PCS Network Survivability

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Abstract

Research and development on the survivability of networks has largely focused on public switched telecommunications networks and high speed data networks with little attention on the survivability of wireless access networks supporting cellular and PCS communications. This paper provides an overview of the survivability issues in PCS networks with emphasis on the unique difficulties presented by user mobility and the wireless channel environment. A multi-layer framework for the study of PCS network survivability is proposed. Metrics for quantifying network survivability are identified at each layer. It is shown that user mobility significantly worsens network performance after even small failures, as disconnected users move among adjacent cells and attempt to reconnect to the network. Thus survivability strategies must be designed to contend with spatial as well as temporal network behavior. Possible survivability strategies and restoration techniques for each layer in the framework are also discussed.

I. INTRODUCTION

The past decade has seen an increase in the deployment of wireless networks supporting mobile communication and an exponential growth rate in the number of users. The majority of recent wireless networks function as wireless access networks to provide mobile users with untethered access to resources that reside primarily in a wired network. Typical wireless access networks include analog and digital cellular/PCS networks, and mobile data services (e.g., Cellular Digital Packet Data (CDPD)). 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. Research is ongoing to extend the scope of services made available to mobile users to achieve the "anytime, anyplace, any form" communications vision. As societal dependence on mobile terminals increases, users will demand the same system functionality, in terms of reliable service, that is characteristic of today's wireline based telecommunications and data networks. This implies that failures that inhibit communications or result in loss of critical data will not be tolerated. The need for research into fault tolerant wireless access networking has been highlighted by recent publicized PCS network outages and the resulting economic impact [9]. Since many of the causes of network failures are out of the control of service providers (e.g, cable cut, natural disasters, etc.) there has been increasing interest in the analysis and design of survivable 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.

Survivable network design refers to the incorporation of strategies into a network to mitigate the impact of failures. 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. For example, the use of dynamic fault recovery routing algorithms to make use of the spare capacity remaining after a failure.

The "ideal" survivability goal is to make a network failure imperceptible to the network user by providing service continuity and minimizing network congestion. However, cost is a factor and the challenge is to provide an acceptable level of service continuity for a set of failure scenarios in a cost effec-

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tive manner. A body of literature exists on survivability techniques for circuit switched networks and there is an emerging literature on the survivability of connection oriented packet networks (e.g., ATM). Survivability of wireless access networks has recently begun to receive attention, mainly focusing on database survivability tailored to the cellular network database (i.e., HLR, VLR, etc.) architecture [2], [10], [12] [3]. This work develops checkpoint algorithms and authentication techniques for the fault recovery of database contents. The design of a survivable landline topology for PCS networks was discussed in [1]. A mixed linear integer programming model for a single link failure survivable mesh topology and capacity allocation design was presented. While this paper is one of the first to mention the topic of survivable wireless access network design, the approach and assumptions used were identical to techniques used for wired backbone network design.

In our opinion, survivability techniques for wired networks are not entirely applicable to wireless access networks, since they must deal with *user mobility*, power conservation in mobile terminals (i.e., battery charge), wireless links that are relatively poor quality (in comparison to wired equivalents) and whose channel capacity is constrained by a regulated frequency spectrum. In this paper we present a framework for facilitating the development of survivable wireless access networks, along with a general discussion of the issues in PCS network survivability.

II. A Wireless Access Network Model

Fig. 1 illustrates a generic wireless network architecture for support of mobile communications [7]. The architecture shown illustrates what is typical of current cellular/PCS networks. The wireless network service area is divided into many small geographical service regions called cells. Each cell is served by a base station (BS) that serves as a fixed access point for all mobile terminals (MT) within the cell. The BS terminates the wireless communication links (or 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 and does radio level channel management and call handoff assist. 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

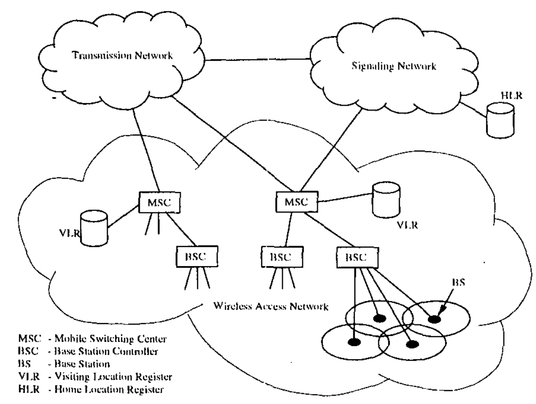

Fig. 1. Wireless access network architecture

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 between the BS, BSC, and MSC are typically wireline or fixed microwave links.

