Wireless networks dependability assessment using Artificial Neural Networks

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***Abstract*— Critical infrastructures such as wireless network systems demand dependability. Dependability attributes addressed in this paper include availability, reliability, maintainability and survivability. This research uses computer simulation and artificial intelligence to introduce a new approach to assess dependability of wireless networks. The new approach is based on the development of a neural network, which is trained to investigate availability, reliability, maintainability, and survivability attributes (ARMS) of a wireless network. In this work, given a variety of reliability and maintainability attribute scenarios for a wireless infrastructure, the resulting impact on network availability and survivability are determined. Component mean time to failure (MTTF) is used to model reliability, while the mean time to restore (MTR) is used for maintainability. Here, unavailability, the complement of availability, is defined as the fraction of time the entire network system is down, while survivability is the fraction of network users who are up. Both availability and survivability can be instantaneous or averaged over some period. The data set, which is used to train the neural network, is obtained from simulation experiments with a small range of component MTTF and MTTR. In addition, the number of times a new regulatory reporting threshold is reached is determined. This research also focuses on the relative performance of neural network modeling compared to analytical and simulation techniques for assessing the ARMS attributes of a wireless network and the additional insights that can be obtained from NN modeling.**

I. Background

OVER the past decade, wireless technology has undergone enormous growth. Surveys have shown that a new wireless subscriber signs up every 2.5 seconds. The number of cellular and personal communication system (PCS) users in the US has passed 100 million [1]. Along with an increasing wireless demand, there has been constant improvement in wireless technologies starting from Advanced Mobile Phone System (AMPS) to 2G, 2.5G, 3G, and 4G. Since 2G sets the foundation of the wireless network, this research deals with 2G architectures. Current wireless technology also supports 911 applications, Short Message Service (SMS), Interactive Multimedia Messaging Service (IMMS) and Wireless Application Protocol (WAP) making it even more popular and well accepted. To support these features and to provide continuous service with minimal call drops and call blocking, wireless carriers must focus on making their networks more dependable. In short, in competitive wireless markets, a wireless carrier must pay foremost attention to dependability for attracting more subscribers and satisfying needs of existing customers. On January 2, 2005, the Federal Communications Commission's (FCC) released a new outage reporting regulation. Now, it is mandatory for wireless carriers to report outages that last at least 30 minutes duration and result in at least 15,000 lost subscriber hours.. The FCC's new action makes it imperative for wireless carriers to place special emphasis on wireless infrastructure dependability [2].

A significant amount of research has been published on network design and security management issues of wireless networks, but very little has been done to explore the importance of availability, maintainability, reliability and survivability (ARMS) in wireless networks. Empirical dependability of wireless networks depends upon the number and size of outages. An outage results from failures that cause service disruptions to a fraction of subscribers for a period of time. The fewer the number of outages and the fewer subscribers impacted, the more dependable the network. Three important measures of outages specified in earlier research are the frequency of outages, the number of subscribers impacted, and the outage duration. Several metrics have been defined in the past for measuring outages, namely, lost line hours, user lost earlangs (ULE), outage index, calls blocked, call dropping probability, and number of disconnected nodes [3] [4] [5] [6]. Some research has focused on the "outage double" i.e. size and duration of the impact, while some has focused on "outage triple" i.e. size, duration and importance or type of service lost.

In the field of wireless networks, both analytical and simulation modeling have been used to determine the reliability of a wireless network. In other complex systems like terminal networks, and cruise missile systems, reliability has also been modeled by neural networks (NN) [7] [8]. NN have been used extensively in wireless networks for mobility prediction, and location connection management [9] [10] [11] [12] [13] [14], but not for determining reliability. This research uses NN to estimate the dependability of wireless networks. The data required for training the NN is obtained by empirical data, analytical analysis, or simulation results. Simulation data has been successively used for training a NN in radar tracking systems, for developing a scheduling advisor, and for designing polymer resins [15] [16] [17] . This research also uses the results of simulation modeling to train a NN. NN modeling is used to more quickly perform sensitivity analysis, and for more insights into wireless network dependability.

