCI greater than or equal to 5,000 customers. Larger networks have higher probabilities due to the additive nature of outages in epochs.

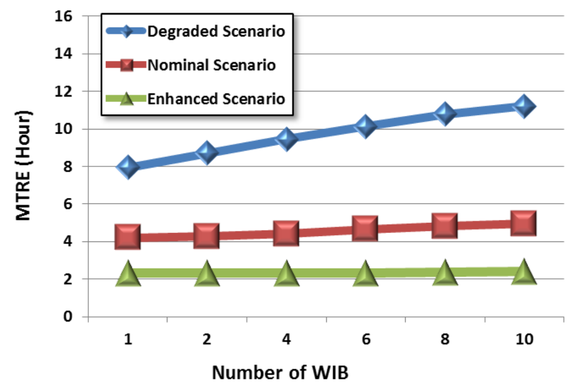

Figure 17. MTRE in Hours

TABLE 11. Mean PCI per Epoch

Scenario	Number of WIB				
	2	4	6	8	10
Degraded	2,932	3,296	3,509	4,407	4,549
Nominal	2,154	2,227	2,579	2,702	2,766
Enhanced	2,176	2,246	2,526	2,654	2,695

TABLE 12. Probability of PCI Over 10,000 and Over 5,000 Customers in 30 Days

Scenario Name	Number of WIB (over 10,000)				Number of WIB (over 5,000)			
	2	4	8	10	2	4	8	10
Degraded	3.3%	4.8%	10.3%	11.1%	18.2%	21.9%	32.1%	33.3%
Nominal	1.0%	1.1%	2.5%	2.7%	10.0%	10.6%	15.7%	16.4%
Enhanced	1.0%	1.1%	2.3%	2.4%	10.0%	10.7%	15.1%	15.6%

C. WPLLH

Similarly, the distribution of WPLLH values for networks of different sizes and scenarios is illustrated in Table 13. These results can predict the probability of PLLH over a threshold for a given time period.

TABLE 13. WPLLH Mean

Scenario Name	Number of WIB 2	4	8	10
Degraded	13,867	18,367	25,094	25,367
Nominal	6,409	6,640	8,088	8,257
Enhanced	3,550	3,735	4,042	4,506

Research Question 4: How will different thresholds help network operators filter impact epochs in a network?

The chance of the PCI and the WPLLH over a certain threshold is much higher in the degraded scenario than that in the nominal and enhanced scenarios. For example, the chance of an epoch in which the PCI is over 10,000

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customers over 30 days in the degraded network is three-to-five times that of the enhanced scenarios. Thresholds are useful for network operators in effectively monitoring networks, given that they filter out lower-priority epochs. In this paper, three different WPLLH threshold levels are used as filters: 5K WPLLH, 10K WPLLH and 15K WPLLH. A 5K WPLLH denotes that the product of impacted customers and impacted duration in an epoch is 5,000. For example, it could mean 5,000 customers are impacted for one hour, or it could signify that 10,000 customers are impacted for half an hour. Fig. 18 indicates the relationship between the numbers of impact epochs versus different thresholds for the degraded scenario.

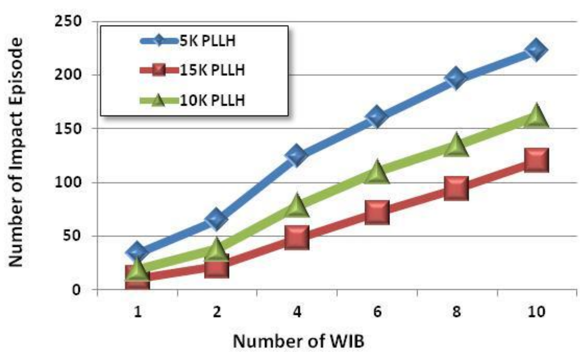

Figure 18. Number of Impact Epochs with Filters in Degraded Scenario

The growth rate of impact epochs over 5K WPLLH in all three scenarios increases rapidly as the network expands in size. At the size of 10 WIB, in the enhanced scenario, the number of impact epochs over 5K WPLLH is 4 times more than enhanced scenario.

This implies that in any scenario where a network expands, the number of impact epochs over a lower threshold can be expected to grow quickly. A network in the degraded scenario has to deal with a large number of epochs over higher thresholds because they grow in number at a much faster rate than that in the enhanced scenario. These insights should aid in network operators' ability to set efficient thresholds. Set too low, a threshold masks important outages; set too high, and too many less significant outages are seen.

VII. CONCLUSION

New dependability metrics have been developed here to investigate concurrent multiple outage epochs. Results indicate that in large networks, the epoch perspective is useful in understanding the complex nature of ongoing concurrent failures. With these new metrics, operators can calculate such things as the probability of a 3-outage epoch over a time period and the probability of an epoch exceeding a specified peak over a time period. Such information is useful to operators in allocating resources. Significant contributions of this work include:

- Defining the impact epoch as a new way to evaluate wireless network infrastructure's dependability.
- Developing new metrics for analyzing RAMS for large networks (MTTE, MTRE, Quiescent Availability, PCI and WPLLH).
- Development of empirically derived wireless traffic profiles to determine the number of customers impacted by component failures by time of day and day of week.

