Multilevel Fault-tolerance for Designing Dependable Wireless Networks

Upkar Varshney
Department of Computer Information Systems
Georgia State University
Atlanta, Georgia 30302-4015
E-mail: uvarshney@gsu.edu

Alisha D. Malloy
Department of Management Information Systems
University of Alabama, Tuscaloosa 35487
E-mail: amalloy@cba.ua.edu

Abstract

As wireless networks are increasingly deployed in the enterprise and other environments and such trends are expected to intensify with the emergence of high performance wireless networks, an important and emerging area of research is the dependability of wireless networks. Although, the dependability problem also arises in wireline counterparts, user mobility, location and link dependence, and fault propagation make dependability a challenging task in wireless networks. The main contribution of this paper is to propose a novel, multi-level, fault-tolerant design for the emerging wireless networks. Extensive simulation results show that increased user mobility can be compensated by deploying multi-level redundancy and the performance of wireless link is not critical in the overall availability as long as the link availability stays above a certain threshold. One major contribution of our work is to demonstrate that optimal dependability performance can only be achieved by fault-tolerance at network level.

1. Introduction

In the last decade or so, a significant amount of research has been conducted in wireless resource allocation, quality of service (QoS) support, mobility and location management, QoS-aware applications and mobile middleware [1-2]. Most of wireless networking research assumes that the QoS is primarily dependent on the availability of resources and the channel allocation schemes. However, we believe that QoS is also affected by the dependability of wireless components and links, and more work is necessary before highly dependable QoS can be provided in the current and emerging wireless networks. The dependability will become more complex and important in the emerging “3G and beyond” networks due to the increased heterogeneity, inter-carrier roaming making the entire infrastructure dependent on the weakest link(s), and, interconnectedness of networks leading to an increased fault propagation. In addition, these networks would support group-oriented applications, thus the impact of dependability problems would propagate to the current and future locations of wireless users. As many ad hoc wireless networks would be back-boned using infrastructure-oriented wireless networks, resulting in an even broader impact of component and link failures. Since cost considerations would preclude network providers from introducing significant redundancies in their networks, a more “selective” fault-tolerant design would be required to compensate for the impact of failures in terms of QoS degradation, the number of users, duration, and the type of services. A dependable QoS support would also become a factor in selecting a provider in areas of overlapped coverage from multiple carriers and networks by a set of users and business requiring highly dependable service.

It has been shown that in general wireline network dependability can be enhanced by designing and deploying fault-tolerant components and sub-systems However, unlike the dependability analysis and evaluation of wireline networks focused on faults such as a failing link or component, wireless dependability work must also include user location, mobility, traffic type, usage patterns, user density, and wireless specific QoS issues. Therefore new models and designs must be considered to support dependable QoS in the emerging wireless networks. So far, wireless dependability work includes two-tiered wireless systems to increase user availability under network failure [3], architectures involving SONET rings, overlapping base stations, and overlay networks connecting universal access points [4], and the fixed building block approach for computing the failures and customers affected in simple scenarios [5]. The work did not address fault tolerance, wireless link characteristics and the impact of user mobility. A preliminary work on fault issues in wireless access networks was presented in [6]. It can be observed that there has been very little work on fault tolerance in wireless networks, and we believe that ours is the first such study on fault tolerance, especially in multi-level,

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and it also analyses the effectiveness of multi-level fault-tolerant network design. It is unique as:

- It introduces fault-tolerance by adding redundancy at component, link, block and interconnection levels
- It compares the improvements in wireless dependability achieved by multi-level fault-tolerance
- It demonstrates that a "selective" redundancy could achieve a desired level of fault tolerance
- It considers wireless link performance in evaluating the dependability of fault-tolerant wireless architecture
- It includes "macro" level mobility to allow a system level evaluation of fault tolerant design
- It demonstrates that the proposed design and results could be applied towards designing both "fixed" and "mobile" dependable wireless networks
- It could be used to derive dependability performance of inter-carrier and interconnected wireless networks
- It supports dependability evaluation of infrastructure-oriented wireless networks of any size and number of users by deploying a modular and scalable approach based on Adaptable Building Blocks (ABBs)

It should be noted here that this study does not consider "micro" level mobility as the focus of this paper is on "aggregated" dependability of wireless networks. We are enhancing the approach to include the user level mobility to derive joint QoS and availability, and user level mobility and its effect on QoS. We are also studying multicast and group level QoS, cost benefit analysis of fault-tolerance, and multi-network dependability.

