The Effects of Failures in PCS Networks

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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 presents the effects of failures and survivability issues in PCS 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 PCS network is described. The discrete-event simulation results show 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. A multi-layer framework for the study of PCS network survivability is presented. Metrics for quantifying network survivability are identified at each layer. Possible survivability strategies and restoration techniques for each layer in the framework are also discussed.

Keywords: Wireless Access Networks, Multilayer Survivability Framework, Survivability Strategies

1. Introduction

Wireless networks have been rapidly growing in the past years to support increasing demands for mobile communications. 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 phone networks, Personal Communication Systems (PCS) networks, wireless local area networks, and mobile wide-area data services (e.g, General Packet Radio Service (GPRS)). Among those, mobile cellular and PCS networks currently represent the fastest growing sector with a current emphasis on mobile data services. 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. This vision is to provide voice, data, and multimedia services to users regardless of location, mobility pattern, or type of terminal used for access. 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. Over the last decade several highly publicized outages in the PSTN and data networks have illustrated that the loss of communication services is very expensive to businesses, the public and the government. The need for research into fault tolerant wireless access networking has been highlighted by recent publicized PCS network outages and the resulting economic impact [1]. 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. An example is the use of dynamic fault recovery routing algorithms to make use of the spare capacity remaining after a failure.

In this paper we focus on the effects of failures in PCS networks on performance metrics developed to quantify the level of impact, as well as the survivability of the wireless access network. In our opinion, survivability techniques, which have been developed and successfully implemented 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, survivability issues in wireless networks must take into account these unique characteristics, especially user mobility. The simulation results given here show that user mobility can significantly degrade network performance shortly after failures occur.

The rest of this paper is organized as follows. Section 2 gives an overview of the wireless mobile network architecture and the simulation model to study the impact of various failure scenarios on a PCS network. Section 3 describes the simulation results and analysis on sample failure conditions. Section 4 defines a multi-layer survivability framework for wireless access networks. Section 5 discusses survivability strategies for each layer in the framework. Conclusions of this paper are given in section 6.

2. Wireless Access Network Architecture and Simulation Model

A generic wireless access network architecture for supporting mobile communications is illustrated in Figure 1. The architecture shown illustrates what is typical of current cellular/PCS networks.

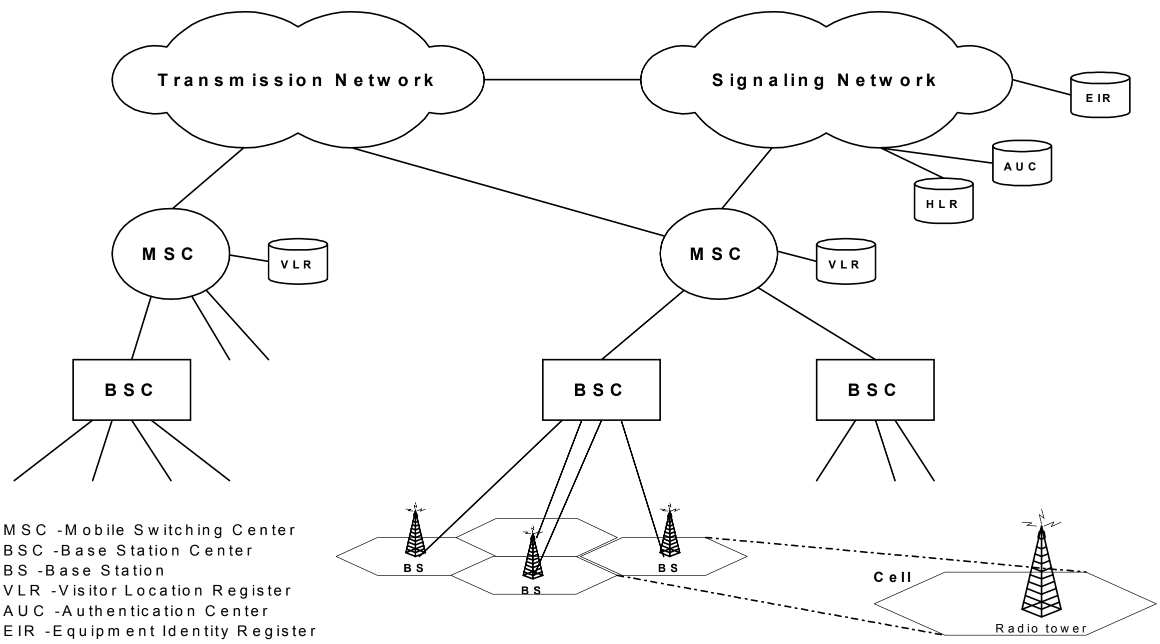

Figure 1. Wireless access network architecture

A wireless access 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 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 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.

