Multi-Episodic Dependability Assessments for Large-Scale Networks

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Abstract— **As a network infrastructure expands in size, the number of concurrent outages can be expected to grow in frequency. The purpose of this research is to investigate through simulation the characteristics of concurrent network outages and how they impact network operators' perspective of network dependability. The dependability investigated includes network reliability, availability, maintainability and survivability. To assess this phenomenon, a new event definition, called an "impact epoch", is introduced. Epochs are defined to be either single, concurrent, or overlapping outages in time, which can be best assessed with new metrics and simulation. These metrics, Mean-Time-To-Epoch, Mean-Time-to Restore-Epoch along with percentage time the network is not in an epoch state (Quiescent Availability) and Peak Customers Impacted, are investigated. A case study based upon a variable size wireless network is studied to see what insights can be garnered through simulation. The new proposed metrics offer network operators valuable insights into the management of restoration resources. Simulation proved invaluable in identifying multi-outage epochs, as modeling their occurrence, frequency, duration and size is analytically intractable for large networks.**

Keywords-simulation, survivability, reliability, maintainability, wireless network infrastructure

I. INTRODUCTION

Telecommunication networks have become 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 and accommodate new customers could be adversely affected. Understanding the characteristics of concurrent outages as a function of network size and 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 customer 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.

A. *Dependability*

Dependability has a number of different attributes. According to Laprie [9], 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 [8]. The higher the survivability, the better 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 ARMS attributes (availability, reliability, maintainability, and survivability) of dependability.

B. *Reliability*

Network reliability is defined as the probability that a network will perform its required functions over a specific period of time [10]. The reliability, for a network 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 [11]:

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

Where λ is expected failure rate and MTTF is the expected 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*

Network maintainability is defined as the ability of a network to recover from failures [11]. Maintainability can be determined from the Mean Time to Restore (MTR). Restore time is a random variable and typically consists of three parts – detection time, travel time to the outage

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location and the actual repair or replacement time. In this research, the lognormal distribution is used since travel time plays an important role.

D. Availability

Network availability is defined as the probability that a network is ready for use when needed [11]. Average availability can be expressed as:

$$A = \frac{MTTF}{MTTF + MTR} \qquad (2)$$

Availability is a good metric to assess the state when the network is experiencing no problems due to failures.

E. Survivability

Network survivability is defined as the ability of a network to provide services to most customers under partial failures. Snow [13] defined Prime Lost Line Hour (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).

$$NS = 1 - \frac{PLLH}{TLLH} \qquad (3)$$

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 [15, 14, and 4].

II. IMPACT EPOCH

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 the state of no customers impacted to a state of having customers impacted; and 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 a single impact epoch, which consists of three overlapping outages, is shown in the Figure 1 in the form of an epoch profile. Time is represented by the X-axis and the Y-axis represents the percentage of customers that can be served in the network. Prior published research has not considered an epoch perspective; hence, this new methodology is investigated in this paper.

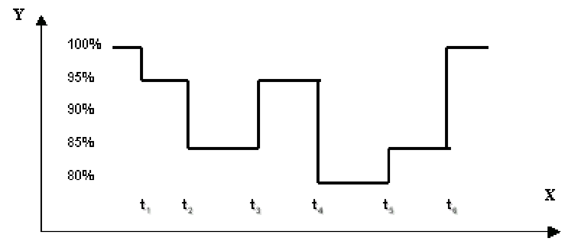

Fig. 1. Single impact epoch due to three overlapping outages

Since epochs are arrival events, 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 lesson 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 gracefully recover 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:

$$A_Q = \frac{MTTE}{MTTE + MTRE} \qquad (4)$$

Survivability from an epoch perspective can still be measured by Equation 3. However, in an environment where there may be concurrent or overlapping outages, peak customers impacted (PCI) may be of interest. For instance, in Figure 1, the PCI is 20%.

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). 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

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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.

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)

III. WIRELESS NETWORKS

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 [3]. On the other hand, research in the world of wireless communication, especially in cell phone networks, is by comparison relatively new. Research into wireless telephone network reliability did not receive much attention until the late 1990s. Over the last 15 years, the wireless network has grown at an amazing rate. According to the Cellular Telecommunications Industry Association (CTIA) wireless Quick Fact Sheet [18], cellular subscribers in the US surpassed 5 million in 1990 and doubled in just two years. By 2000, cellular subscribers exceeded 100 million in the US and wireless penetration rate was over 65%. There were over 182 million customers in the US as of May 11, 2005.

