A FRAMEWORK FOR FAST HANDOFF SCHEMES IN WIRELESS ATM NETWORKS

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Declaration

I declare that this thesis is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or material are indicated in the acknowledgements or references as appropriate.

This work is being submitted for the Degree of Doctor of Philosophy in Electrical Engineering at the University of Cape Town. It has not been submitted to any other University for any other degree or examination.

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Date:

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ABSTRACT

One of the primary problems in sustaining Quality of Service (QoS) to mobile clients in Wireless ATM (WATM) networks occurs when a Mobile Terminal (MT) moves from one cell to an adjacent one, whilst still maintaining connectivity between the end users. This process is referred to as *handoff*. This problem is difficult because when dealing with ATM networks the handoff differs from conventional voice handoff in that a mobile user may have several active connections with different bandwidth requirements and QoS constraints. The design goal of handoff is to prevent any service disruption during and after handoff; small handoff delay and lossless handoff must be insured. In an intra-cluster handoff the resulting route is optimal. However, in an inter-cluster handoff the new connection needs to be re-routed very fast during the handoff procedure.

In this research, we focus on providing a framework that extends the fixed ATM standard to support user mobility in future WATM networks. The WATM architecture allows for the migration of fixed ATM networks without major modifications. Thus most of the mobility functions are implemented on the wireless access network. The most important component supporting mobility in a cluster is the Mobility Enhanced Switch (MES). We propose using direct links between adjacent MESs to support Permanent Virtual Channels (PVCs) in order to facilitate fast inter-cluster handoff with minimum handoff latency.

This research addresses a framework on handoff mobility by proposing three fast handoff re-routing schemes based on the support of PVCs. The performance of the proposed handoff schemes have been evaluated analytically and by simulation as a function of system parameters such as mean originating call rate, call holding time, cell sojourn time, and mean optimization time. We compute and study the handoff blocking probability due to the lack of PVCs and calculate the required number of PVCs, PVC holding time, and inter-cluster handoff processing

load. The objectives are to show the validation of our proposed models but most importantly that they achieve better performance than other existing methods currently researched.

In the first scheme a path extension method is proposed in which the route is extended from the original connection at the old MES to the destination connection at the new MES, where the new Access Point (AP) exists. This scheme places the handoff processing load in the MES, which is specially designed for high processing performance. This path extension method is fast and simple to implement. PVCs are reserved between MESs offering easy and fast handoffs and a re-routing path for call handoffs without the support of Call Admission Control (CAC), which otherwise may result in unacceptably long connection delays. This scheme supports a very fast handoff with minimum disruption time and minimum processing load. In the second scheme, a new fast two-phase handoff technique using multiple optimization processes is proposed using reserved PVCs in the first phase to avoid handoff latency, followed by the second phase where the optimization process is triggered *instantly* and *concurrently* with the other active optimization processes. The main objective of this scheme is to minimize the route optimization delay so that the QoS disruption for the parameters related to time sensitive applications will be kept to a minimum. In the third scheme, we propose a novel fast handoff re-routing scheme policy to support real time applications by introducing a cluster structure that allows shared cells at the cluster boundaries to support seamless handoff and optimization. An inter-cluster handoff is in effect replaced with an intra-cluster handoff when migrating to an adjacent cluster, followed then by path optimization. We propose to use reserved PVCs between any two adjacent MESs and between any MES and the shared cells at cluster boundaries. The purpose of PVC reservation is to reduce the processing delay and blocking probability during the handoff process. This scheme results in fast route optimization with a very low inter-cluster handoff processing load.

Results from this research show that the first scheme can be used for those application that are delay non-sensitive. For real time multimedia applications, both the second and the third schemes are used, achieving better performance in terms of the route optimization delay than the current used techniques. Although the third scheme performs better than the second in terms of the average optimization delay, it is more complex and needs more resources.

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LIST OF ABBREVIATIONS

AAL	ATM Adaptation Layer
ABR	Available Bit Rate
AP	Access Point
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
CAC	Call Admission Control
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CDV	Cell Delay Variation
CLR	Cell Loss Ratio
COS	Crossover Switch
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTD	Cell Transfer Delay
DLC	Data Link Control
FDMA	Frequency Division Multiple Access
LAN	Local Area Network
MAC	Medium Access Control
MES	Mobility Enhanced Switch
MT	Mobile Terminal
NIU	Network Interface Unit

NNI	Network-to-Network Interface
PCS	Personal Communications Services
PCs	Personal Computers
PDAs	Personal Digital Assistants
PIAs	Personal Information Assistants
PVC	Permanent Virtual Channel
QoS	Quality of Service
SVC	Switched Virtual Channel
TDMA	Time Division Multiple Access
UBR	Unspecified Bit Rate
UNI	User-to-Network Interface
VBR	Variable Bit Rate
VC	Virtual Channel
VCI	Virtual Channel Identifier
VPI	Virtual Path Identifier
WATM	Wireless ATM
WC	Wireless Control

Chapter 1

Introduction

1.1 An Overview of Wireless ATM Networks

Recently, considerable interest has begun to focus on the extension of broadband-wired Asynchronous Transfer Mode (ATM) into the wireless medium [1-14]. This extension has been motivated by the increasing importance of portable computing and telecommunications applications in both the business and the consumer markets. The rapid penetration of cellular phones and laptop Personal Computers (PCs) is proof that users place significant value on portability as a key feature, which enables tighter integration of such technologies with their daily lives. In the last decade, first-generation multimedia capabilities (such as CD-ROM video) have become available on portable PCs, reflecting the increasingly mainstream role of multimedia in computer applications. As multimedia features continue their inevitable migration to portable devices such as laptop PCs, Personal Digital Assistants (PDAs), and Personal Information Assistants (PIAs), wireless extensions to broadband networks will have to support user requirements. Such broadband wireless services could first start in the private Local Area Network (LAN), gradually moving to microcellular public Personal Communications Services (PCS) systems if the technology proves feasible for general consumer use. The extension of the wired broadband networks into the wireless medium will provide these portable applications with global access to any other application anywhere. With the growing acceptance of ATM as the standard for broadband networking, it has become appropriate to consider the feasibility of standard ATM services into next generation microcellular wireless and PCS scenarios. The use of ATM protocols in both fixed and wireless networks promises the important benefit of seamless multimedia services with end-to-end Quality of Service (QoS) control. The wireless ATM specification provides an option to existing ATM networks that wish to support terminal mobility and radio access while still retaining backward compatibility with ATM equipments [15-19].

The current developments on Wireless ATM are mainly based on the ATM as the backbone network with a wireless-last-hop extension to the mobile host. Mobility functions are implemented into the ATM switches and the base stations. Wireless ATM helps to bring multimedia to mobile computers compared with the wireless LANs that have a limitation of bandwidth to support multimedia traffic and slow handoff. The bandwidth of existing mobile phone systems is sufficient for data and voice, but it is still insufficient for real-time multimedia traffic. ATM has a more efficient networking technology for integrating services, flexible bandwidth allocation and service type selection for a range of applications. Figure 1.1 shows a network diagram illustrating the wireless/wired ATM network concept. By using the ATM network as the network backbone, Mobile Terminals (MTs) and handheld devices will be able to access varied data and information on the ATM network. Multimedia services such as audio, video, and still images, with certain QoS levels will be retrieved by wired and wireless system. From Figure 1.1, the mobile ATM network consists of Access Points (APs) along with components of a standard ATM network; such switches and fixed terminals interconnected via wireline links.

In this network architecture, APs provide connectivity to MTs via a wireless links. Each AP in the above architecture operates at a different radio frequency in relation to neighboring APs to avoid channel interference. Thus when a MT moves to a different AP it needs to change its operating frequency to that of the AP. The radio coverage areas under adjacent APs overlap, and a handoff procedure is always executed between adjacent APs. The Mobility Enhanced Switch (MES) provides mobility support to the wireless terminals.

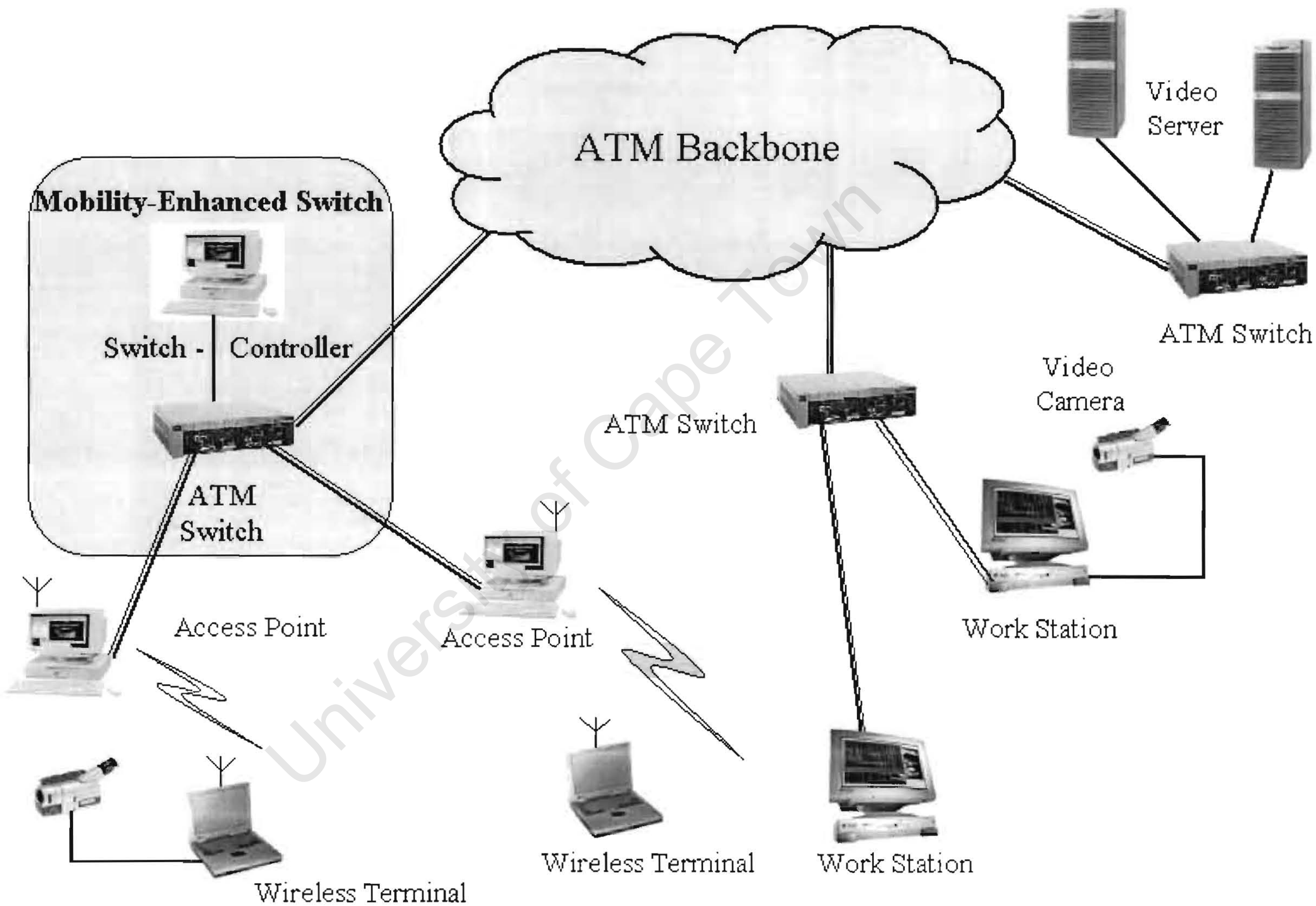

Figure 1.1: Wireless/Wired ATM network.

1.1.1 Motivation for Mobile Wireless ATM

The motivation of the mobile Wireless ATM (WATM) can be summarized as follows [11][20-21]:

1- Wireless Access to the existing ATM networks without any protocol converting overhead.

2- Freedom of movement for end users that wireless networks provide, and the statistical multiplexing (flexible bandwidth allocation) and QoS guarantees that wired ATM networks provide. Such qualities are not supported in the existing wireless LANs, which were designed with mainly conventional LAN data traffic in mind.

3- Flexible selection of bandwidth and service type for a range of applications.

4- Efficient multiplexing of bursty data and multimedia sources, with supporting QoS requirements.

1.1.2 Problems Related to Wireless ATM

The ATM was designed for a very rich environment in terms of the availability of the resources, where also the hosts do not move. However, several challenging issues must be addressed before the complete success of the seamless integration between wireline and wireless ATM networks. These challenges can be summarized as follows [11][22]:

- The ATM was designed for a medium whose bit error rates are very low (about 10^{-10}). However, the wireless medium is characterized by a very noisy and timevarying environment, in which the Bit Error Rate (BER) is around 10^{-4} to 10^{-3}. This high BER will seriously degrade the efficiency of transmission of the ATM packets.

- The wireless medium has limited (with a maximum rate of about 34Mb/s) and expensive resources in terms of bandwidth, whereas ATM was designed for a bandwidth-rich environment.

- The wireless entities require their own control protocol stack. This generates an extra overhead in the packet header, which results in unnecessary reduction in the efficiency of the wireless channel bandwidth. This overhead is highly undesirable in such an expensive medium, and keeping it to a minimum is a research challenge.

- The major challenge in WATM is to guarantee QoS, which are affected by the high BER of the wireless medium and mobility issues.

1.1.3 Service Requirements

WATM is intended as a direct extension of the fixed ATM network, indicating the need to maintain service classes and QoS parameters. Typical applications of multimedia services are listed in Table 1.1. They include voice, data, still-pictures, and motion video. Service classes currently supported in ATM networks are Available Bit Rate (ABR), Unspecified Bit Rate (UBR), Variable Bit Rate (VBR) and Constant Bit Rate (CBR). Although WATM should be designed to work with same service classes, quantitative limits on bit-rate, delay, cell-loss, etc. are experienced due to constraints imposed by the available radio medium [20][23-24].

Application	Type of services	Delay	Required error rate	Bit rate
Voice/Audio	CBR	Bounded	Medium	8-128 Kb/s
Digital data	ABR/UBR	Unbounded	Low-medium	0.1-1 Mb/s
Video telephony	CBR	Bounded	Low	3874 Kb/s
Motion-video	CBR/VBR	Bounded	Low	1.5-6 Mb/s
Filter transfer	ABR/UBR	Unbounded	Low-medium	1-10 Mb/s

Table 1.1: Typical service requirements for Wireless ATM.

1.1.4 Wireless ATM System Architecture

The concept of extending the standard ATM protocol over a wireless network interface was first proposed in [25], and has since been an active Research and Development (R&D) topic in many organizations worldwide [26-29]. It is indeed possible to use standard ATM protocols to support seamless wired + wireless networking via the incorporation of new wireless-specific protocol sublayers (e.g. Medium Access Control and Data Link Control), together with a limited number of mobility extension to existing ATM control protocol layers.

In order to provide mobile communication services over an ATM infrastructure, it is appropriate to add "mobile ATM" functionalities to existing signaling/control protocols to support terminal mobility [7][19][30-32]. The mobile ATM concept is illustrated in Figure 1.2. Such a mobility-enhanced ATM network may be used in cellular/PCS/wireless data networks, while providing a smooth migration path to the future seamless ATM-based mobile multimedia scenario.

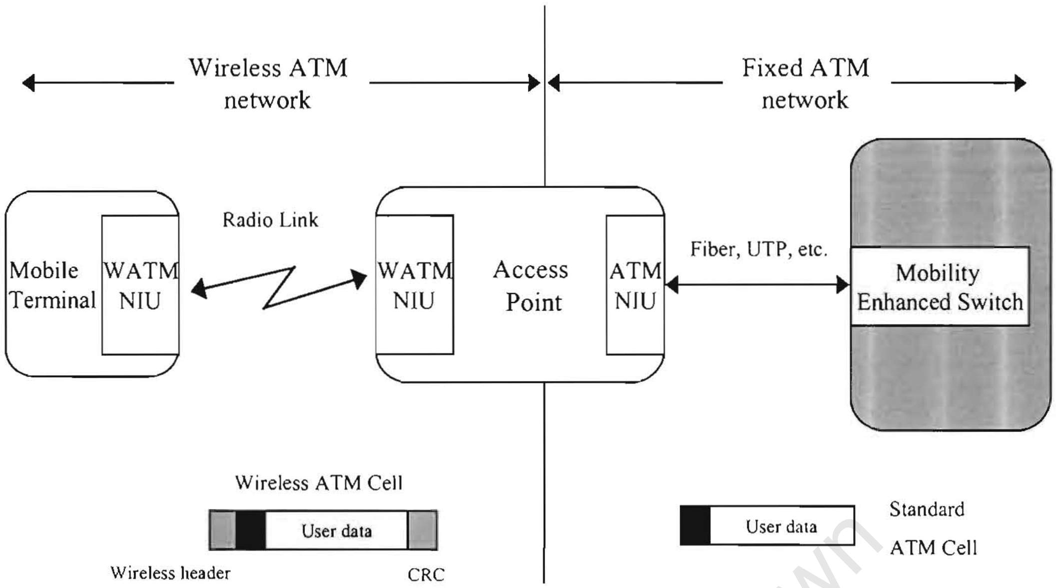

Figure 1.2: Interface between wireless and fixed ATM network.

1.1.5 The Protocol Stack of Wireless ATM

In order to reduce the complexity of the gateway between the wired and wireless networks, it is very important that a wireless ATM network is designed so as to provide seamless inter-working with the wired ATM network. This means that full integration of mobile ATM terminals into fixed ATM network requires transmission of ATM cells over the air interface. Thus the radio link is integrated transparently into the wired ATM network. Figure 1.3 shows the protocol stack for full integration of mobile ATM terminals into a fixed ATM network.

Since broadband ATM connections will be stretched over wireless links, end-to-end performance of connection will be primarily determined by the performance over the wireless links. Two major issues are introduced into ATM technology development when the wireless aspect is added: the 'radio access layer' to provide high bandwidth wireless transmission with appropriate medium access control, data link control, etc.; and the 'mobile ATM' network for interconnection of APs with an appropriate support of mobility related functions, such as handoff and location management. [31][34].

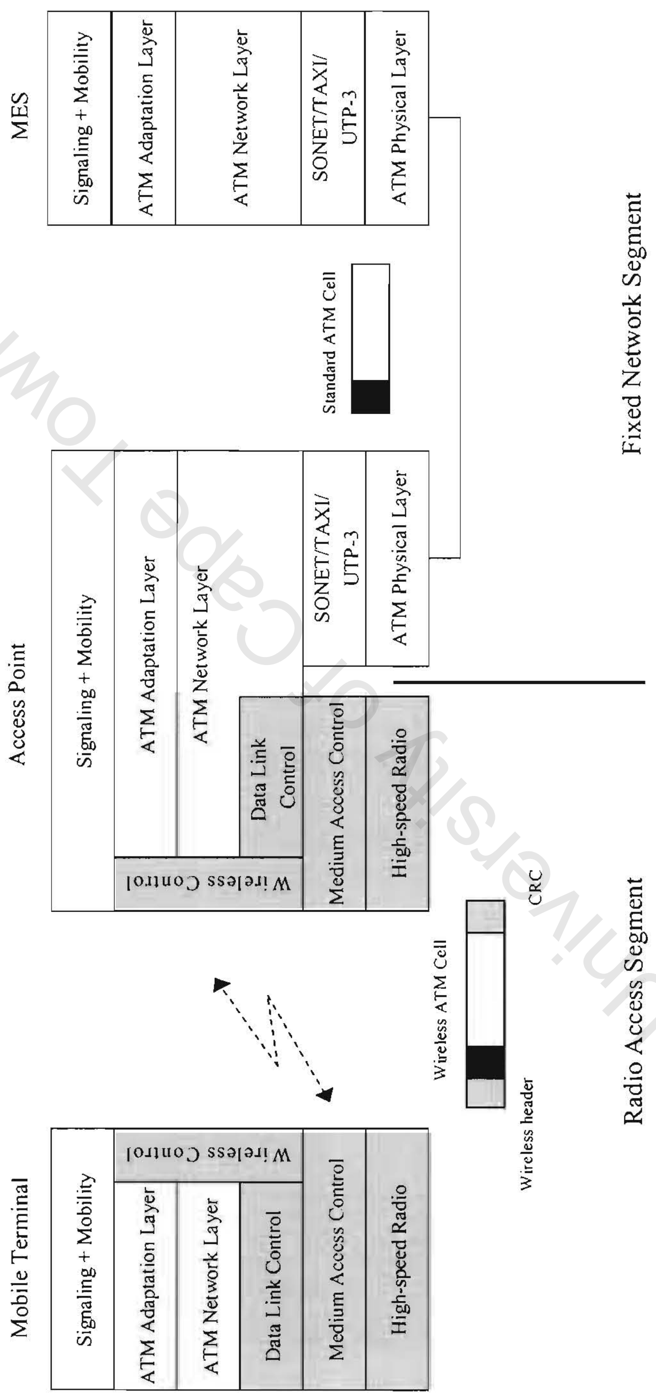

Figure 1.3: Wireless ATM protocol stack.

1.1.6 Wireless ATM Design Issue

1.1.6.1 Radio Access Layer

The radio access layer consists of several new protocol sublayers necessary to extend ATM services over a wireless link. The major functions of this layer include high-speed physical-level transmission/reception, medium access control for channel sharing by multiple terminals, data link control for amelioration of radio channel impairments, and wireless control for radio resource management and metasignaling. The radio access layer can be further decomposed into the following design components:

- **Radio Physical Layer (PHY)**

  The physical layer deals with the actual transmission of data over the physical medium, for example by means of a radio or an optical transmitter/receiver pair. Wireless ATM requires a high-speed radio modem capable of providing reasonable reliable transmission in microcell and picocell environments with cell radius in the range of 100-500m. Such systems may operate in various frequency bands depending on national and international regulatory policies.

- **Medium Access Control (MAC)**

  A MAC protocol is a set of rules to control the access to a shared wireless communication medium among various users, and an attempt to efficiently and equitably allocate use of a communications channel to independent, competing users. These users are active within the cell, handoffs from neighboring cells, and new users requesting access within the cell.

For WATM, the defined MAC protocol must provide support for standard ATM services as defined in existing ATM standards, including continuous CBR, VBR, ABR, and UBR traffic classes with associated QoS controls. Therefore, the defined MAC must expand the statistical multiplexing of wired ATM multiplexers into the wireless scenario along with the means of supporting mobility and maintaining QoS [11][22].

- **Data Link Control (DLC)**

  The DLC protocol is needed to improve the cell error rate caused by the physical wireless channel and the MAC protocol, thus isolating the ATM layer above it from these errors. It can also provide the retransmission control for damaged or lost packets [31][33-34].

- **Wireless Control (WC)**

  The WC sublayer is responsible for overseeing all the functions that must be introduced to support wireless access, including mobile identification assignment at startup, MAC layer control, handoff, and transmitter/receiver control (frequency and power management).

1.1.6.2 Mobile ATM

Mobile ATM is used to denote the set of enhancements needed to support terminal mobility within a fixed ATM network. The major functions of mobile ATM are location management for mapping of user names to their current locations, handoff control for dynamic re-routing of Virtual Channels (VCs) during terminal migration, routing, addressing, and traffic management.

- **Location Management**

  Location management is a generic capability required in networks to support MT migration and it contains two functions: *tracking* the current position of a MT, and *handling* any queries about the location of a MT. Once the call is initiated, then the network must capable to locate the called MT and deliver the call. Location management functions can be based on methods similar to those in cellular system, via the similar "home location/visitor location" concept used in GSM and IS-41.

  Due to the expected high handoff in the future WATM network, the location management mechanism of a WATM network must be able to update user location quickly and efficiently. Therefore the location services should be modified to meet the requirements of the ATM protocol [35].

- **Handoff Management**

  Handoff control in ATM networks has been studied in many research papers [36-41]. The handoff occurs when a MT moves from its current cell to an adjacent cell while the session is in progress and the continuity of the connection must be maintained with the same quality. The wireless control must be switched from the old AP to the new AP, which is currently serving the MT. The process of transferring the control from an ongoing connection due to a movement of a MT is known as *handoff management*. The design goal is to prevent service disruptions and degradation during and after handoff process. In general, a handoff event may result in a significant change in the optimal route of each active virtual circuit associated with the MT. Typically, this implies that a portion of the VC's route in the vicinity of the mobile terminal must be re-established according to suitable cost/performance criteria.

There are two key issues regarding how handoff affects the QoS of an existing connection. First, when a MT moves to another AP, which is unable to provide the same QoS as that provided by the previous AP. In this situation, the end-to-end QoS parameters of the connection will needed to be *renegotiated.*

The second issue is that of minimizing the effects of QoS disruption during the process of handoff. For example handoff blocking due to limited resources at target APs, cell loss during handoff, or the speed of the whole handoff process are some of the critical factors for QoS.

One way to minimize QoS disruption during handoff is to ensure a "lossless handoff". To ensure a lossless handoff, all cells in transit during the handoff process are buffered within the network (at a switch or an AP) to maintain in–sequence cell delivery (without loss) to the MT. Transfer of buffered cells from the existing AP to the new AP ensures that cells are not delivered out of order, and buffering cells at both APs ensure that cells are not lost. For some applications, the Cell Transfer Delay (CTD) and Cell Delay Variation (CDV) may be more important than avoiding cell loss. In this case, depending on the allowable delay variation, the current AP may transfer the buffered cells to the new AP without waiting for the marker cell to arrive [21][87].

1.2 Work Motivation and Contributions

Our research focuses on the mobile ATM handoff control required to support MT migration from one wireless ATM microcell to another. The main challenges to support wireless users in WATM networks are due to the mobility of the wireless users. The handoff function caters for the ongoing connection to be re-routed to another AP in a seamless manner with QoS being maintained between the end users. Re-routing is critical to wireless networks which needs to maintain connectivity to a wireless user through multiple, geographically dispersed radio APs. Re-routing must be done quickly to maintain connectivity to the network during a handoff event.

The addressed challenging issues to support user mobility in WATM networks include:

- Designing a WATM network architecture required to support the roaming of the mobile end users.
- Maintaining end-to-end connections when the end-user moves between wireless cells (hands off).
- Fitting the augmented handoff functions into the ATM protocol suite in order to avoid the overhead of the protocol conversion.
- Preserving the cell sequence of a handoff connection.
- Maintaining the QoS requirements during handoff:
  - Minimizing the connection disruption time during the handoff. This is essential for real time applications.
  - Achieving lossless handoff.
  - Minimizing Cell Delay Variation (CDV) and delay to real-time applications.

The main contributions of this research include the following:

- A WATM network architecture that is fully integrated with the current ATM-base networks, without major modifications.
- A fast and simple handoff re-routing scheme with a minimum processing load based on extending the paths through assigned PVCs between any adjacent MESs.
- A new fast two-phase handoff scheme that overcomes the current techniques [77]. Our proposal is based on using reserved PVCs for the first phase, followed by the second phase where the optimization process is triggered instantly and concurrently with the other active optimization processes.
- A novel fast handoff re-routing scheme suitable for multimedia real time applications based on the sharing of information at the cluster boundaries in order to obtain a fast handoff and low optimization delay while minimizing the effect of inter-cluster handoff at the cluster boundaries.
- Analytical models for all the proposed handoff schemes in order to evaluate the performance. The important parameters include the reserved wired bandwidth, expected holding time for the PVC handoff connection, and inter-cluster handoff processing load.
- Simulation models for all the proposed handoff schemes for validation and comparison of results with the analytical models.

1.3 Thesis Layout

The remainder of the thesis is organized as follows. In Chapter 2, we provide the background information regarding mobility management over WATM networks. We classify the handoff schemes as proposed in the literature in order to implement the re-routing of the connection during handoff. Each scheme is described in detail, including the advantages and disadvantages for each scheme.

In Chapter 3, we first introduce the design of a new WATM network architecture. This network architecture separates the core ATM backbone from the wireless access network. This separation allows us to provide the user with mobility functionality without major modifications on the deployed ATM backbone network. The Permanent Virtual Channels (PVCs) are used to give a support for fast and efficient handoff. Based on this WATM network, we propose a signaling protocol to support both intra and inter-cluster handoff schemes.

Chapter 4 explains in details a handoff re-routing scheme based on path extension between adjacent MESs with the support of the PVCs to achieve fast and efficient handoff with minimum processing load. The analytical and simulation analysis are used to evaluate the performance of this scheme in terms of wired link resources between adjacent MESs, and the PVC holding time.

In Chapter 5, we examine a new two-phase handoff optimization scheme based on *triggering* the path optimization procedure *instantly* and *concurrently* with the other active optimization processes. Also the proposed scheme has been evaluated analytically and by simulation in terms of PVC holding time and wired link resources between adjacent MESs. A comparison of results has been made with the scheme explained in Chapter 4 and other two-phase optimization scheme in the literature. The comparison includes PVC bandwidth, and PVC holding time.

Chapter 6 investigates the performance of a new fast re-routing scheme suitable for multimedia real time applications. This new scheme is based on the shared cells at the cluster boundaries to obtain a low inter-cluster handoff processing load and route optimization delay. The analytical and simulation models are used to evaluate the inter-cluster handoff processing load, wired link resources between MESs and between any MES and shared cells, and PVC holding time. A comparison of results with the new two-phase scheme, explained in Chapter 5 has been studied and shows better performance.

Finally, Chapter 7 draws conclusions on the proposed handoff schemes, showing a greater improvement when compared to other handoff schemes alluded to in the literature. The proposed future work is recommended particularly on the QoS guarantees when a MT migrates to another cell with limited resources.

1.4 Published Work

Original work that we present in this thesis has been published at various conferences, including some IEEE conferences. These publications are:

[1] Jamal Elbergali, and Neco Ventura, "Performance evaluation of a new fast path re-routing for inter-cluster handoff scheme in wireless ATM networks", IEEE ICCS'02, 2002, Singapore.

[2] Jamal Elbergali, and Neco Ventura, "Performance evaluation of a new fast inter-cluster handoff scheme in Wireless ATM networks," IEEE GLOBECOM'02, 2002, Taiwan.

[3] Jamal Elbergali, and Neco Ventura, "Performance modeling of an inter-cluster handoff path extension scheme in Wireless ATM networks," IEEE Africon'02, 2002, South Africa.

[4] Jamal Elbergali, and Neco Ventura, "An adaptive route optimization for inter-cluster hand scheme in wireless ATM networks," SATNAC'02, 2002, South Africa.

[5] Jamal Elbergali, and Neco Ventura, "A new inter-cluster handoff technique to support real time applications in Wireless ATM networks," ICWN'02, 2002, Las Vegas, USA.

[6] Jamal Elbergali, and Neco Ventura, "Performance evaluation of an efficient inter-switch handoff scheme for wireless ATM Networks," SATNAC'01, 2001, South Africa.

[7] Jamal Elbergali, and Neco Ventura, "Backward and forward inter-switch handoff scheme for wireless ATM networks," SATCAM'00, 2000, South Africa.

Chapter 2

Background and Related Work

In this chapter, we present background information to the related study of the mobility management over WATM networks, including the handoff requirements and the classifications of handoff. After that, we classify and review the handoff re-routing schemes proposed in the literature. The advantages and disadvantages of each scheme have been discussed and explained in details.

2.1 Mobility Support in WATM Networks

A key feature of any mobile wireless network is the capability to support handoff [42-43]. Handoff is an action of switching a call in progress in order to maintain continuity and the required QoS of the call when a MT moves from one cell to another. In mobile ATM network, a MT can have several active connections with different QoS requirements. These VCs with different QoS introduce challenges to the handoff protocol. In general, handoff with multi-rate ATM connections must be supported with low cell-loss, latency and control overhead. The QoS constraints for each individual connection should be maintained during the MT migration.