Important conclusions include:

- An impact epoch perspective gives key insights into network dependability. Lacking empirical outage data, these perspectives are best investigated with simulation.
- Component maintainability has a large effect on a network's quiescent availability. Effective monitoring and efficient management of repair resources can shorten the time when a network is in an episodic state.
- The number of small network impact epochs is not critical.

With respect to the last point, network operators should be very careful when expanding their infrastructure in order to accommodate more customers. Results here indicate that the number of concurrent outage epochs is sensitive to both component reliability and maintainability. Reliability and maintainability should not be degraded in the expanded network. Additionally, it may be necessary to increase reliability and/or maintainability in order to keep multi-outage epochs to an acceptable minimum.

REFERENCES

[1] Andrew Snow, Gary Weckman, and Yachuan Chen, "Multi-Episodic Dependability Assessments for Large-Scale Networks", ICN 2011: The Tenth International Conference on Networks, pp. 441 to 448, IARIA, St. Maarten, The Netherlands Antilles, January 23-28, 2011, ISBN: 978-1-61208-113-7.

[2] S Hariri, S., et al, "Impact analysis of faults and attacks in large-scale networks", Security & Privacy, IEEE Sept.-Oct. 2003, Volume: 1, Issue: 5, Page(s): 49 – 54.

[3] B. Bassiri and S. Heydari, "Network Survivability in Large-Scale Regional Failure Scenarios", Proceedings C3S2E '09 Proceedings of the 2nd Canadian Conference on Computer Science and Software Engineering, Pages 83-87, ISBN: 978-1-60558-401-0, ACM New York, NY, USA 2009.

[4] J. Appleyard, "Outage management portal leveraging back-end resources to create a role and user tailored front-end interface for coordinating outage responses", Patent US 8,171,415 B2, May 1, 2012.

[5] Avižienis, A., Laprie, J.-C., Randell, B., & Landwehr, C. (2004). Basic Concepts and Taxonomy of Dependable and Secure Computing. IEEE Transactions on Dependable and Secure Computing, 1(1), (pp. 11–33).

[6] J. Knight, E. Strunk, and K. Sullivan, "Towards a rigorous definition of information system availability". Proceedings of the DARPA Information Survivability Conference and Exposition, IEEE, 2003.

[7] A. Birolini, Reliability *Engineering: Theory and Practice*, Six edition, Springer, 2010.

[8] M. Ayers, *Telecommunications System Reliability Engineering, Theory, and Practice*, IEEE Press Series on Network Management, John Wiley and Sons, 2012..

[9] A. Snow, "A survivability metric for telecommunications: insights and shortcomings", 1998 Information Survivability Workshop – ISW'98 IEEE Computer Society, FL, October, 1998, pp.135-138.

[10] A. P. Snow, "Assessing pain below a regulatory outage reporting threshold", Telecommunications Policy", Vol. 28/7-8, 2004, pp. 523-536.

[11] Andrew P. Snow, "The failure of a regulatory threshold and a carrier standard in recognizing significant communication loss", TPRC 2003, November 2003.

[12] Carol Y. Carver and Andrew P. Snow, "Assessing the impact of a large-scale telecommunications outage", Proceedings of the 7th International Conference on Telecommunication Systems, March, 483-489, 1999.

[13] H. Cankaya, A. Lardies, and G. Ester, "Availability-aware analysis and evaluation of mesh and ring architectures for long-haul networks", Applied Telecommunications Symposium, pp. 116 – 121, 2004.

[14] CTIA Wireless Quick Facts, retrieved from www.ctia.org in September 2012.

[15] U. Varshney and A. Malloy, "Multilevel fault-tolerance for designing dependable wireless networks", Proceedings of the 36th Annual Hawaii International Conference on System Sciences, HICCS 03, IEEE, Jan. 2003.

[16] FCC , Report and Order and Future Notice of Proposed Rule Making, retrieved from http://www.fcc.org in August, 2005.

[17] FCC, Public Safety and Homeland Security Bureau, www.fcc.gov/911/enhanced/, retrieved September 2012.

[18] K.. Du, and M. Swamy, *Wireless Communication Systems: From RF Subsystems to 4G Enabling Technologies*, Cambridge University Press, 2010.

[19] A. Snow, U. Varshney, and A Malloy, "Reliability and survivability of wireless and mobile networks"., IEEE Computer Magazine, July, 2000, pp. 49-55.

[20] Committee T1, T1A1.2 Working Group on Network Survivability Performance, "Enhanced Network Survivability Performance", Technical Report, November 2000.

[21] M. Albaghdadi and K. Razvi, "Efficient transmission of periodic data that follows a consistent daily pattern", 9th IFIP/IEEE International Symposium on Integrated Network Management, IEEE Operations Center, Piscataway NY, pp 511-526, 2005.

[22] W. Fawaz, F. Martignon, K. Chen, and G. Pujolle, "A novel protection scheme for quality of service aware WDM networks", IEEE, 0-7803-8939-5, 2005.

[23] U.S. Census Bureau reports, retrieved from http://quickfacts.census.gov/qfd/states/ in September, 2012.

[24] BestFit 4.5, Palisade Corporation.

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