We have developed a simulation model to study the impact of various failure scenarios in wireless mobile networks as follows. Consider a typical GSM network following the architecture shown in Figure 1. We assume that a mobile network has 100 cells per MSC with 1 VLR, 20 BSCs, and 9 Location Areas (LA) as shown in Figure 2. Each BSC can control up to 7 BSs and each LA consists of a maximum of 14 BSs. The cell radius for a BS is 3 km. In general, the GSM system has 124 radio channels which will be equally divided into 2 set of channels for different network providers in the same service area. 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 average 70 traffic channels per cell.

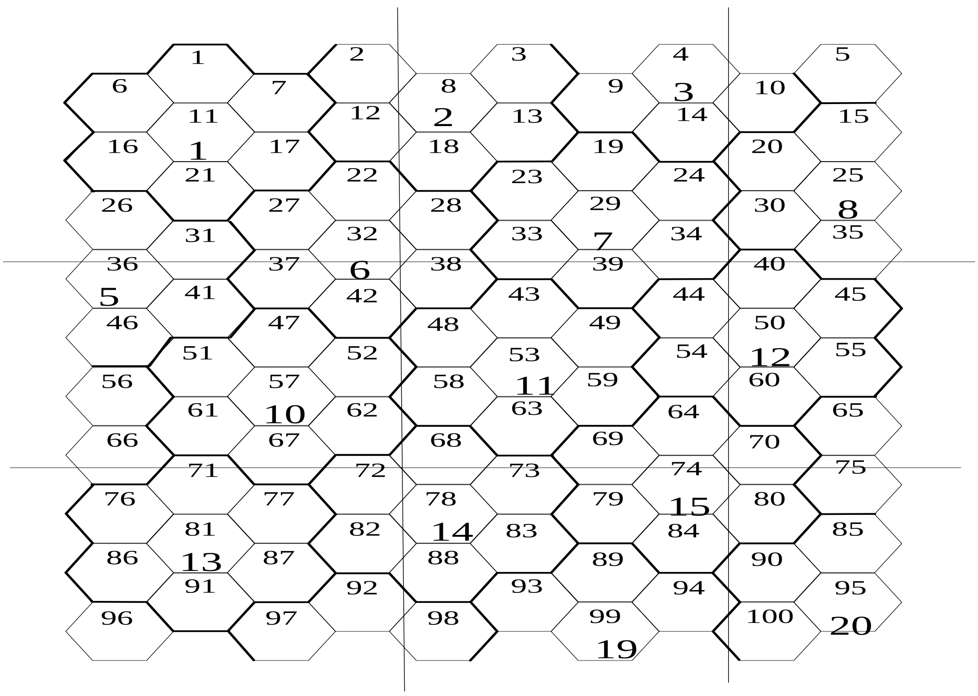

Figure 2. Simulation model architecture

To represent user mobility, a mobile user can move into any cell with random mobilty following the model of [2-4], specifically in between 0 and 80 km/h. In the simulation model, two types of calls are generated. They are mobile originated call (MOC) and mobile terminated call (MTC). The percentage of each call type is assumed as 70% MOC and 30% MTC. We assume the system has Poisson arrivals of calls with 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. In order to meet the target ITU benchmark mean delay in processing a call handling request (1 sec) and a location update (2 sec.), we scale the processing time and set related parameters in this simulation model 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. This simulation model is used to study the effects of various failure scenarios. The results of simulation are described in the following section.