II. INTRODUCTION

Reliability is defined as the network's ability to perform a designated set of functions under certain conditions for specified operational times. It is a function of component mean time to failures (MTTF). Maintainability is explained as the ability to perform a successful repair action within a given time. It is a function of mean time to restore (MTR) [18]. Average availability tells whether the system is up or down. Lastly, survivability is explained as the percentage of network user up-time. Other features of dependability such as data integrity and confidentiality are excluded from the scope of this study. Security, an important aspect in wireless networks, comprising of confidentiality, availability and integrity, is not considered here. Integrity helps prevent unauthorized modification or deletion of data whereas confidentiality deals with preventing unauthorized disclosure of information [19]. This research uses ARMS, a novel perspective of dependability. For this research a wireless infrastructure capable of serving 100,000 customers is used. Figure 1 shows the general wireless architecture of a single wireless infrastructure building (WIB) [20]. Although wireless systems typically consist of multiple WIBs, this study focuses on one WIB.

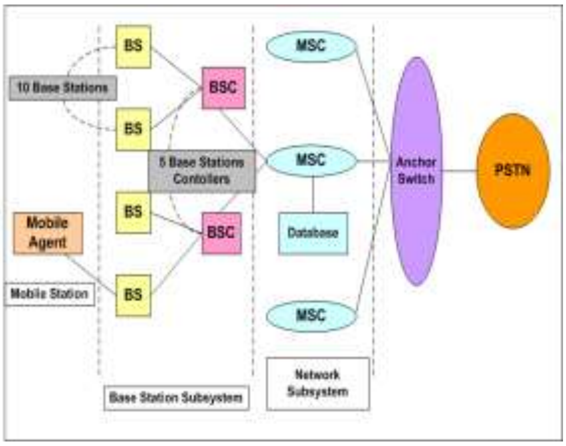

Figure 1: Architecture of One WIB (2 G)

Future research will incorporate these larger infrastructures into the study.

A Mobile Agent (subscriber instrument) selects a base station (BS) by using either direct spread spectrum or frequency hopping method to access the network, depending upon the wireless technology deployed. The base station is typically connected to a base station controller (BSC) through a wire-line mechanism, which in turn is connected to the corresponding mobile switching center (MSC). One WIB block is made up of one mobile switching center, one database (home location register (HLR), one visitor location register (VLR)), base station controllers and multiple base stations. Mobile switching centers are interconnected to enable a wireless call between users of different wireless infrastructure building blocks [21] [22]. The MSC sets up a connection between a mobile user and a fixed user via the Public Switching Telecommunication Network (PSTN) over Signaling System Numbering 7 (SS7) links. It also sets up a connection between two remote mobile users by establishing MSC-PSTN-MSC connection.

When a mobile subscriber moves from one cell to another, its connection with the old BS fades away and a new traffic channel must be established before signal loss results inability to register or, if a call is in progress, in circuit termination. The MSC recognizes that the subscriber is changing cells and pages all other base stations to find the base station with the strongest signal. Once the new BS is recognized, a new traffic channel is established between the two BS's. The system makes this change in fractions of a second without either interrupting the call or alerting the user. This whole process of switching terminals for better quality of signal is referred to as a handoff. Internal handover involves switching within the same BSC without the involvement of MSC as in the cases of channels (time slots) in the same BS cell and other BS cells under the control of the same BSC. External handover is handled by an MSC in cases such as switching of cells under the control of different BSC's belonging to the same MSC and switching cells under the control of a different MSC. Inefficient handovers lead to call blocking and call drops, which have been used in previous research as a metric to measure dependability of wireless networks. If all the traffic channels assigned to the nearest BS are busy and a user is trying to dial a number, then after a preconfigured number of tries, the user is given a busy tone. Such a scenario is called call blocking. However, if the BS is unable to maintain minimum threshold signal strength due to interference or weak signal spots in intermediate areas, the circuit is dropped and the MSC is informed. This problem is classified as a call drop.

III. METHODOLOGY

In previous work by Snow, Varshney, and Malloy, dependability was shown to consist of reliability, availability and maintainability [21] [22] [23]. In this research, survivability is also considered as a part of dependability. Therefore, dependability consists of the following attributes: availability, reliability, maintainability and survivability (ARMS).