To evaluate the effectiveness of the proposed design and approach, we have developed a simulation model. The model has been verified and validated using the adaptable building block (ABB) and analytical modeling. Using this validated model, we derived and compared network availability and survivability attributes using component, block, and network level fault tolerance. The extensive simulation results demonstrate a significant improvement in both availability and survivability attributes of wireless networks. We believe that this is first integrated treatment of wireless dependability using fault tolerance and our multi-level approach and simulation results represent a significant contribution to the wireless research.

The rest of the paper is as follows. We present multi-level fault tolerance for wireless design in section II. In section III, we present the simulation model and results showing. In section IV, we make concluding remarks.

2. Fault-tolerance in wireless networks

We propose a multi-level network design using fault-tolerance techniques for enhancing the dependability performance of wireless networks. The fault-tolerance can be added at component, link, block and network level. To study the effectiveness, we used an Adaptable Building Block (ABB) approach where building blocks containing several levels and multiple components/links are used to model a wireless network of any size and number of users. It should be noted that this differs significantly from WIB approach, using fixed levels and components, designed to study the dependability performance for very simple cases [5]. Unlike WIB, the ABB approach supports wide range of "macro" and "micro" mobility and several different types of wireless links. Since the focus of our work is on multi-level fault-tolerance, we choose ABB approach that allows dynamic blocks with variable levels and multiple different types of components with a range of reliability. The components and links contained in an ABB are similar to those provided and described by the Telephone Industry Association (TIA) standards for cellular networks. The components involve Mobile Switching Center (MSC), Home/Visitor Location Registers (HLR/VLR), base station controllers (BSCs), and base stations (BSs) [7]. The links may involve MSC to BSC, BSC to BS, and BS to wireless subscriber. The BS system could consist of an individual base station or a group of base stations managed by a base station controller (BSC), which also performs radio level channel management and call handoff assistance. The BS and/or BSC are connected to a mobile switching center (MSC), which provides switching functions, coordinates location tracking/updating and performs call delivery. The MSC is also connected to PSTN along with signaling system 7 (SS7). Although, SS7 could use its own mesh-type configuration of links to provide a degree of fault-tolerance, however we do not assume redundancy support from the signaling system. Our focus is on the components and links within an ABB and its interconnection to multiple ABBs via different architectures including those providing fault-tolerant operation at the interconnection level. The home/visitor location registers (HLR/VLR), associated with the MSC and SS7, provide information such as user profile (i.e. service type), user location, as well as information concerning visiting subscribers within the MSC coverage area. The size of a building block, the number of levels in a block, the number of components and links, and the size of components and links could be manipulated to optimize one or more of the dependability attributes of wireless networks. An adaptable building block with multiple levels is shown in Figure 1, where each level includes multiple components of different types and reliability levels. Even among the components of the same type, differences in terms of the maximum number of users, MTBF and MTR values, and hardware/software functionalities are assumed to exist.