2.1.1 Phases in a Handoff Procedure

There are three phases in a handoff procedure. These phases can be summarized as follows:

1- ***Measurements***: The MT performs several continuous measurements, for example QoS parameters or the signal strength, which may be measured as a reference to some threshold point.

2- ***Decision***: The decision is to be made from the MT based on some measurements, for example if one of the QoS parameters is violated or the signal strength falls below the threshold level.

3- ***Execution***: The actual handoff is performed in this phase. There are essentially three sub-phases in the execution of the handoff [44].

  - Establishing a new link.
  - Re-routing of data from the old link to the new link, including all the buffering requirements.
  - Releasing the old link.

2.1.2 Handoff Requirements

To ensure seamless and lossless handoff in WATM networks, the following handoff requirements should be maintained [21][45-46].

1. **QoS Guarantee:** QoS guarantees associated with each WATM connection should be preserved during handoff. However, since this is not always possible, a handoff mechanism should be capable of QoS re-negotiation or dropping of certain VCs on a priority basis. The important traffic parameters such as Cell Loss Ratio (CLR) and Cell Delay Variation (CDV) will be limited by the length of transport interruption and degree of cell loss. The CLR parameter is important for the data. The CDV parameter is important for time-sensitive traffic such as video and audio.

2. **Low Signaling Traffic:** During handoff, the load of the signaling traffic should be kept to a minimum in order to reduce the overall traffic load on the system.

3. **Low Buffering:** Low buffering should be achieved during the handoff to avoid handoff latency and minimize the system cost. And the tradeoff between buffering (to ensure lossless handoff) and cell loss (to ensure a seamless handoff) is made based on the QoS requirements.

4. **Scalability:** The handoff protocol should maintain the handoff initiation of as many MTs as possible, so that the performance of the handoff protocol should not be degraded as the number of active VCs per MT increases.

5. **Low Handoff Latency:** The delay and delay variation should be very low during the handoff to maintain the QoS requirements, so that the decision to do the handoff should be valid for the current position of the MT after the handoff is completed.

6. **Lossless Handoff and Data Integrity:** This requirement is specific to WATM environment and must support the following:
   - Avoiding cell losses is a very important factor, specifically for the data.
   - Avoiding cell duplication during handoff.
   - Maintaining the cell sequence for each connection during handoff to avoid loss of information during the handoff.

7. **Minimum Service Disruption:** This is defined as the period during which the MT is not in communication with the other end during handoff. And it is

desirable to minimize the transmission interruption time during handoff such that the QoS will be supported. To ensure this, the switching of the active VCs from the old data path to new path should be as efficient as possible.

8. **Exclusive Handoff:** This is very important in multimedia sessions as more than one ATM connection (audio, video and data) should be handed off simultaneously.

9. **Resource Utilization**: During handoff, network resources should not be reserved for longer than is necessary to ensure QoS guarantees.

2.1.3 Classifications of Handoff

The handoff types can be classified based on the following parameters [4][47]:

2.1.3.1 Number of Active Connections

There are two types of handoffs based on this classification [48]:

- **Hard Handoff:** The MT switches the communication suddenly from the old connection at old AP to the new connection at the new AP. Thus, there is only one active connection from the MT to the AP at any time.

- **Soft Handoff:** The MT keeps connected simultaneously to two APs. As it moves from one cell covered by an AP to another cell covered by another AP. When connected to two APs, the network combines information received from both routes to obtain better quality.

  Soft handoff will be a basic feature in high-tier mobile ATM systems, as air interface technologies for next generation wideband mobile services will enable soft handoff, e.g., 3rd generation CDMA technology. Soft handoff poses the highest requirements on the radio technology. Since it requires the MT to be able to communicate concurrently with two APs. Therefore, in the overlapping boundary region it enables dynamic selection of the best radio path. Provided that the overlapping region is sufficiently large and both APs can maintain a sufficiently strong signal in this region, this ensures enhanced QoS for the connection as well as handoff reliability [21].

2.1.3.2 Direction of the Handoff Signaling

There are two types of handoffs based on this classification [49]:

- **Forward Handoff:** After the MT decides the cell to which it will make a handoff; it contacts the new AP controlling that cell. The new AP initiates the handoff signaling to link the MT from the old AP. This is actually useful if the MT suddenly loses contact with the current AP (this happens for example, due to interference or fast-moving terminals), so there is no time to perform backward handoff.

- **Backward Handoff:** The MT initiates the handoff via the current AP and it contacts the current AP, which initiates the signaling to handoff to the new AP. The MT continues maintaining the communication with the old AP while the handoff procedure continues.

2.1.3.3 Viewpoint of the Network

There are two types of handoffs based on this classification [50-52]:

- **Intra-cluster Handoff:** This occurs when a MT moves from an area covered by an AP to another area covered by another AP, and both APs are connected to the same MES.

- **Inter-cluster Handoff:** This occurs when a MT moves from an AP connected to specific MES to another AP connected to another MES.

2.2 Connection Re-routing Schemes for WATM

There are several re-routing schemes to support the handoff connection [5][16][43][53-61], and it is classified depending on the type of handoff, such as intra or inter cluster handoff.

2.2.1 Connection Re-routing Schemes to Support both Intra and Inter-Cluster Handoff

2.2.1.1 Handoff using Advance Setup of Paths

This class of routing schemes involves setting up paths in advance. There are two possible ways to do that. The first way is the multicasting scheme, which is used to establish connections from the AP currently controlling a MT to all the neighboring APs (refer to Figure 2.1). Subsequently, in whatever direction the MT moves, a handoff path has already been established. So when a MT moves to one of the neighboring APs, data is immediately available. After a handoff occurs, the network adapts by adding new neighborhood APs connections and deleting connections to APs that are no longer in the neighborhood.

Also, since the data is being multicast, it continues to flow without interruption. This scheme ensures a lossless, fast and seamless handoff. However, since data is being multicast to the entire set of nodes, most of which are unused, bandwidth is being utilized very inefficiently. Furthermore, if a MT is at the edge of two cells, it is very likely that it might get two copies of the data packets. This leads to other complications like AP synchronization. The scheme enables fast handoff and guarantees QoS even during handoff, as network resources are pre-allocated. However, it consumes too many resources and results in network inefficiency [62].

A more efficient approach is based on prediction. This scheme is called *predictive mobility handoff.* It predicts the possible locations that a MT is likely to move to and setup paths to those locations instead of multicasting. A predictive mobility scheme using the movement circle and movement track models is presented in [63]. The advantages of the predictive mobility handoff include less waste of bandwidth while disadvantages include increased processing due to the prediction algorithm and the cost of the prediction error.

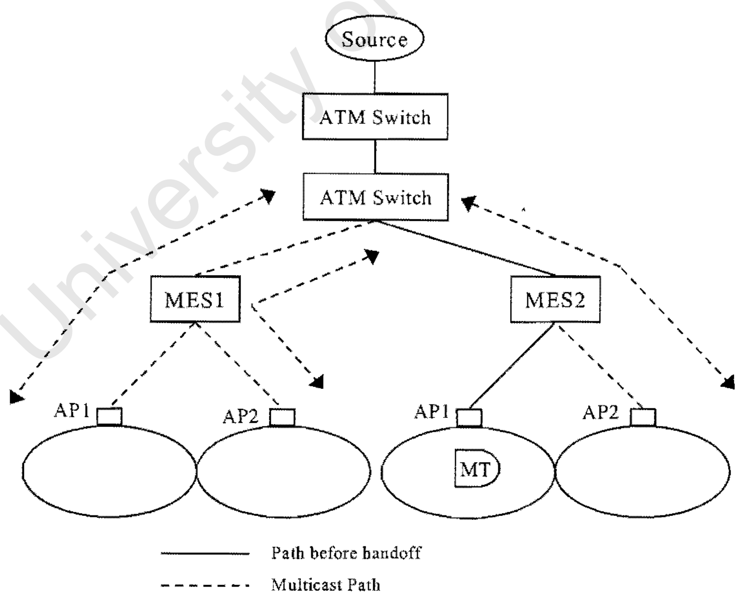

Figure 2.1: Handoff using multicasting.

2.2.1.2 Handoff using Path Extension

For each handoff, the traffic path is elongated from the current AP (AP1) to the new AP (AP2), by appending one hop to the existing connection. This hop is a separate virtual connection between the current and new APs through the wired network [64-65].

The advantages of this scheme are that: 1) it is very simple; 2) the cell sequence can be easily preserved; 3) the handoff process is very fast; 4) there is no need for routing functionalities; 5) no modification to ATM switches is required; 6) there is a low handoff disruption delay. The disadvantages include: 1) non-optimal extended path; 2) the need for switching and buffering capabilities at all APs to perform connection extension, and a possible bottleneck at the APs; 3) when a large number of handoffs are carried out by the MT, the path would be continuously elongated, which leads to path inefficiency; 4) it may result in the formation of data-forwarding loops when a MT migrates back to the old AP; 5) it increases the end-to-end delay. Figures 2.2 and 2.3 show the intra and inter-cluster handoff using path extension between APs.

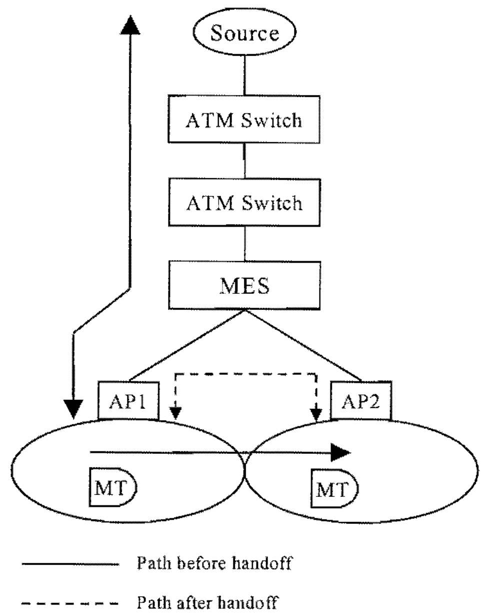

Figure 2.2: Intra-cluster handoff using path extension.

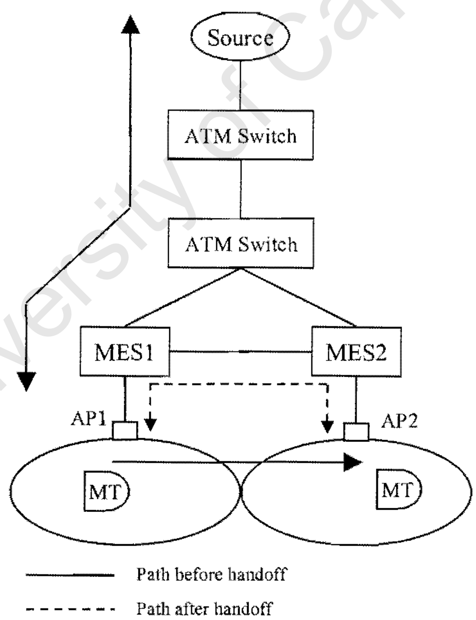

Figure 2.3: Inter-cluster handoff using path extension.

2.2.2 Connection Re-routing Scheme to Support Intra-cluster Handoff

2.2.2.1 Handoff using Anchor Switch

In this scheme, the connection is re-routed from the old AP (AP1) to the new AP (AP2) through the same MES, which is called an Anchor switch. The resulting route is optimal, and the switching is performed very quickly through the powerful Anchor switch. Figure 2.4 shows the intra-cluster handoff using the Anchor switch.

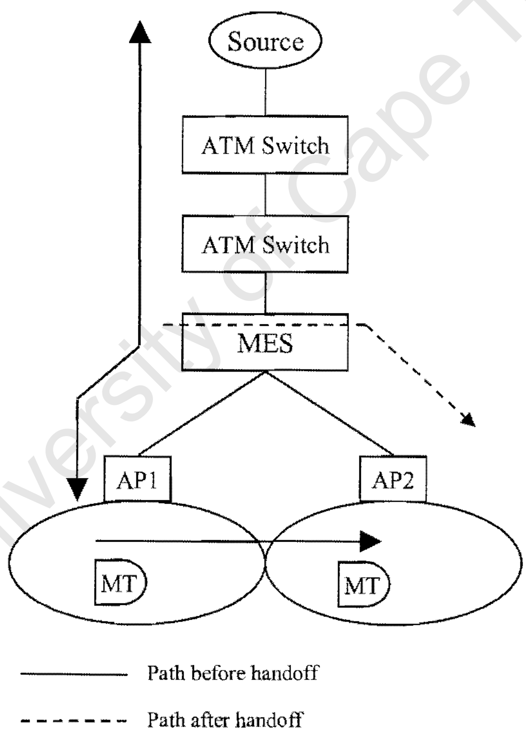

Figure 2.4: Intra-cluster handoff using Anchor switch.

2.2.3 Connection Re-routing Scheme to Support Inter-cluster Handoff

2.2.3.1 Handoff using Full Re-establishment

In this scheme, a complete new route is established from the source to destination every time a MT moves to a different MES [66]. Using this scheme, the network can choose the most efficient route to the new destination every time the handoff occurs.

The advantages of this scheme include: 1) no need for routing functionalities; 2) no modification to ATM switches; 3) an optimal path to the mobile user is always used. The disadvantages include: 1) requires large connection handoff processing load each time handoff occurs; 2) poor reuse of network resources, causing severe interruptions to traffic flow; 3) long handoff delay; 4) since both ends are explicitly involved, this handoff scheme is not transparent. Figure 2.5 shows the inter-cluster handoff using full re-establishment.

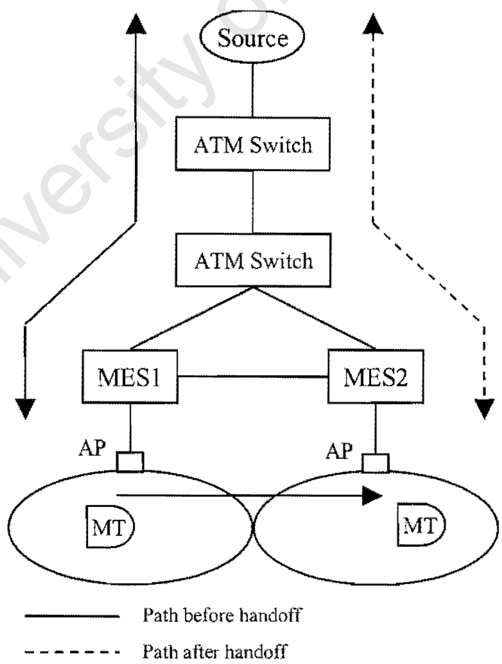

Figure 2.5: Inter-cluster handoff using full re-establishment.

2.2.3.2 Handoff using Anchor Path Extension

The idea is to extend the original connection from the current MES where the current AP exists, to the new MES where the new AP is connected [67-71]. Referring to Figure 2.6, the path is extended from the Anchor switch (MES1) to the target switch (MES2) where the new AP is located. This Anchor path extension scheme is done through powerful MESs, which have a high switching speed and enough buffers to guarantee the lossless of data during handoff. This scheme is fast and simple to implement. QoS degradation, such as cell loss, duplicate cells, and miss-sequence cells, do not occur.

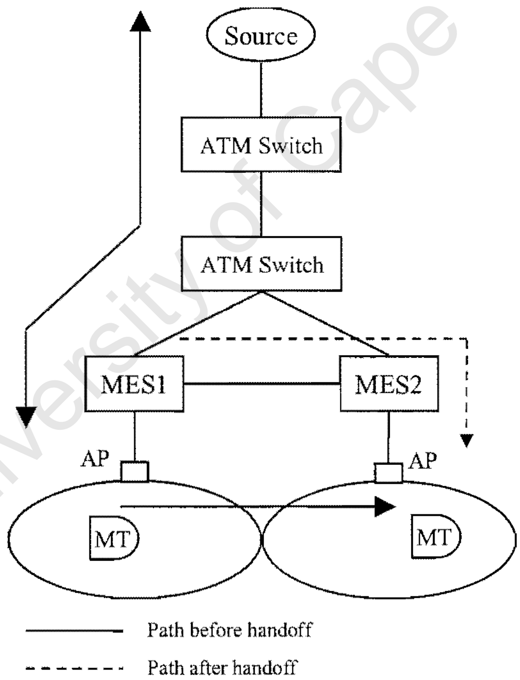

Figure 2.6: Inter-cluster handoff using Anchor path extension.

2.2.3.3 Handoff using Partial Re-routing

This method is a modified of anchor re-routing technique, where the anchor is assigned to an ATM switch that has the shortest path to a target MES. One of the intermediate switches on the original route of the connection is picked to become the Anchor switch (also known as Crossover Switch COS). The COS is a re-routing point where the new partial path meets the old path. The idea is to reuse as much of the existing connection that form part of the optimized route, creating only a new partial path between the COS and the new AP. Buffering is done at the COS, which ensures in-order delivery of cells [61][72-75]. The connection path is modified by creating a new partial path between the COS and the target MES (MES2) and removing the path between the old MES (MES1) and the COS.

The time to determine the location of COS and the delay involved in setting up new Virtual Connection (VC) for establishing the new partial path will be highly variable and depends on the number of intermediate switches and the processing load at each switch. Figure 2.7 shows the inter-cluster handoff re-routing scheme using COS discovery.

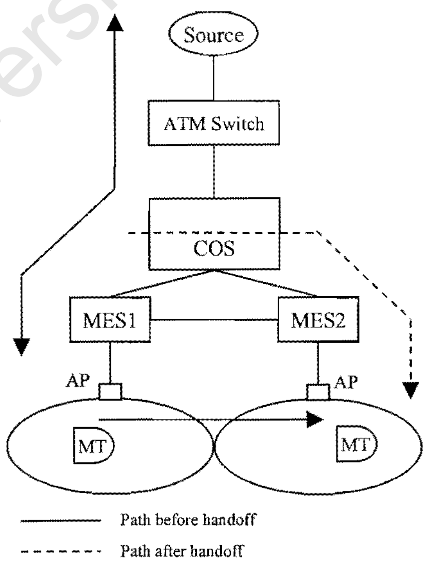

Figure 2.7: Inter-cluster handoff re-routing using COS discovery.

Crossover Switch Discovery Algorithms:

There are mainly five types for COS selection algorithms, which can be classified as follows [61][75]:

- ***Loose Select Discovery***

  In the loose select COS discovery scheme, the minimum-hop path from the new location at the new AP to the destination is determined. The querying of the destination address is achieved through the location management scheme. This scheme does not take into consideration the already existing path from the original (old AP) to the destination during the discovery of the COS. If the chosen path from the new AP to the destination shares (overlaps) some part of the original path, then the convergence point is chosen as the COS. This is shown in Figure 2.8.

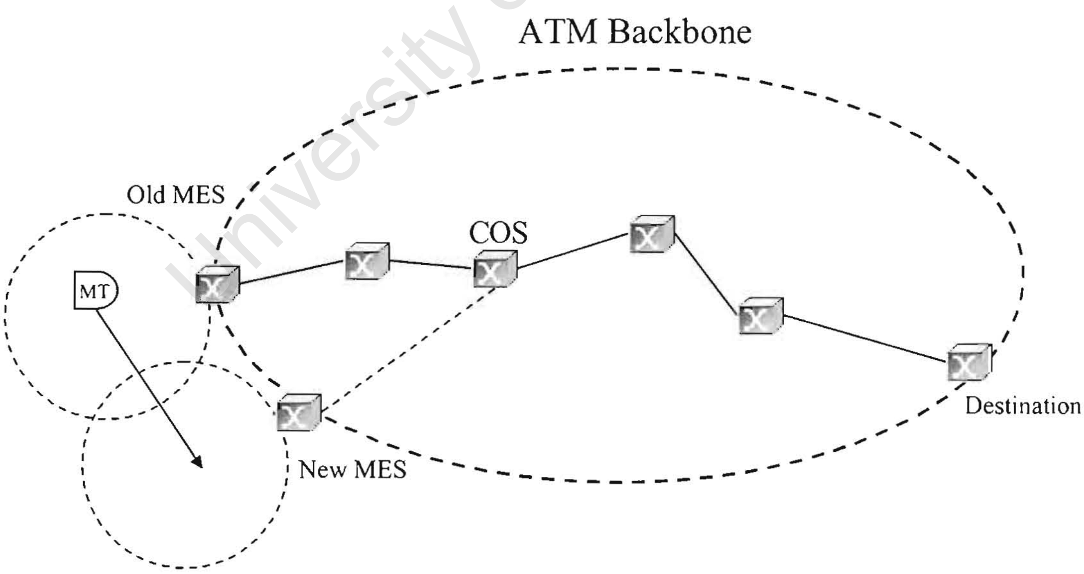

Figure 2.8: Loose Select Crossover Switch Discovery.

- ***Prior Path Knowledge Discovery Scheme***

  In this handoff scheme, the path from the source to the destination is known, i.e. the addresses of the switches involved are known. The COS is discovered by the new AP. The new AP computes the distance from itself to each of the nodes in the old path. It then selects the node with the least distance as the COS. If there are multiple nodes with the same minimum hop count, then the one nearest to the old AP is chosen. This scheme is shown in Figure 2.9.

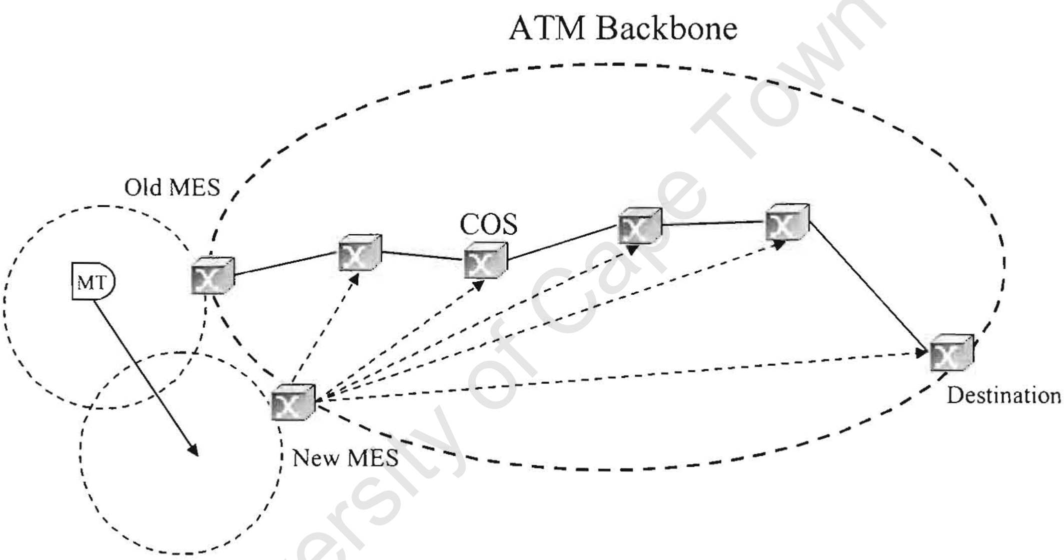

Figure 2.9: Prior Path Knowledge Discovery Scheme.

- ***Prior Path Optimal Resultant Discovery Scheme***

  This scheme is derived from the prior path knowledge discovery scheme. This scheme ensures that the resultant new path that is formed after the handoff has fewer or equal number of hops than the old path. In this scheme, the new AP computes the distance from itself to all the convergence nodes in the old path and compares these distances with the number of hops in the old path. Only those convergence paths that are equal or shorter than their respective old partial paths will be valid. If there are multiple nodes with the same minimum hop count, it chooses the one that is closest to the old AP (See Figure 2.9).

- ***Distributed Hunt Discovery Scheme***

  The distributed hunt scheme is, however, independent of the location management and connection management schemes. The discovery of the COS is distributed. This is done by modifying the nodes in the network to maintain a list of active connections that pass through it in a Local Connectivity Table (LCT). When the MT migrates to a new AP, the new MES connected to the AP broadcasts messages asking for potential COS nodes to respond with their distance to the new AP. It then chooses the node with minimum number of hops from itself as the COS. If there are multiple nodes with the same hop count, a node is picked arbitrarily. This is shown if Figure 2.10.

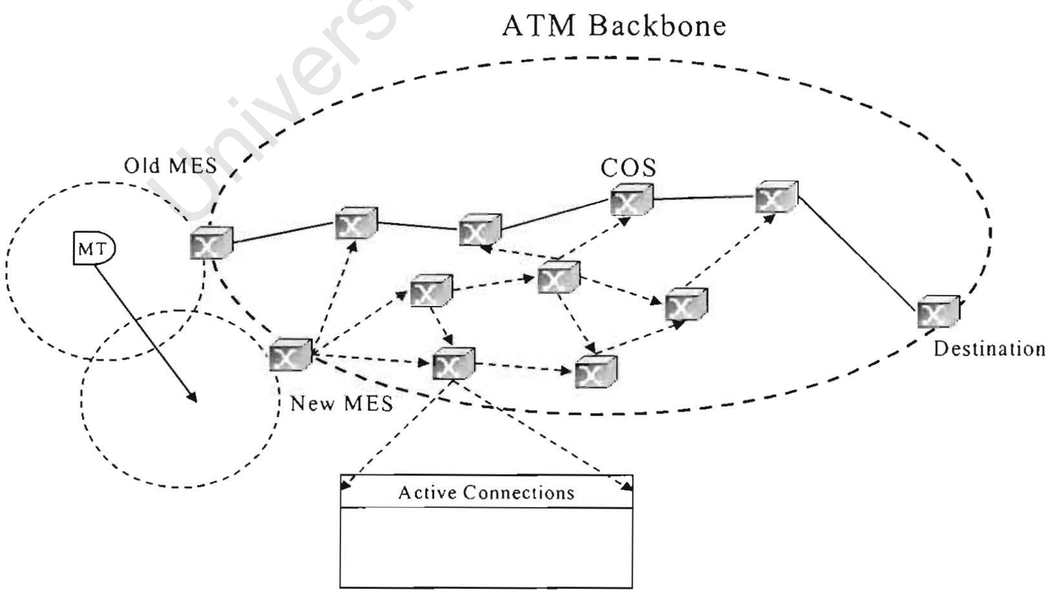

Figure 2.10: Distributed Hunt Crossover Switch Discovery.

- ***Backward Tracking Crossover Switch Discovery***

In this scheme, the new AP instigates (signals) the old AP to start the backward tracking algorithm to determine the COS. The old AP backtracks the COS along the original source-to–destination route, one hop at a time starting from the original MES. Each node on the way determines whether it uses the same interface to reach both the old and the new base station. If it does not then it backtracks to the previous node. If it is using the same interface to reach both the old and the new COS, then the node one hop down the line is the COS. The COS then establishes partial paths to the new AP. This is shown in Figure 2.11.

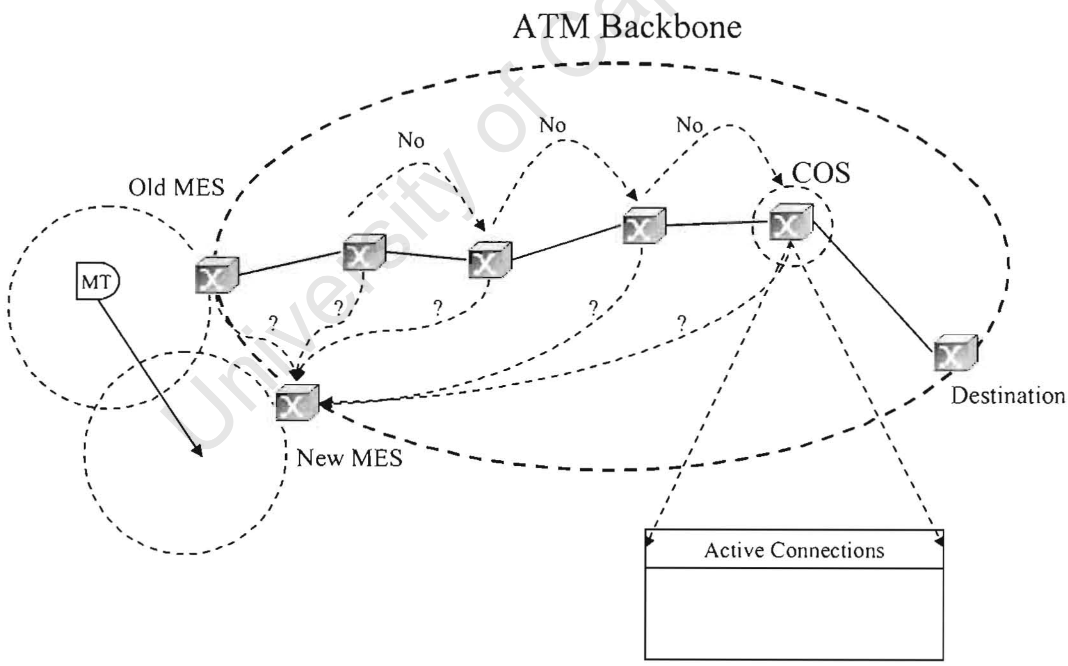

Figure 2.11: Backward Tracking Crossover Switch Discovery.

2.2.3.4 Handoff using Two-phase Protocol

A two-phase handoff protocol has been proposed to support inter-cluster handoff in WATM networks, combining the advantages of path extension scheme and partial re-routing schemes [76-81].

The two-phase handoff protocol consists of two phases, that is: path extension[1], and path optimization. Path extension is performed after each inter-cluster handoff. Since the extended path is longer than the original one, certain QoS requirements, such as Cell Transfer Delay (CTD) and Cell Delay Variation (CDV), may not be guaranteed after handoff and the resulting path is not optimal. Path optimization is activated after the path extension. The aim of the two-phase handoff is to shorten the handoff delay and at the same time to use the network resources efficiently. The path extension ensures fast handoff, and path optimization enables the efficient use of network resources (See Figure 2.12).

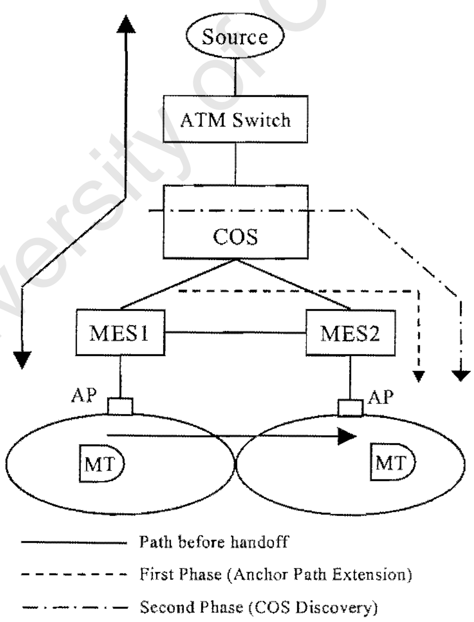

Figure 2.12: Inter-cluster handoff using two-phase scheme.

[1] For the rest of the thesis, the term "path extension" is used to refer to the "Anchor path extension" technique explained in Section 2.2.3.2.

Although path optimization can increase the network utilization by re-routing the connection to a more efficient route, transient QoS degradation, such as ATM cell loss and an increase in cell delay variation may occur. In addition, path optimization increases the processing load of certain switches and increases the signaling load of the network. Thus, path optimization after each path extension may not be necessary or desirable. Since the MT is still communicating over the extended path via the current AP while the path optimization takes place, this gives enough time for the network to perform the necessary routing functions while minimizing any service disruptions.

Path Optimization Procedure:

The path optimization procedure consists of two phases: the path optimization *initialization* phase and the path optimization *execution* phase. The path optimization can be initiated based on the following parameters [82-83]:

1- ***QoS-based Path optimization Scheme:***

In this scheme, the path optimization of each mobile connection is triggered based on the current QoS measures. For example, path optimization can be initiated if the number of hops of the path is greater than a certain number, or if the end-to-end cell transfer delay bound is violated. To implement those QoS-based path optimization schemes, information about the quality of the current path in terms of the defined QoS measurement (e.g. hop count, current average delay) must be maintained by the network.