In 1992, the FCC at first ruled that wire-line carriers had to report all outages that impacted more than 50,000 customers for at least 30 minutes. This threshold was quickly lowered to 30,000 customers for 30 minutes in 1993 [12]. 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 [6]. 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 [7].

A. Wireless Network Infrastructure

The general structure of a wireless network with most of the required functional components is shown in Figure 2 [5]. 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) [5].

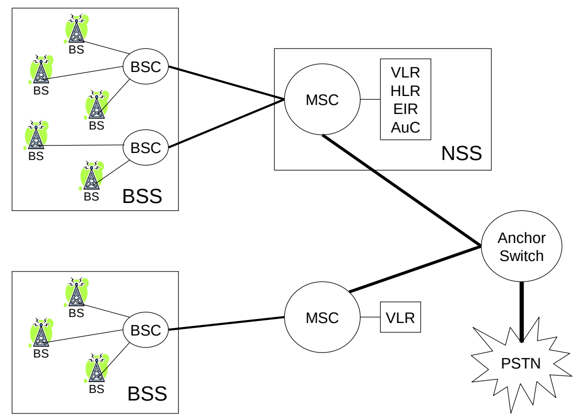

Fig. 2. Wireless network infrastructure

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) [5]. 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, [16], 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 MTR in a WIB might affect the network's dependability [16]. The topology used in a WIB is the star topology. Large wireless infrastructures consist of multiple WIBs.

B. Wireless Traffic

Advantages of using the star topology include supporting modular expansion, and simplified monitoring and trouble-shooting. The largest disadvantage of star topology is the creation of 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 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 [17]. According to historical statistics [13], heavy traffic load in wire-line networks occur between 9:00am and 4:00pm on weekdays.

TABLE 2

Number of Components in One WIB and Maximum Failure Impact

Component	Number in One WIB	**No. 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	2000
Anchor-MSC Link	N	100,000
Anchor Switch	N	N * 100,000
Anchor Link	N	N * 100,000

Note: N is the number of WIBs in the wireless infrastructure

In this work, a new traffic profile for wireless networks is developed. The reason is that 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 time of day a call is placed. For example, many cell phone plans offer free calls at weekends and after 9:00pm on weekdays. Some people could wait until 9:00pm to place calls and take the advantage of this plan. Such phenomena results in different weekday and weekend traffic profiles in wireless networks. In Albaghdadi and Razvi [1], the authors studied an actual 1320 cell GSM network. In this research, the results reported in this GSM network were used to develop five-day weekday traffic and weekend traffic profiles as shown in Figures 3**.** These profiles were developed to create a wireless PLLH outage impact metric, called hereafter the WPLLH.

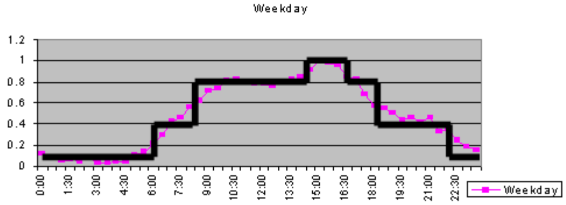

Fig. 3. Wireless Weekday Time Factor

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

C. *Network Component MTTF and MTR*

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 MTRs Used In the Study

Component Name	**Nominal MTTF (Yrs)**	**Enhanced MTTF (Yrs)**	**Degraded MTR (Hours)**	**Nominal MTR (Hours)**	**Enhanced MTR (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 and 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 [16]. 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.

A component's maintainability is represented by its MTR. In order to understand the role that MTR plays in dependability, three MTR scenarios are used in the simulation: nominal, degraded and enhanced. Nominal MTR was obtained from [16]. The degraded MTR was taken as three times the nominal MTRs except for switches. Table

3 also lists the component MTRs 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

D. Simulation Model

Inputs for the simulation include all component MTRs and MTTFs, wireless traffic profile, the network size and an operational time of one year. Outputs from the program are network survivability, 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]. Figure 4 displays the input and output process of the simulation and the derived results.