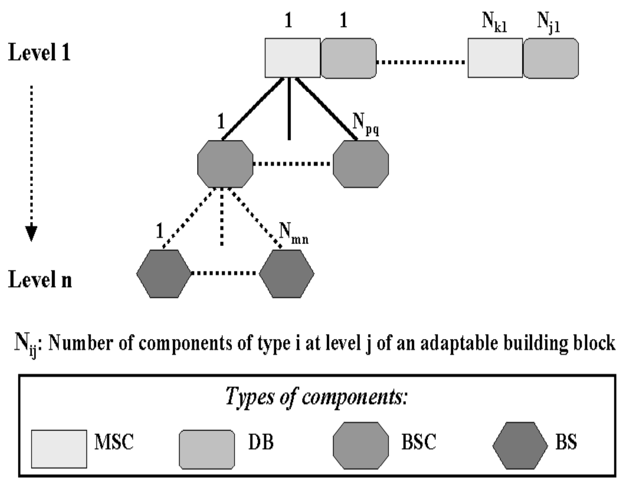

Figure 1. A generalized adaptable building block

Using a combination of the following parameters, the dependability of wireless network can be optimized or a certain desired level of dependability could be achieved:

- Size and number of building blocks (relate to number of users, user density, and dependability attributes)
- Number of levels in a block (relates to availability and survivability attributes)
- Number of different types of components (may affect fault-propagation and MTR value)
- The number of components of a certain type in a given level (relates to the survivability attribute)
- The size of different components in terms of number of customers supported (relates to the survivability attribute)
- Characteristics of components such as MTBF and MTR (relate to reliability and availability attributes)
- The number of links and interconnection among multiple blocks (relates to survivability and availability attributes)

One or more of these parameters could be chosen to derive optimal values of dependability attributes of wireless networks under a given number of users and user density. The user density in a block varies according to the level of user mobility and thus the impact of component, link and block failures would be both time and location dependent. We believe that dependability optimization could be performed with a fair accuracy by considering higher level mobility (macro mobility) and not individual user mobility, which would make such optimizations intractable and also very sensitive to small changes in user mobility. If dependability optimization is not desired, then one of several combinations of these system parameters could be selected to provide the required levels of dependability in different locations served by a wireless network. If needed, different levels of dependability performance could also be supported in different locations, as the dependability required in highly congested business areas could differ significantly from that required in rural areas. In theory, it is desirable to have the same level of ultrahigh dependability everywhere in every network, but the cost and complexity considerations may preclude such design and deployment in wireless networks. Therefore, it is more likely that certain areas or locations would be pre-selected where highest levels of dependability could be provided, irrespective of cost, due to the types of customers and businesses served in these locations.

Besides location-sensitive dependency in the network of a single carrier, a large-scale network could be deployed to interconnect multiple wireless networks of diverse dependability levels from several carriers, thus creating significant impact in future wireless networks involving large numbers of users receiving advanced services. To avoid such a scenario, we believe that considerable efforts must be directed towards enhancing dependability attributes on both the local and global scale during the design of such future networks.

In general terms, fault-tolerance could be introduced in wireless networks at multiple levels including device, cell, switch, block, network, and inter-network, leading to several configurations for fault-tolerant wireless networks. Fault tolerance at device level could be supported using either multiple interfaces to the same network (replication) or to one interface to each of several different networks (network diversity). Fault tolerance at cell level could be supported by deploying multiple base stations per cell or overlapping (hierarchical cell structure) cell structure, and the extent of such replication or overlapping could be determined using the available reliability level of base stations and the required dependability of the wireless network. Fault tolerance at switch level could be supported by a combination of fault tolerant interconnecting architecture, internal redundancy of components, and multi-homing. Fault-tolerance at the block level could be provided by using block level replication or partial redundancy and the network level fault-tolerance could be achieved by deploying a fault tolerant architecture (SONET ring) to interconnect multiple ABBs. Fault tolerance at inter-network level would involve the access to two or more co-located or overlapping wireless networks. In this study, we focus on fault-tolerance at three different levels: component and link, block and network level and such an architecture for wireless networks is shown in Figure 2. In this architecture, redundancy and replication techniques are used for components and links in a block. Then the blocks are replicated and interconnected by one or more fault-tolerant rings. The exact numbers of components, links, levels in a block, and blocks can be determined based on the desired values of dependability attributes, implementation cost and complexity. The proposed fault-tolerant architecture will allow isolating and bypassing parts of the networks where failures have occurred.