This research investigates four research questions relating to a wireless network infrastructure. The first question deals with proactive actions (make components more reliable) and reactive actions (restore failed components faster). In other words, what is best for survivability and availability – making components more reliable or fix failed components faster? This question is examined by reliability growth, constancy, and deterioration (RG/RC/RD) scenarios, and by maintainability growth, constancy, and deterioration scenarios (MG/MC/MD). These scenarios are shown in Figure 2. The question also deals with identifying which single component type has the most positive impact on survivability and availability. The second question studies the effect of various traffic profiles on wireless dependability. The third deals with how often an outage severity threshold, defined by the FCC is exceeded. The fourth, and final research question addresses the ability of a neural network to model large-scale distributed wireless systems. In other words, this research attempts to find out the optimized value of reliability (MTTF) and maintainability (MTR) in order to obtain the best possible values for availability and survivability. Cost optimization is excluded from this research and will be examined in the future.

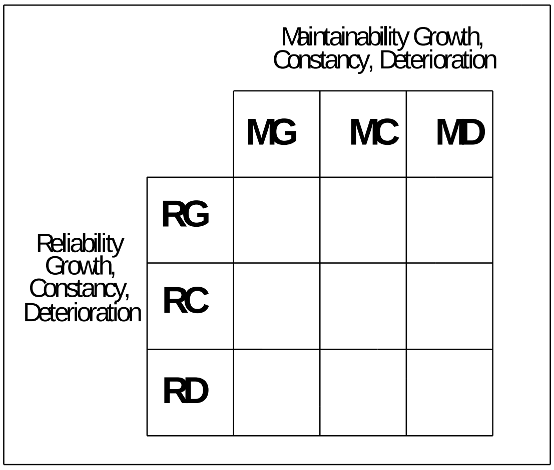

Figure 2: Reliability and Maintainability Growth, Constancy, Deterioration Scenario Matrix

As one WIB is studied, external call handover, interface to either PSTN or other WIB's is not in the scope of the study. These items can be included when the research investigates infrastructures capable of handling more than 100,000 subscribers.

The failure frequency of various components of a wireless network such as BS, BSC, MSC, BS-BSC links, BSC-MSC links is included by using MTTF data. Both MTTF and MTR data from other published research was used. A simulation model was first used to assess dependability attributes (ARMS). Traffic scenarios are also considered in this work. Various traffic profiles by the time of the day i.e. morning, afternoon, evening and night are taken into account while assessing the dependability of the wireless networks. In addition, the study investigates how a NN can be trained to measure dependability of wireless networks and whether sensitivity analysis is beneficial in analyzing the dependability of wireless networks.

The first step in the methodology consists of constructing and verifying a discrete time event simulation model for the wireless system. Next, the simulation results are used to train and validate the neural network. Once trained, the neural network is used to investigate (1) a wide range of scenarios such as RG/RC/RD/MG/MC/MD and traffic scenarios, (2) the number of times the outage severity threshold is exceeded over time, and, (3) the sensitivity of reliability and maintainability in trying to maximize survivability and availability. In this work, RG/RD is modeled as a non-homogeneous Poisson process with 10% growth/deterioration per year over a five year period. Additionally, MTR distribution is modeled as lognormal, with different means over time to approximate MG/MD (also 10% growth/deterioration per year).

3.1 Simulation Model

Analytical equations are difficult to determine for complex systems, therefore this research uses a discrete time event simulation written in VC++ to model a wireless network WIB. The simulation program checks for component failures every 5 minutes based on the exponential distribution. If a component fails the program determines a repair time from a Lognormal. The program will not check the component again until the repair time is passed and component is back to work.
The program also calculates for each outage the total number of customers affected, and also checks and accounts for simultaneous outages. There are six main components in a single WIB serving 100,000 customers (see Table 1). Initial customers affected by failure of each component are shown in Table 2. Figure 3 shows the simulation block diagram.