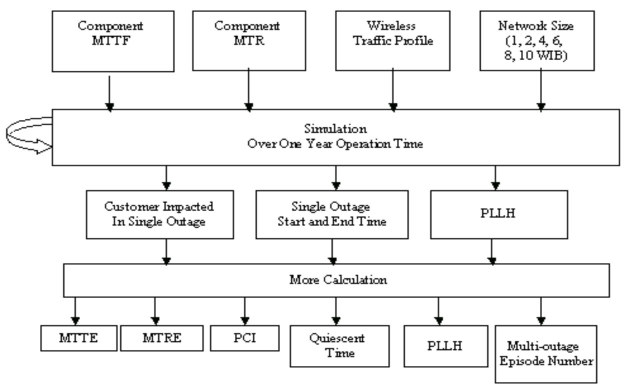

Fig. 4. Process of simulation and results

The process was conducted separately for different size networks (size determined by the number of WIBs) based on three scenarios: nominal, degraded maintainability, and 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 4, showing four component outages, starting at 308.465 days into the year. Figure 5 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:

$$Q_t = \sum_{i=1}^{n} TTE_i = TotalSimulationTime - \sum_{i=1}^{n} TRE_i \qquad (5)$$

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 Figure 5.

TABLE 4

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

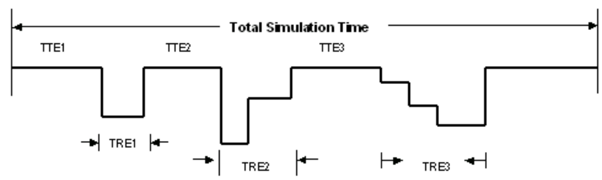

Fig. 5. Relationship of TTE, TRE and simulation time

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

$$MTTE = \frac{\sum_{i=1}^{n} TTE_i}{n} \qquad (6)$$

$$MTRE = \frac{\sum_{i=1}^{n} TRE_i}{n} \qquad (7)$$

$$Total\_Simulaiton\_Time = (MTTE + MTRE) \bullet n \qquad (8)$$

IV. RESULTS

As expected, 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. Figure 6 illustrates the relationship between the total numbers of impact epochs at different network size for each scenario over a one-year interval. 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 fewer components online at any instant that can fail. As it turns out, the degraded case has less epochs, but more multi-outage epochs. Remember – a one WIB network serves 100,000 customers while a ten WIB network serves 1,000,000.

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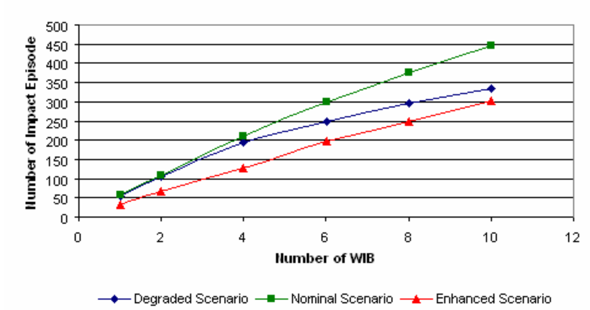

Fig. 6. Total number of impact epoch

Figure 7 displays the actual number of multi-outage epochs for each network size scenario. 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 5 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.

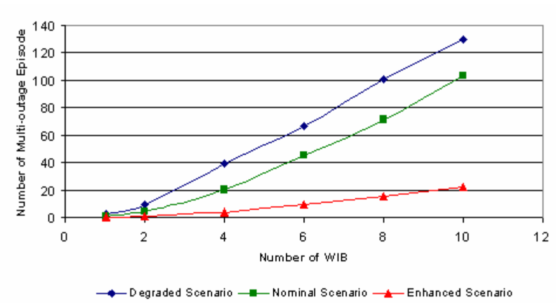

Fig. 7. Multi-outage epoch number

TABLE 5

Multi-Outage Impact Epoch Composition

# WIB	2 or more concurrent outages			3 or more 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 degraded and enhanced scenario 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 scenario. 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 Figure 8. As the network expands, its quiescent availability decreases, almost linearly. In the degraded scenario, the total non-episodic time of a one 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 30% improvement over the degraded scenario.

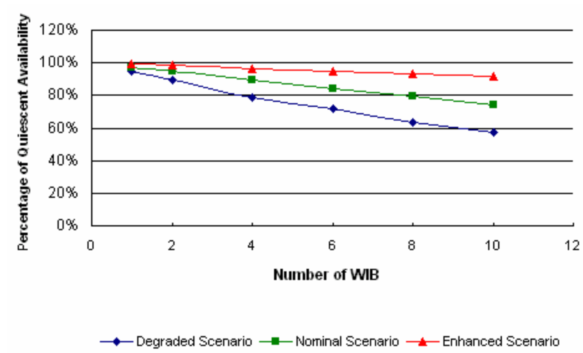

Fig. 8. Percentage of quiescent availability

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. Figure 8**,** demonstrates that 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.