2- ***Network-based Schemes:***

Network-based path optimization schemes trigger path optimizations for a group of connections based on the existing traffic load of a switch or the utilization of the network. For example, a network switch can initiate path optimization for a group of mobile connections whenever the new call dropping probability of a certain traffic class exceeds a particular threshold. During path optimization, a number of connections will be re-routed to some other switches, thereby reducing the traffic load of that switch.

3- ***Time-based Path optimization Scheme:***

In this scheme, the path optimizations are triggered at time instants, which are independent of the current QoS of the connection or the utilization of the network. The time-based instants can be deterministic or random. For example, the time between path optimization can based on some random processes. In addition, it can also be a function of the velocity of the MT, the dwell time, and the residual service time of the mobile connection.

4- ***Handoff-based Scheme***:

In the handoff-based path optimization scheme, the path optimizations are triggered based on some criteria after each inter-cluster handoff. Thus, it can be a function of the number of previous handoffs, the velocity of the MT, and the residual service time.

The major steps during the path optimization *execution* phase involve [84]:

- Determining the location of the COS.
- Establishing of a new path between COS and new AP.
- Replacing of the old connection path (between COS and old AP) with the new path (between COS and the new AP).
- Terminating the old branch connection.

Chapter 3

Framework on PVC-Based WATM Handoff Signaling Protocols

In this chapter, we investigate the issues of extending the ATM capabilities in mobile wireless networks, focusing on presenting a framework to support handoff signaling protocols in order to achieve a fast and seamless handoff. The design objective is to prevent any service disruption during and after handoff. We first present the cluster handoff model, and then we discuss the proposed WATM network architecture, which is supported by the Permanent Virtual Channels (PVCs) for an efficient and fast handoff. Finally, the signaling protocols for both intra and inter-cluster handoff schemes are explained in detail.

3.1 The Cluster Handoff Model

A cluster is a collection of cells. A cell is a small geographical coverage area. Since the bandwidth is shared and spatially re-used by many cells, co-channel interference may occur. Reducing the size of the cell coverage area to accommodate greater capacity per unit area increases handoff rate. An AP is assigned to each wireless cell. A cluster, however, is a collection of APs connected to a cluster switch called a Mobility Enhanced Switch (MES). We assume that the overlapping of wireless cells results in a cell having six edges. Referring to Figure 3.1, a ring is defined as a single or a group of boundary wireless cells. A cluster however is made up of several rings. The inter-edges are the boundary edges of the outermost ring of a cluster. The remaining edges inside a cluster are called intra-edges.

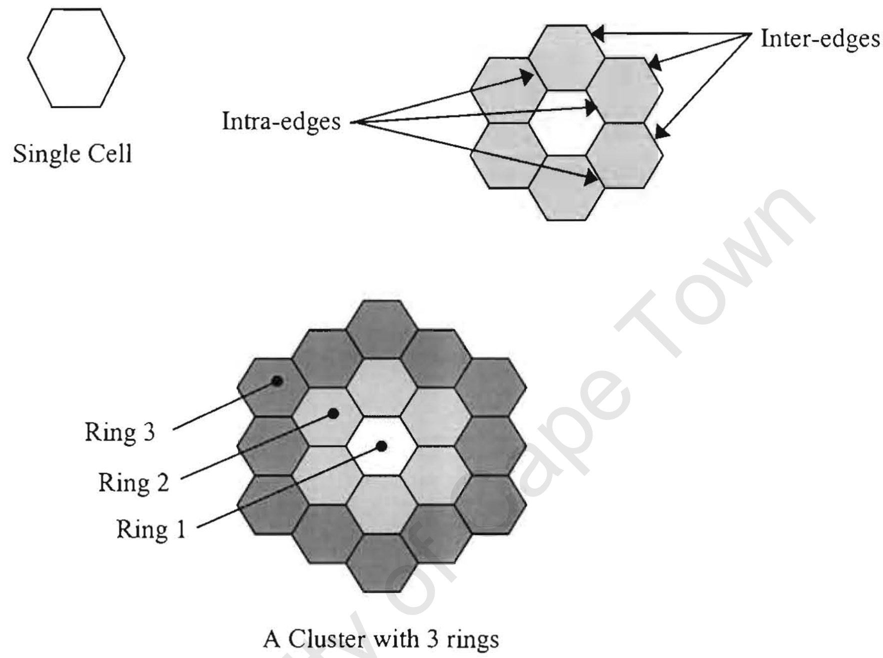

Figure 3.1: The cluster handoff model.

Letting I_{Er} and I_{Ar} be respectively the number of inter and intra-edges in the cluster with r rings (where $r = 1,2,3,..$) and T_{Cr} be the total number of cells in a cluster with r rings, then the following relationships hold [85]:

$$I_{Er} = 12r - 6 \tag{3.1}$$

$$I_{Ar} = 9r^2 - 15r + 6 \tag{3.2}$$

$$T_{Cr} = 3r^2 - 3r + 1 \tag{3.3}$$

The intra and inter-edge migrations are called intra and inter cluster handoff. The grouping of APs to a MES results in fast handoff for MTs with intra-cluster migrations. Hence a cluster of wireless cells is the region where fast handoffs can be achieved. Inter-cluster handoffs as a result of MTs migrations between clusters give rise to slower handoffs, since the handoff management entity is performed by more than one MES and may need re-routing through the ATM backbone switches [85]. It is desirable to have greater frequency of intra than inter-edge migration, i.e. $I_{Ar} > I_{Er}$, so that a larger number of fast handoffs can be achieved. For $r \geq 3$ rings, I_{Ar} will be greater than I_{Er}.

3.2 The Proposed WATM Network Architecture

In order to provide mobile communication services over an ATM infrastructure, it is appropriate to add "mobile ATM" functionality to existing signaling/control protocols to support terminal mobility [2][7][17]. Figure 3.2 describes the system architecture for a proposed WATM network architecture with mobility support. Such a mobility-enhanced ATM network may be used in cellular/PCS/wireless data network, while providing a smooth migration path to the future seamless ATM-based mobile multimedia scenario.

In this network architecture, APs provide connectivity to MTs via a wireless link (e.g. radio). Each AP in the above architecture operates at a different radio frequency in relation to neighboring AP to avoid channel interference. Thus, when a MT moves to a different AP, it needs to change its operating frequency to that of the AP. The radio coverage areas under adjacent APs overlap, and a handoff procedure is always executed between adjacent APs.

The MTs communicate with APs to access the wireline ATM Network. A cluster of APs close to each other connects to the same MES, which serves as a gateway between the wireless network and the wireline ATM backbone. The MES receives ATM cells from the wireline ATM backbone network and translates them into a format suitable for wireless networks and sends them to the corresponding APs. On the other hand, for the data received from APs, it translates them into ATM cells with correct VPI/VCI and sends them to the wireline ATM backbone network.

There are direct physical links between any two adjacent MESs. The purpose of these direct links is to support reserved PVCs between the MESs. The advantages of PVCs are to guarantee the availability of a connection that no call set up procedures is required between MESs. In our method, wired link resources should be reserved in the form of PVCs between any two adjacent MESs, so the adjacent MESs are fully connected with PVCs in order to quickly execute the inter-cluster handoff with minimum handoff latency. There is a capacity limit on the MES, in terms of how many MTs can be supported simultaneously. This capacity limit is designed such that the MESs are properly loaded and prevented from becoming bottlenecks. Thus the area covered by a MES is not fixed. A MES may cover a large area, such as the suburb of a city, where the communication traffic is mostly light. Or it may cover a relatively small area, such as the downtown area of a city, where communication traffic is generally heavy. The key issue of our design system architecture is that we minimize the effect of the wireless ATM network on the fixed ATM network, so that the MES will isolate both networks [86-87].

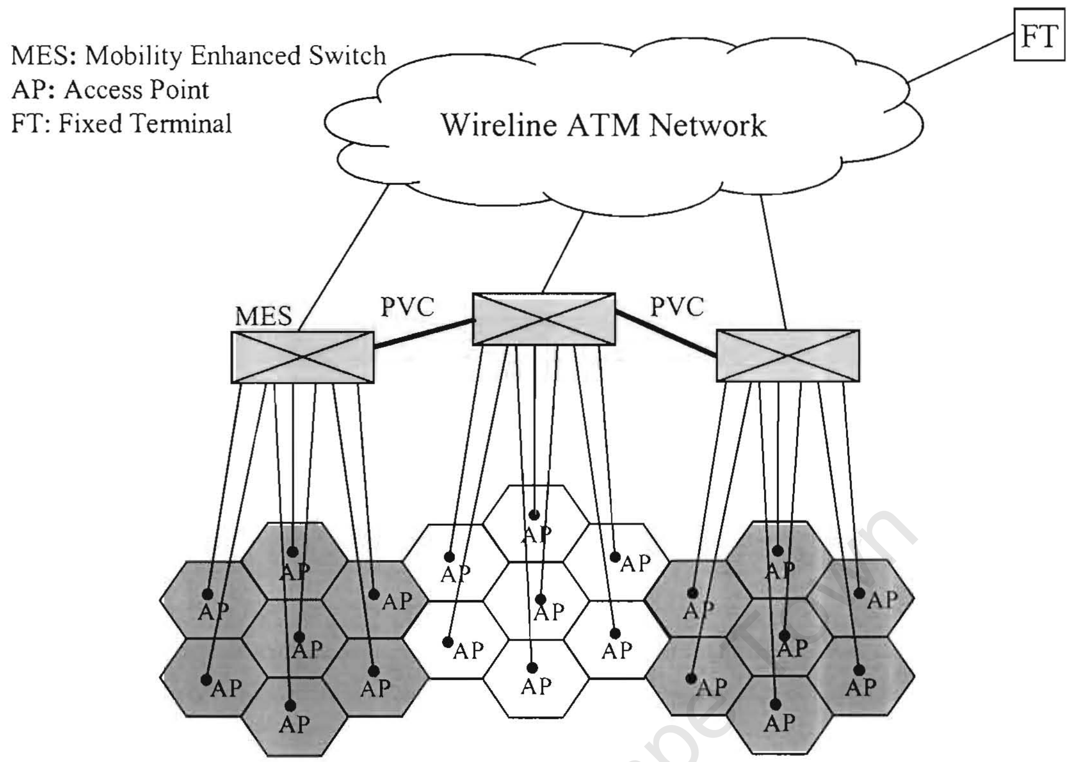

Figure 3.2: The proposed WATM network architecture.

3.3 The Proposed Signaling Protocols

During a call setup, the communication path to a mobile is established using Switched Virtual Channels (SVCs) between the MES and the AP in the cell where the mobile is currently roaming. If a mobile enters a new cell then the signaling protocol achieved depends on the type of handoff [49][77][88-89]. There are two types of handoff schemes: intra, and inter-cluster handoff. In our signaling protocols, we assume the MT supports two way VCs and only one active call is requested. In our proposed signaling protocol, the soft handoff policy can offer a seamless handoff in the overlapping areas between any adjacent APs.

3.3.1 Signaling Protocol for the Intra-Cluster Handoff

Intra-cluster handoff occurs when MT moves inside a cluster, i.e. when a MT moves from an AP connected to a MES to another AP connected to the same MES. Intra-cluster handoff requires only one new SVC to be established between the MES and the new AP. In our proposal, we adopt intra-cluster handoff using the Anchor switch, which results an optimal route. Therefore there is no need for any re-routing of the paths after the handoff. This scheme was discussed in Section 2.2.2.1. Figure 3.3 presents this handoff scheme.

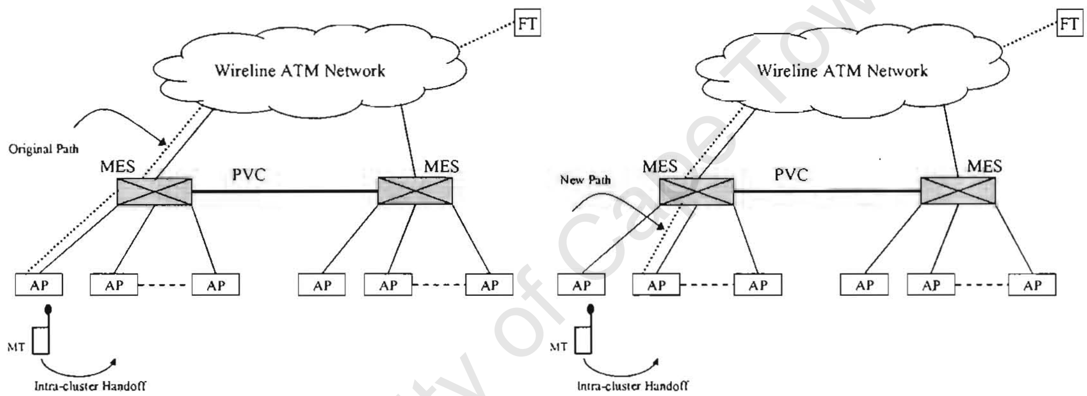

Figure 3.3: Intra-cluster handoff fast re-routing.

A signaling procedure for intra-cluster handoff can be explained as follows:

1- If a MT needs a handoff call to a new AP (using signal strength measurements), it sends to its MES via its AP (AP1) a HO_REQUEST (1) message requesting a handoff to a new AP (AP2). The MT includes the identity of the target AP in the message. (See Figure 3.4).
2- The MES sends a message RR_ALLOCATE (2) to a new AP to allocate radio resources according to the expected QoS and bandwidth requirements.

The resource allocation is completed when a new AP sends a message RR_COMPLETE (3) to the MES.

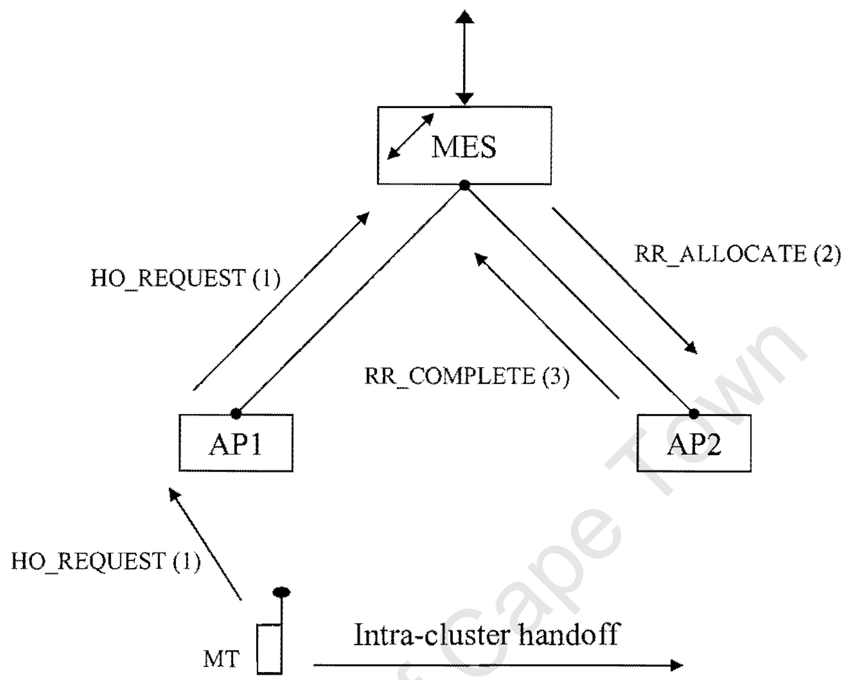

Figure 3.4: Initiation of the intra-cluster handoff.

3- In Figure 3.5 the handoff can proceed, so the MES informs a MT that the handoff will be made to AP2 by sending a HO_RESPONSE (4) message via AP1. At the same time, the old downlink direction is switched to AP2 (5), and AP2 starts to buffer downlink cells.

4- When downlink switching has been done, the MES (via the virtual connection VC of the old connection) sends a Down_ready (6) inband mark, indicating the end of downlink data stream. The HO_RESPONSE indicates that the mobile can proceed to initiate radio handoff. However, the MT is aware that the downlink connection has already been re-routed. Both uplink and buffered downlink cells are still transmitted normally over the radio interface.

5- A MT can wait for AP1 to send all buffered cells. AP1 indicates the last cell sent to MT with No_more_traffic (7) flag.

6- When a MT receives a No_more_traffic signal, it stops transmitting the uplink cells and starts buffering the uplink cells.

7- AP1 transmits any remaining uplink cells and sends the MES an inband mark called Up_ready (8) indicating the last cell in the uplink buffer.

8- After receiving Up_ready, it is now safe to allow AP2 to start transmission so the cell order of the connection is maintained.

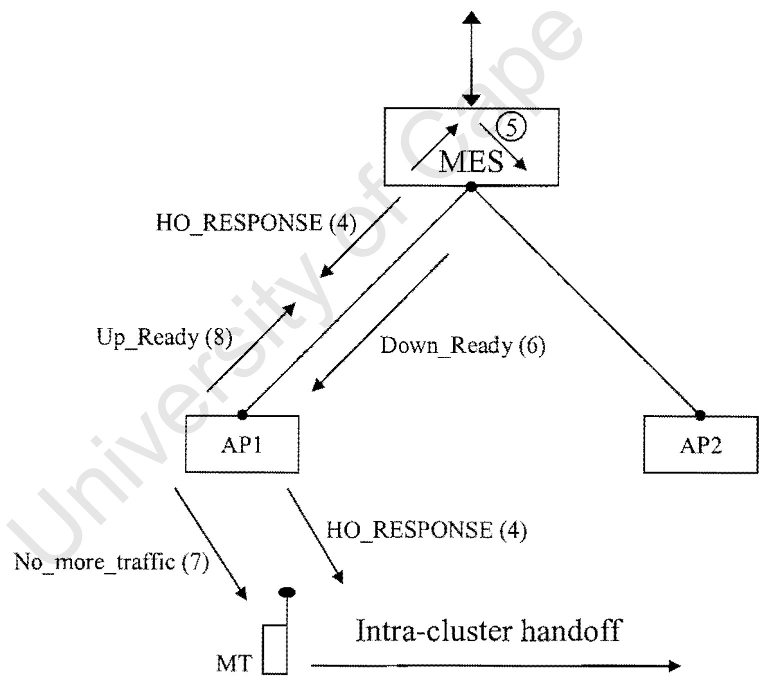

Figure 3.5: Handoff acknowledgment and re-routing the downlink from AP1 to AP2.

9- In Figure 3.6, the MT establishes a radio link with AP2 and releases the radio link with AP1. A MT completes the radio handoff by establishing a radio link with AP2. The MT next sends a CONN_ACTIVATE (9) message to AP2. This message indicates to the AP2 that a MT is ready to receive downlink cells, and AP2 starts sending downlink traffic to a MT. Then MT releases the radio link (10).

10- When a MES receives Up_ready inband mark, it updates the uplink connection (11) towards AP2 and informs AP2 using a CONN_SWITCHED (12) message that it has completed uplink connection reconfiguration.

11- When AP2 received a CONN_SWITCHED message, it sends a CONN_ACTIVE (13) message to a MT. This message tells a MT that it can start transmission uplink cells and that the handoff has been completed.

12- The only outstanding task is for the MES to release the resources reserved for the MT in the old AP (AP1). This is done by sending a CONN_RELEASE (14) message to AP1.

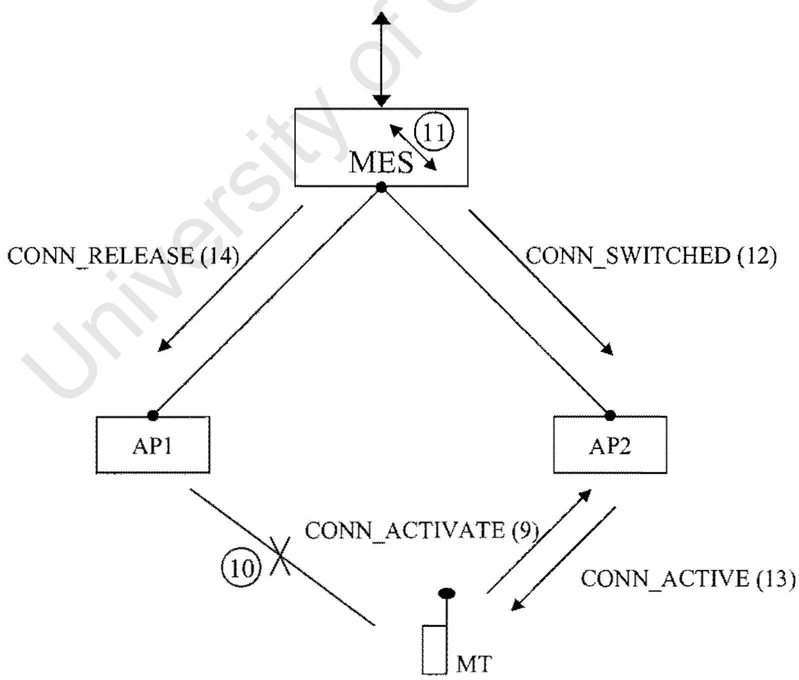

Figure 3.6: Releasing the old resources, radio link re-establishment and uplink switching.

A signaling protocol for the proposed intra-cluster handoff is shown in Figure 3.7. A switching event is illustrated with **(X)** in the figure.

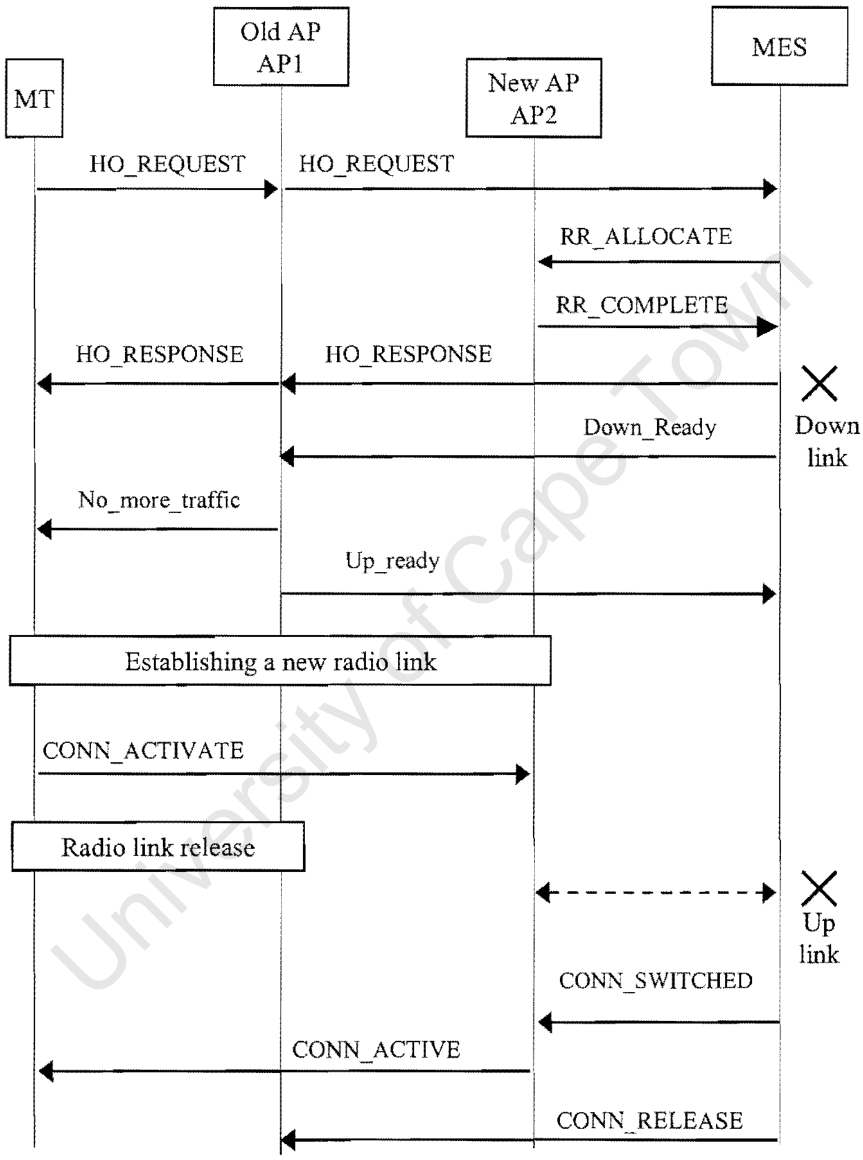

Figure 3.7: Signaling protocol for intra-cluster handoff.

3.3.2 Signaling Protocol for the Inter-Cluster Handoff

Inter-cluster handoff is applied when MT migrates to another cluster, i.e. when a MT moves from an AP connected to a MES to another AP connected to a different MES. The inter-cluster handoff is the most complex part of our handoff scheme, in which the processing time is longer than intra-cluster handoff and the signaling protocol involves two MESs and requires path re-routing. The proposed PVCs yield fast handoff processing on wired links and maintain the cell sequence integrity. This scheme was discussed in Section 2.2.3.2. Figure 3.8 presents this handoff scheme.

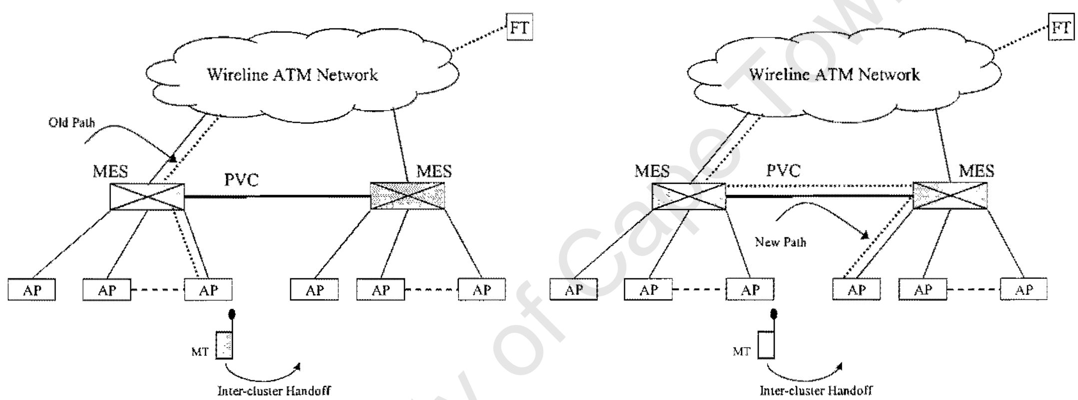

Figure 3.8: Inter-cluster handoff fast re-routing.

A signaling procedure for inter-cluster handoff can be explained as follows:

1- Using signal strength measurement, a MT determines that a handoff is needed when it moves to a new cell. The handoff is initiated (see Figure 3.9), and the MT sends to its MES (MES1) a HO_REQUEST (1) message via its AP (AP1) requesting a handoff to a new AP (AP2). The MT includes the identity of the target AP in the message. In the example, the MT requests a handoff to AP2.

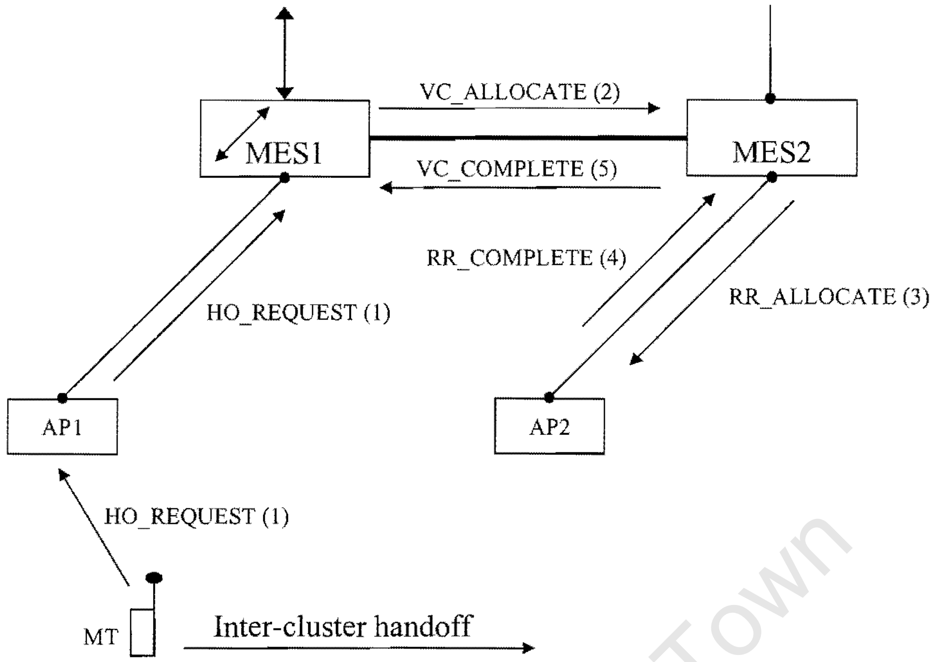

Figure 3.9: Initialization of inter-cluster handoff.

2- The old MES (MES1) determines that the new AP (AP2) is connected to an adjacent MES (MES2). The old MES (MES1) checks if PVC is available in PVC pool for handoff. If yes then MES1 sends VC_ALLOCATE (2) message to new MES (MES2). The VC_ALLOCATE message includes the identity for the new AP. If PVC is not available to support the inter-cluster handoff call then the call will be dropped.

3- After the new MES has received a VC_ALLOCATE message, it sends RR_ALLOCATE (3) message requesting AP2 to allocate radio resources according to the expected QoS and bandwidth requirements.

4- On receiving the RR_ALLOCATE message, the new AP checks the availability of the radio resources and reserves them for the handoff call. The new AP then sends a RR_COMPLETE message (4) to the new MES. The RR_COMPLETE message indicated the availability of the radio resources at

AP2. Then MES2 sends a VC_COMPLETE (5) message to the MES1 informing that all the resources have been allocated to support the handoff.

5- In Figure 3.10 the handoff can proceed, so the MES1 informs a MT that handoff will be made to AP2 by sending a HO_RESPONSE (6) message via AP1.

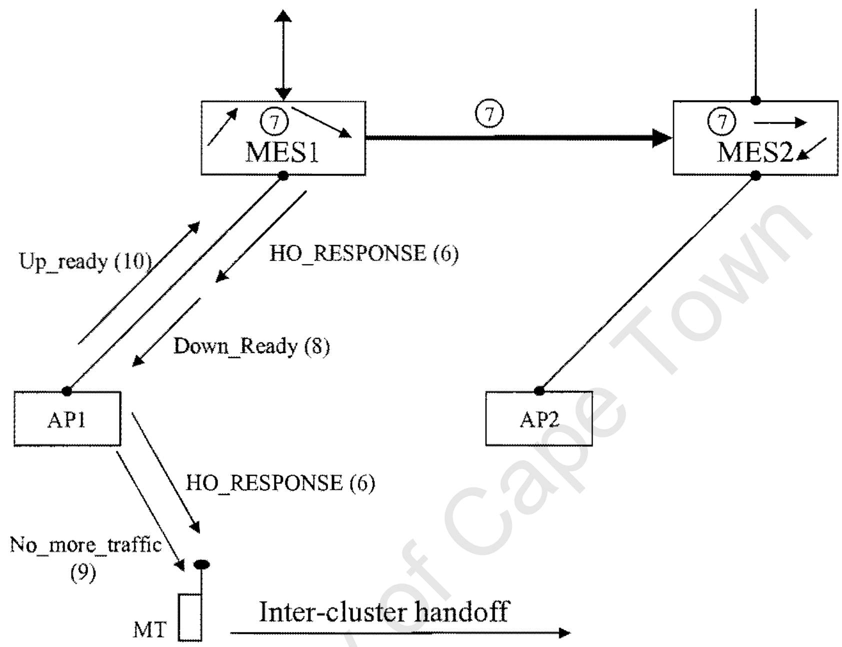

Figure 3.10: Handoff acknowledgment and re-routing the downlink from AP1 to AP2.