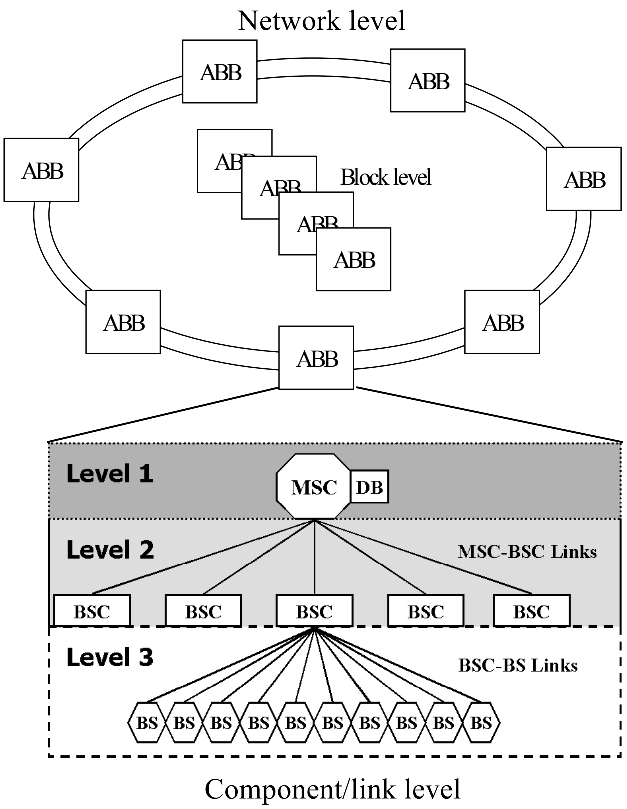

Figure 2. An integrated fault-tolerant architecture for wireless networks

Using the proposed architecture and extensive simulation results, we have evaluated the improvements in dependability attributes by using redundancies at component, block, and interconnection level. Our results are very interesting in many ways, as one of the results demonstrates that a small amount of redundancy at block level could enhance the network availability to near-optimal values, thus effectively masking the effects of all possible faults in the wireless network. Another result show that the proposed architecture could lead to optimal or near optimal survivability levels by using a combination of interconnection level fault tolerance with either the block level or component level redundancies.

3. Modeling and performance evaluation

To evaluate the effectiveness of fault–tolerance at multiple places in a wireless network, we developed and used a discrete event simulation model using the adaptable building block (ABB) approach. The programming language utilized was C++ due to its expressiveness and speed, and our familiarity and prior experiences. The simulator can produce dependability performance of wireless networks with varying degrees of fault-tolerance including both single and multi-level fault-tolerance, thus providing a platform to study the impact of various design changes for enhancing the dependability attributes of wireless networks. To support a realistic assessment of fault-tolerant designs, the simulation model supports multiple distributions for failures and repairs. The model can simulate wireless networks from single block to several hundred blocks, with multiple levels and types of components. These blocks are connected by several different types of interconnection architectures. The input parameters were:

- number of users
- size of building block
- the number of levels and the number and size of different components
- values of MTBF and MTR of each component, link, and interconnecting architecture along with chosen distributions
- levels of fault tolerance and levels of redundancy

Although the number of components and links contained within a building block may vary, we used certain values for a building block for cases where a user did not specify the building block (or ABB). We used 1 MSC, HLR, VLR, 5 BSCs, and 50 BSs in a block, serving 100,000, 20,000 and 2000 users, respectively, and also used low, nominal, and high ranges as shown in Table 1 [5]. MTRs used in the simulation varied from 2 hours for BS to 6 hours for MSC.