Table 1: Number of components in a single WIB

Components	Quantity in Each WIB
Database	1
Mobile Switching Center	1
Base Station Controller	5
Links between MSC and BSC	5
Base Station	50
Links between BSC and BS	**50**

Table 2: Number of customers served by component type

Components	Customers Affected
Database	100,000
Mobile Switching Center	100,000
Base Station Controller	20,000
Links between MSC and BSC	20,000
Base Station	2,000
Links between BSC and BS	**2,000**

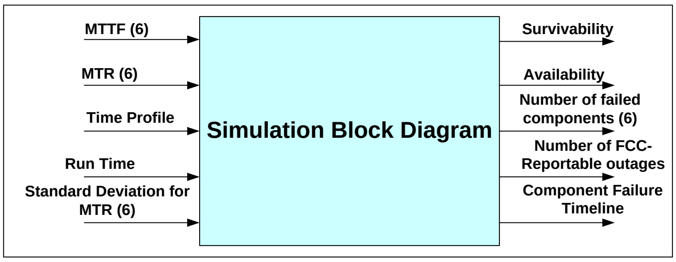

Figure 3: Simulation Block Diagram

Independent variables for this simulation are MTTFs and MTRs of each component, MTR standard deviation for MTR for each component, simulation frequency (operational time being simulated), and traffic profile to represent variable traffic load. Dependent variables are Survivability, Availability, the number of times each component failed, the number of FCC-Reportable outages, and Component failure timeline.

The following assumptions have been made in constructing the simulation model:

- Impact isolated to one WIB, so impact to other WIBs in a larger architecture not considered
- 2,000 subscribers are equally distributed in a cell served by one Base Station
- MTTF and MTR of components of the same type are equal
- MTTFs and MTRs are invariant over the operational time
- Invariant MTTF means exponential failure distribution, a homogeneous Poisson Process (HPP).
- Invariant MTRs drawn from a lognormal distribution with standard deviation of 1.
- Reliability growth/deterioration (non-HPP) over a five year period is approximated by five one-year simulation runs, changing MTTFs by 10% per year
- Maintainability growth/deterioration over a five year period is approximated by five one-year simulation runs, changing MTRs by 10% per year

3.2 Simulation Validation

The validation of the simulation model is based on the Chi-Square test and distribution fitting. Chi-square is used to validate the number of failures. Analytical modeling gives the expected number of failures, which is then compared with the number of observed outages from the simulation. Using the results from many runs, the Chi-square tests supported the hypothesis that their was no difference between the expected and observed failure numbers.

The MTR values are validated by fitting the simulation MTRs to a lognormal distribution using “Bestfit”. Bestfit uses maximum likelihood estimators and provides the statistical degree of it. Once again, the results allow confirmation of the hypothesis that the MTRs came from lognormal distribution with the proper means. Therefore, it can be concluded that simulation was validated for failure rates and restoral times.

3.3 Neural Networks

Figure 4 shows the NN black box design used in this research. There are three aspects related to development of a neural network model. The *first* is the choice of the training, cross-validation and testing data sets and their sizes. The *second* is the selection of suitable architecture, training algorithm and learning constants, while the third is the determination of the termination criteria. In this case, the simulation data was divided into three parts: 65% of data for training, 15% for cross-validation and 20% for testing the NN.

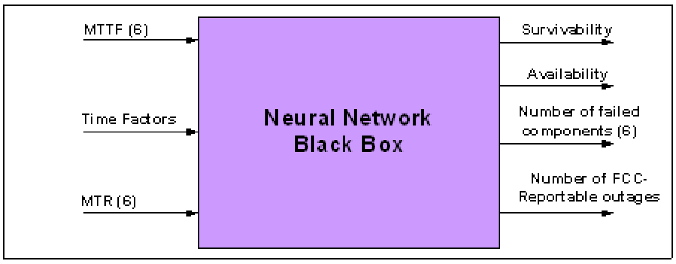

Figure 4: Neural Network Black Box

After the division of simulation results, the training data is fed to the NN for the learning process. Once a NN is trained, it is verified by cross validation. Testing the NN generates output results predicting the availability, reliability, maintainability and survivability of a wireless network. Sensitivity analysis can then be carried out to find the overall impact of independent variables to the dependent variables. An overview of the research methodology is shown in Figure 5.

Sensitivity analysis is a method for extracting the cause and effect relationship between the inputs and outputs of the NN. Traditional sensitivity analysis involves varying each input variable across its entire range while holding all other input variables constant, so that the individual contributions of each variable can be assessed. This would be an extremely time consuming approach using just simulation, instead of a neural network. The basic idea is that the inputs to the network are shifted slightly (defined number of standard deviations, both +/-) and the corresponding change in the output is observed.