III. A Survivability Framework

Note that, the typical wireless access network shown in Figure 1 has a root-branch-leaf topology, with the MSC the root. For the network to be survivable, alternate routes must exist between the network components with appropriate traffic restoration methods or intelligent spare components must be provisioned (e.g., spare link between BS-BSC with automatic protection switching at end points). In order to facilitate survivable analysis and design of wireless access networks we have developed a survivability framework similar to the approaches of [19], [11], [18] for wired backbone networks.

We view the wireless access network has having three layers [5] [14] with survivability strategies possible at each layer. Note, the layering/partitioning adopted here is **not** to be confused with the seven layer OSI model. The components and functions supported at each layer are listed in Table I. 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 ther wireless links within a cell. This includes the mobile terminal and BS wireless communication scheme for multiple access, modulation, error correction, control channels, etc. 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 landline 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

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 I
Wireless Access Network Survivability Layers

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.) using SS7 signaling protocols. Together the three layers of Table I support network mobility with respect to terminals, users and services.

Given the framework above to conduct a survivability analysis, one must identify performance-oriented *survivability 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 II lists examples of possible survivability metrics and sample failure conditions at each layer in the framework. Table II also lists some of the potential *impacts* of a failure in terms of the area affected and network service disruption. 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, where as the forced call termination probability measures the percentage of calls which are prematurely terminated, including those dropped at 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 II. Such metrics are defined for an entire MSC/VLR coverage area and have target mean and .95 percentile values recommended by ITU [8], [13]. 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 *information accuracy probability* at the HLR. The information accuracy probability measures the percentage of queries to the HLR that result in accurate responses (e.g., location information request).

In order to see the area affected by a failure one must consider both the steady state and *transient* network performance of the network after a failure. Note that, as listed in Table II, the region of impact of a failure is generally larger than the actual service area covered by the failed devices, due to transient conditions. Transient conditions occur after a failure due to a combination of delays in detecting a fault, reporting it and invoking restoration algorithms; coupled with increased call-initiation requests from disconnected users attempting to reconnect in circuit switched networks or dropped packets needing retransmission in packet networks. The importance of transient conditions after a failure has been documented for circuit switched, packet switched (both connectionless and connection oriented) and signalling networks. In wireless access networks, user mobility only worsens transient conditions as disconnected users move among geographical areas to attempt to reconnect to the network.

A. The User Mobility Problem

To illustrate the difficulties that user mobility poses we report some preliminary survivability results for a sample network. Consider a typical GSM network following the architecture shown in Figure 1. We assume a symmetric network with 102 cells per MSC, four cells, per BSC , a frequency reuse cluster size of four, 13 carriers per cell, with 103 traffic channels and one control channel per cell. For 2% call blocking each cell can support a load of about 91 Erlangs. Assuming Poisson arrivals of calls with exponentially distributed holding times with a mean of 180 seconds and one call per user in the busy hour, each user offers .05 erlangs load, resulting in 1820 subscribers per cell. Following [13], we scale the VLR databases using a M/M/1 queueing model to meet the target ITU benchmark mean delay in processing a call handling request (1 sec) and a location update (2 sec.).

This approach results in a mean processing time of call requests of 6.4 msec and a mean processing time of 3 msec for location updates. Each MSC service coverage area is divided into 8 location areas (2 of 8 cells and 6 of 9 cells). Following [16] a coupled differential equation model of the network was developed and solved, modeling the cells by M/M/C/C queues and the signalling network components with M/M/1 queues.