Table 1. Low-nominal-high MTBF values (years)

Component/Link	Low	Nominal	High
MSC	5	7.5	10
DB	2	3	4
MSC-BSC	3	4	5
BSC	3	4	5
BSC-BS	1	3	5
BS	1	2	3

Before discussing our simulation results, we would like to add few things here:

- We used exponential distribution for inter-arrival intervals of failures and Weibull for the repair time distribution.
- To address the issue of wireless link performance, we assumed a high level of link availability, achievable by physical level enhancements, link redundancies, and careful resource allocation.
- To support mobility and its impact of fault tolerance, we introduced "macro-level" mobility, where groups of users are considered in deriving the system level fault tolerance, as our focus is on aggregated performance and not on individual users. Our future work will combine individual level dependability with quality of service under both resource and failure constraints.
- In wireless environment, dependent failures are likely to occur where failures in an ABB can also affect customers in other ABBs. Certainly, such impact is also dependent on the user mobility patterns. The interconnection pattern of ABB may also lead to dependent failures.
- To evaluate the fault-tolerance at interconnection level, we have considered three common architectures for interconnecting seven different ABBs.

We divide our results in three different parts: (1) network size and dependability, (2) mobility and fault-tolerance and (3) multi-level fault-tolerance.

3.1. Impact of network sizing on fault-tolerance

the total number of users was kept at a fixed 100,000 and the number of ABB was varied as 10, 50 and 100. For all scenarios, the MTBFs and MTRs of the components remained the same. We assumed that redundancies exist at wireless link and interconnection levels, but we ignored redundancies at component or link levels inside an ABB. To evaluate the effectiveness of fault-tolerance on network sizing, the percentage of redundancy at block level was varied between 0% and 100% in increments of 10%. The figure 3 and 4 show the results, where it can be seen that a network with lower size (more blocks) is likely to perform better than those with larger blocks up to a limit. It can be observed that there is little difference in dependability between networks that have 50 ABBs and those with 100 ABBs. This is important when cost-benefit analysis is done concerning the optimal size of a network. It should also be noted here that after a certain level of redundancy, such differences do not seem to persist. So, depending on the level of redundancy provided at a block level in the network, the network sizing might affect the overall dependability performance. We are fully aware that there are other factors such as population density, required coverage area as well as other dependability attributes that may restrict the use of a network of such size.

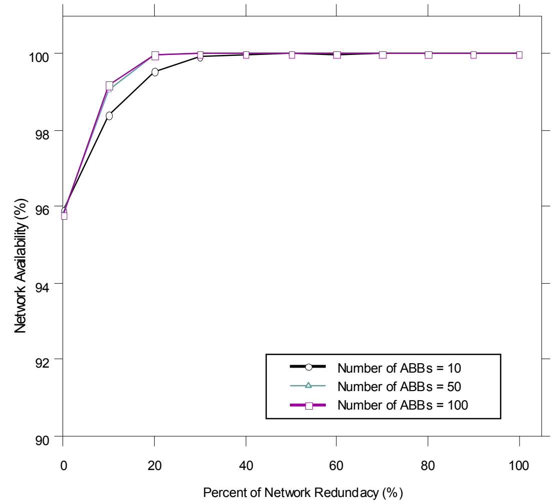

Figure 3: Network availability vs block-level fault-tolerance with block size as a parameter

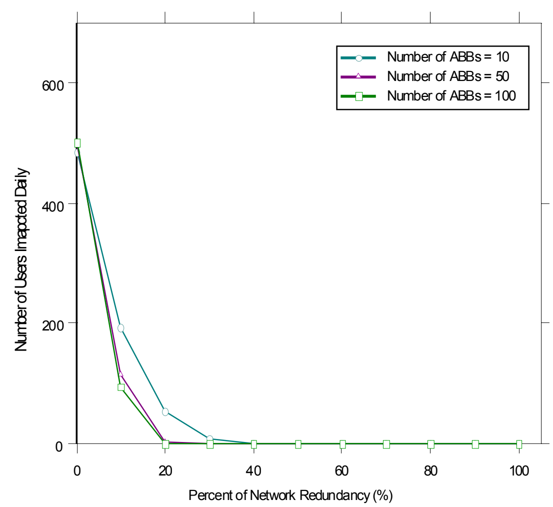

Figure 4: Network survivability vs block-level fault-tolerance with block size as a parameter

3.2. Impact of mobility on wireless dependability

One important aspect of wireless dependability is the impact of user mobility, therefore, we introduced macro-level mobility in our simulation model and investigated both the availability and survivability attributes. In simple terms, macro-level mobility can be defined as the percentage of users registered in a block but roaming in the neighboring blocks. We found that as the mobility level is increased, the network availability reduces and the number of users impacted after failures is increased. These results are shown in Figure 5 and 6. These results were obtained with reduced MTBF (4 times lower than nominal) and increased MTR (4 times higher). It can be observed that mobility can be compensated by an increased level of redundancy, thus a network with higher mobility will require a higher redundancy to achieve a certain level of fault tolerance.