6- At the same time, the old downlink direction of the connection is re-routed and extended by the MES1 to AP2, through the MES2 (7), using the pre-assigned PVC to bypass the traffic.

7- AP2 starts to buffer downlink cells. When the old downlink is re-routed, the MES1 (via the VC of the old connection) sends a Down_ready (8) inband mark. Down_ready indicates the end of downlink data stream. The HO_RESPONSE indicates that the mobile can proceed to initiate radio handoff. Also the MT knows that the downlink connection has already been re-routed. However, both up link and buffered downlink cells are still transmitted normally over the radio interface.

8- The MT can wait for AP1 to send all buffered cells. AP1 indicates the last cell sent to MT with a No_more_traffic (9) flag.

9- AP1 transmits any remaining uplink cells and sends the MES1 an inband mark called Up_ready (10) indicating the last cell in the uplink buffer. After receiving Up_ready, it is now safe to allow AP2 to start transmission so that the cell order of the connection is maintained.

10- In Figure 3.11, a MT completes the radio handoff by establishing a radio link with AP2. The MT next sends a CONN_ACTIVATE (11) message to AP2. This message indicates to the AP2 that a MT is ready to receive downlink cells and AP2 can start sending downlink traffic to a MT. Then a MT releases the radio link (12).

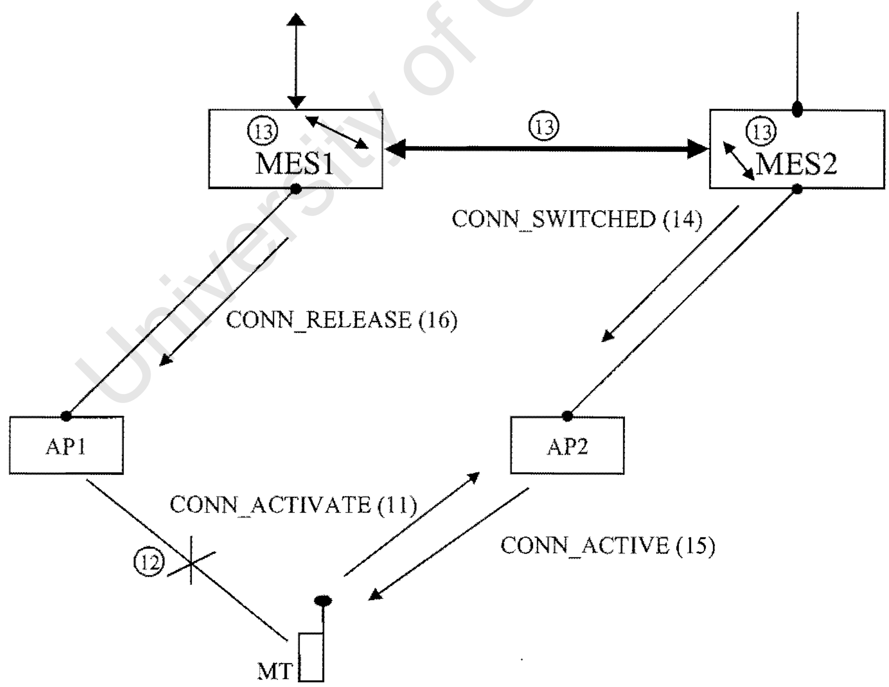

Figure 3.11: Releasing the old resource, radio link re-establishment and uplink switching.

11- The uplink connection routing is updated in the MES2 (13) (towards the MES1) using the pre-assigned PVC. The MES2 informs the AP2 using CONN_SWITCED (14) message, that it has completed the uplink connection reconfiguration.

12- When AP2 receives the CONN_SWITCHED message, it sends a CONN_ACTIVE (15) message to MT. This message tells the MT that it can start transmission uplink cells and that the handoff has been completed.

13- The only outstanding task is for the MES1 to release the resources reserved for the MT in old AP (AP1). This is achieved by sending a CONN_RELEASE (16) message to AP1.

A signaling protocol for Inter-cluster handoff is shown in Figure 3.12. A switching event is illustrated with **X** in the figure.

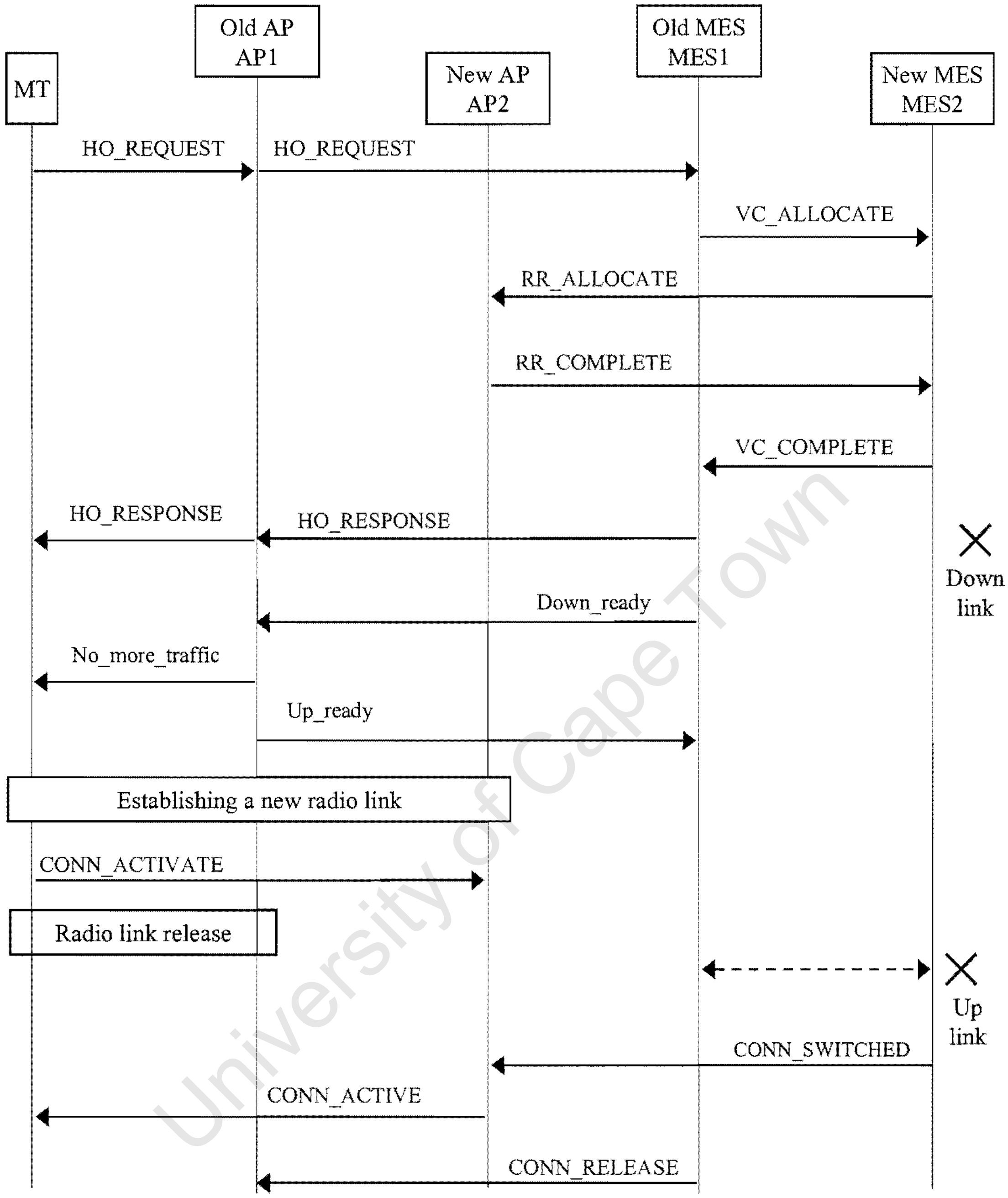

Figure 3.12: Signaling protocol for inter-cluster handoff.

3.4 Conclusions

In this chapter we have presented the cluster handoff model by defining the wireless cells and the construction of the cluster, indicating the difference between the intra and inter-cluster handoff migration.

Next, we have explained in details our proposed WATM architecture to view WATM as an integral part of wired ATM by enhancing the MESs with mobile specific features. The MES supports both mobile users and fixed users. This integration structure allows us to construct a WATM network without a major modification to the fixed ATM network. Most mobility support functions are performed in the wireless access network. The PVCs are used to inter-connect between any MESs to support fast handoff with no call setup.

Finally, we have explained in detail the signaling protocols both for intra and inter-cluster handoff, focusing on an efficient, simple and cost effective handoff mechanism. The signal flow diagram for each handoff scheme had been illustrated step by step. Our scheme achieved the following handoff solutions:

1) The radio link resource allocation scheme of APs is allocated on demand whenever handoff is required. This will save the resources.
2) By using PVC technique, we can provide fast handoff connection with no Call Admission Control (CAC) overhead.
3) Achieve lossless handoff.
4) Achieve preserving of the cell sequencing during the handoff call.

Chapter 4

Performance Modeling of PVC-Based Inter-Cluster Handoff Path Extension Scheme

In current wireless networks, as the population of mobiles increases, the cell radii will be further reduced so the handoff will occur more frequently. The inter-cluster handoff scheme is more involved as the new connection needs to be re-routed. In this scheme, a path extension method is proposed in which the route is to be extended from the original MES to an adjacent MES that connects to the new AP. This scheme places the handoff processing load in the MES, which is specially designed for high processing performance. The path extension method is fast and simple to implement. The PVCs reserved between adjacent MESs provide a high-speed handoff connection. The re-routing path for call handoffs does not require a Call Admission Control (CAC) support, which may incur an unacceptably long connection delay.

In this chapter, we present an analysis of the proposed scheme including the traffic system model and the inter-cluster handoff model to calculate the total handoff rate at the cluster boundaries. The PVC reservation analytical model is derived to calculate the PVC connection holding time and the PVC bandwidth in terms of the number of PVC connections to be assigned between MESs. The simulation model is presented for comparison purposes to ensure the validity of the analytical model. Finally, the performance of the proposed scheme is evaluated.

4.1 Description of The Scheme

Referring to Figures 3.2, 3.3, and 3.8, it is clear the MES is connected to an aggregation of cells and every adjacent MESs are connected by reserved PVC. The advantages of PVCs are that they guarantee the availability of a connection, and that no call setup procedures are required between switches to perform fast handoff.

If a MT moves from one AP to another at the same cluster, then an intra-cluster handoff will occur and the signaling protocol described in Section 3.3.1 is performed. If a MT moves from AP to another in different clusters, then an inter-cluster handoff is performed using the Anchor path extension between the adjacent MESs. In this case the signaling protocol described in Section 3.3.2 is used to perform the path extension [71]. During inter-cluster-handoff two VPI/VCI mappings are required, the first mapping between the old MES and the new MES, and the second mapping between the new MES and the new AP.

4.2 The Analytical Model of the Proposed Scheme

In cellular networks, there are usually two classes of calls: new calls, and handoff calls. New calls are those just starting, and handoff calls are calls that are already ongoing but have moved onto new cell and need to connect to a new AP.

Figure 4.1 shows the traffic process in a typical cell. New calls and handoff calls arrive at the cell. Based on the availability of channels in the cell, new calls can be blocked or put through, and arriving handoff calls can be dropped out or be handed off successfully to the cell. The departed calls from the cell either complete or are handed off to other cells. The two following performance metrics are commonly used for the design and performance evaluation. [90]:

- *Call blocking probability* (P_o): The probability that a new call (originating call) is blocked.

- *Handoff blocking probability* (P_f): The probability that a handoff call is blocked.

Since P_f is highly related to P_o, a tradeoff between guaranteeing the ongoing calls during handoff and accepting new calls should be taken into consideration [90].

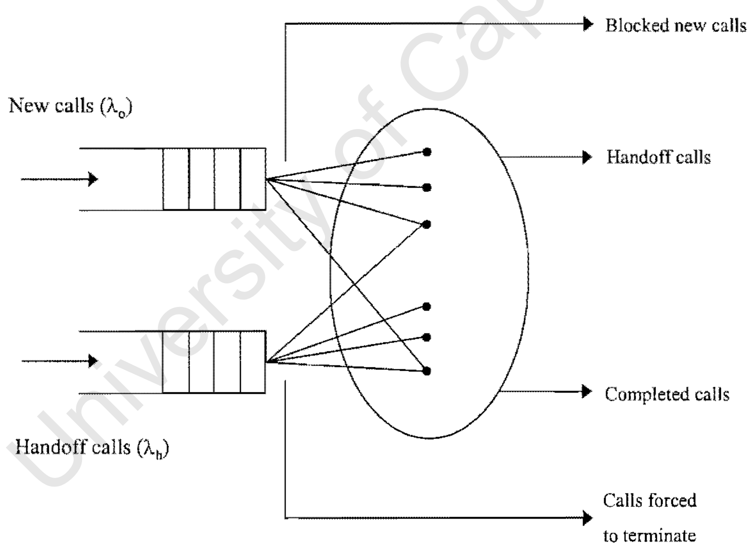

Figure 4.1: New and handoff traffic process in a typical cell.

4.2.1 The Proposed Traffic and System Model

In this section, we consider that every mobile session uses one connection with an identical bandwidth requirement. An analytical modeling is used to calculate the average PVC connection holding time and a wired PVC bandwidth (number of PVCs) for a given handoff blocking. The analytical model can be explained as follows:

1) We assume that the network operates under homogeneous traffic conditions. Homogeneous traffic is defined as one where all cells have the same total number of channels, the same number of channels available for handoff calls and new calls, as well as the same mean new call arrival rate and handoff arrival rate.
2) The MTs and their traffic are uniformly distributed over a given cell. Furthermore, the MTs are equally likely to move in any direction with respect to the cell boundary.
3) The originating arrival calls in a cell follow a Poisson process with rate λ_o.
4) The call holding time T_M is exponentially distributed with mean $1/\mu_M$. Hence, $F_{T_M}(t) = 1 - e^{-\mu_M t}$ is the distribution of T_M.
5) The time interval R during which a mobile resides in a cell whilst a connection is active, called the cell sojourn time, has an exponential distribution with mean $1/\mu_R$. The cell sojourn times, $R^{(1)}, R^{(2)}, \ldots$, consecutively induced by a movement of a mobile are independent and exponentially distributed.
6) Hexagonal-shaped cells are arranged in a plane.
7) PVC supports a two-way call.

It has already been shown that the handoff call arrival rate in a cell is given by the following formula [3][91-92]:

$$\lambda_h = \frac{\mu_R(1-P_o)}{\mu_M + \mu_R P_f}\lambda_o \tag{4.1}$$

4.2.2 Inter-Cluster Handoff Mobility Model

In this section, we derive the inter-cluster handoff rate, λ_P in our general hexagonal cluster environment. The handoff rate across any cell boundary contributed by one cell is $\lambda_h/6$. As shown in Figure 4.2, in the case of cluster size of two rings, there are three cell boundaries contributing to the total inter-cluster handoff. Therefore, the total inter-cluster handoff arrival rate $\lambda_P = 6\cdot\lambda_h/6$, and hence $\lambda_P = \lambda_h$. Generally the total handoff arrival rate at any cluster boundary is given by:

$$\lambda_P = \frac{(2r-1)}{3}\lambda_h \quad , r = 1,2,3,... \tag{4.2}$$

Where r is the number of rings.

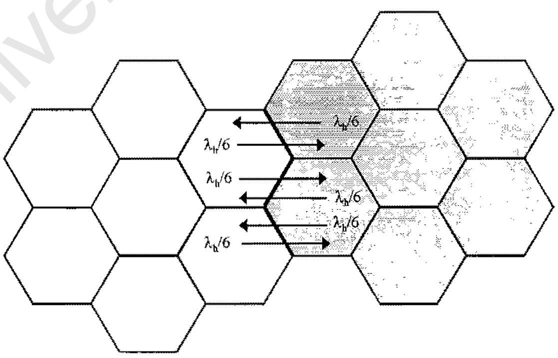

Figure 4.2: Handoff rates across a cluster boundary.

4.2.3 PVC Reservation Analytical Model

Suppose that a call has just been handed off successfully across the cluster boundary, and a PVC connection has been allocated. The PVC holding time T_P is defined as the duration from the instant that PVC has been allocated to a handoff call to the instant that PVC is released. The PVC allocation can be released due to one of the following: 1) the connection is naturally terminated; 2) the connection is forced to be terminated due to the handoff blocking when it moves to another cell.

The PVC holding time T_P can be written as:

$$T_P = \min(T_M, T_R) \tag{4.3}$$

Where:

- T_M: The holding time of a PVC call is considered to be the duration from the time that the PVC call is created to the time that the call is completed by the mobile user without any blocking.

- T_R: The total sojourn time of N cells before the handoff blocking, i.e. $T_R = R^{(1)} + R^{(2)} + \ldots + R^{(N)}$. Here N is the number of cells in which the mobile generating the call resides before the handoff blocking, and is assumed to be a random variable with geometric probability distribution, $P(N = n) = P_f(1 - P_f)^{n-1}, n = 1,2,\ldots$.

The Laplace-Stieltjes Transform (LST) of T_R is given by:

$$T_R^*(s) = N[R^*(s)] \tag{4.4}$$

Where, $N[z]$ is the generating function of the random variable N.

Now,

$$N[z] = \sum_{n=0}^{\infty} z^n P(N = n)$$

$$= P_f \sum_{n=1}^{\infty} z^n (1 - P_f)^{n-1}$$

$$= P_f (1 - P_f)^{-1} \sum_{n=1}^{\infty} [z(1 - P_f)]^n$$

$$N[z] = \frac{zP_f}{1 - z(1 - P_f)} \tag{4.5}$$

The distribution of T_P can be found as follows:

$$P[T_P > t] = P[\min(T_M, T_R) > t]$$

Where the random variables T_M, T_R are independent.

$$= P[T_M > t, T_R > t]$$

$$= P[T_M > t]P[T_R > t]$$

Now,

$$F_{T_P}(t) = P[T_P \le t]$$

$$= 1 - P[T_P > t]$$

$$= 1 - P[T_M > t]P[T_R > t]$$

$$= 1 - [1 - P[T_M \le t]][1 - P[T_R \le t]$$

$$= 1 - [1 - F_{T_M}(t)][1 - F_{T_R}(t)]$$

Where $F_{T_R}(t)$, is the distribution of T_R.

Hence;

$$F_{T_P}(t) = F_{T_M}(t) + F_{T_R}(t) - F_{T_M}(t)F_{T_R}(t) \tag{4.6}$$

Now: $F_{T_M}(t) = 1 - e^{-\mu_M t}$

The distribution of T_P is written as:

$$F_{T_P}(t) = 1 - e^{-\mu_M t} + F_{T_R}(t) - (1 - e^{-\mu_M t})F_{T_R}(t)$$

$$F_{T_P}(t) = 1 - e^{-\mu_M t} + F_{T_R}(t)e^{-\mu_M t} \tag{4.7}$$

To obtain the mean of T_P, we derive $T_P^*(s)$, the LST of T_P.

Let $f_{T_P}(t)$ be the density function of T_P and $f_{T_R}(t)$ be the density function of T_R. We have:

$$f_{T_P} = \frac{d}{dt}F_{T_P}(t) = \mu_M e^{-\mu_M t} - \mu_M F_{T_R}(t)e^{-\mu_M t} + f_{T_R}(t)e^{-\mu_M t} \tag{4.8}$$

Now,

$$T_P^*(s) = \int_0^\infty f_{T_P}(t)e^{-st}dt \tag{4.9}$$

$$= \mu_M \int_0^\infty e^{-(s+\mu_M)t}dt - \mu_M \int_0^\infty F_{T_R}(t)e^{-(s+\mu_M)t}dt + \int_0^\infty f_{T_R}(t)e^{-(s+\mu_M)t}dt \tag{4.10}$$

Now, $\int_0^\infty F_{T_R}(t)e^{-(s+\mu_M)t}dt$, can be calculated using integration by parts.

With $u = F_{T_R}(t)$, $\quad du = f_{T_R}(t)dt$ and

$e^{-(s+\mu_M)t}dt = dv$, $\dfrac{-e^{-(s+\mu_M)t}}{s+\mu_M} = v$

It follows that:

$$\int_0^\infty F_{T_R}(t)e^{-(s+\mu_M)t}dt = \Big[\frac{-F_{T_R}(t)e^{-(s+\mu_M)t}}{s+\mu_M}\Big]_0^\infty + \frac{1}{s+\mu_M}\int_0^\infty f_{T_R}(t)e^{-(s+\mu_M)t}dt$$

Using Equation 4.4 we get:

$$\int_0^\infty F_{T_R}(t)e^{-(s+\mu_M)t}dt = \frac{1}{s+\mu_M}N[R^*(s+\mu_M)] \qquad (4.11)$$

With the assumption that R is exponentially distributed with mean $1/\mu_R$, then $R(t) = 1 - e^{-\mu_R t}$. Under this assumption, the LST of R can be expressed as:

$$R^*(s) = \frac{\mu_R}{s+\mu_R} \qquad (4.12)$$

Now, from Equations 4.4, 4.10, and 4.11, it follows that:

$$T_P^*(s) = \frac{\mu_M}{s+\mu_M} - \frac{\mu_M}{s+\mu_M}N[R^*(s+\mu_M)] + N[R^*(s+\mu_M)]$$

$$= \frac{\mu_M}{s+\mu_M} + \frac{s}{s+\mu_M}N[R^*(s+\mu_M)]$$

Using Equation 4.5 we get:

$$T_P^*(s) = \frac{\mu_M}{s+\mu_M} + \frac{s}{s+\mu_M}\,\frac{P_f R^*(s+\mu_M)}{1-[1-P_f]R^*(s+\mu_M)}$$

Using Equation 4.12, we get:

$$T_P^*(s) = \frac{\mu_M}{s+\mu_M} + \frac{s}{s+\mu_M} \frac{\frac{\mu_R}{s+\mu_R+\mu_M} P_f}{1 - \frac{\mu_R}{s+\mu_R+\mu_M}(1-P_f)} \quad (4.13)$$

And finally,

$$T_P^*(s) = \frac{\mu_M}{s+\mu_M} + \frac{s}{s+\mu_M} \frac{\mu_R P_f}{s+\mu_M+\mu_R P_f} \quad (4.14)$$

Now,

$$\frac{d}{ds} T_P^*(s) = \frac{-\mu_M}{(s+\mu_M)^2} + \frac{\mu_M}{(s+\mu_M)^2} \frac{P_f \mu_R}{(s+\mu_M+\mu_R P_f)} + F(s)$$

Where $F(s)$, is a function of 's' with $F(0) = 0$.

$$\frac{d}{ds} T_P^*(s) = \frac{-\mu_M}{(s+\mu_M)^2} \left\{ \frac{s+\mu_M}{s+\mu_M+\mu_R P_f} \right\} + F(s) \quad (4.15)$$

The mean of T_P is given by:

$$E[T_P] = -\frac{d}{ds} T_P^*(s)\Big|_{s=0} \quad (4.16)$$

$$E[T_P] = \frac{1}{\mu_M + \mu_R P_f} \quad (4.17)$$

The number of PVCs reserved between any adjacent MESs, N_P can be evaluated using the Erlang-B formula [93], which calculates the handoff blocking probability due to lack of PVCs between adjacent MESs, and is obtained as follows:

$$P_f = \frac{\frac{[\lambda_P E(T_P)]^{N_P}}{N_P!}}{\sum_{n=0}^{N_P} \frac{[\lambda_P E(T_P)]^n}{n!}} \tag{4.18}$$

4.3 Simulation Analysis

In this section, we present the simulation model for the comparison with the numerical model. In this model, the inter-cluster handoff arrival rate forms a Poisson process with mean arrival rate of λ_P. The handoff inter-arrival time is exponentially distributed with mean $1/\lambda_P$. The call holding time T_M is exponentially distributed with mean $1/\mu_M$. The exponential distribution is generated using an exponential distribution random number generator. The total sojourn time T_R of a user connection is the total sojourn time of N cells that a MT visits before the handoff is blocked. N, a random variable with a geometric distribution, is generated using a geometric distribution random number generator. A cell sojourn time has also an exponential distribution with mean $1/\mu_R$.

4.3.1 Simulation Language and Methodologies

The simulation environment has been developed using ***C-language***, as it is very flexible to design, change and implement. Our simulation environment is based on the discrete-event model. The state variables of our simulation (i.e. number of PVCs, PVC expiration time, and the size of the Queues) change instantaneously at discrete points and depend on the mean of the inter-arrival time for the handoff calls. From Figure 4.4, we see the states of our system (events) are only changed (occurred) in separated discrete points in time ($t_1, t_2, t_3, \ldots\ldots$). The time between any two adjacent discrete points is called the handoff inter-arrival time, and it is considered to be an exponential distribution with mean $1/\lambda_P$.

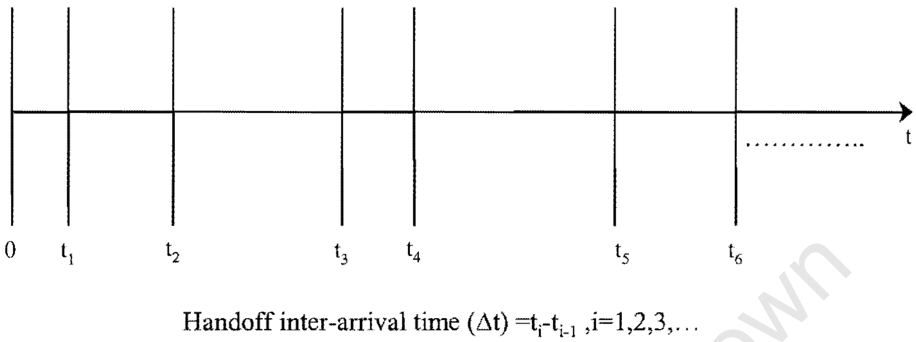

Figure 4.3: A sample path of the Poisson arrival process.

4.3.2 Random Number Generators

Any computer simulation of a system that involves randomness must include a method for generating sequences of random numbers. These random numbers must satisfy long-term average properties of the process they are simulating. The transformation method was used to generate random variables for the desired probability distributions. This method is based on generating random numbers that are Uniform distribution (U) in $[0,1]$ [93].

4.3.2.1 Exponential Distribution Random Number Generator

To generate an exponentially distributed random variable X with parameter λ, we need to invert the expression $u = F_X(x) = 1 - e^{-\lambda x}$, thus obtaining $X = -\frac{1}{\lambda}\ln(1-U)$. Since $(1-U)$ is also uniformly distributed in $[0,1]$, then this formula can be simplified to:

$$X = -\frac{1}{\lambda}\ln(U) \tag{4.19}$$

4.3.2.2 Geometric Distribution Random Number Generator

By similar method, the geometric distribution random number can be generated using this formula:

$$K = \frac{\ln(U)}{\ln(1-p)}, \; K = 1,2,\ldots \text{ and } 0 \le p \le 1 \tag{4.20}$$

4.3.3 Call Holding Time Generator

The call holding time, T_M of the PVC connection (*Call_Holding_Time*) is generated using the formula $(-1/\mu_M)\ln(U)$, where $1/\mu_M$ is the mean call holding time.

4.3.4 Total Sojourn Time Generator

The total sojourn time, T_R (*Total_Sojourn_Time*) is the total sojourn time of N cells where the MT resides before the handoff blocking. Figure 4.4 shows a flow chart to generate the total sojourn time, and it can be described as follows:

1- Generate a random number N with a geometric distribution using the formula: $\frac{\ln(U)}{\ln(1-P_f)}$, where P_f is the handoff blocking probability.

2- Generate N residual times R using the formula: $-(1/\mu_R)\ln(U)$, where $1/\mu_R$ is the mean residual time.

3- Add all N residual times to get the *Total_Sojourn_Time* .

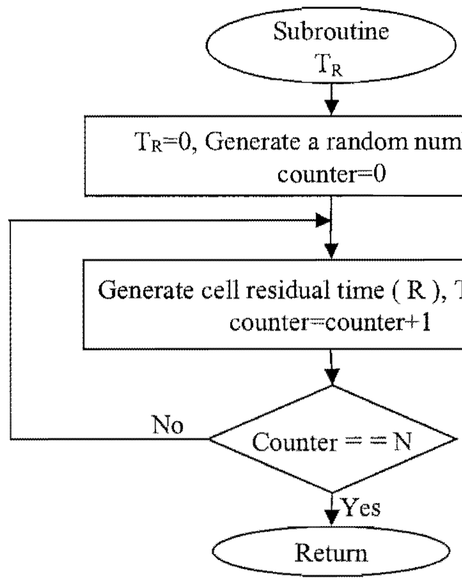

Figure 4.4: Generate the total sojourn time (T_R).

4.3.5 Handoff Call Inter-Arrival Time Generator

The handoff call inter-arrival time is generated using the formula $(-1/\lambda_P)\ln(U)$, where $1/\lambda_P$ is the mean handoff call inter-arrival time.

4.3.6 The Expiration Time Priority Queue

In our simulation, we use a queue called "*Expiration_Time_Priority_Queue*". The idea of this queue is similar to the "FIFO", but after each insertion the contents are *re-ordered* in a time-priority basis. Each content of the queue-element is called "*PVC_Expiration_Time*" state variable and its priority is based on "time" value. The smaller the time, the higher is the priority to remove that call from the queue. Figure 4.5 describes the idea of this time priority queue. The resulting number of elements of this time priority queue equals the number of PVCs (*PVC_BW*).

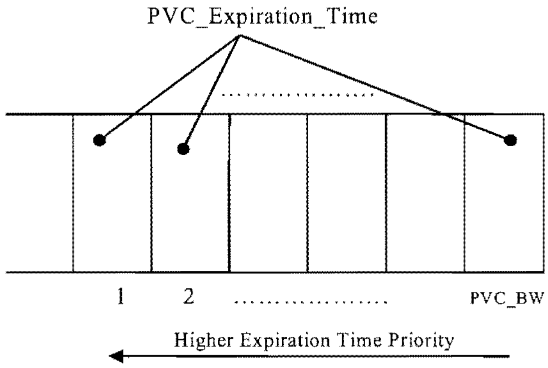

Figure 4.5: The expiration time priority queue.

Each user connection has a *PVC_Expiration_Time* state variable, which reflects the expiration of the PVC connection. The PVC expiration can happen due to the following reasons:

1- Natural termination of the call (i.e. $T_M = 0$).

2- Termination of the call due to handoff blocking (i.e. $T_R = 0$).

The PVC connection is released as a result of the PVC expiration. (i.e. *PVC_Expiration_Time*=0).

4.3.7 The Simulation Logic

The algorithm searches the PVC pool for the values of *PVC_BW* that cause blocking probability, $P_f^* \leq P_f$ where P_f^* is the simulation blocking probability and P_f is the desired blocking probability. The *PVC_BW* is considered to be the simulation value of N_P (i.e. refer to Equation 4.18).

One way to achieve this condition ($P_f^* \leq P_f$) is shown in the flow chart, Figure 4.6. In this method, every time the *PVC_BW* is incremented by *one* and the resulting blocking probability P_f (which is calculated after 50,000 iterations) is compared with the desired blocking probability P_f^*. Although this algorithm achieves the correct results, the convergence time is very large.