3. Simulation results and survivability analysis

A variety of failure scenarios have been studied. Typical results for the case of the failure of four cells and a BSC-MSC link failure, which results in the failure of a cluster of seven cells, are shown in Table 1. The mean results of random movement case for the network 10 min. post failures are listed in the table. Some of performance metrics used to evaluate the effects of failures are the MOC blocking probability, the MTC blocking probability, and the mean location update time for the entire MSC service area. We consider a random movement case where the mobile user can move into any cell with equal probability. After network failures, with equal probability either the mobile user or PSTN user will make 1 attempt to reconnect interrupted calls.

Metric	No Failure	Four Cells Failure	BSC-MSC Link Failure
MOC blocking (%), P_o	1.64 %	9.57%	15.5%
MTC blocking (%), P_t	7.29%	16.3%	22.6%
Location Update Delay (sec), LD	0.257	5.23	3.85

Table 1. Mean results for 10 min. post failure.

From the mean results in Table 1, it is obvious that the MOC and MTC blocking rate increase as the number of failed cell increases because of the greater number of affected users. In general, the MTC blocking probability is higher than the MOC blocking probability because there are other factors involved, for example, the called mobile terminal is busy or the paging operation failed to reach the called terminal. For location update delay, the time in the case of failures is greater than that of no failure. However, the Location update delay for BSC-MSC link failure is less than the delay in the case of four cells failed. This is because the number of requests to VLR in the case of BSC-MSC link failure is less that the other. When mobile terminals enter the failed cells, they do not trigger a location update. Therefore, the location update delay at VLR reduces as the number of requests to VLR decreases.
Based on our extensive study in many failure scenarios, several interesting observations are identified as follows.
(1) The impact of failures is greater than the area failed, for example the mean location update delay of four cells case increases from 0.25 to 5.23 sec. after failures.
(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. The performance metrics can exceed the ITU recommended bechmarks [5] for long periods of time.
(3) The shape of the failed area contributes to the effects of failures in the network. We found that failures of separated cells are worse than failures in a cluster of cells. For example, the failures of 7 cells which are cell no. 18, 23, 47, 49, 63, 79, 82 in Figure 2 have handoff call blocking rate, P_h = 13% and location update delay, LD =4.16 sec. while a BSC-MSC link failure has P_h =6.6% and LD = 3.85 sec.
(4) The location of failures also matters. The failures of non-boundary cells are worse than those of boundary cells. For example, the case of 4 non-boundary cells which fails at cell no. 47, 49, 53, 89 in Figure 2 has MTC setup time 7.2 seconds. while the case of 4 boundary cells which fails at cell no. 32, 42, 72, and 74 has MTC setup time 3.5 seconds.
(5) The user movement is important. The deterministic movement is worse than the random movement. The deterministic movement is 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). This is consistent with the highway movement pattern and can result in longer transient periods after failures. In addition, the speed of user movement can significantly worsen the performance metrics. For example, in the case of random movement with two cells failures, the user speed of 0-80 km/h has MTC blocking rate, P_t = 11.8% while the user speed of 10-100 km/h has P_t = 34.8%.
(6) The user behavior also matters. In our previous study, we assumed that only one party of failed connection attempts to reconnect 1 time. Our ongoing research considers both parties may attemp to reconnect for several times before giving up.

From the simulation results and observations described above, several unique characteristics, especially user mobility, in wireless mobile networks play an important role in the event of failures. Therefore, survivability strategies must be incorporated into the network to minimize the effects of failures. In the next section, we present a framework for facilitating the development of survivable wireless networks.

4. A Survivability Framework

In this section, we present a multi-layer survivability framework developed in part in [6]. The survivability framework for wireless access networks consists of three layers with survivability strategies possible at each layer. Note that the logical layers defined here are independent of the physical implementation of the network and should not be confused with layers defined in other contexts, such as the OSI layers. Each layer is characterised by network functions, network components, and communication links as illustrated in Table 2.

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. Wireless access network survivability layers

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 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 3 lists examples of possible survivability metrics and sample failure conditions at each layer in the framework. Table 3 also lists some of the potential impacts of a failure in terms of the area affected and network service disruption.

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

Table 3. Typical failure scenarios and survivability metrics at each layer

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 3. Such metrics are defined for an entire MSC/VLR coverage area and have target mean and .95 percentile values recommended by 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 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).

5. Survivability Strategies

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 4.

