Survivability Analysis for Mobile Cellular Networks

David W. Tipper*, Chalermpol Charnsripinyo*, Hyundoo Shin*
Teresa A. Dahlberg**
***Department of Information Science and Telecommunications, University of Pittsburgh**
Pittsburgh, PA 15260
****Department of Computer Science, University of North Carolina at Charlotte**
Charlotte, NC 28223
tipper, charnsri@tele.pitt.edu , tdahlber@uncc.edu

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Abstract

The rapid growth of wireless communications has been witnessed from new services and emerging technologies in the past years. As societal dependence on mobile services increases, especially for emergency services, failures that inhibit communications or result in loss of critical data can not be tolerated. This paper discusses the effects of failures and survivability issues in mobile cellular networks with emphasis on the unique difficulties presented by user mobility and the wireless channel environment. A simulation model to study a variety of failure scenarios on a GSM network is described and the results show that user mobility significantly worsens network performance after failures, as disconnected users move among adjacent cells and attempt to reconnect to the network. The result from the analysis suggests that survivability strategies must be designed specifically to contend with spatial as well as temporal network behavior in mobile cellular networks.

1. INTRODUCTION

The rapid growth of wireless communications has been witnessed from new services and emerging technologies in the past years. As social and business activities rely increasingly on wireless communications, wireless access networks become crucial to providing the mobile users with untethered access to resources that reside primarily in fixed infrastructure networks (e.g., the public switched telecommunication network (PSTN) and the Internet, etc.) Typical wireless access networks include analog and digital cellular phone networks, Personal Communication Systems (PCS) networks, wireless local area networks, and wide-area mobile data service networks (e.g., General Packet Radio Service in GSM systems, etc.). Among these, mobile cellular and PCS networks currently represent the fast-growing sector with current emphasis on mobile data services. Research is ongoing to extend the capabilities of wireless access networks for mobile users in order to provide voice, data, and multimedia services at higher data rates regardless of location, mobility pattern, or type of terminal used for access.

In general, the flexibility provided by mobility has satisfied users of current wireless networks, despite the lower quality and reduced service offerings as compared to wired networks. However, as societal dependence on mobile services increases, especially for emergency services, users will demand the same system functionality, in terms of reliable services, that characterizes today's wired telecommunications and data networks. This implies that failures inhibiting communications or resulting in loss of critical data will not be tolerated. The critical importance of providing communication service in the face of failures has been recognized in the public switched telephone network and a great deal of attention has been paid to making these networks survivable and self-healing. However, little work has been placed on understanding or improving the performance of wireless access networks after network failures. The unique aspects of wireless access networks (e.g., user mobility, wireless channel, power conservation, etc.) suggest that the available survivability techniques for dealing with network failures in wired networks may not be directly applicable. Therefore, it is important to understand the effects of various failure scenarios before any survivability mechanism can be successfully implemented in mobile cellular networks.

Survivability is used to describe the available performance of a network after a failure. A survivability analysis measures the degree of functionality remaining in a system after a failure and consists of evaluating metrics which quantify network performance during failure scenarios as well as normal operation. A variety of failure scenarios can be defined, determined by the network component that fails and it's location. Examples of failure scenarios in cellular/PCS networks would include failure of a base station, loss of a mobile switching center and loss of the link between a base station and mobile switching center. Metrics used to assess the survivability of a network focus on network performance and traffic restoration efficiency. For example, call blocking probability and % demand restored are typically used in circuit switched networks. The ″ideal″ survivability goal is to make a network failure imperceptible to the user by providing service continuity and minimizing network congestion.

Strategies to improve network survivability can be classified into three categories: 1) prevention, 2) network design and capacity allocation, and 3) traffic management and restoration. Prevention techniques focus primarily on improving component and system reliability. Some examples are the use of fault tolerant hardware architectures in network switches and provisioning backup power supplies for network components (e.g., backup batteries at cell sites). Network design and capacity allocation techniques try to mitigate system level failures such as loss of a network link, by placing sufficient diversity and capacity in the network topology. For example, designing the topology and determining the capacity of links in a backbone network so that the network can carry the projected demand even if any one link is lost due to a failure. Traffic management and restoration procedures seek to direct the network load such that a failure has minimum impact when it occurs and that connections affected by the failure are restored while maintaining network stability. An example is the use of dynamic fault recovery routing algorithms to make use of the spare capacity remaining after a failure.