A variety of failure scenarios have been studied, here we discuss the failure of a BSC-MSC link which results in the failure of a cluster of four cells. Consider a worse case user mobility scenario where all users disconnected by a failure move en masse to adjacent working cells (the two immediately above and below the failed cluster - as is consistent with highway movement) and try to reestablish interrupted calls. Further idle customers in the cells that fail move to the adjacent cells and require location updates. Adopting such a worse case scenario illustrates some interesting points. First as one would expect the call blocking probability in the adjacent cells quickly saturates at one in the adjacent cells. Secondly, the control channels (paging, access grant, etc.) at the radio level are not a bottleneck. However, the signalling network components, (HLR, VLR, SS7 network) are easily overloaded. In particular, the mean location update delay for the *entire MSC service area* reaches 22.6 seconds immediately after the failure and exceeds the target value for more than one hour! Discrete event simulation results using random user mobility behavior (rather than worse case) similarly show many cases where rather small failures (e.g., 7 cells out of 102) result in mean metric values exceeding recommended ITU values by considerable amounts over the *entire coverage area.* For example the mean call setup delay increases from 5 secs. to an unacceptable 50 seconds.

IV. Survivability Strategies

As noted earlier, for the wireless access network to be survivable, some type of either redundancy (e.g., spare backup component) or robust network design (e.g. mesh topology) together with appropriate traffic restoration must be added to the network. In general, survivability techniques can be deployed at each layer of the framework of Table I for specific failure scenarios. Examples of the types of survivability strategies possible at each layer are listed in Table III. At the access layer - radio level the primary failure to be guarded againist is failure of the wireless link to the user. Due to the constraints of a regulated frequency spectrum, allocation of spare radio channels for use in case of the failure decreases the radio channel capacity available during normal operating modes and such an approach is not econmically feasible. A possible approach discussed in detail in [6] is to design the network with an overlapping cell site architecture along with a dynamic channel allocation algorithm and adaptive power control to provide dual-homing at the wireless link level. At the access layer link level and transport layer, the primary concern is component/link failure in the landline portion of the network. Traditional survivability strategies such as a mesh type architecture (at least two connected), automatic protection switching, and self-healing rings can be deployed. For example, at the access layer link level all of the base stations in a cluster together with their associated BSC could be connected with a self-healing ring. Similarly, at the transport layer, a mesh type architecture between BSCs and MSCs with at least dual homing of every node could be adopted along with appropraite traffic restoration protocols. However, caution must be employed it adopting such a strategy as transient conditions must be consider in the network and traffic restoration protocol design. The importance of consider transient condition is illustrated in two recent works. In [17] it was shown that traffic restoration schemes (in this case fault recovery routing) can have identical steady state performance (% connection blocking probability and % demand restored) and very different transient behavior in terms of the magnitude and duration of congestion. Secondly in [4] it was shown that incorporating transient congestion effects into a survivable network design (Virtual Path ATM network - for surviving any single link failure) can in some cases result in a 50% increase in network capacity requirements over a design that ignores transient effects (and thereby does not meet QoS requirements). Lastly, at the intelligent layer, database diversity together with checkpointing protocols or hot standby databases are options. Considerable future work remains to be done on developing detailed design tools and comparing the options at each layer and among layers.

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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/release delay paging/location update/registration delays
Intelligent	Loss of VLR	loss of roaming service in a MSC coverage area	lost user load (Erlangs) information accuracy prob.

TABLE II
Typical failure scenarios at each layer

Layer	Robustness and Redundancy	Traffic Restoration
Access-Radio level	Spare RF components Overlapping/scaleable cells	Load sharing protocols, dynamic channel allocation, adaptive channel quality protocols
Access-Link level	spare BS-BSC link multi-homing BS to BSCs ring topology for BS-BSC interconnect	automatic protection switching dynamic rerouting protocols self-healing rings
Transport	spare BSC-MSC link, ring topology for BSC-MSC interconnect, multi-homing BSC to MSCs	automatic protection switching, self-healing rings, dynamic rerouting, call gapping
Intelligent	Physical diversity in signal networking links, Physical database diversity	dynamic routing checkpoint protocols

TABLE III
Typical survivability strategies

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