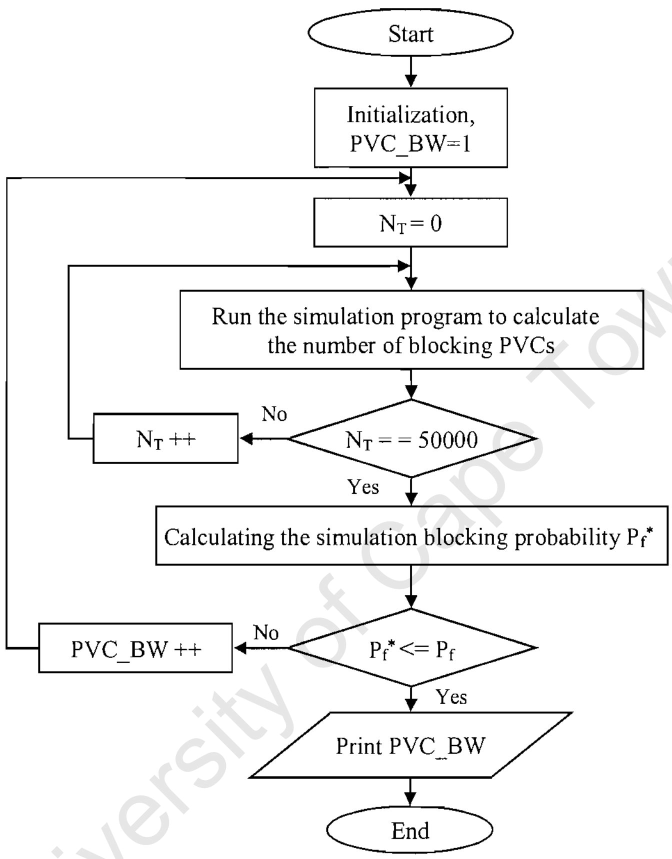

Figure 4.6: Slow searching of PVC_BW in the PVC pool.

This led to the development of faster technique to search for the *PVC_BW* in the PVC pool. Figure 4.7 shows the flow chart for this algorithm. The program is initiated by assuming that the *PVC_BW* is equal to a very large value, in order to calculate the maximum simulation value of the PVC with $P_f^* = 0$. The resulting (*MAX_Capacity*) of PVC is slightly larger than the actual *PVC_BW* because the designed blocking probability P_f is also very small. The *MAX_Capacity* is only calculated for the "First Run" of the program. After that the *PVC_BW* is decremented until we get the exact value.

Note: The exact value of *PVC_BW* is calculated by adding *one* to the previous value of a *PVC_BW* in order to achieve the condition $P_f^* \leq P_f$.

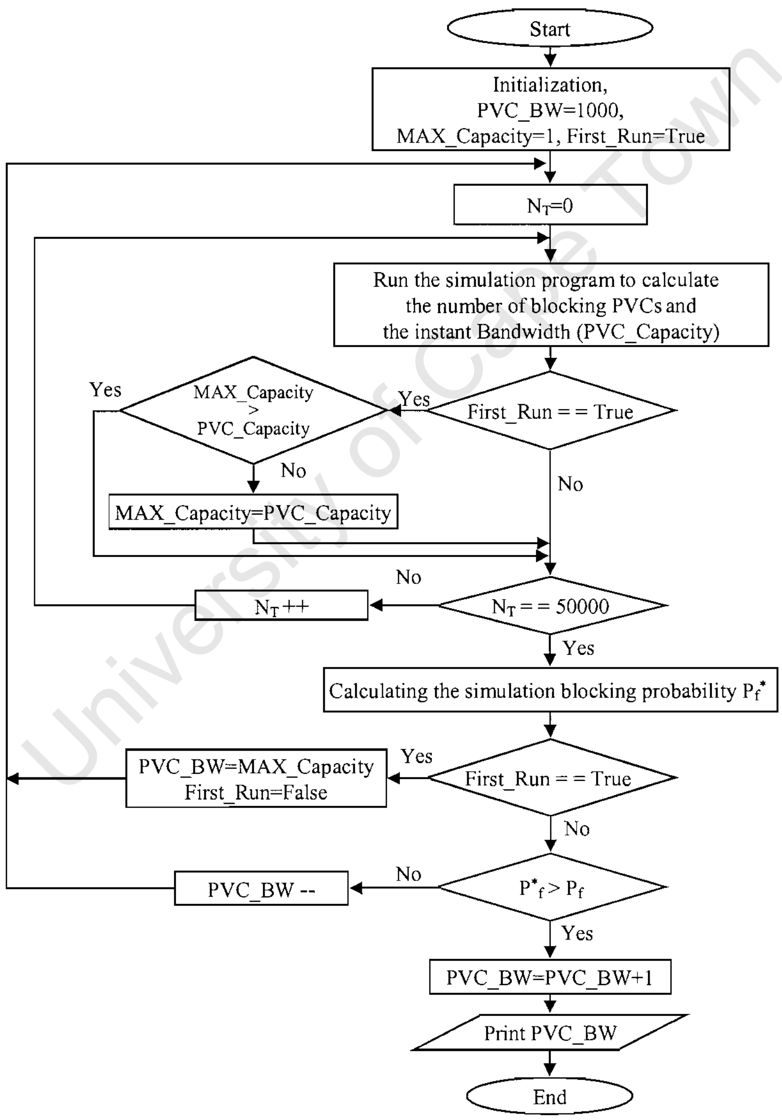

Figure 4.7: Fast searching of PVC_BW in the PVC pool.

Figure 4.8 gives the full program and captures the essence of the algorithm described in Figure 4.7. The program starts by assigning a large value of the PVC bandwidth (*PVC_BW*), assigning Maximum PVC capacity to be initially 1, and First Run is true. The simulation runs up to the value N_T=50,000, where N_T is the total number of handoff arrivals events. Then the simulation blocking probability P_f^* is executed and compared with the required value P_f. The First Run is used to calculate the approximation value of the *PVC_BW* (under the condition $P_f^* = 0$). The PVC connection is decremented until the number of assigned PVC connections produces blocking probability P_f^*, which is greater than P_f.

In our simulation, a user connection will remain assigned to PVC until that connection is expired. Each user connection has a *PVC_Expiration_Time* state variable, which reflects the expiration and releasing of the PVC connection. The PVC expiration can happen due to the following reasons:

1) Natural termination of the call (i.e. $T_M = 0$).
2) Termination of the call due to handoff blocking (i.e. $T_R = 0$).

Referring to Figure 4.8, the details of the simulation can be described as follows: Steps (1) and (2) are used for the initialization. The first handoff arrival event is generated with the state variable *PVC_Expiration_Time* equal to zero, and then inserted in the generated *Expiration_Time_Priority_Queue*. Then the *PVC_Capacity* is initialized to 1. In step (3), the next handoff inter-arrival time (Δt) will be generated and the parameter N_T is incremented, then the value (Δt) is subtracted from the contents of the *Expiration_Time_Priority_Queue*. In step (4) the program checks the expiration of the PVC connections by checking the values of the *PVC_Expiration_Time* state variable in the front of the queue. If the values are less than or equal to zero, then the connections have been already expired, and in step (5) we delete the connection and decrement the PVC capacity.

In step (6), we check the availability of PVCs. If the bandwidth is not available, meaning that the PVC capacity is equal to the reserved bandwidth *PVC_BW*, then the call is blocked and N_B is incremented (step 7). Otherwise, in step (8), all the attributes of the connection are generated (call holding time T_M, total sojourn time T_R), and then the initial value of the state variable *PVC_Expiration_Time* is calculated by taking the minimum values of both T_M, and T_R. The *PVC_Expiration_Time* variable is inserted the time priority queue and the PVC capacity is incremented.

In step (9), we check the *First_Run*. If it is true then the MAX_Capacity is updated (steps (10) and (11)). In step (12), we check the termination of the total iterations by comparing the total handoff arrivals with 50,000. In step (13), the simulation blocking probability P_f^* is executed. If the condition in step (14) is true then the *PVC_BW* is assumed to be *MAX_Capacity* (step 15) and the program is restarted again.

In step (16), if the simulation blocking probability P_f^* greater than the desired blocking probability P_f, then the simulation program is terminated and the *PVC_BW* is calculated in step (18) by adding 1 to the previous value of *PVC_BW*, in order to achieve the condition $P_f^* \leq P_f$. If the condition in step (16) is not achieved then the *PVC_BW* is decremented and the program is restarted again. Finally, the *PVC_BW* is printed in step (19).

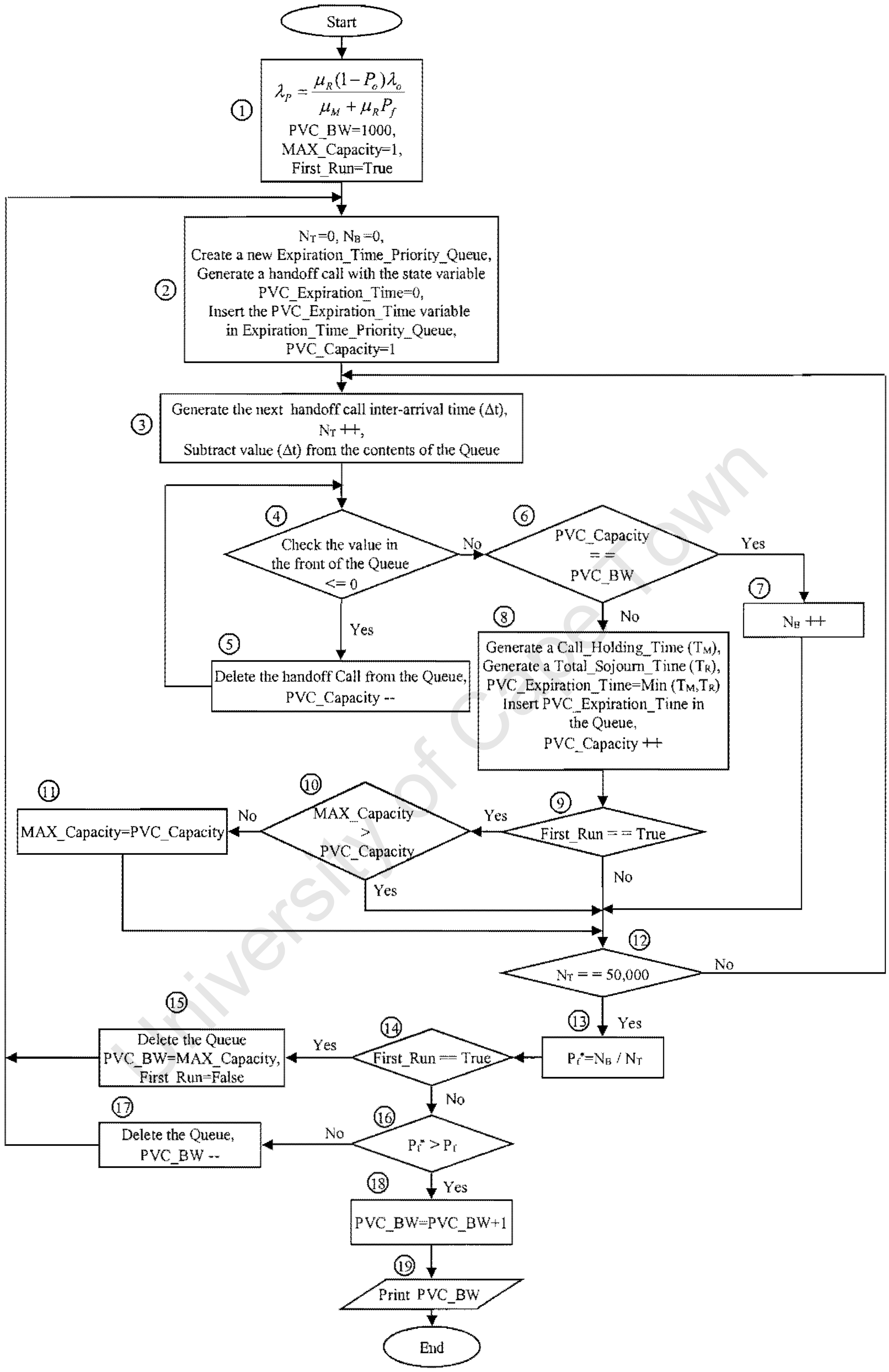

Figure 4.8: The simulation flow chart for the PVC path extension scheme.

4.4 Performance Results

In this section, we evaluate the performance of this proposed scheme, considering numerical results obtained from both the analytical and simulation models. Appendices A.1 and B.1 contain the source code for the analytical and simulation models. The performance results have been studied as a function of the system parameters, i.e. mean originating call arrival rate, call holding time, and residual time.

In these examples, the following are assumed: the new call arrival rate is 0.2 calls/sec, originating calls are blocked with probability 0.01, the handoff blocking probability is 0.001, the average cell sojourn time is 4 minutes, and the average call holding time is 2 minutes [3][67]

Figures 4.9 and 4.10 show the analytical and simulation results for the number of PVCs required between adjacent MESs versus originating call arrival rate for different number of cluster sizes (rings). The figures show the minimum number of PVCs required between any adjacent MESs to maintain the handoff blocking probability less than 0.001. It can be seen that as cluster size increases, the required number of PVCs increases; as the call arrival rate increases, the required number of PVCs also increases. This is because the handoff rate between clusters increases; so that the number of PVCs required to support this extra handoff rate also increases.

For the number of rings is 2, Figure 4.11 shows the required number of PVCs between any adjacent MESs versus the average call holding time. We see from the figure that as the average call holding time increases, the required number of PVCs increases; this is because the handoff rate across the boundaries will increase due to long call duration. Figure 4.12 shows the required number of PVCs between any adjacent MESs versus the average cell sojourn time. We see from the figure that as cell sojourn time increases, the handoff frequency rate will decrease (i.e. due to less chance of a MT to move out of the cell), and thus the required number of PVCs to support the handoff will decrease.

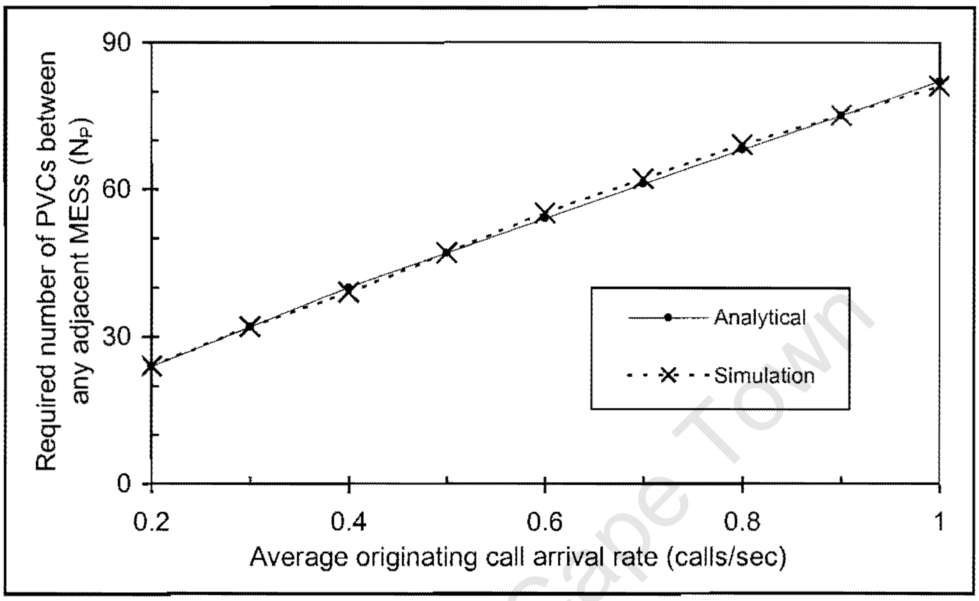

Figure 4.9: The required number of PVCs for a cluster size of two rings.

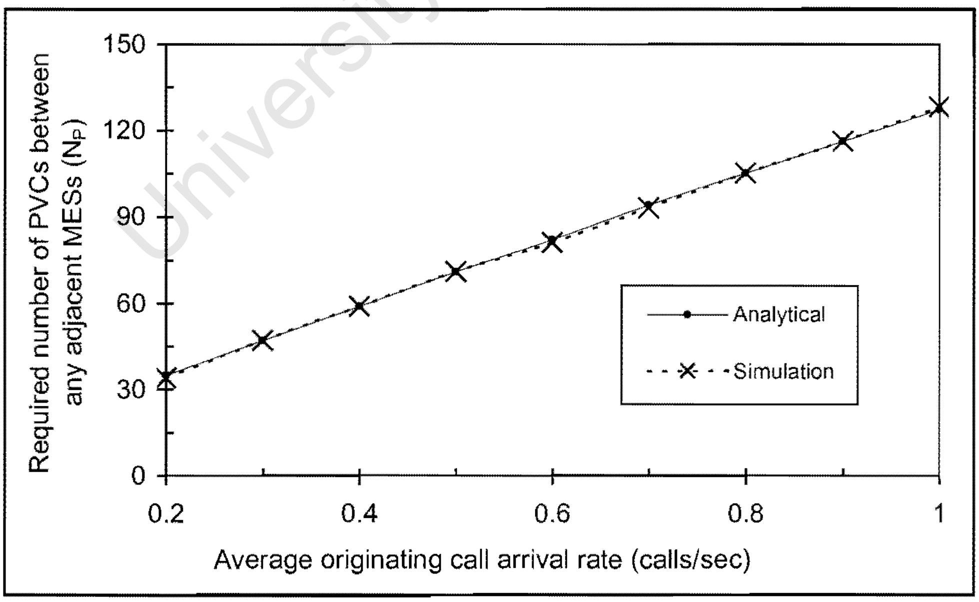

Figure 4.10: The required number of PVCs for a cluster size of three rings.

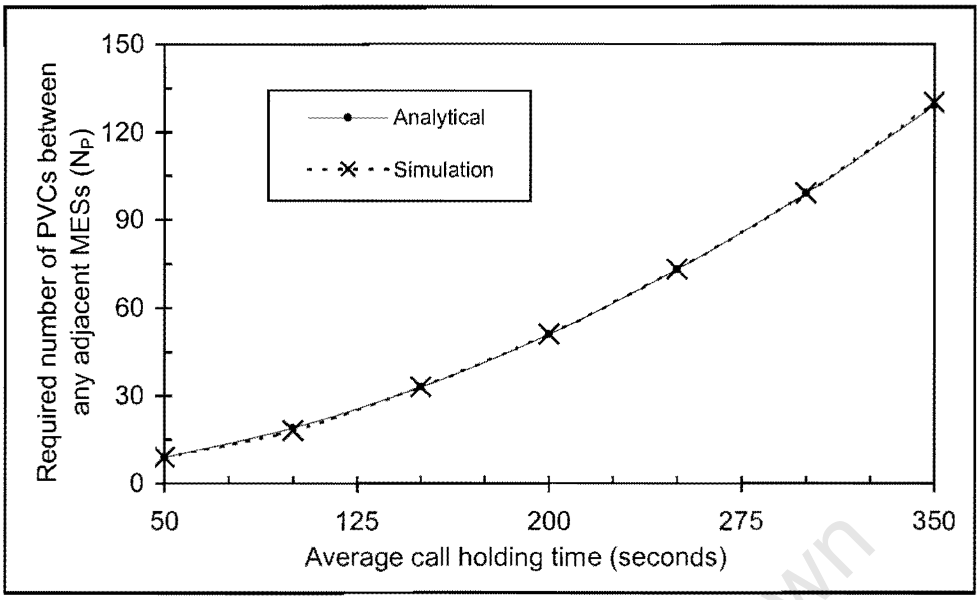

Figure 4.11: The required number of PVCs versus call holding time.

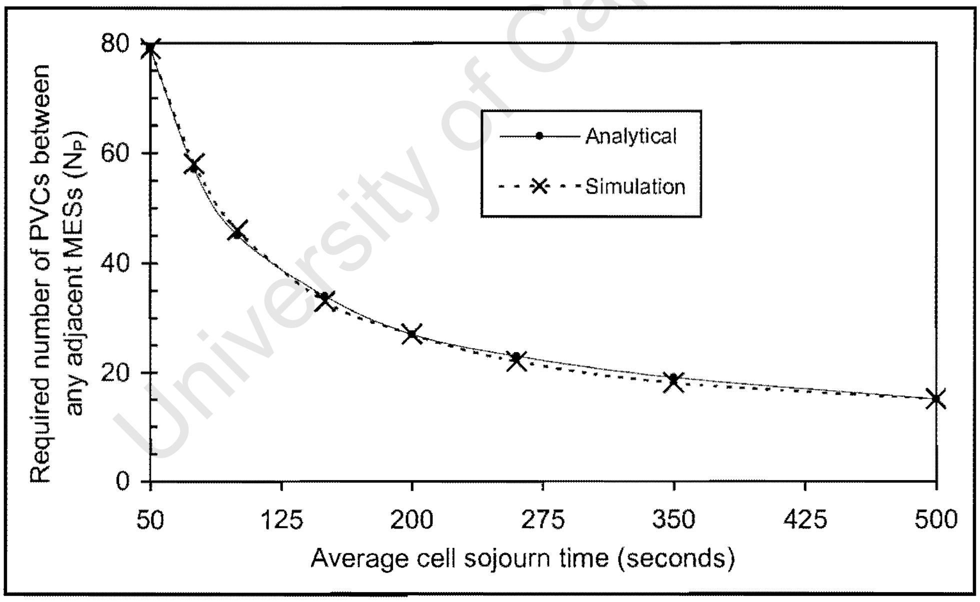

Figure 4.12: The required number of PVCs versus cell sojourn time.

4.5 Conclusions

In this chapter, we have examined a very fast handoff scheme based on extending the routes through MESs, using reserved PVCs between any adjacent MESs. Firstly, the scheme supports fast and simple handoff with minimum processing load and minimum handoff latency. Secondly, the inter-cluster re-routing scheme does not require a Call Admission Control (CAC). Thirdly, a path extension is supported by the MESs, thus requiring a high switching speed and enough buffers to guarantee a low cell loss rate during handoff. The performance of our proposal was evaluated by calculating the required number of PVCs between any adjacent MESs as a function of a number of system load parameters. These parameters include the mean originating call arrival rate, call holding time, and cell sojourn time. Finally, the analytical and simulation results indicate similar and comparable results.

Chapter 5

An Efficient Fast Two-Phase Optimization Scheme

A two-phase handoff protocol has been adopted to support the re-routing of the connection after inter-cluster handoff, employing rapid path extension for the first phase, followed by path optimization to establish the new connection in the second phase. As the extended path resulting from the first phase is longer than the original one, it is obvious that certain QoS requirements such as CTD and CDV may not be guaranteed after the first phase, depending largely on the routing time needed to establish a new connection in the second phase. In this chapter, we propose an efficient and fast re-routing scheme based on a two-phase optimization technique. The reserved PVCs are used in the first phase to minimize handoff latency. Upon completion of the first phase, the optimization process is *triggered instantly* and *concurrently* with other active optimization processes still in the execution phase. The main objective of our scheme is to minimize the route optimization delay such that the QoS disruption due to path extension is kept to a minimum. Both analytical and simulation models are presented to evaluate the required number of PVCs to support the first phase and to calculate the PVC connection holding time. Finally, a comparison of results is presented to compare the performance of this scheme with the scheme proposed in Chapter 4 and another two-phase optimization scheme proposed in the literature.

5.1 Description of The Route Optimization

With reference to Figures 3.1 and 3.2, the proposed scheme can be described as follows [94]:

First Phase:

To achieve low handoff latency, a rapid inter-cluster re-routing scheme with path extension, as detailed in Chapter 4, is used.

Second Phase:

After the completion of the inter-cluster handoff, the route optimization process is *instantly triggered* and executed by the new MES requesting an optimal path. The optimization process is initiated *concurrently* with the other optimization processes still in the execution phase.

The main objective of this operation is to minimize the route optimization delay so that the QoS disruption of the first phase (i.e. cell transfer delay and cell delay variation) is minimized. The optimization process involves path re-routing, where a portion of the connection is re-routed at the COS, creating only a new partial path between the COS and the new AP.

5.2 The Proposed Analytical System Model

This analytical model is an extension of the model referred to in Section 4.2. The following points need also to be considered in this model:

- All inter-cluster handoff connections require route optimization.
- The PVC holding time T_{OP} is defined as the duration from the time that PVC has been allocated to the time of its release.

If the MT moves across one of the cluster boundaries and has successful first phase handoff, i.e. a new PVC connection has been allocated. This PVC connection will remain established until it is released due to one of the following:
1) natural termination of the call; 2) forced termination of the call due to handoff blocking; 3) route optimization.

The following analysis is used to derive the average PVC holding time in order to calculate the number of PVCs between any adjacent MES required to support the inter-cluster handoff in the first phase. The PVC holding time indicates how fast the PVC connection is released in the second phase, and it has a proportional affect on the QoS disruption of those parameters that are time-sensitive.

The PVC holding time T_{OP} can be written as:

$$T_{OP} = \min(T_M, T_R, T_Z) \tag{5.1}$$

where:

- T_M : Call holding time.
- T_R : Total sojourn time.
- T_Z : The route optimization time. Let the mean optimization rate be (μ_Z) with arrival rate of an optimization request rate (λ_P). According to the proposed instant and concurrent optimization process, the optimization process is modeled as $M/M/m/m$ queuing system. There are 'm' concurrent optimization processes with no waiting rooms, so all the connections will be served instantly. Hence, $F_{T_Z}(t) = 1 - e^{-\mu_Z t}$ is the distribution of T_Z with mean $1/\mu_Z$. μ_Z is the optimization rate and is acting as an indicator of the signaling and processing load imposed on the fixed ATM network node elements as a result of initiating the route optimization.

The Laplace-Stieltjes Transform (LST) of T_R is given by:

$$T_R^*(s) = N[R^*(s)] \tag{5.2}$$

The generating function can be written as:

$$N[z] = \frac{zP_f}{1 - z(1 - P_f)} \tag{5.3}$$

The distribution of T_{OP} can be found as follows:

$$P(T_{OP} > t) \;\; = P[\min(T_M, T_R, T_Z) > t]$$

Where the random variables T_M , T_R and T_Z are independent.

$$= P[T_M > t, T_R > t, T_Z > t]$$

$$= P[T_M > t]P[T_R > t]P[T_Z > t]$$

Now,

$$\begin{aligned} F_{T_{OP}}(t) &= P[T_{OP} \le t] \\ &= 1 - P[T_{OP} > t] \\ &= 1 - P[T_M > t]P[T_R > t]P[T_Z > t] \\ &= 1 - [1 - P[T_M \le t]][1 - P[T_R \le t]][1 - P[T_Z \le t]] \\ &= 1 - [1 - F_{T_M}(t)][1 - F_{T_R}(t)][1 - F_{T_Z}(t)] \end{aligned}$$

$$\begin{aligned} F_{T_{OP}}(t) = F_{T_M}(t) + F_{T_Z}(t) + F_{T_R}(t) - F_{T_M}(t)F_{T_Z}(t) - F_{T_M}(t)F_{T_R}(t) - F_{T_Z}(t)F_{T_R}(t) \\ + F_{T_M}(t)F_{T_Z}(t)F_{T_R}(t) \end{aligned} \tag{5.4}$$

The distribution of T_{OP} is written as:

$$F_{T_{OP}}(t) = 1 - e^{-(\mu_M + \mu_Z)t} + F_{T_R}(t)e^{-(\mu_M + \mu_Z)t} \tag{5.5}$$

To obtain the mean of T_{OP}, we derive $T^*_{OP}(s)$, the LST of T_{OP}.

Let $f_{T_{OP}}(t)$ be the density function of T_{OP} and $f_{T_R}(t)$ be the density function of T_R.

We have:

$$
\begin{aligned}
f_{T_{OP}}(t) &= \frac{d}{dt} F_{T_{OP}}(t) \\
&= \frac{d}{dt}[1 - e^{-(\mu_M + \mu_Z)t} + F_{T_R}(t) e^{-(\mu_M + \mu_Z)t}] \\
&= (\mu_M + \mu_Z) e^{-(\mu_M + \mu_Z)t} - (\mu_M + \mu_Z) F_{T_R}(t)\, e^{-(\mu_M + \mu_Z)t} + f_{T_R}(t)\, e^{-(\mu_M + \mu_Z)t} \qquad (5.6)
\end{aligned}
$$

Now,

$$T^*_{OP}(s) = \int_0^\infty f_{T_{OP}}(t) e^{-st} dt$$

$$= (\mu_M + \mu_Z) \int_0^\infty e^{-(s+\mu_M+\mu_Z)t} dt - (\mu_M + \mu_Z) \int_0^\infty F_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t} dt + \int_0^\infty f_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t} dt \qquad (5.7)$$

Now, $\int_0^\infty F_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t} dt$ can be calculated using integration by parts.

With $u = F_{T_R}(t)$, $du = f_{T_R}(t)dt$ and $e^{-(s+\mu_M+\mu_Z)t} dt = dv$, $\dfrac{-e^{-(s+\mu_M+\mu_Z)t}}{s + \mu_M + \mu_Z} = v$

It follows that:

$$\int_0^\infty F_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t} dt = \left[\frac{-F_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t}}{s + \mu_M + \mu_Z}\right]_0^\infty + \frac{1}{s + \mu_M + \mu_Z} \int_0^\infty f_{T_R}(t) e^{-(s+\mu_M+\mu_Z)t} dt$$

Using Equation 5.2 we get:

$$\int_0^\infty F_{T_R}(t)e^{-(s+\mu_M+\mu_Z)t}dt = \frac{1}{s+\mu_M+\mu_Z}N[R^*(s+\mu_M+\mu_Z)] \tag{5.8}$$

From Equations 5.2, 5.7 and 5.8, we get

$$\overset{*}{T}_{OP}(s) = \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z} - \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z}N[R^*(s+\mu_M+\mu_Z)] + N[R^*(s+\mu_M+\mu_Z)]$$

$$= \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z} + \frac{s}{s+\mu_M+\mu_Z}N[R^*(s+\mu_M+\mu_Z)]$$

Using Equation 5.3, we get:

$$= \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z} + \frac{s}{s+\mu_M+\mu_Z}\,\frac{P_f[R^*(s+\mu_M+\mu_Z)]}{1-R^*(s+\mu_M+\mu_Z)[1-P_f]} \tag{5.9}$$

With the assumption that R is exponentially distributed, Equation 5.9 becomes:

$$= \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z} + \frac{s}{s+\mu_M+\mu_Z}\,\frac{P_f\dfrac{\mu_R}{s+\mu_R+\mu_M+\mu_Z}}{1-\dfrac{\mu_R}{s+\mu_R+\mu_M+\mu_Z}[1-P_f]}$$

It then follows that:

$$\overset{*}{T}_{OP}(s) = \frac{\mu_M+\mu_Z}{s+\mu_M+\mu_Z} + \frac{s}{s+\mu_M+\mu_Z}\,\frac{\mu_R P_f}{s+\mu_M+\mu_Z+\mu_R P_f} \tag{5.10}$$

Since,

$$\frac{d}{ds}\overset{*}{T}_{OP}(s) = -\frac{(\mu_M+\mu_Z)}{(s+\mu_M+\mu_Z)^2} + \frac{\mu_M+\mu_Z}{(s+\mu_M+\mu_Z)^2}\,\frac{P_f\mu_R}{(s+\mu_M+\mu_Z+\mu_R P_f)} + F(s)$$

(5.11)

Where $F(s)$ is a function of 's' with $F(0)=0$. The mean of T_{OP}, $E(T_{OP})$ is given by:

$$E[T_{OP}] = -\frac{d}{ds}\overset{*}{T}_{OP}(s)\Big|_{s=0}$$

$$= \frac{1}{\mu_M + \mu_Z + \mu_R P_f} \tag{5.12}$$

Where $E[T_{OP}]$ is the average PVC holding time and will be largely sensitive to the mean optimization time $(1/\mu_Z)$. $(1/\mu_Z)$ is usually considered to be very small compared to the call holding time and cell sojourn time.

Using the Erlang-B formula, the handoff blocking probability due to lack of PVCs between MESs is obtained as:

$$P_f = \frac{\dfrac{[\lambda_P E(T_{OP})]^{N_{OP}}}{N_{OP}!}}{\displaystyle\sum_{n=0}^{N_{OP}} \frac{[\lambda_P E(T_{OP})]^n}{n!}} \tag{5.13}$$

Where N_{OP} is considered as the number of active optimization processes or the number of PVCs reserved between any adjacent MESs.