This paper presents a general overview of survivability issues and a sample survivability analysis in mobile cellular networks. The simulation results on a typical Global System for Mobile communication (GSM) network are used to assess the performance of mobile cellular networks in the presence of network failures. The rest of this paper is organized as follows. Section II describes the mobile cellular network architecture representing a typical GSM network. Section III discusses survivability issues and defines a multi-layer survivability framework for mobile cellular networks. Section IV discusses a sample survivability analysis in mobile cellular networks. A simulation model developed to study the impact of various failure scenarios on a mobile cellular network is first described. Results and analysis of the simulation study are then presented. Several factors that can affect the performance of mobile cellular networks during the course of failures are identified. Lastly, section V presents the conclusion in this paper.

II. CELLULAR NETWORK ARCHITECTURE

A mobile cellular network can generally be described as a fixed infrastructure consisting of network elements that allow mobile users to access network services through radio channels. A typical architecture of current cellular/PCS networks is illustrated in Figure 1.

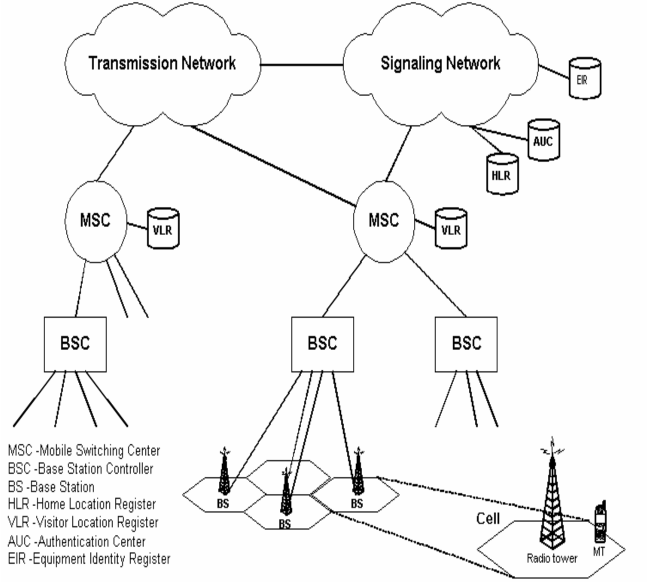

Figure 1. Mobile cellular network architecture

A mobile cellular network typically covers a large geographical service area which is partitioned into many small regions called cells. Each cell is served by a base station (BS) that acts as a fixed access point for all mobile terminals (MT) currently residing within the cell. The BS terminates the wireless communication links (or radio channels) to the user on the network side of the user-to-network interface. The wireless links between the BS and MTs within a cell are digital and employ either time division multiple access (TDMA) or spread-spectrum code division multiple access (CDMA) techniques. The network may include base station controllers (BSC), which manage a group of base stations, as well as do radio level channel management and assist call handoffs. The BSs and BSCs are connected to backbone networks via mobile switching centers (MSC). The MSC is connected both to the transmission networks and to the signaling network which uses Signaling System 7 (SS7) for network control. The MSC provides switching functions, coordinates location tracking/updating and call delivery. Associated with the signaling network and MSCs are databases to support user and service mobility (e.g., authentication and roaming). These databases include a Home Location Register (HLR), Visitor Location Register (VLR), and possibly an Equipment Identity Register (EIR), and Authentication center (AUC). The HLR contains user profile information such as the types of service subscribed, billing information and location information. The VLR stores information about the mobile users visiting an associated MSC coverage area. The communications links that carry traffic between the BS, BSC, and MSC are typically wired lines or fixed microwave links.

III. SURVIVABILITY ISSUES

A typical mobile cellular network as shown in Figure 1, consists of a collection of components inter-working with each other and has a root-branch-leaf topology with the MSC at the root. Any of the components in the cellular network infrastructure can fail and results in different degrees of impacts on the system. Major component failures include BS, BSC, MSC, HLR/VLR, as well as communication links. For the network to be survivable, alternate routes must exist between the network components with appropriate traffic restoration methods. In order to facilitate survivable analysis and design of wireless access networks, a survivability framework similar to the approaches of [1] for wired backbone networks has been developed in [2-3] as shown in Table 1. The survivability framework for wireless access networks consists of three layers: access, transport, and intelligent. Note that the layering/partitioning defined in the survivability framework should not be confused with the seven-layer OSI model. The components and functions supported at each layer are also listed in Table 1. The access layer has two sub-layers, radio level and link level, in order to distinguish between the wireless component and the landline portion.