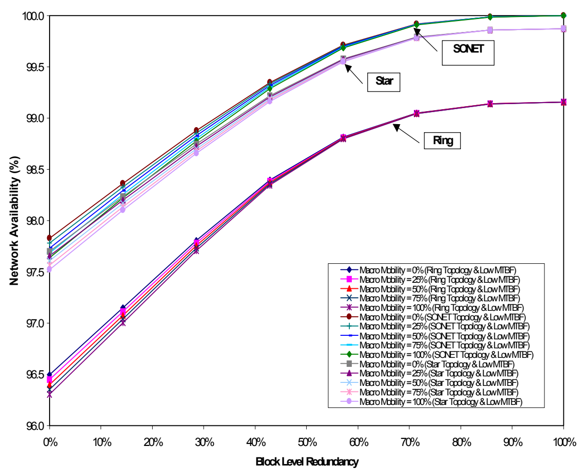

Figure 5: Macro-mobility impact on network availability (Low MTBFs)

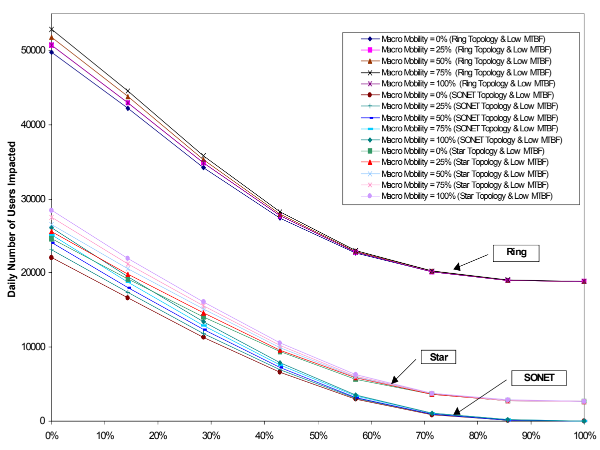

Figure 6: Macro-mobility impact on number of users impacted daily (Low MTBFs)

3.3. Fault-tolerance & multi-level redundancies

To evaluate the impact of multi-level fault-tolerance, we introduced redundancy at all possible levels, assumed full link availability and varied the component and block level redundancies. The interconnection level was supported with three different types of architecture (Ring, Star and SONET), providing different levels of dependability in the interconnected blocks. The component and block level redundancy was varied from 0 to 100% using proportional number of backup components and blocks. We assumed 700,000 users spread over 7 building blocks. From figures 7 and 8, it can be observed that redundancy at either of link, component and block levels is not sufficient for achieving optimal or near-optimal network availability or survivability. The network or interconnection level redundancy is necessary, in addition to redundancies at link, component, or block levels, if a very high level of wireless dependability is required. It should also be noted here that for implementation purposes, a cost-benefit analysis should be done by comparing the cost of providing redundancy at each level and estimating the improvements of several different combinations.