5.3 Simulation Model

In this section, the analytical model results are evaluated against those obtained by simulation. The simulation detailed in Section 4.3 is now extended to include the route optimization time T_Z, which is assumed to be exponentially distributed. This is generated using the formula $(-1/\mu_Z)\ln(U)$, where $1/\mu_Z$ is the mean of the optimization time. Although not implemented, the simulation model could easily be extended to accept different distributions for the optimization time.

A simulation flow chart is presented in Figure 5.1. In the simulation, a user connection will remain assigned to the PVC until the connection is released. Each PVC connection has a *PVC_Expiration_Time* state variable, which reflects the expiration and releasing of the PVC connection.

The PVC expiration can happen due to one of the following reasons:

1- Natural termination of the call (i.e. $T_M = 0$).

2- Termination of the call due to handoff blocking (i.e. $T_R = 0$).

3- Optimization of the connection (i.e. $T_Z = 0$).

The aim of this simulation program is to calculate both the PVC bandwidth (*PVC_BW*) and the average PVC holding (*Avg_PVC_Holding_Time*), both of which are considered respectively to be as N_{OP} (i.e. refer to Equation 5.13), and $E(T_{OP})$ (i.e. refer to Equation 5.12) in the analytical derivation.

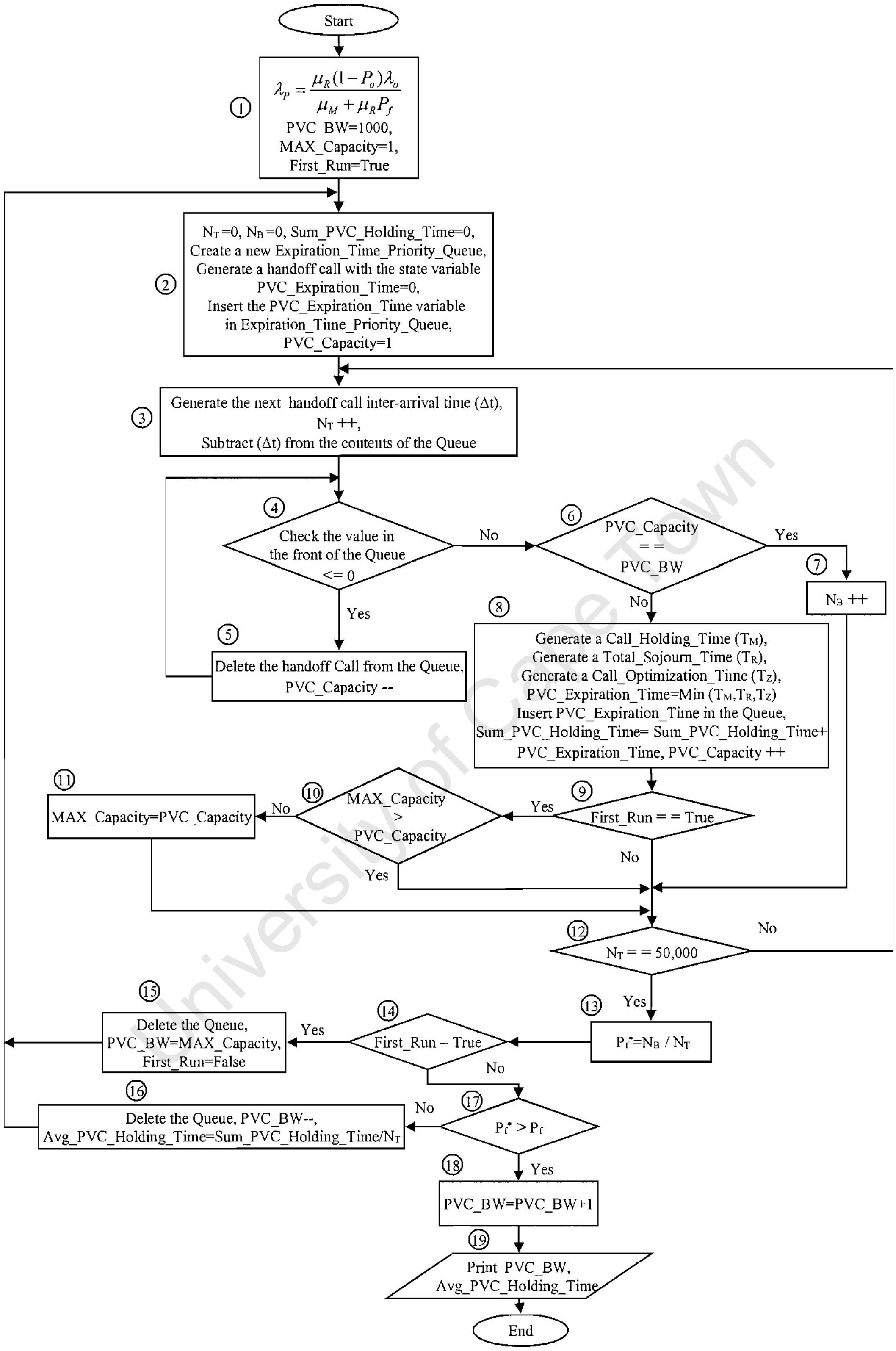

Figure 5.1: The simulation flow chart for the PVC two-phase optimization scheme.

5.4 Performance Results

In this section, we study the performance of our proposed new two-phase handoff scheme by considering some numerical results for both the analytical and simulation models. Appendices A.2, and B.2 contain the source code for the analytical and simulation models.

In these examples, the following are assumed: the new call arrival rate is 1.0 calls/sec, originating calls are blocked with probability 0.01, the handoff blocking probability is 0.001, the average cell sojourn time is 2 minutes and the average call holding time is 4 minutes, and the number of rings is 2. The mean route optimization times ($1/\mu_Z$) are chosen to be 2, 5, and 10 seconds.

Figures 5.2, 5.3, and 5.4 show the required number of PVCs reserved between any adjacent MESs versus the originating call arrival rate, call holding time, and cell sojourn time. It can be seen from the figures that as optimization time decreases the required number of PVCs decreases; this is because the PVC holding time becomes smaller due to optimization re-routing. Also, the figures show similar results between the analytical and simulation models.

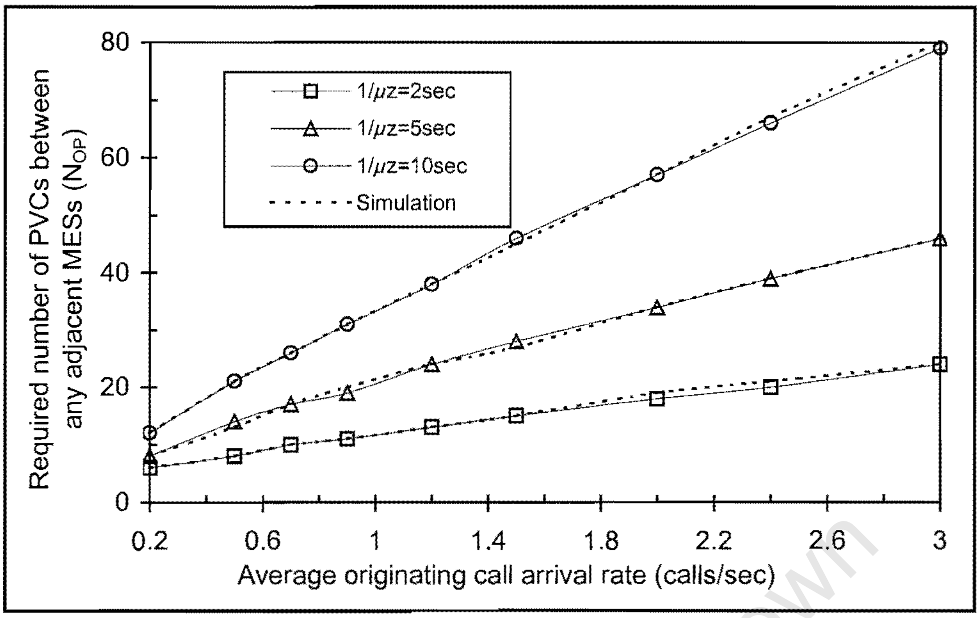

Figure 5.2: The required number of PVCs versus originating call arrival rate.

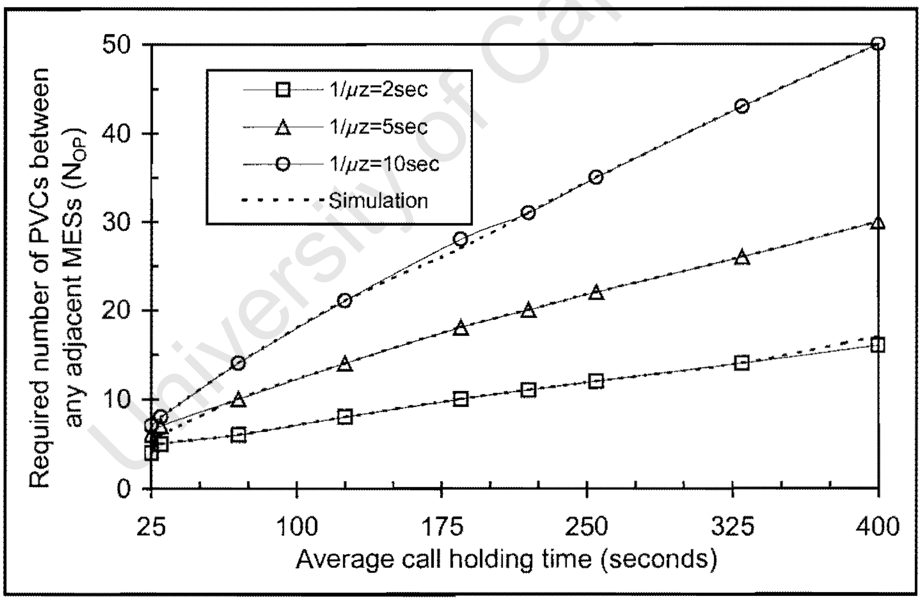

Figure 5.3: The required number of PVCs versus call holding time.

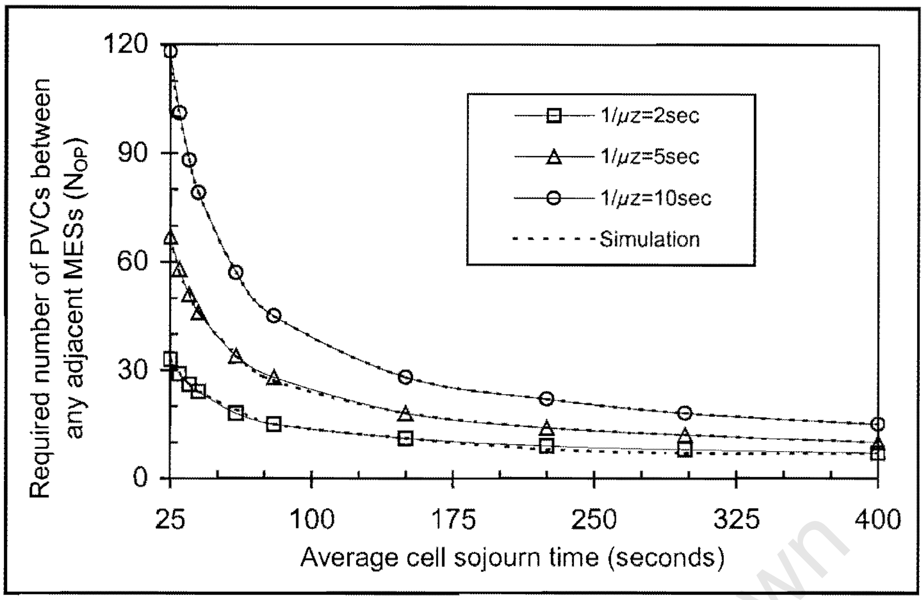

Figure 5.4: The required number of PVCs versus cell sojourn time.

5.5 Comparison of Results and Discussion

In this section, we present a comparison of results between our new two-phase optimization scheme and another two handoff schemes; the first scheme is the handoff using the path extension, explained in Chapter 4, and the second scheme is a two-phase optimization scheme proposed in the literature [77], which used only one single optimization process and allows only one optimization request to be processed at a time.

In the scheme proposed by [77], the WATM network architecture is different from our proposal. The MESs are connected to the WATM network and the optimization process is done through the WATM network instead of the fixed ATM network as we have proposed. Also, in [77] the reserved Handoff Permanent Virtual Path (HO PVP) is used to connect between adjacent MESs in the WATM network.

For simplicity, we use the term PVC to refer to the number of reserved channels between MESs for all the handoff schemes.

The comparison of results are made in terms of the number of reserved PVCs between adjacent MESs to support the handoff in the first phase and the PVC holding time that affects QoS parameters sensitive to time.

In the numerical examples, we assume a mean residual time of 4 minutes, and a mean call holding time of 2 minutes. Originating calls are assumed to be blocked with probability of 0.01, while handoff blocking probability is assumed to be 0.001. Mean route optimization time is assumed to be 2 seconds. The number of rings is assumed to be 2.

We first study the required number of PVCs to support the handoff as a function of the originating call arrival rate. Figure 5.5 shows the required number of PVCs versus the call arrival rate for the different handoff schemes. It can be seen from the figure that in our new two-phase optimization scheme, the number of PVCs increases very slowly with the increase of the arrival rate. We can also see that, in scheme [77], the number of PVCs increases dramatically as ($\lambda_o > 0.8$) and the system becomes unstable when $\lambda_o > 1.0$, which means that this scheme is not suitable when a heavy load is applied to the system.

We next study the PVC holding time for all the handoff schemes. Figure 5.6 shows the comparison of results in terms of PVC holding time as a function of the call arrival rate. We see from the figure that our scheme has a very low PVC holding time compared to the other two schemes, ensuring the QoS requirements for those multimedia applications that are time sensitive. As mention before, scheme [77] becomes unstable for heavy load, which leads to large increasing in the PVC holding time.

We conclude that our scheme requires fewer PVCs, and less PVC holding time, showing a very significant improvement, and ensuring the QoS requirements for the multimedia applications that are time sensitive. On the other hand our system results in more signaling and processing load needs for the optimization process, compared to the other schemes. The path extension scheme is very simple and did not need any optimization processing that results an extra signaling load.

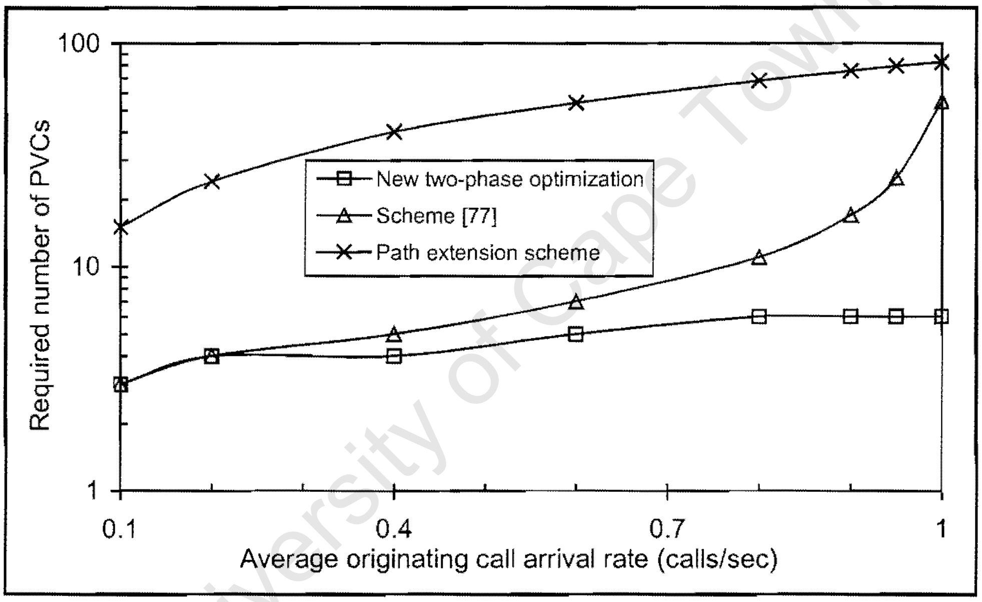

Figure 5.5: Comparison of results in terms of number of PVCs.

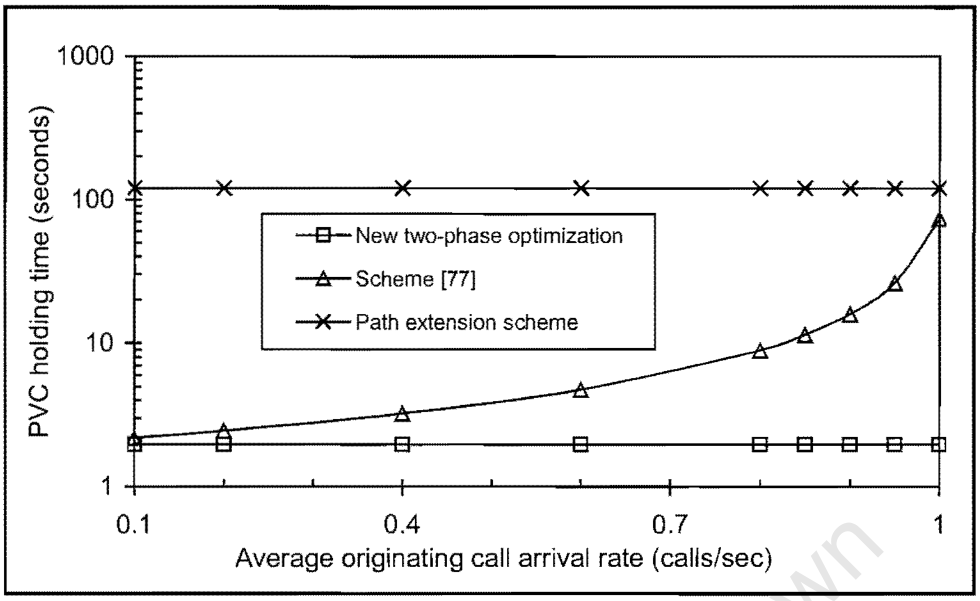

Figure 5.6: Comparison of results in terms of PVC holding time.

5.6 Conclusions

In this chapter we have examined a new re-routing handoff scheme based on a two-phase optimization technique. We propose using reserved PVCs between adjacent MESs in the first phase to avoid the inter-cluster handoff latency, and for the second phase, the optimization process is *triggered instantly* and *concurrently* with the other optimization processes so that multiple optimization processes are in effect active at the same time. The main objectives in our scheme are to save wired link resources in the first phase and to minimize the route optimization delay in the second phase so that the disruption of QoS parameters that are sensitive to the time constraint will be kept to a minimum. The performance of our proposal was evaluated using both analytical and simulation models in terms of wired link resources and PVC holding time. Although both the analytical and simulation results are same, they showed a very significant improvement when the results were compared to other handoff schemes described in Chapter 4, and against those proposed in [77].

Chapter 6

Performance Evaluation of a New Fast Inter-Cluster Handoff Scheme in Wireless ATM Networks

One of the major challenges in mobile WATM networks is to support high-speed ATM services like real time multimedia applications with stringent QoS requirements. To support these broadband applications with mobile services, the WATM networks must cater for the re-routing of the connections during inter-cluster handoff so as to yield path optimization of new routes. In existing handoff techniques, a two-phase handoff protocol has been proposed: path extension followed by the path optimization of the new connection. These current handoff techniques result in large signaling and processing overheads causing both handoff latency and possible QoS disruption due to both path extension and optimization. We are now proposing a new inter-cluster handoff technique for real time applications based on the sharing of information at the cluster boundaries so that intra-cluster handoff is invoked, followed by path optimization. Both analytical and simulation models are presented to evaluate the performance in terms of wired link resources, PVC holding time, and the inter-cluster handoff processing overhead. Finally, this chapter ends with a comparison of results with the other handoff scheme proposed in Chapter 5.

6.1 Network Architecture

Figure 6.1 describes the system architecture for the proposed WATM network. In this model we adopt both the architecture proposed by [86] and the idea of shared cells [95]. There are direct physical links between any two immediate adjacent MESs. The purpose of these direct links is to further facilitate seamless handoffs. In order to provide a mobile user with migration transparency and multimedia services, we introduce the idea of shared cells between MESs. From the figure, the cells C1, C2, C3, and C4 are shared cells between MES1 and MES2. The PVCs between any MES and the shared cells are used to facilitate the MTs' migration at the cluster boundaries.

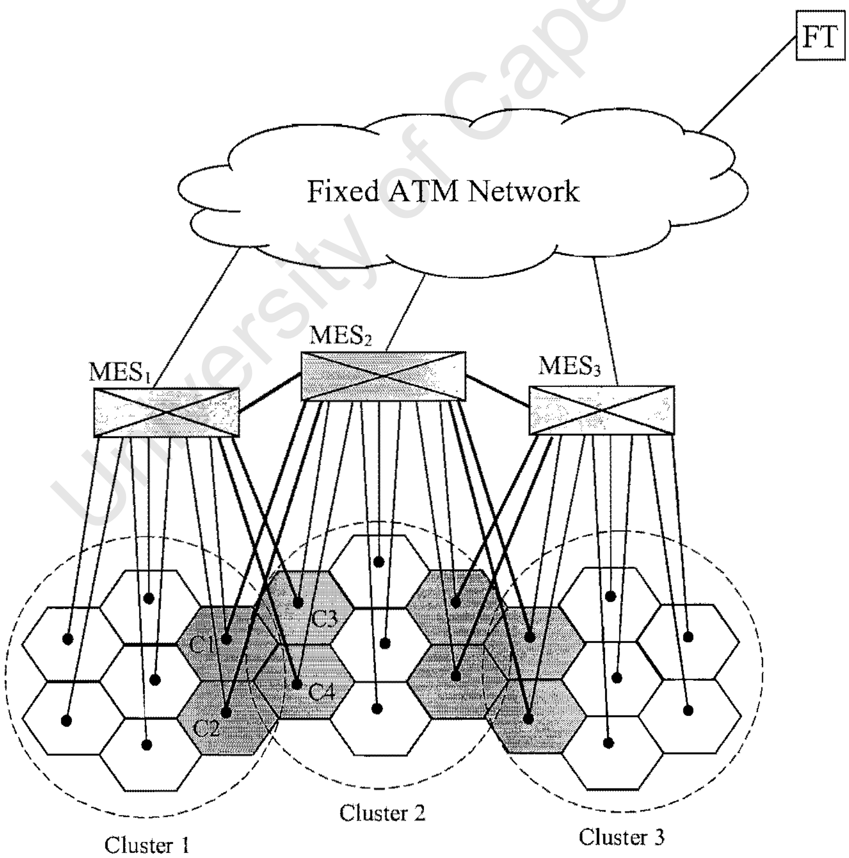

Figure 6.1: The proposed WATM network.

6.2 Description of The Proposed Scheme

From Figure 6.1, clusters 1, 2, and 3 are connected to MES1, MES2, and MES3 respectively. If a MT moves to an adjacent cell connected to the same MES (i.e. within the same cluster), then an intra-cluster handoff occurs; the resulting route is optimal because the new AP is connected directly to the same switch. In this case, only SVCs are needed between the APs and the MES. If a MT roams to an adjacent cell connected to another MES (e.g. from C1 located at cluster 1 to C3 located at cluster 2), and since C3 is beyond the MES1 domain, re-routing of the communication path is required. Thus the processing of conventional inter-cluster handoff is longer than that of the intra-cluster handoff. In our proposed scheme the inter-cluster handoff is in effect replaced with an intra-cluster handoff at the inter cluster boundaries.

In this case, an intra-cluster handoff will occur at the shared cell C3, and the PVCs between MES1 and C3 are used to support and facilitate the intra-cluster handoff through MES1. At the same time, the optimization process is initiated in the shared cell C3 in order to optimize the connection through MES2 (this is called the *intra-path-optimization* process). An intra-cluster handoff is applied when migrating between any cells followed by an optimization at the shared cells. If the optimization process is still in progress while a MT moves out of the shared cell C3 to another cell at cluster 2, then the intra-path-optimization will be blocked and a path extension between MES1 and MES2 is used; in such a case, an inter-cluster handoff occurs, and using reserved PVCs between MES1 and MES2, the path will be extended from the old MES (MES1) to the new MES (MES2); also the path optimization process is re-initiated in order to optimize the new extended connection (this is called the *inter-path-optimization* process).

The main objective of this scheme is to have a minimum number of inter-path-optimization processes, in order to have fast handoff and to guarantee QoS (i.e. cell transfer delay and cell delay variation) [96-98].

6.3 The Proposed Analytical System Model

In this section, a performance study using an analytical model of two important parameters of our new scheme is presented. The first parameter is the required bandwidth (number of PVCs) to support and facilitate the connections during handoff. The second parameter is inter-cluster handoff processing load due to the signaling and processing load imposed at the MESs (as a result of the *inter-path optimization* process).

6.3.1 PVC Analysis

In this section, we will derive analytically the number of PVCs to support this new handoff scheme.

6.3.1.1 PVC Analysis Between MESs and Shared Cells

Here, we derive the number of PVCs required to support the intra-cluster handoff at the cluster boundaries. The handoff rate across any cell boundary, contributed by one cell, is $\lambda_h / 6$. As shown from Figures 6.1 and 6.2, in the case of cluster size of two rings, there are three cell boundaries contributing to the total inter-cluster handoff. The movement of a MT from C1 to C3 across the cluster boundary introduces a handoff arrival rate $\lambda_{n_1} = \lambda_h / 6$. And the movement of MTs from C1 to C4, and C2 to C4 introduce a handoff arrival rate $\lambda_{n_2} = 2.\lambda_h / 6 = \lambda_h / 3$. Therefore, the total inter-cluster handoff arrival rate introduced by the movement of MTs from cluster 1 to cluster 2 is $\lambda_{n_1} + \lambda_{n_2} = \lambda_h / 2$. In our example, n_1 is the number of reserved PVCs between MES1 and C3 or between MES2 and C2; and n_2 is the number of reserved PVCs between MES1 and C4 or between MES2 and C1. In our model we will consider only two rings.

When a MT enters a shared cell at a new cluster, the PVC connections are occupied at the cluster boundary to support fast intra-cluster handoff.

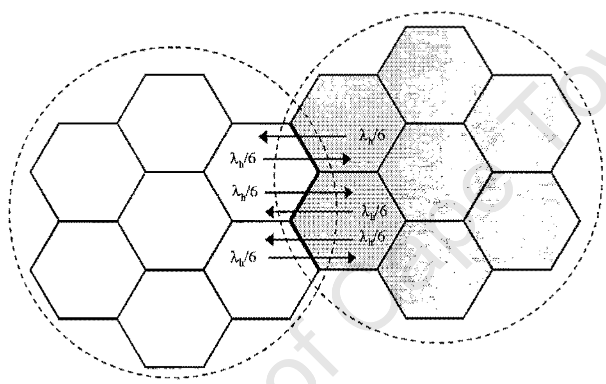

Figure 6.2: Handoff rates across cluster boundaries.

This PVC allocation can be released due to one of the following: 1) natural termination of the call; 2) movement of a MT outside a shared cell before the route optimized is completed; 3) route optimization.

The PVC holding time T_{PI} can be written as:

$$T_{PI} = \min(T_M, T_{R1}, T_{ZI}) \quad (6.1)$$

Where:

- T_M : Call holding time.

- T_{R1}: The total sojourn time of one cell, i.e. $T_{R1} = R$, as all the routes in a new shared cell must be re-established (optimized or extended), so the value of $N = 1$.
- T_{ZI}: The route optimization time (i.e. *intra-path-optimization*), which is assumed to be an exponential distribution with mean $1/\mu_{ZI}$. Hence, $F_{T_{ZI}}(t) = 1 - e^{-\mu_{ZI}t}$ is the distribution of T_{ZI}.

The Laplace-Stieltjes Transform (LST) of T_{R1} is given by:

$$T_{R1}^{*}(s) = R^{*}(s) \tag{6.2}$$

The distribution of T_{PZ} can be written as:

$$F_{T_{PI}}(t) = F_{T_M}(t) + F_{T_{ZI}}(t) + F_{T_{R1}}(t) - F_{T_M}(t)F_{T_{ZI}}(t) - F_{T_M}(t)F_{T_{R1}}(t) - F_{T_{ZI}}(t)F_{T_{R1}}(t) + F_{T_M}(t)F_{T_{ZI}}(t)F_{T_{R1}}(t) \tag{6.3}$$

The distribution of T_{PI} is written as:

$$F_{T_{PI}}(t) = 1 - e^{-(\mu_M + \mu_{ZI})t} + F_{T_{R1}}(t)e^{-(\mu_M + \mu_{ZI})t} \tag{6.4}$$

To obtain the mean of T_{PI}, we derive $T_{PI}^{*}(s)$ the LST of T_{PI}

$$\begin{aligned} T_{PI}^{*}(s) &= \frac{\mu_M + \mu_{ZI}}{s + \mu_M + \mu_{ZI}} - \frac{\mu_M + \mu_{ZI}}{s + \mu_M + \mu_{ZI}} R^{*}(s + \mu_M + \mu_{ZI}) + R^{*}(s + \mu_M + \mu_{ZI}) \\ &= \frac{\mu_M + \mu_{ZI}}{s + \mu_M + \mu_{ZI}} + \frac{s}{s + \mu_M + \mu_{ZI}} R^{*}(s + \mu_M + \mu_{ZI}) \end{aligned} \tag{6.5}$$

With the assumption that R is exponentially distributed with mean $1/\mu_R$, we have

$$R^*(s) = \frac{\mu_R}{s + \mu_R}$$

$$T_{PI}^*(s) = \frac{\mu_M + \mu_{ZI}}{s + \mu_M + \mu_{ZI}} + \frac{s}{s + \mu_M + \mu_{ZI}} \frac{\mu_R}{s + \mu_R + \mu_M + \mu_{ZI}} \tag{6.6}$$

Since

$$\frac{d}{ds} T_{PI}^*(s) = -\frac{(\mu_M + \mu_{ZI})}{(s + \mu_M + \mu_{ZI})^2} + \frac{\mu_R}{s + \mu_R + \mu_M + \mu_{ZI}} \frac{\mu_M + \mu_{ZI}}{(s + \mu_M + \mu_{ZI})^2} + F(s) \tag{6.7}$$

Where $F(s)$ is a function of 's' with $F(0) = 0$, the mean of T_{PI}, $E(T_{PI})$, is given by:

$$E[T_{PI}] = -\frac{d}{ds} T_{PI}^*(s)\Big|_{s=0}$$

$$= \frac{1}{\mu_R + \mu_M + \mu_{ZI}} \tag{6.8}$$

The handoff blocking probability due to the lack of PVCs between any MES and shared cells at the cluster-boundaries can be expressed using the Erlang-B formula:

$$P_f = \frac{\dfrac{[\lambda_{n_1} E(T_{PI})]^{n_1}}{n_1!}}{\sum_{n=0}^{n_1} \dfrac{[\lambda_{n_1} E(T_{PI})]^n}{n!}} \quad \text{and} \quad P_f = \frac{\dfrac{[\lambda_{n_2} E(T_{PI})]^{n_2}}{n_2!}}{\sum_{n=0}^{n_2} \dfrac{[\lambda_{n_2} E(T_{PI})]^n}{n!}} \tag{6.9}$$

$N_{PI} = n_1 + n_2$, denotes the total number of PVCs reserved between any MES and any shared cells.