The access layer at the radio level defines the physical interface for communication over their wireless links within a cell. The access layer at the link level includes the BSs, BSC, and radio resource management schemes (e.g. channel allocation and handoff). The transport layer supports call management functions (e.g. connection setup/teardown) and mobility management (e.g. location tracking) functions using the wired interconnection of BS, BSC, and MSC; with the MSC as the primary controller. The MSC at the transport layer uses the signaling network and services provided by service data management functions, implemented at the intelligent layer, to support call and mobility management. The intelligent layer supports service data management functions to provide the transport layer access to system databases (HLR, etc.).

Given the above framework, to conduct a survivability analysis, one must identify performance metrics along with techniques for evaluating the metrics over various modes of operation. The modes of operation include normal, single-failure, and multiple-failure modes. Table 2 lists examples of possible survivability metrics and sample failure conditions at each layer in the framework.

At the access layer, a typical failure would be the loss of a BS, with appropriate survivability metrics of call blocking probability and forced call termination probability. The call blocking probability measures the percentage of call requests turned down due to lack of resources, whereas the forced call termination probability measures the percentage of calls which are prematurely terminated, including those dropped due to handoff. At the transport layer a typical failure would be the loss of a BSC-MSC link, resulting in loss of service to a cluster of cells. Appropriate metrics include call blocking probability, forced call termination probability as in the access layer case. Since a large number of users are affected by the failure and may attempt to reconnect one must also consider metrics such as the call setup delay, call release delay and location update delay among other metrics listed in Table 2. Such metrics are defined for an entire MSC/VLR coverage area and have target mean and .95 percentile values recommended by the ITU. At the intelligent layer a possible failure scenario would be the loss of a VLR database, resulting in the partial or complete loss of roaming service in a VLR/MSC coverage area. Possible survivability metrics would include, the lost user load (i.e., user lost Erlangs), and the percentage of queries to the HLR that results in accurate responses.

The following section describes a sample survivability analysis using simulation approach to evaluate survivability metrics during failure scenarios as well as normal operation.

IV. SURVIVABILITY ANALYSIS

In the following simulation based survivability analysis, a variety of failure scenarios are considered at each layer in the framework. The impact of failures is then measured according to the survivability metrics of Table 2.

A. Simulation Model

We have developed a simulation model to study the impact of various failure scenarios in the mobile cellular network based on the architecture of Figure 1 as follows. Consider a typical GSM (Global System for Mobile Communications) network serving a medium size city, we assume that the mobile network has 100 cells per MSC with 1 VLR, 20 BSCs, and 9 Location Areas (LA) as shown in Figure 2. Each cell is represented by a hexagonal shape and is numbered from 1 to 100. The location of BSCs are denoted by the 20 numbers with a larger font size. Each BSC controls a cluster of cells which are outlined by a heavy line with a maximum of 7 cells per BSC. For example, BSC 5 controls the set of cells numbered {36, 26, 31, 41, 46}. The location areas can be differentiated by the shade of cells and are also marked by the two long horizontal and vertical dotted lines. The cell radius for a BS is 3 km. In North America, the GSM system has 124 radio channels which are equally divided into two set of channels for different network providers in the same service area. Thus, we assume the system in the simulation model has 62 radio channels, with a frequency reuse cluster size of seven. Therefore, in a cluster of cells, there are 6 cells with 9 radio channels per cell, and one cell with 8 radio channels per cell. A GSM radio channel has 8 time slots, and there is one control channel per cell. This results in an average of 70 traffic channels per cell.

Table 1. Wireless access network survivability layers

Layer	Components	Communication Links	Function
Access-Radio level	mobile units, base stations	digital radio channels with TDMA, FDMA, or CDMA	Define physical interface for radio communication
Access-Link level	base stations, BS controllers	wireline links and/or terrestrial microwave	BS cluster management, Radio channel management
Transport	BS,BSC,MSC, signaling network	wireline links and/or terrestrial microwave, SS7 wireline links	Call/connection management, Mobility management
Intelligent	MSC, HLR, VLR, EIR, AUC, signaling network	wireline links and/or terrestrial microwave, SS7 wireline links	Service management, Mobility management

Table 2. Typical failure scenarios and survivability metrics at each layer

Layer	Failure Scenario	Potential Impact	Possible Metrics
Access	Loss of BS	Partial/full service loss in cell, Increased traffic in cells adjacent to failure	Call blocking probability, Forced call termination probability
Transport	Loss of BSC-MSC link	Partial/full service loss in a cluster of cells, Increased traffic in cells adjacent to failure	Call blocking probability, Forced call termination probability, Call setup delay, Call release delay, Paging/location update/registration delays
Intelligent	Loss of VLR	Loss of roaming service in a MSC coverage area	Lost user load (Erlangs), Database access delay, Information accuracy probability