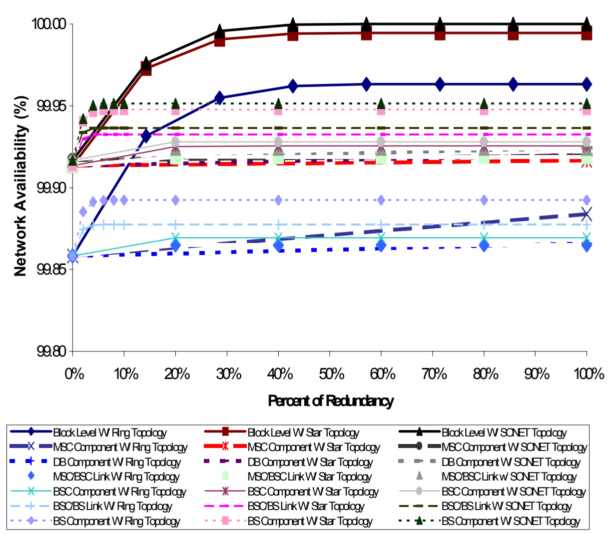

Figure 7: Network availability with fault-tolerance at component, block and interconnection levels

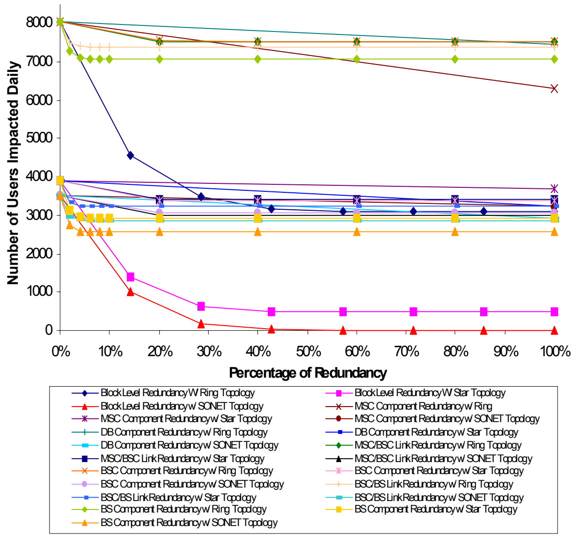

Figure 8: Network survivability with fault-tolerance at component, block and interconnection levels

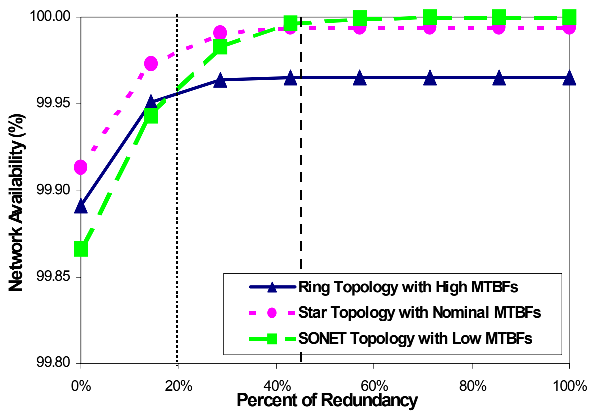

Figure 9. Component reliability and varying levels of block and network level redundancies

Finally, we wanted to observe the interplay of the reliability of components and links against fault-tolerance at block and network level. As shown in Figure 9, we found that it is possible to achieve near optimal dependability performance even with components of lower reliability levels. This required much higher level of block redundancy and highly dependable interconnection architecture. Using the cost-performance ratio, a combination of component reliability, block level redundancy and network level architecture could be selected to achieve an optimal fault-tolerant performance.

4. Conclusions and future research

In this paper, we proposed multi-level fault-tolerance for designing highly dependable wireless networks. More specifically, we introduced fault-tolerance at component, block, and interconnection levels. We found that fault-tolerance show substantial improvements in both network availability and survivability attributes. We observed that the behavior of wireless links affect the overall availability of wireless infrastructure, while user mobility affects both the survivability and availability attributes of wireless dependability. Although the level of mobility affects the dependability performance, however our results demonstrates that a network with high level of mobility can still achieve a given level of dependability using an increased level of redundancy. We also found that in many cases, the performance of wireless link is not the critical component in the overall availability of wireless infrastructure, except when the link availability is below a certain threshold. It is also shown that to achieve optimal or ultra-high fault-tolerance, redundancy at link, component or block level alone is not sufficient and interconnection level redundancy must be deployed.

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