IV. RESULTS

Considerable experimentation was necessary to achieve a good network model of the data. The software “NeuroSolutions” developed by NeuroDimensions Incorporated is used for development and testing of the neural network model. A number of NN models were used to model the WIB simulation output. The indicators used for training include the 6 MTTF, 6 MTR, and traffic profiles. These inputs were used to create a separate NN model which would predict each output of Survivability, Availability, Reportable Outages, and Failed components. For example, the architecture of the NN used for predicting Reportable Outages was a Multilayer Perceptron (MLP) based on 14 inputs with 10 processing elements (PE)s in the first hidden layer, and 5 PEs in the second hidden layer. The hidden layers used the Tanh Axon. The Tanh Axon applies a Bias and Tanh function to each neuron in the layer. Figure 6 shows an output (Reportable outages) indicating a very well trained NN, which can be used to find how reportable outages are impacted by reliability/maintainability growth/deterioration scenarios, sensitivity analysis and decision tree analysis if the goal is to decrease reportable outages.

Figure 7 illustrates how Reportable Outages vary over a range of values for BSC-BS link MTTF (years) and Figure 8 illustrates how Reportable Outages vary over a range of values for BSC MTR (hours). This would provide feedback as to which input variables are the most significant relative to other input variables as show in Figure 9.