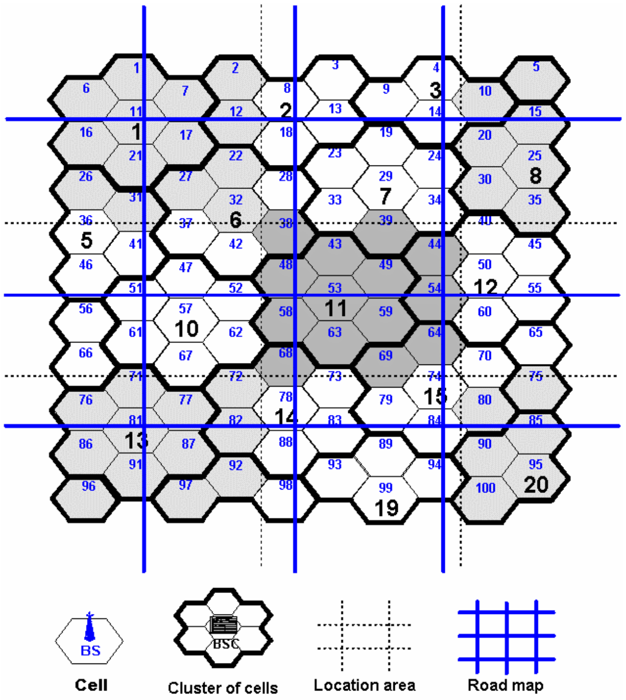

Figure 2. Simulation model architecture

In the simulation model, two types of calls are generated. They are mobile originated calls (MOC) and mobile terminated call (MTC). The percentage of each call type is 70% MOC and 30% MTC as in [4]. We assume that calls arrive to the system according to a Poisson process and the calls have an exponentially distributed holding times with a mean of 120 seconds. For 2% call blocking with 70 traffic channels, each cell can support a load of about 59.1 Erlangs. The total number of subscribers in the system is set at 100,000. When a mobile terminal (MT) needs a channel for establishing a call, answering to a page, or performing a location update, the mobile at first has to use the random access control channel (RACH) in the serving cell to send initial messages. If the MT can not access the RACH within a pre-defined number of attempts, it will be considered as a failure. When the system receives a call request, it contacts the VLR for location information of the called MT, and then pages the MT. If the system fails to find the MT within a number of paging attempts, the call request is discarded. In order to meet the target ITU benchmark mean delays [5-6] in processing a call handling request (1 sec) and location update (2 sec.), processing time and related parameters in this simulation model are scaled as follows: the post-selection delay is 58.4 msec, the location id query processing time is 8 msec, and the location update processing time is 9 msec.

To represent user mobility, the random mobility model of [7] was adapted to the simulation model. Specifically, the users are randomly placed in the network and the distance from the base station in a cell and direction of movement are randomly selected. The speed of a user is constant within a cell and is uniformly distributed between 0 and 80 km/h. When a user crosses a cell boundary their direction of movement is again chosen randomly and a new speed is selected randomly as well. We also consider the deterministic movement case where a large number of users move in the same direction. This is consistent with highway travel. To represent user mobility in the deterministic case, a road map is specifically defined within the simulation model as illustrated in Figure 2. A portion of users (a parameter to the simulation) is assigned to have deterministic movement where they are always on the roads. Initially, these users are randomly placed on the roads with different direction of movement according to the direction on the road map. A user also randomly chooses to turn left, right or go straight when there is an intersection. The speed of users in the deterministic movement case is uniformly distributed between 10 and 100 km/h and remains constant within a cell. When a user crosses a cell boundary, a new speed is randomly selected again.

B. Simulation Results and Analysis

Based on the simulation model previously described, a variety of failure scenarios were studied with details of random movement case given in [8]. The simulation results for both random and deterministic movement cases are shown in this paper to provide some insight of effects of failures in mobile cellular networks. The performance metrics used to evaluate the effects of failures are the MOC blocking probability, the MTC blocking probability, the handoff call blocking probability, the MOC setup time, the MTC setup time, and the mean location update time for the entire MSC service area. Typical results for the failure of one, two, four disconnected cells and a BSC-MSC link failure, which results in the failure of a cluster of seven cells, are shown in Table 3-4. The mean performance results for the network 10 min. post failures are given in the tables.