6.3.1.2 PVC Analysis of The Adjacent MESs

In this section, we will analysis the bandwidth between any adjacent MESs to support the inter-cluster handoff. In Section 6.3.1.1, some connections will be blocked from the optimization service, as some MTs will move out from the shared cells before the connections are optimized. We can calculate the optimization blocking probability (P_{OB}) as follows:

$$P_{OB} = \frac{\mu_R}{\mu_M + \mu_R + \mu_{ZI}} \tag{6.10}$$

All the connections, which are blocked from the optimization service, are extended through the MESs. So the total number of handoff arrival requests between any two MESs that need path extension is given by:

$$\lambda_{PE} = \lambda_h P_{OB}(1 - P_f) \tag{6.11}$$

To calculate the number of PVCs connecting between any two adjacent MESs, we follow similar steps as per section 6.3.1.1. The PVC allocation can be released due to one of the following: 1) natural termination of the call; 2) forced termination of the call due to the handoff blocking when it moves to another cell; 3) route optimization.

The PVC holding time T_{PE} can be calculated as follows:

$$T_{PE} = \min(T_M, T_R, T_{ZE}) \tag{6.12}$$

Where:

- T_M : Call holding time.
- T_R : Total sojourn time.

- T_{ZE} : The route optimization time (i.e. *inter-path-optimization*), which is assumed to be an exponential distribution with mean $1/\mu_{ZE}$. Hence, $F_{T_{ZE}(t)} = 1 - e^{-\mu_{ZE}t}$ is the distribution of T_{ZE}.

The generating function can be written as:

$$N[z] = \frac{zP_f}{1 - z(1 - P_f)} \tag{6.13}$$

So the mean of T_{PE} is given by:

$$E[T_{PE}] = \frac{1}{\mu_M + \mu_{ZE} + \mu_R P_f} \tag{6.14}$$

The handoff blocking probability due to the lack of PVCs between MESs is obtained as:

$$P_f = \frac{\dfrac{[\lambda_{PE} E(T_{PE})]^{N_{PE}}}{N_{P_E}!}}{\sum_{n=0}^{N_{PE}} \dfrac{[\lambda_{PE} E(T_{PE})]^n}{n!}} \tag{6.15}$$

Where N_{PE}, the number of PVCs reserved between adjacent MESs.

6.3.2 Inter-Cluster Handoff Processing Load Analysis

In this section, we calculate the inter-cluster handoff processing load, P_L, of this new handoff scheme, defined as follows:

$$P_L = \frac{\textit{Number of handoffs requiring path extension}}{\textit{Total number of handoffs}} \tag{6.16}$$

Using Equations 6.11 and 6.16 we get:

$$P_L = (1 - P_f)P_{OB} \approx P_{OB} \tag{6.17}$$

Our objective is to have minimum values of P_L. For a specific design value, r, the inter-cluster handoff processing load can be minimized by decreasing the optimization blocking probability, P_{OB}, which implies lowering the optimization time.

6.4 Simulation Analysis

In the simulation model, the handoff arrival rates form a Poisson process with mean arrival rates of (λ_{n_1} or λ_{n_2}). The handoff inter-arrival time is exponentially distributed with mean inter-arrival times ($1/\lambda_{n_1}$ or $1/\lambda_{n_2}$). The call holding time T_M is exponentially distributed with mean $1/\mu_M$. The cell sojourn time (R) is exponentially distributed with mean $1/\mu_R$. The route optimization times (T_{ZI} or T_{ZE}) are exponentially distributed with means ($1/\mu_{ZI}$ or $1/\mu_{ZE}$). The exponential distribution is generated using an exponential distribution random number generator. The total sojourn time (T_R) of a user connection is the total sojourn time of N cells that a MT visits before the handoff is blocked. N is a random variable with a geometric distribution, generated using a geometric distribution random number generator.

6.4.1 Simulation Analysis for the PVC Reservation Between any MES and the Shared Cells

A flow chart is presented in Figure 6.3. In our simulation, a user connection will remain assigned to the PVC until the connection is expired. Each user connection has a *PVC_Expiration_Time* state variable, which reflects the expiration and releasing of the PVC connection. The PVC connection expires due to one of the following reasons:

1- The call is naturally terminated (i.e. $T_M = 0$).

2- Releasing of the connection due to the migration of a MT outside the cell before ending the route optimization (i.e. $T_{R1} = 0$).

3- Intra-path optimization (i.e. $T_{ZI} = 0$).

The simulation program is used to calculate the simulation value of the PVC bandwidth, which is considered to be as N_{PI} in the analytical model (i.e. refer to Equation 6.9).

We run the simulation program twice; the first time, to calculate the simulation value *PVC_BW* that is considered to be n_1 with arrival rate of λ_{n_1} (in step 1); the second time to calculate the simulation value *PVC_BW* that is considered to be n_2 with arrival rate of λ_{n_2} (in step 1). Now the simulation value of N_{PI} can be evaluated by adding both the simulation values: $n_1 + n_2$

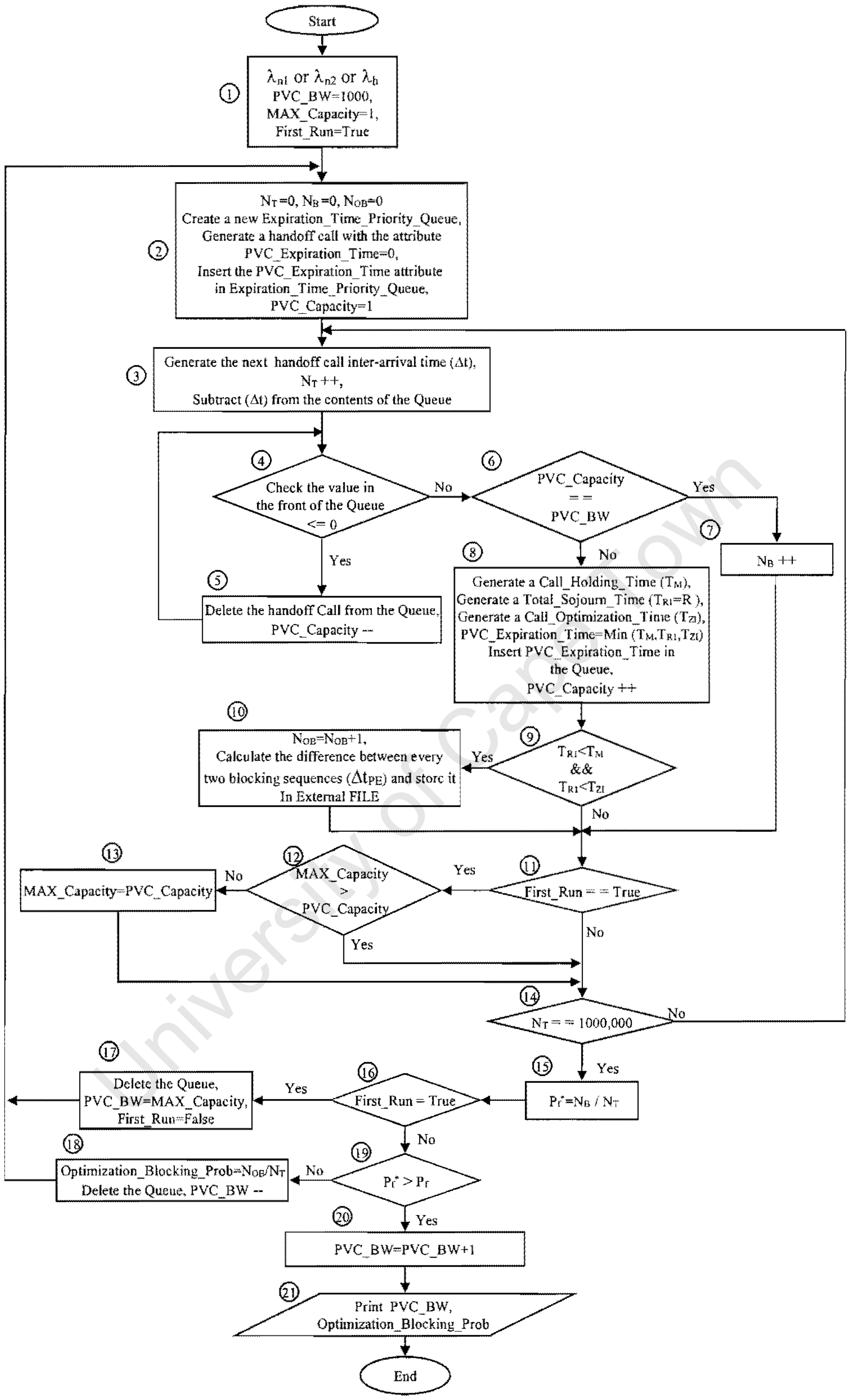

Figure 6.3: The simulation flow chart for the PVC intra-path-optimization scheme.

6.4.2 Simulation Analysis for The Inter-cluster Handoff Processing Load

The inter-cluster handoff processing load can be evaluated using the flow chart has already illustrated in Figure 6.3. Firstly, the simulation program with handoff arrival rate of λ_h (in step 1) is executed. Then the counter for the optimization blocking (i.e. $N_{OB} = 0$ in step 2) is initialized.

The optimization process is blocked if the condition in step (9) is true; that means the MT moves to an adjacent shared cell before the connection is optimized and before the termination of the call. The optimization blocking counter is then incremented (step 10) and the handoff inter-arrival time Δt_{PE} is calculated and saved in external FILE. Δt_{PE} represents the handoff inter-arrival time for the connections requiring the path extension. Finally, the simulation optimization blocking probability (*Optimization_Blocking_prob*) is calculated in step (18) resulting in the simulation value of P_{OB} (i.e. refer to Equation 6.10).

6.4.3 Simulation Analysis for The PVC Reservation Between Adjacent MESs

A flow chart is presented in Figure 6.4. In our simulation, the PVC connection expires due to one of the following reasons:

1- Natural termination of the call (i.e. $T_M = 0$).

2- Releasing due to migration outside the cell before optimization (i.e. $T_R = 0$).

3- Inter-path optimization (i.e. $T_{ZE} = 0$).

The simulation program calculates the value of *PVC_BW*, considered to be the simulation value of N_{PE} (i.e. refer to Equation 6.15). The simulation program already described in Figure 6.3 was used to generate a handoff inter-arrival rate (Δt_{PE}) and saved to an external FILE.

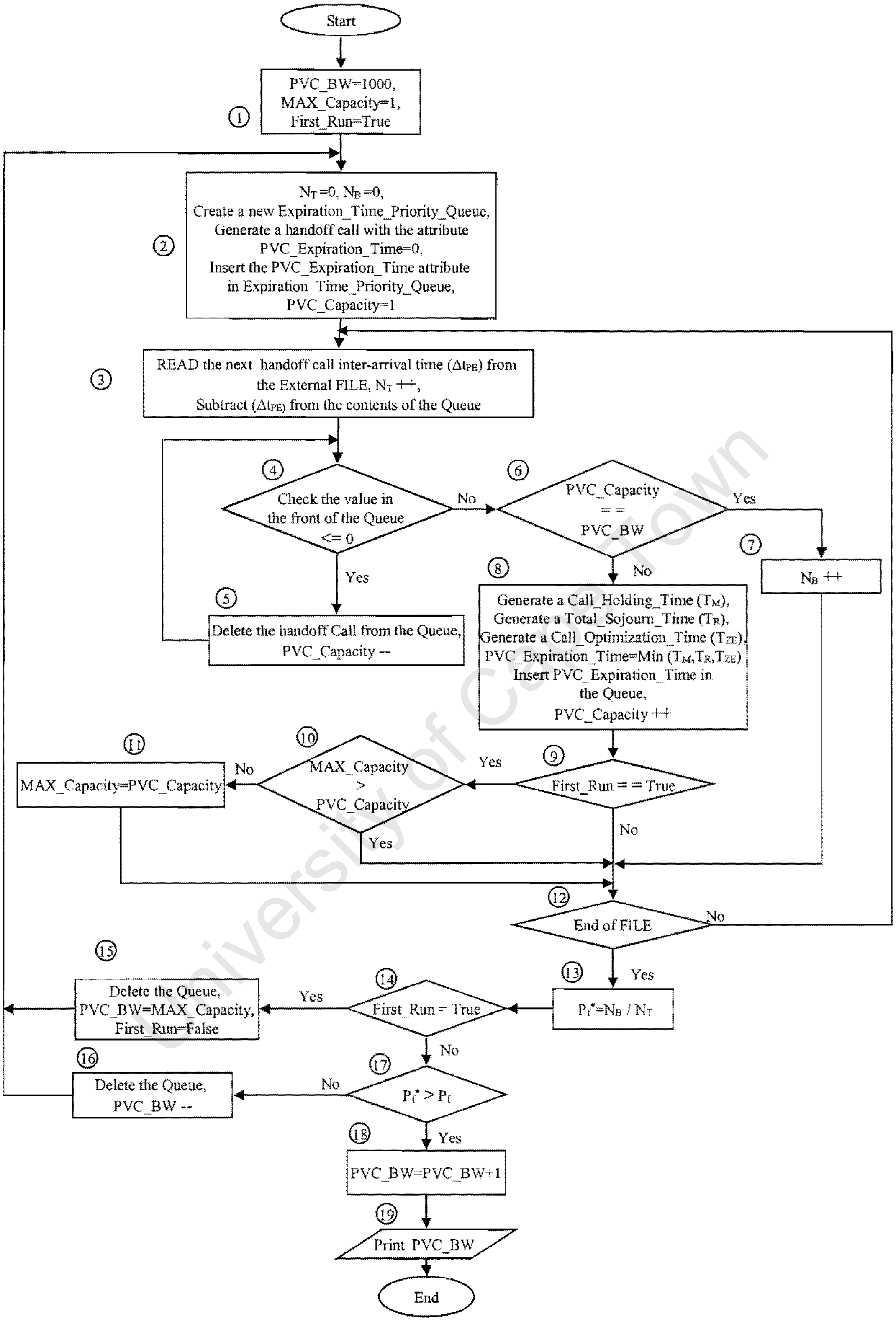

Figure 6.4: The simulation flow chart for the PVC inter-path-optimization scheme.

6.5 Performance Results

In this section, we study the performance of our proposed handoff scheme by considering some numerical results for both the analytical and simulation models. Appendices A.3, A.4, B.3, and B.4 contain the source code for the analytical and simulation models. We assume that the originating calls are blocked with probability 0.01, the handoff blocking probability assumed to be 0.001, average call holding time to be 4 minutes, the average cell sojourn time as 2 minutes, the originating call arrival rate as 2 calls/sec, and the number of rings as 2.

6.5.1 Performance Results of the PVC Analysis Between MESs and Shared Cells

In this section, the mean route optimization times ($1/\mu_{Zl}$) are chosen to be 2 and 10 seconds. We see from Figures 6.5, 6.6, and 6.7 that the number of PVCs between any MES and any adjacent shared cells can be minimized by decreasing the optimization time ($1/\mu_{Zl}$).

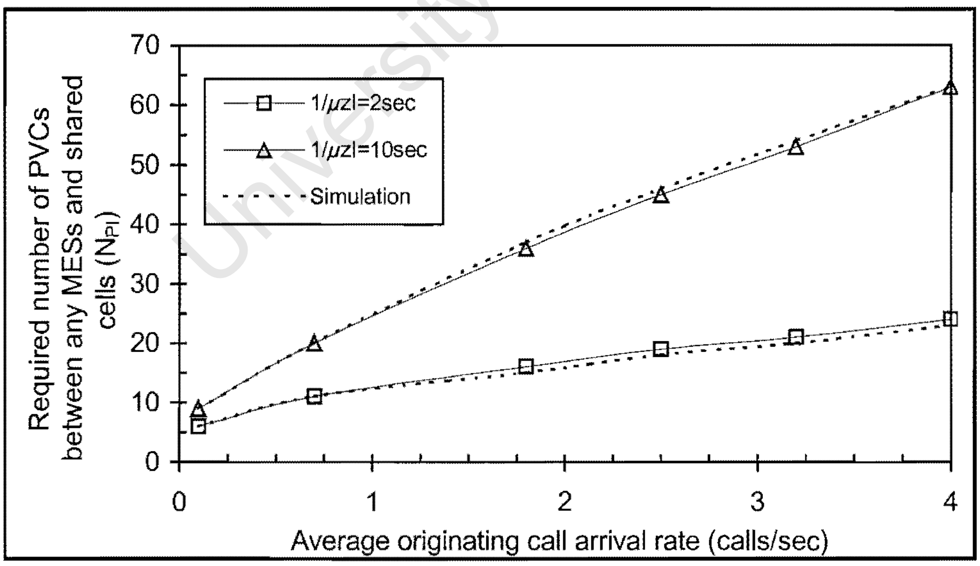

Figure 6.5: The required number of PVCs reserved between any MES and adjacent shared cells versus originating call arrival rate.

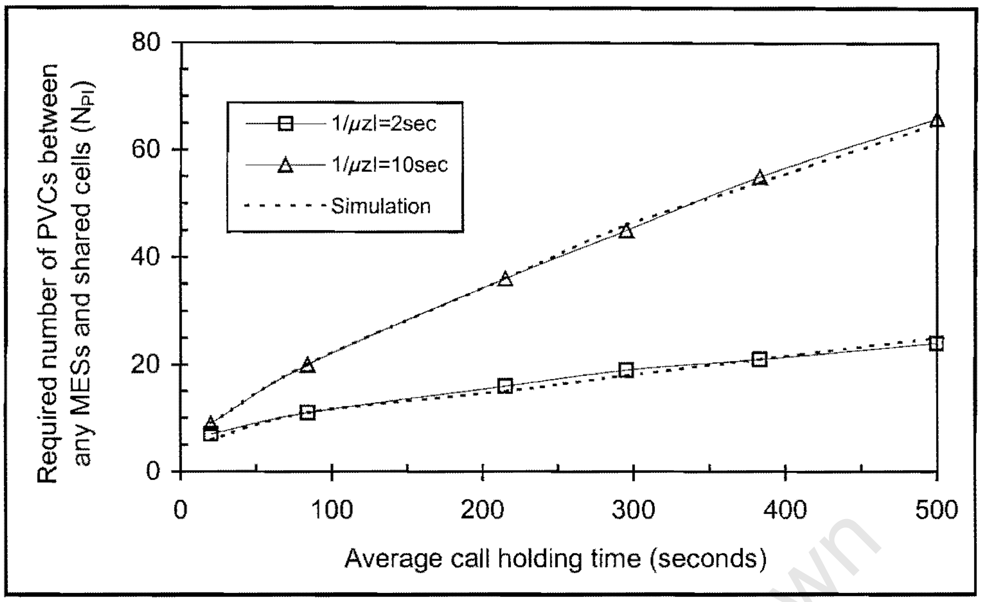

Figure 6.6: The required number of PVCs reserved between any MES and adjacent shared cells versus call holding time.

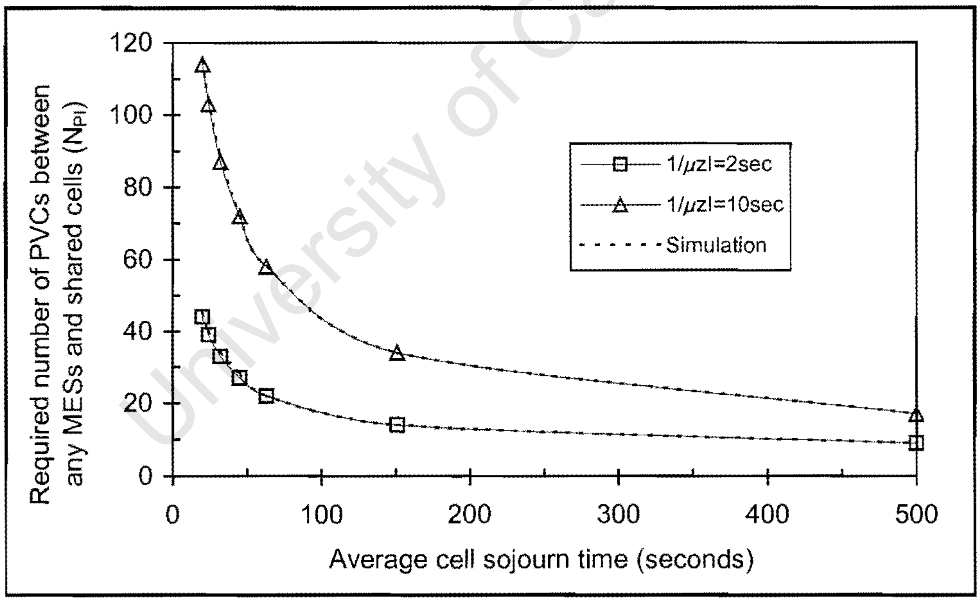

Figure 6.7: The required number of PVCs reserved between any MES and adjacent shared cells versus cell sojourn time.

6.5.2 Performance Results of the Inter-cluster Handoff Processing Load

In this section, the mean route optimization times ($1/\mu_{ZI}$) are chosen to be 2 and 10 seconds. We can see from Figures 6.8, 6.9, and 6.10 that the inter-cluster handoff processing load can be minimized by decreasing the mean optimization time. Furthermore, Figure 6.8 shows the processing load is completely independent of the system load, which ensures the reliability and stability of our proposed scheme.

From Figure 6.9 it can be seen that for higher values of call holding time the inter-cluster handoff processing load becomes independent of call holding time; this is because for long calls most of the connections will be optimized or moved out from the current cluster to an adjacent cluster.

From Figure 6.10, it can be seen that the processing load can be minimized by increasing the cell size so that most of the calls will be naturally terminated or optimized.

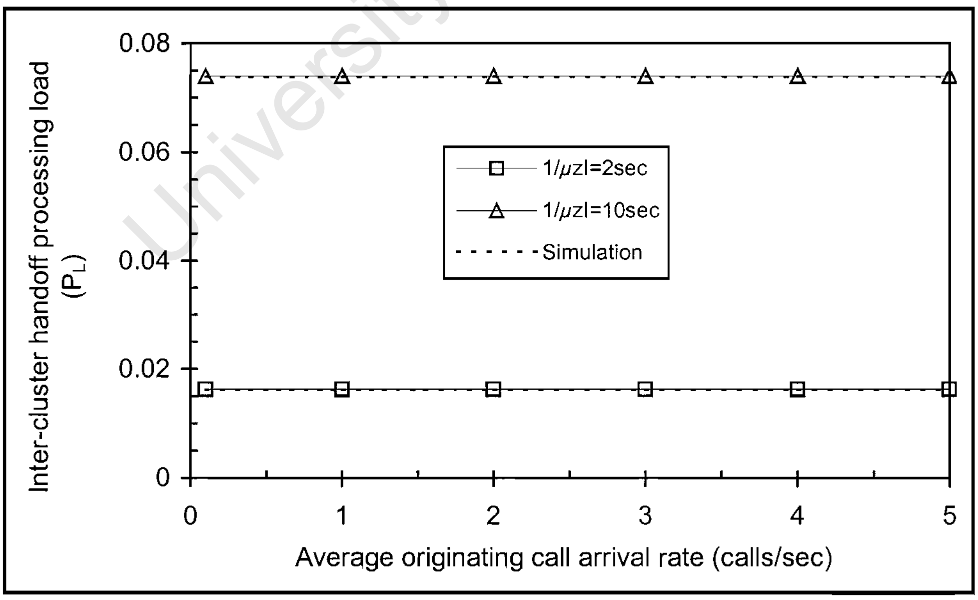

Figure 6.8: Inter-cluster handoff processing load versus originating call arrival rate.

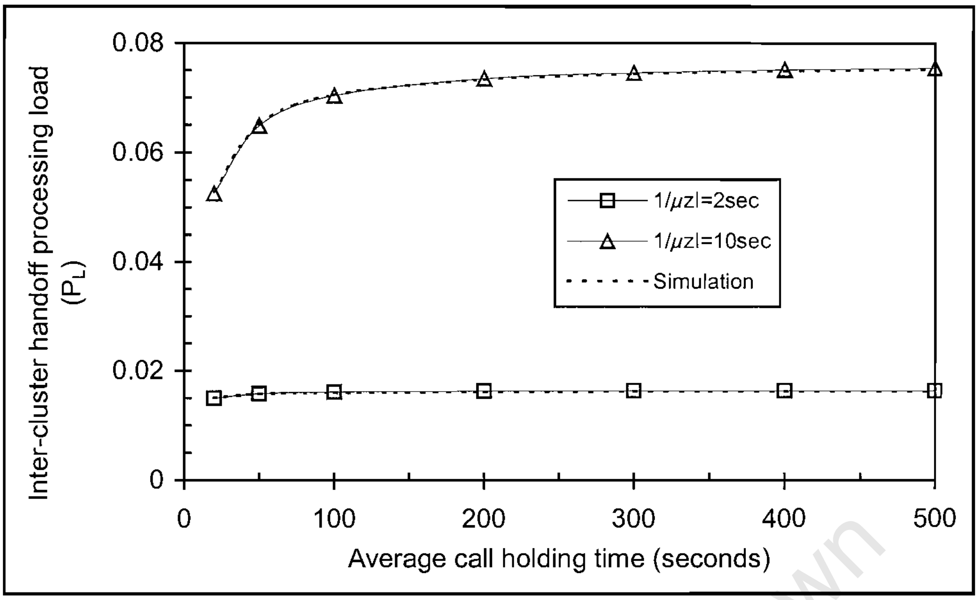

Figure 6.9: Inter-cluster handoff processing load versus call holding time.

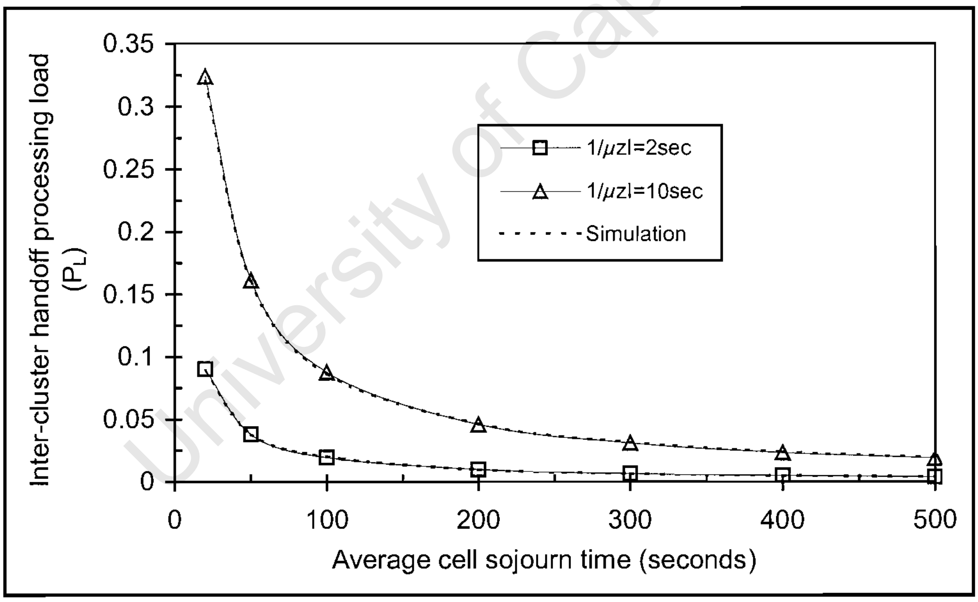

Figure 6.10: Inter-cluster handoff processing load versus cell sojourn time.

6.5.3 Performance Results of the PVC Analysis Between adjacent MESs

In this section, the mean route optimization times ($1/\mu_{ZE}$) are chosen to be 2 and 10 seconds. The route optimization time ($1/\mu_{ZI}$) is assumed to be 10 seconds. We see from Figures 6.11, 6.12, and 6.13 that the number of PVCs between any adjacent MESs can be minimized by decreasing the optimization time ($1/\mu_{ZE}$).

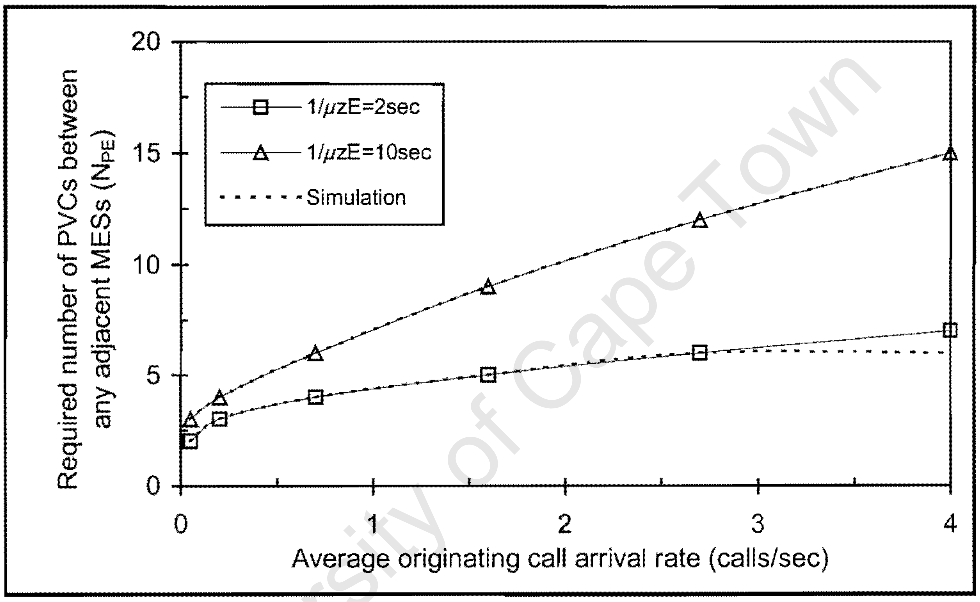

Figure 6.11: The required number of PVCs reserved between adjacent MESs versus originating call arrival rate.

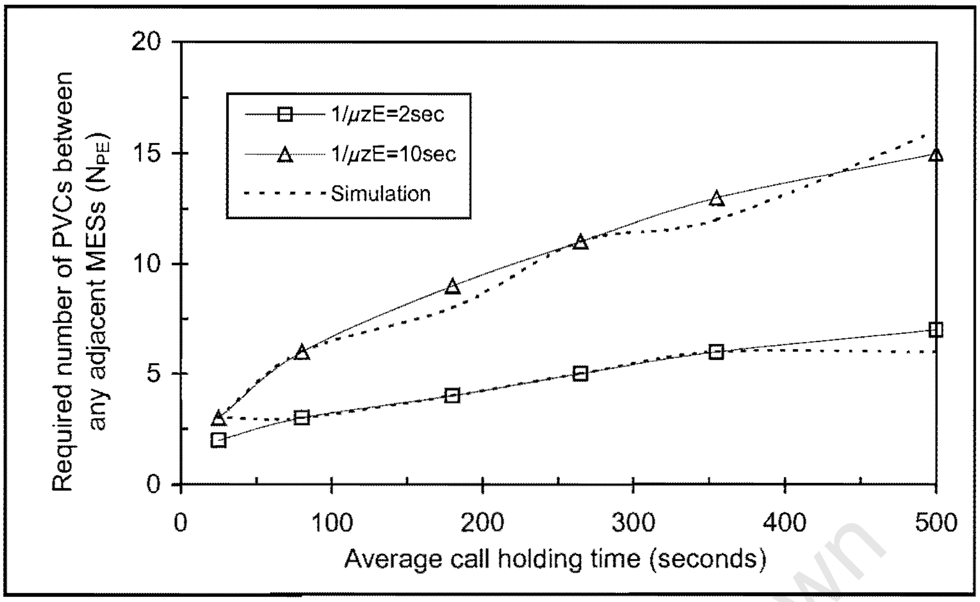

Figure 6.12: The required number of PVCs reserved between adjacent MESs versus call holding time.