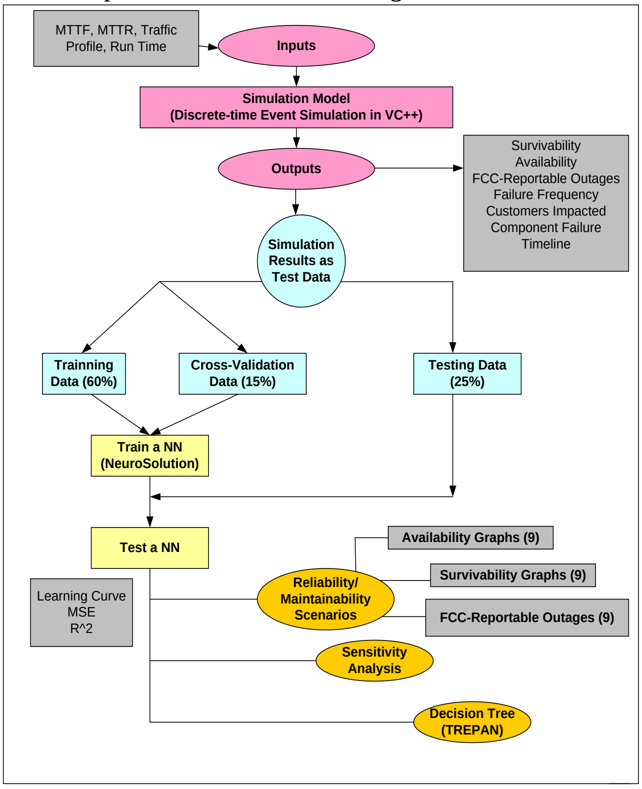

Figure 5: Research Methodology

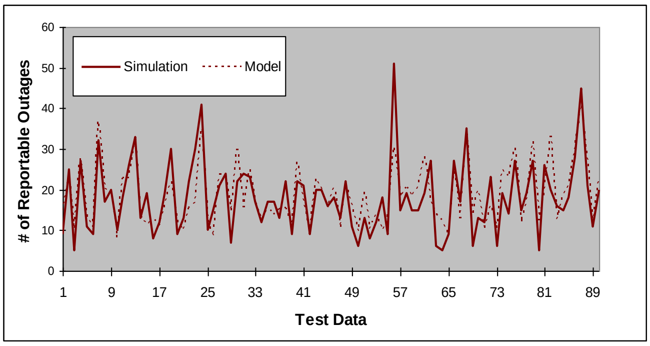

Figure 6: Actual versus NN Output for test data

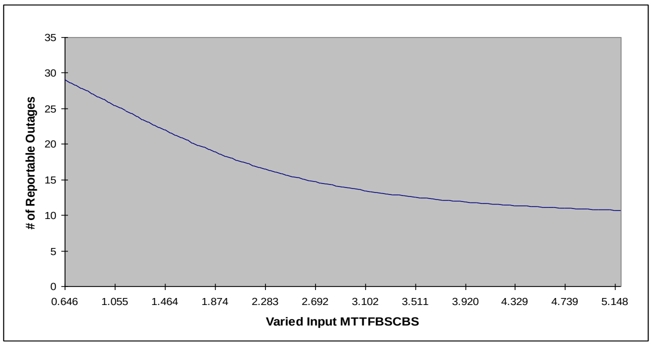

Figure 7: Reportable Outages vs MTTF BSC-BS Link

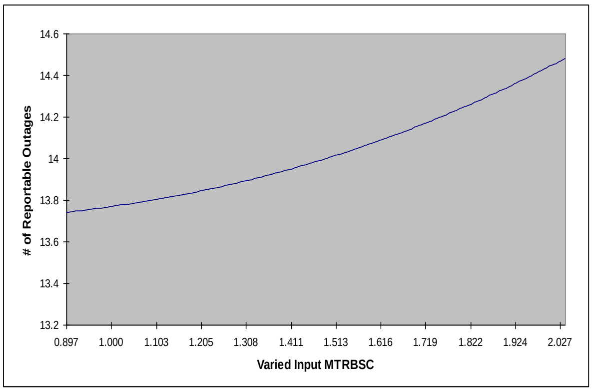

Figure 8: Reportable Outages versus MTR BSC

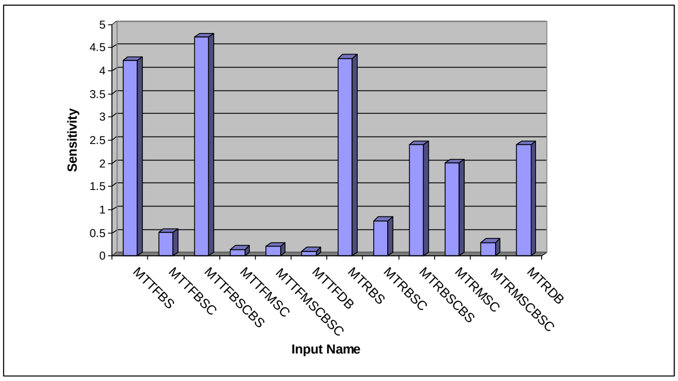

Figure 9: Sensitivity of Inputs versus Reportable Outages

V. Conclusions and Future Research

Preliminary results indicate neural networks can be used to examine a wide range of reliability, maintainability, and traffic scenarios to investigate wireless network survivability, availability, and number of FCC-Reportable outages. Not only is NN a more efficient modeling method to study these issues, but additional insights can be readily observed.

There are however, some limitations. This research analyzes only one wireless infrastructure building block (WIB) and does not include the entire wireless network integrated with PSTN. It does modeling for 2G generation and the model is not applicable for 3G and 4G generations. The size of the WIB and the network topology are fixed. Wireless signaling outside one WIB is not considered i.e. failures outside the WIB is not taken into account. Optimization is completed without the involvement of a cost function and hence economic considerations are not entertained.

Future simulation modeling can be extended to the entire wireless architecture and investigate time factors, type of traffic impacted, various reliability and maintainability growth, constancy and deterioration. Simulation modeling can be further extended for different network topologies such as WIB star and WIB rings to evaluate the performance for different network topologies. Cost functions can be developed and simulation can be designed for an optimal set of dependability and cost of WIB. This analysis could be further applied to 3G and 4G wireless technology.

Effectiveness of neural network modeling can be evaluated for entire PCS architecture and different network topologies and variable sized WIB. Reverse engineering can be carried out for neural networks in order to find the optimal set of inputs when the ARMS attributes are provided for a wireless network. In addition, techniques could be explored that would allow the investigator to go beyond the limitations typically referred to as a "black box". By extracting knowledge into a comprehensible form, further relationships between input and output variables can be explored and can be used to support the generation rule based systems. These extracted comprehensible rules aid in developing a more usable prediction tool and enhance the understanding of the wireless network.

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