Table 3 shows the mean results for the random movement case where the mobile user can move into any cell with equal probability. From the mean results in Table 3, it is obvious that the MOC and MTC blocking rate increase as the number of failed cells increases because of the greater number of users affected. In general, the MTC blocking probability is higher than the MOC blocking probability because other factors are involved, for example, the paging operation failed to reach the called terminal. The handoff blocking rate which is another important performance measure also increases after network failures because calls in progress are dropped when mobile users move into the failed cells. In addition, radio channels in cells adjacent to the failed area may be fully utilized and not available for handoff calls. For the MTC setup delay and the mean location update delay, the time in the case of failures is greater than that of no failure. However, the MTC setup and location update delay for BSC-MSC link failure is less than the delay in the case of four cells failed because the number of requests to VLR in the case of BSC-MSC link failure is less than the other. When mobile terminals enter the failed cells, they do not trigger a location update to the VLR. Therefore, the delay at VLR reduces as the number of requests to VLR decreases. In addition, the MTC setup delay has to take paging time into account as the called MT move into the failed cells. Lastly, the MOC setup delay also decreases as the MOC call blocking rate increases because those blocked calls do not generate further requests to the system.

Table 4 shows results of deterministic movement cases where 10% of total subscribers travel on the road map. The results tend to follow those of the random movement case. However, the blocking rate in the deterministic case is greater than the random movement case as it was expected because many users move in the same direction and try to compete for radio channels. Even though there is no failure in the network, the MOC blocking rate is 3.29% for the deterministic case and increases to 10.25% when 30% of subscribers have deterministic movements.

Based on the study of different failure scenarios, several interesting observations were identified as follows.
(1) The impact of failures is greater than the coverage area failed. For example, the mean location update delay of four cells case increases from 0.27 to 4.78 seconds after the failure in the random movement case.
(2) The transient behavior, which takes place during a time period immediately following a failure, is important. During the transient period, those users, whose calls were prematurely terminated attempt to re-establish the calls at the same time. This incident will cause network congestion and increase the call blocking probability for long periods of time.
(3) The shape of the failed area contributes to the effects of failures in the network. It was found that failures of separated cells are worse than failures in a cluster of cells.
(4) The location of failures also matters. For example, the failure of non-boundary location area cells is worse than those of location area boundary cells.

Table 3. Mean results after 10 min. post failure for random movement

Failure Scenario	MOC blocking (%)	Handoff blocking (%)	MTC blocking (%)	MOC setup delay (sec)	MTC setup delay (sec)	Location update delay (sec)
No failure	1.63	1.65	7.29	3.58	3.35	0.27
1 cell	3.36	3.29	9.01	1.51	3.40	0.32
2 cells	4.67	4.68	10.06	0.91	3.49	0.46
4 cells	7.86	7.44	13.35	0.58	7.68	4.78
1 BSC	13.01	7.05	17.74	0.39	3.92	0.73

Table 4. Mean results after 10 min. post failure for deterministic movement (10% of subscribers)

Failure Scenario	MOC blocking (%)	Handoff blocking (%)	MTC blocking (%)	MOC setup delay (sec)	MTC setup delay (sec)	Location update delay (sec)
No failure	3.29	3.4	8.75	3.21	3.29	0.22
1 cell	5.0	5.2	10.13	1.35	3.31	0.28
2 cells	6.54	6.65	11.47	1.23	3.3	0.31
4 cells	9.13	9.12	13.96	0.57	4.29	1.4
1 BSC	14.3	8.3	19.74	0.42	4.21	1.2

(5) User movement is very important. For example deterministic movement was found to be worse than the random movement.
(6) User behavior matters. It can worsen the network performance if many users attempt to reconnect the prematurely terminated calls simultaneously several times before giving up.

It is crucial to understand those factors involved so that proper mechanisms could be incorporated to mitigate the impact of failures and improve the performance of networks after a failure.

V. CONCLUSION

This paper presented a survivability analysis for mobile cellular networks. The simulation results show that unique characteristics in wireless mobile networks especially user mobility can significantly worsen network performance after a failure. Unlike wired networks, the impact of a failure in a wireless network depends on a variety of factors like the location and shape of failed area, user mobility, and user behavior. This survivability analysis can be used to facilitate wireless mobile network design to meet users' demand in terms of reliable services. For future research, the survivability framework and simulation model will need to be modified to consider characteristics of emerging 2.5G and 3G data services in wireless mobile networks. For example, the rate of packet loss can be used as a performance metric to study the impact of failures for data services instead of call blocking rate in voice services. Additional research work is also needed on survivable wireless network design.

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