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 4. Typical survivability strategies

At the acces 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 [7] is to design the network with an overlapping cell site architecture along with frequency reuse partitions, a dynamic channel allocation algorithm and adaptive power control to provide dual-homing at the wireless link level. A cell-site architecture with overlapping coverage area for radio-level survivability is shown in Figure 3.

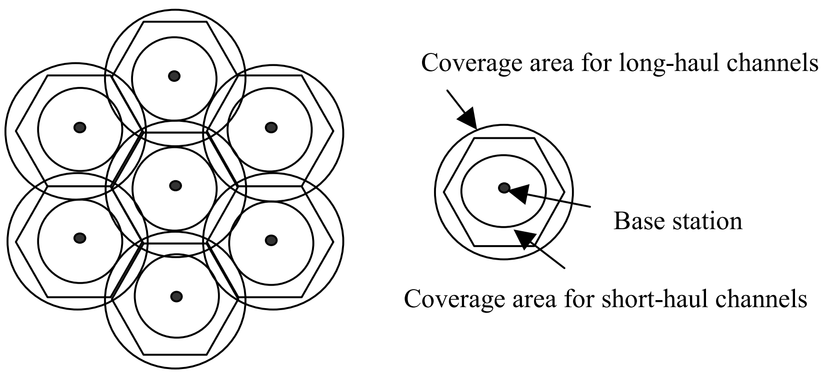

Figure 3. Cell site overlapping architecture

Each hexagon represents a cell with the BS in the center of cell. Each BS supports two groups of radio channels which are short-haul channels and long-haul channels. The short-haul channels are used within the small circle while the long-haul channels cover areas of the larger circle. Ideally, the cell size and coverage areas of both radio channel groups are selected so that all mobile terminals can access at least two channel groups. This means each mobile terminal can access either long-haul channels from at least two BS or short-haul and long-haul channels from the same BS. Therefore, the greater overlap provides more access channels to each mobile terminal but it also increases cochannel interference.

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, 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. An example of employing self-healing ring architecture for a MSC and multiple BSCs in a wireless access network is illustrated in Figure 4.

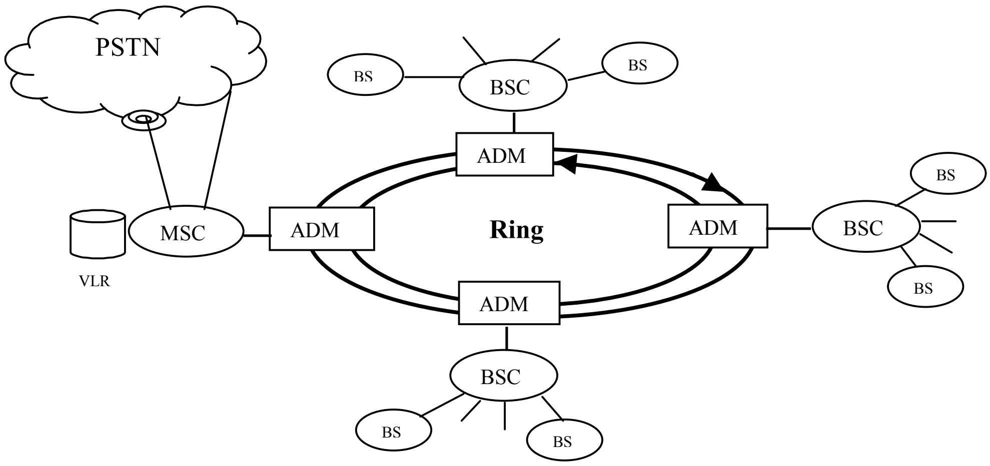

Figure 4.5. Ring architecture in a wireless access network

Lastly, at the intelligent layer, the primary components are system databases such as home location register and visitor location register. Survivability strategies such as database diversity together with checkpointing protocols [8] or hot standby databases could be deployed to provide robustness against database failures.

6. Conclusions

In this paper we presented a sample survivability analysis of a PCS network. Unique characteristics in wireless mobile networks especially user mobility can significantly worsens network performance after failures. 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. A multi-layer survivability framework was presented to facilitate survivable wireless network design. This framework includes metrics for quantifying network survivability, possible survivability strategies and restoration techniques for each layer. Additional work is needed on survivable network topology design and specific fault recovery protocols.

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