Figure 8 shows the quiescent availability of a network in different scenarios. 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, which is a measure of the network's maintainability. PCI and PLLH are 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.

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 Figure 9 A, B, C, D. Among these four patterns shown in Figure 9, pattern "A" does not increase TRE since repair time of the second outage totally occurred within the repair time of the first outage (TRE in pattern "A" equals to the MTR 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. Figure 10 illustrates the simulation output of the MTRE changes due to network size.

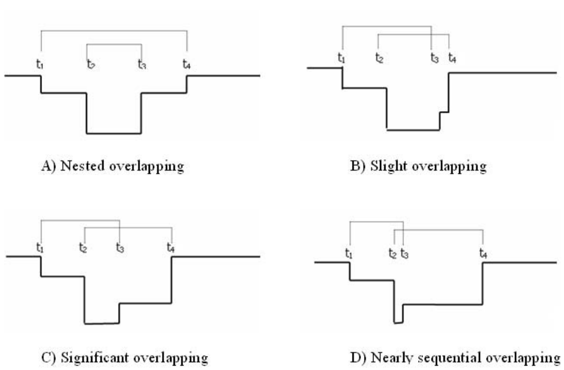

Fig. 9. Different Overlapping Patterns

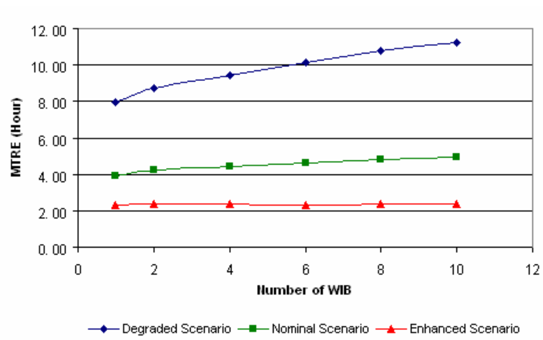

Fig. 10. MTRE in hours

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 nominal and enhanced scenarios. The MTRE of a 10 WIB network in the degraded scenario increased by approximately 28% (about 144 minutes) from the single WIB network, while a 10 WIB network in the enhanced scenario increased by only 5.4 minutes longer than the one 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 [2] with a high degree of significance (p value = 0.0000). This allowed easy calculation of probabilities of peak outages. Table 6 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.

Table 6

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%

Similarly, the distribution of WPLLH values for networks of different sizes and scenarios are illustrated in Table 7. These results can predict the probability of PLLH over a threshold for a given time-period.

Table 7

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

The chance of the PCI and the PLLH 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 customers over 30 days in the degraded network is three to five times than 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. Figure 11 indicates the relationship between the numbers of impact epoch versus different thresholds, for the degraded scenario.

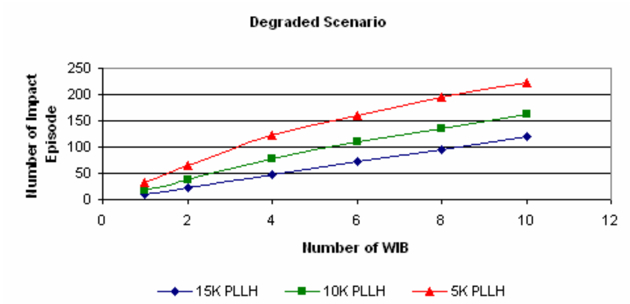

Fig. 11. Number of impact epochs with filters in degraded scenario

The growth rate of impact epochs over 5K WPLLH in all three scenarios increased 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 52, while in the degraded scenario, the number is 223 (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, too many less significant outages are seen.

V. CONCLUSION

This work indicates 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 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:

- Defined the impact epoch as a new way to evaluate wireless network infrastructure's dependability.
- Developed new metrics for analyzing ARMS for large networks (MTTE, MTRE, Quiescent Availability, PCI and WPLLH).
- Development of empirically derived wireless traffic profiles to determine 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 no. 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 component reliability or 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 a minimum.

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