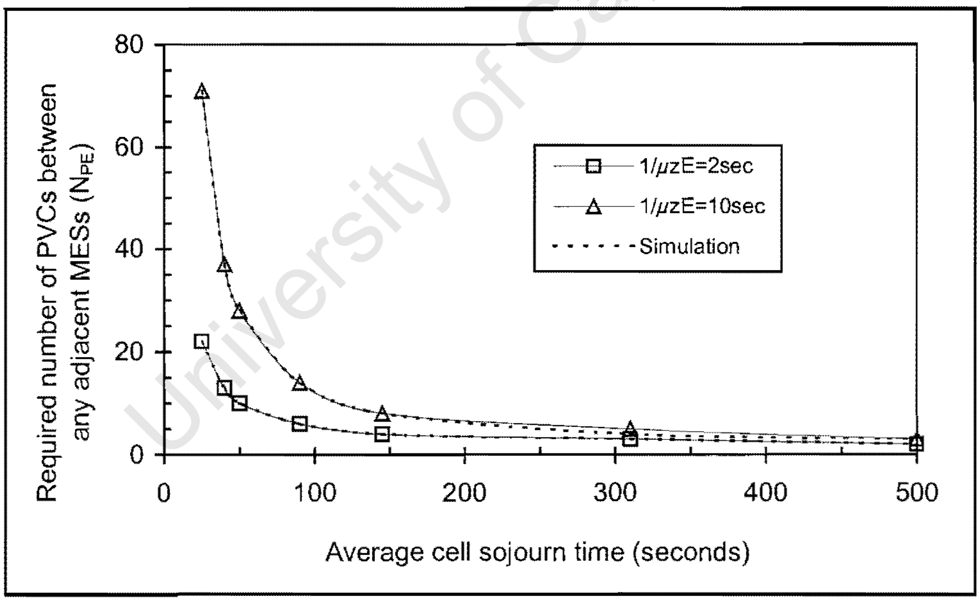

Figure 6.13: The required number of PVCs reserved between adjacent MESs versus cell sojourn time.

6.6 Comparison of Results and Discussion

In this section, we present a comparison of results between this fast handoff scheme with the new two-phase optimization scheme already explained in Chapter 5. The comparison is made in terms of the PVC bandwidth required to support handoff, the PVC holding time required to release the PVC, and an inter-cluster handoff processing load used as an indicator for the extra signaling overhead.

In the numerical examples, we assume a mean residual time of 2 minutes, and a mean call holding time of 4 minutes. Originating calls are assumed to be blocked with probability of 0.01, while handoff blocking probability is assumed to be 0.001. The mean route optimization times ($1/\mu_{ZI}$ and $1/\mu_{ZE}$) are assumed to be 2 seconds. The number of rings is assumed to be 2.

1- **PVC bandwidth:**

The PVC bandwidth is calculated as the number of PVCs required to support the handoff between any adjacent MESs, and is equal to ($N_{PE} + 2.N_{PI}$) for the new fast handoff scheme. Figure 6.14 shows a comparison of results in terms of the number of PVCs, indicating that the new handoff technique needs more PVCs to support the fast handoff.

2- **PVC holding time:**

In the new handoff scheme there are two types of PVCs. The first type supports the intra-cluster handoff, and the second type supports the path extension between MESs. Here one is concerned with the PVC holding time of the PVCs that support the path extension, as they affect the QoS of the connection. The average PVC holding time of the new handoff scheme can be calculated using this formula: $P_{OB}/(\mu_R P_f + \mu_M + \mu_{ZE})$, where $P_{OB} = \mu_R/(\mu_R + \mu_M + \mu_{ZI})$.

Figure 6.15 shows the comparison of results in terms of the PVC holding time, indicating very low PVC holding time for the new scheme, which supports the QoS and ensures the fast handoff.

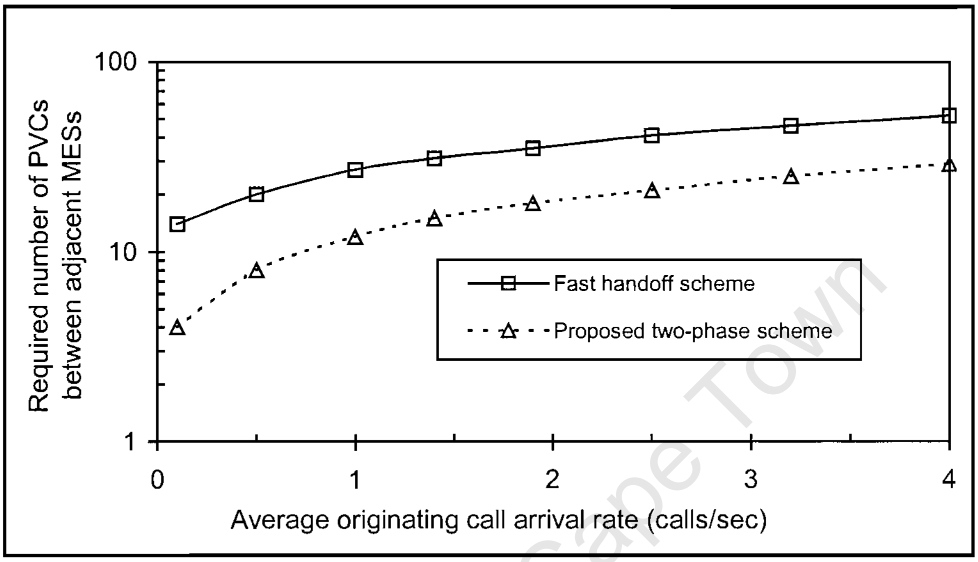

Figure 6.14: Comparison of results in terms of number of PVCS between any adjacent MESs.

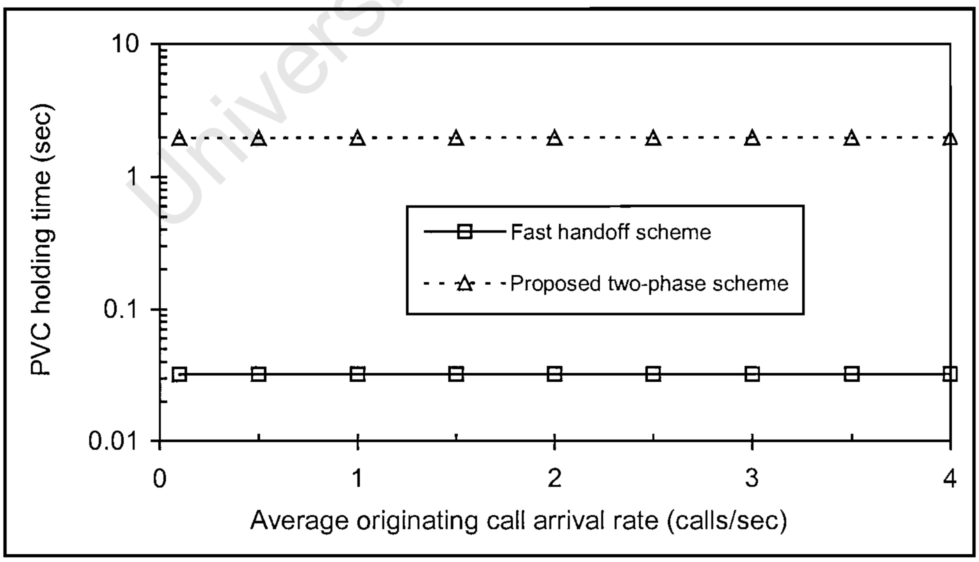

Figure 6.15: Comparison of results in terms of PVC holding time.

3- **Inter-cluster handoff processing load:**

This is an indicator of the extra signaling overhead when the *inter-path optimization* process is applied, and the design objective is to minimize the inter-cluster handoff processing load.

Figure 6.16 shows that the inter-cluster handoff processing load is very small compared to the proposed two-phase handoff scheme, which is always equal to *one*. (i.e. the optimization process always happens after each path extension).

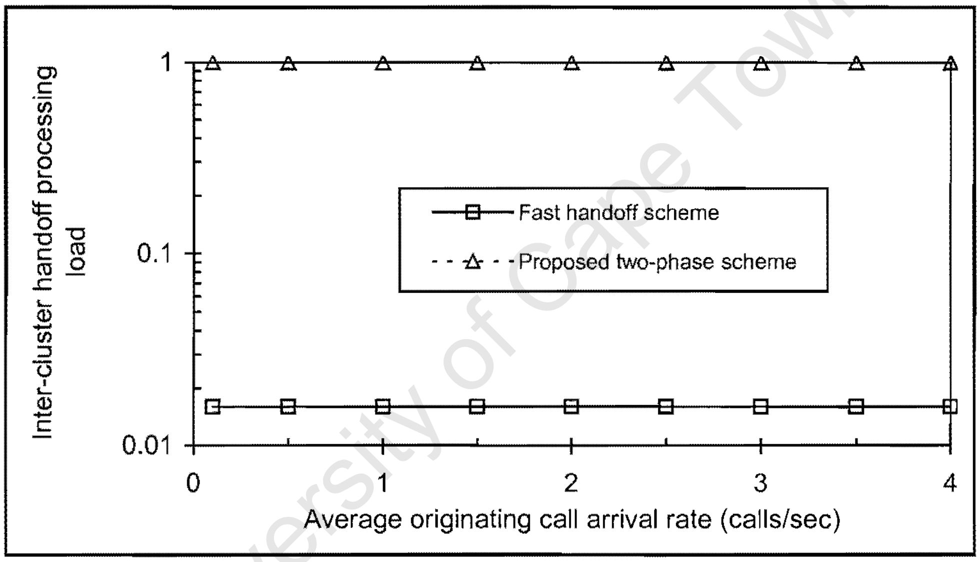

Figure 6.16: Comparison of results in terms of inter-cluster handoff processing load.

6.7 Conclusions

In this chapter, a new re-routing scheme for an inter-cluster handoff protocol based on the shared cells at the cluster boundaries is proposed. The resulting path is optimal and the effect of the inter-cluster handoff is minimized with very low handoff disruption. Our scheme is very useful for time sensitive multimedia applications. The function of the shared cells at the cluster edges is to share the information between any adjacent clusters so that fast intra-cluster handoff will be invoked each time a MT migrates to a new cluster instead of the conventional long path extension, followed by path optimization. We propose using reserved PVCs between any two MESs and between any MES and the shared cells. The function of PVCs is to re-route the connections without requiring a Call Admission Control and minimum handoff and processing delay. Both analytical and simulation models are presented to study the system performance in terms of the wired link resources to support the reserved PVCs and the path extension (inter-cluster handoff) processing load. By decreasing the mean optimization time, the performance of our scheme will be improved. When compared with the proposed two-optimization schemes described in Chapter 5, the simulation and analytical results show a very low PVC holding time and path extension processing load, which is very useful for multimedia applications. Our system requires a larger number of PVCs to support this fast handoff.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This research addressed the framework to handle fast handoff re-routing schemes in WATM networks through the design of a WATM network and the development of fast handoff re-routing schemes. The proposed WATM network architecture separated the wireless access network from the main ATM backbone network, placing the mobility support functionality on the wireless access network. The Mobility Enhanced Switch (MES) was used as a gateway between the access wireless network and the ATM backbone with the Permanent Virtual Channels (PVCs) connecting any adjacent MESs in order to maintain the continuity of the connection while the MT is roaming within the infrastructure of the WATM network. Thus, they support the inter-cluster handoff without the need of Call Admission Control (CAC), resulting in fast and low latency handoff. This handoff scheme can also handle a high handoff frequency without affecting the ATM network.

The signaling protocols used to achieve both fast intra-cluster handoff and fast inter-cluster handoff based on the PVCs were discussed in detail in Chapter 3, and they achieve fast routing with minimum handoff disruption, maintaining the cell sequence, and providing lossless handoff.

Three different fast handoff re-routing schemes based on the PVC WATM networks were studied both analytically and by simulation. A discrete-event simulation was developed for the purpose of evaluating the performance of these handoff schemes and the results were compared with those of the analytical model. We have studied the performance of these handoff schemes as a function of system parameters including average originating call arrival rate, call holding time, cell sojourn time, and optimization time.

The first handoff scheme was studied in Chapter 4, where a very fast inter-cluster handoff scheme based on extending the paths between the adjacent MESs was examined, using reserved PVCs between any adjacent MESs. Firstly, the scheme supports fast and simple handoff mechanism with a minimum processing load and minimum handoff latency. Secondly, the inter-cluster re-routing scheme does not require CAC. Thirdly, a path extension scheme is achieved through MESs, with a high switching speed and enough buffers to guarantee lossless handoff. The performance of our proposal was evaluated by analytical and simulation models in terms of the PVC holding time and the required link resources between MESs. The analytical and simulation models obviously gave similar results. However, since the extended path is longer than the original, certain QoS requirements such as CTD and CDV may not be guaranteed after handoff for those time-sensitive applications.

In Chapter 5, a second handoff scheme with a fast two-phase optimization method was introduced. Reserved PVCs between MESs in the first phase was proposed to avoid the inter-cluster handoff latency, followed by the second phase where the optimization process is *triggered instantly* and *concurrently* with other active optimization processes. The main objective in our scheme was to minimize the route optimization delay, resulting in the saving of the wired link resources and guaranteeing the QoS requirements for the time-sensitive applications. The performance of this scheme was evaluated using both analytical and simulation models in terms of wired link resources and PVC holding time. Although both the analytical and simulation results are the same, they showed a very significant improvement when compared with both schemes as proposed in Chapter 4 and other two-phase optimization scheme discussed in the literature [77], however increasing the signaling and processing load.

In Chapter 6 the third handoff scheme was discussed, investigating the performance of a new novel fast re-routing scheme suitable for multimedia real time applications. This new scheme is based on the shared cells at the cluster boundaries to obtain both a low inter-cluster handoff processing load and route optimization delay. This ensures the QoS requirements for real time applications. The PVCs between MESs and the shared cells and between any adjacent MESs are used to support the migration of MTs between the cluster boundaries. Both analytical and simulation models are presented to study the system performance in terms of the wired resources to support the reserved PVCs, PVC holding time, and inter-cluster handoff processing load. Results when compared with the proposed two-phase handoff scheme show lower PVC holding time and inter-cluster handoff processing load, ensuring a very low handoff latency, however with a greater level of added complexity and an increase in resources.

7.2 Future Work

An extension to this research is to include a QoS guarantee for multimedia applications when the mobile users are roaming between wireless cells. The availability of the resources in the WATM networks is different from cell to cell and the QoS contract may be violated because of the non-availability of sufficient resources when the handoff occurs. Connections with violated QoS will be either forced to terminate or re-negotiated. Hence the forced termination rate is highly related to the new originating call blocking rate. The tradeoff between guaranteeing the QoS of the on going calls during handoff and accepting new calls in the cell is an important future study issue.

Because of the widespread use of the Internet, which is based on the TCP/IP protocol, it is necessary to support the TCP protocol over WATM networks. One of the major concerns when dealing with TCP over wireless networks is high frequency of the handoff with small wireless cells. The extension of this research is to study the TCP connection performance when the proposed handoff schemes are applied. Also, it would be of value to compare the performance of a mobile-IP approach with the performance of our proposed approach.

Further work may include an experimental implementation of the proposed fast handoff schemes for validation purposes. This requires building a prototype test-bed of the proposed WATM network architecture with ATM switches, MESs, and wireless devices to support the required signaling protocols and researched handoff schemes.

APPENDIX A

ANALYTICAL CODE LISTING

A.1:

```
/*****************************************************************
 This program is used calculate the analytical results for the
handoff re-routing scheme  explained in Chapter 4, flow chart Figure
4.8
 ****************************************************************/

# include <stdio.h>
# include <math.h>

main ()
{
double factorial (int n1); /* function to calculate the factorial */


int N_P,       /* PVC bandwidth */
    n;


double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       PVC_Holding_Time, /* PVC holding time*/
       P_f,  /* Desired handoff blocking probability */
       P_o,           /* Originating call blocking probability*/
       sum,sum1,sum2; /* Variables used to calculate Erlang-B
Formula */
       float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);

PVC_Holding_Time=1.0 /(
(1.0/mean_sojourn_time)*P_f+(1.0/mean_holding_time));

printf ("PVC Holding Time= %f seconds\n",PVC_Holding_Time);
N_P=0;
while (true)
{
N_P=N_P+1;
sum1=1;
```

```
for (n=1;n<=N_P;n++) sum1=sum1+(pow (mean_handoff_rate*
                       PVC_Holding_Time,n))/factorial (n);


sum2= pow(mean_handoff_rate*PVC_Holding_Time, N_P)/factorial (N_P);
sum=sum2/sum1;
if (sum <= P_f )
{
printf ("PVC_BW= %d\n",N_P);
return(0);
}

}
}

double factorial (int n1)
{
int j;
double fac;
fac=1;
for (j=1;j<=n1;j++) fac=fac*j;
return fac;
}
```

A.2:

```
/*******************************************************************
 This program is used calculate the analytical results for the
handoff re-routing scheme  explained in Chapter 5, flow chart Figure
5.1
 *******************************************************************/

# include <stdio.h>
# include <math.h>

main ()
{
double factorial (int n1); /* function to calculate the factorial */


int N_OP,       /* PVC bandwidth */
    n;


double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       mean_optimization_time, /* Mean call optimization time */
       PVC_Holding_Time, /* PVC holding time*/
       P_f,  /* Desired handoff blocking probability */
```

```
        P_o,            /* Originating call blocking probability*/
        sum,sum1,sum2; /* Variables used to calculate Erlang-B
Formula */
        float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time=2.0;
P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);

PVC_Holding_Time=1.0 /(
(1.0/mean_sojourn_time)*P_f+(1.0/mean_holding_time)
                    + (1.0/mean_optimization_time) );

printf ("PVC Holding Time= %f seconds\n",PVC_Holding_Time);
N_OP=0;
while (true)
{
N_OP=N_OP+1;
sum1=1;
for (n=1;n<=N_OP;n++) sum1=sum1+(pow (mean_handoff_rate*
                        PVC_Holding_Time,n))/factorial (n);


sum2= pow(mean_handoff_rate*PVC_Holding_Time, N_OP)/factorial
(N_OP);
sum=sum2/sum1;
if (sum <= P_f )
{
printf ("PVC_BW= %d\n",N_OP);
return(0);
}

}
}

double factorial (int n1)
{
int j;
double fac;
fac=1;
for (j=1;j<=n1;j++) fac=fac*j;
return fac;
}
```

A.3:

```
/****************************************************************
 This program is used calculate the analytical results for the
handoff  re-routing scheme  explained in Chapter 6, flow chart
Figure 6.3
 ****************************************************************/

# include <stdio.h>
# include <math.h>

main ()
{
double factorial (int n1); /* function to calculate the factorial */


int N_PI,       /* PVC bandwidth */
    n;


double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       mean_optimization_time, /* Mean call optimization time */
       PVC_Holding_Time, /* PVC holding time*/
       Optimization_Blocking_Prob, /*Optimization Bolcking
Probability*/
       P_f,  /* Desired handoff blocking probability */
       P_o,            /* Originating call blocking probability*/
       sum,sum1,sum2; /* Variables used to calculate Erlang-B
Formula */
       float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time=2.0;
P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);

PVC_Holding_Time=1.0 /(
(1.0/mean_sojourn_time)+(1.0/mean_holding_time)
                 + (1.0/mean_optimization_time) );
Optimization_Blocking_Prob=(1.0-P_f)*(1.0/mean_sojourn_time)/
```

```
((1.0/mean_sojourn_time)+(1.0/mean_holding_time)   +
(1.0/mean_optimization_time) );

printf ("PVC Holding Time= %f seconds\n",PVC_Holding_Time);
printf ("Optimization Blocking
Prob=%f\n",Optimization_Blocking_Prob);
N_PI=0;
while (true)
{
N_PI=N_PI+1;
sum1=1;
for (n=1;n<=N_PI;n++) sum1=sum1+(pow (mean_handoff_rate*
                      PVC_Holding_Time,n))/factorial (n);


sum2= pow(mean_handoff_rate*PVC_Holding_Time, N_PI)/factorial
(N_PI);
sum=sum2/sum1;
if (sum <= P_f )
{
printf ("PVC_BW= %d\n",N_PI);
return(0);
}

}
}

double factorial (int n1)
{
int j;
double fac;
fac=1;
for (j=1;j<=n1;j++) fac=fac*j;
return fac;
}
```

A.4:

```
/****************************************************************
 This program is used calculate the analytical results for the
handoff re-routing scheme  explained in Chapter 6, flow chart Figure
6.4
 ****************************************************************/

# include <stdio.h>
# include <math.h>

main ()
{
double factorial (int n1); /* function to calculate the factorial */
```

```
int N_PE,        /* PVC bandwidth */
    n;


double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       Tot_handoff_rate, /* Total handoff rate between two clusters
*/
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       mean_optimization_time_ZI, /* Mean intra-optimization time */
       mean_optimization_time_ZE, /* Mean inter-optimization time */
       PVC_Holding_Time, /* PVC holding time*/
       P_f,  /* Desired handoff blocking probability */
       P_o,            /* Originating call blocking probability*/
       P_OB, /* Optimization bloocking probability */
       sum,sum1,sum2; /* Variables used to calculate Erlang-B
Formula */
       float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=2.0;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time_ZI=10.0;
mean_optimization_time_ZE=temp;
P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);

PVC_Holding_Time=1.0 /(
(1.0/mean_sojourn_time)*P_f+(1.0/mean_holding_time)
                    + (1.0/mean_optimization_time_ZE) );

printf ("PVC Holding Time= %f seconds\n",PVC_Holding_Time);

P_OB=(1.0-P_f)*(1.0/mean_sojourn_time)/( (1.0/mean_sojourn_time)+
(1.0/mean_holding_time) + (1.0/mean_optimization_time_ZI) );

Tot_handoff_rate=mean_handoff_rate*P_OB;
N_PE=0;
while (true)
{
N_PE=N_PE+1;
sum1=1;
for (n=1;n<=N_PE;n++) sum1=sum1+(pow (Tot_handoff_rate*
                      PVC_Holding_Time,n))/factorial (n);
```

```
sum2= pow(Tot_handoff_rate*PVC_Holding_Time, N_PE)/factorial (N_PE);
sum=sum2/sum1;
if (sum <= P_f )
{
printf ("PVC_BW= %d\n",N_PE);
return(0);
}

}
}

double factorial (int n1)
{
int j;
double fac;
fac=1;
for (j=1;j<=n1;j++) fac=fac*j;
return fac;
}
```

APPENDIX B

SIMULATION CODE LISTING

B.1:

```
/*****************************************************************
 This program is used to simulate the handoff re-routing scheme
 explained in Chapter 4, flow chart Figure 4.8
 ****************************************************************/

# include <stdio.h>
# include <math.h>
# include <stdlib.h>

#define loop 50000  /* Define the total number of handoff arrivals
*/
/* Initialization used for random number generating */
double  A1;
double  A2;
double  A3;
double  A4;
double  A5;
double  M ;
static double r_seed1;
static double r_seed2;
static double r_seed3;
static double r_seed4;
static double r_seed5;


main ()
{

/* Definition of the time priority Queue */
struct list {double PVC_Expiration_Time; struct list *next;}
*front,*p,*p1,*p2;

double dlp (double lp1); /* Function for handoff call inter-arrival
time*/
double TM (double TM1);  /* Function for call holding time */
double TR (int N1, double TR1); /* Function for total residual time
*/
double min(double TR,double TM);/*Function for PVC_Expiration_Time*/

int geometric (double P_f1); /* Function for N cells to be visited
by a MT*/

int PVC_BW,        /* PVC bandwidth */
    PVC_Capacity,  /* Instant PVC bandwidth */
    MAX_Capacity,  /* Used to get approximate value of PVC_BW */
    First_Run,     /* Used to identify the First Run */
    N_B,           /* Number of handoff calls weer blocked */
    N_T,           /* Counter for number of handoff arrivals */
    N;             /* This variable is used to identify N visiting
cells */
```

```
double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       Call_Holding_Time, /* Instant call holding time */
       Total_Sojourn_Time,/* Instant total sojourn time */
       D_lp, /* Instant handoff inter-arrival time */
       Sum_PVC_Holding_Time, /*Sum of PVC holding time*/
       Avg_PVC_Holding_Time, /* Average PVC holding Time*/
       P_f,  /* Desired handoff blocking probability */
       P_f_Simulation, /* Simulation handoff blocking probability */
       P_o,            /* Originating call blocking probability*/
       logic; /* Used for re-ordering control of the contents of the
Queue*/

       float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=120.0;
mean_sojourn_time=120.0;

P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);


MAX_Capacity=1;
PVC_BW=1000;
First_Run=1;


while (true)
{
/* initialization for generating independent streams of random
numbers */
  A1=   16801.0;
  A2=   16802.0;
  A3=   16803.0;
  A4=   16804.0;
  A5=   16805.0;
  M =  2147483647.0 ;
  r_seed1=1.0;
  r_seed2=2.0;
  r_seed3=3.0;
  r_seed4=4.0;
  r_seed5=5.0;
```

```
Sum_PVC_Holding_Time=0.0;

PVC_Capacity=1;
p=new(list); /* Create a time priority Queue */
p->next=NULL;
p->PVC_Expiration_Time=0.0;
front=p;
N_B=0;

for (N_T=1;N_T<= loop;N_T++)
{
    D_lp=dlp(mean_handoff_rate); /* Generating the handoff inter-
arrival time*/

/* subtract D_lp from the contents of the queue and delete values <=
0.0 */
    p=front;
    while (p !=NULL)
      {
       p->PVC_Expiration_Time=p->PVC_Expiration_Time-D_lp;
       p=p->next;
      }

   p=front;
 while (p != NULL)
        {
              if (front->PVC_Expiration_Time > 0) p=NULL;
                 else
                   {
                        PVC_Capacity=PVC_Capacity-1;
                        front=p->next;
                        delete (p);
                        p=front;
                   }
        }


 if (PVC_Capacity==PVC_BW)  N_B=N_B+1;

 if (PVC_Capacity < PVC_BW)
  {
/* calculating the PVC_Expiration_Time and insert it in the queue */
    PVC_Capacity=PVC_Capacity+1;
         Call_Holding_Time=TM (mean_holding_time);
         N=geometric (P_f);
    Total_Sojourn_Time=TR(N,mean_sojourn_time);
         p=new (list);
         p-
>PVC_Expiration_Time=min(Total_Sojourn_Time,Call_Holding_Time);
         Sum_PVC_Holding_Time=Sum_PVC_Holding_Time+p-
>PVC_Expiration_Time;
    if (front==NULL)
```

```
            {
              p->next=NULL;
              front=p;
            }
           else
{

         if (p->PVC_Expiration_Time < front->PVC_Expiration_Time)
           {
             p->next=front;
             front=p;
            }
else{
           logic=1; p2=front;p1=p2->next;
           while (p1 != NULL) {
                        if (p->PVC_Expiration_Time < p1-
>PVC_Expiration_Time) {
                                     logic=0;
                                     p->next=p1;
                                     p2->next=p;p1=NULL;}
                               else { p2=p2->next;p1=p2->next; }
                              }
if (logic==1) {p->next=NULL; p2->next=p;}
    }

}


}
if (First_Run == 1) {

 if (MAX_Capacity < PVC_Capacity) MAX_Capacity=PVC_Capacity; }

}


P_f_Simulation=N_B*1.0/loop;


if (PVC_BW ==1) {printf ("PVC_BW=%d
                 Average PVC holding
time=%f\n",PVC_BW,Avg_PVC_Holding_Time)
                  ;return(0);}
if (First_Run==0) {

if (P_f_Simulation>P_f){printf("PVC_BW=%d
                      \n Average PVC  holding time=%f\n"
                       ,(PVC_BW+1), Avg_PVC_Holding_Time);
                        return(0);}
PVC_BW=PVC_BW-1;
Avg_PVC_Holding_Time=Sum_PVC_Holding_Time/loop;

}
```

```
if (First_Run==1) {
First_Run=0;
PVC_BW=MAX_Capacity;
}

}

// return(0);
}



double dlp (double lp1)
{
double rnd_lp;
r_seed1=fmod(A1*r_seed1,M);
rnd_lp=r_seed1*4.656612875e-10;
return -log(rnd_lp)/lp1;

}

double TM (double TM1)
{
double rnd_TM;
r_seed2=fmod(A2*r_seed2,M);
rnd_TM=r_seed2*4.656612875e-10;
return -log(rnd_TM)*TM1;

}



double TR (int N1,double TR1)
{
double rnd_TR,T_R; int k;
T_R=0.0;
for (k=1;k<= N1; k++)
   { r_seed4=fmod(A4*r_seed4,M);
     rnd_TR=r_seed4*4.656612875e-10;
     T_R=T_R+(-log(rnd_TR)*TR1);
   }
return T_R;
}


int geometric (double P_f1)
{
double rnd_geo;
r_seed5=fmod(A5*r_seed5,M);
rnd_geo=r_seed5*4.656612875e-10;

return int ( ceil(log(rnd_geo)/log(1.0-P_f1)) );

}
```

```
double min(double TR,double TM)
{
double minimum;

minimum=TR;
if (TM < minimum) minimum=TM;
return minimum;
}
```

B.2:

```
/**************************************************************
 This program is used to simulate the handoff re-routing scheme
 explained in Chapter 5, flow chart Figure 5.1
 *************************************************************/

# include <stdio.h>
# include <math.h>
# include <stdlib.h>

#define loop 50000  /* Define the total number of handoff arrivals
*/
/* Initialization used for random number generating */
double  A1;
double  A2;
double  A3;
double  A4;
double  A5;
double  M ;
static double r_seed1;
static double r_seed2;
static double r_seed3;
static double r_seed4;
static double r_seed5;


main ()
{

/* Definition of the time priority Queue */
struct list {double PVC_Expiration_Time; struct list *next;}
*front,*p,*p1,*p2;

double dlp (double lp1); /* Function for handoff call inter-arrival
time*/
double TM (double TM1);  /* Function for call holding time */
double TR (int N1, double TR1); /* Function for total residual time
*/
double TZ (double TZ1);         /* Function for call optimization
time*/
```

```
double min(double TR,double TM,double TZ);/*Function for
PVC_Expiration_Time*/

int geometric (double P_f1); /* Function for N cells to be visited
by a MT*/

int PVC_BW,       /* PVC bandwidth */
    PVC_Capacity, /* Instant PVC bandwidth */
    MAX_Capacity, /* Used to get approximate value of PVC_BW */
    First_Run,    /* Used to identify the First Run */
    N_B,          /* Number of handoff calls weer blocked */
    N_T,          /* Counter for number of handoff arrivals */
    N;            /* This variable is used to identify N visiting
cells */



double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       mean_optimization_time, /* Mean call optimization time */
       Call_Holding_Time, /* Instant call holding time */
       Total_Sojourn_Time,/* Instant total sojourn time */
       Call_Optimization_Time, /* Instant call optimization time */
       D_lp, /* Instant handoff inter-arrival time */
       Sum_PVC_Holding_Time, /*Sum of PVC holding time*/
       Avg_PVC_Holding_Time, /* Average PVC holding Time*/
       P_f,  /* Desired handoff blocking probability */
       P_f_Simulation, /* Simulation handoff blocking probability */
       P_o,            /* Originating call blocking probability*/
       logic; /* Used for re-ordering control of the contents of the
Queue*/

       float temp;/* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time=2.0;
P_o=0.01; P_f=0.001;

mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);


MAX_Capacity=1;
PVC_BW=1000;
First_Run=1;
```

```
while (true)
{
/* initialization for generating independent streams of random
numbers */
  A1=   16801.0;
  A2=   16802.0;
  A3=   16803.0;
  A4=   16804.0;
  A5=   16805.0;
  M =  2147483647.0 ;
  r_seed1=1.0;
  r_seed2=2.0;
  r_seed3=3.0;
  r_seed4=4.0;
  r_seed5=5.0;

Sum_PVC_Holding_Time=0.0;

PVC_Capacity=1;
p=new(list); /* Create a time priority Queue */
p->next=NULL;
p->PVC_Expiration_Time=0.0;
front=p;
N_B=0;

for (N_T=1;N_T<= loop;N_T++)
{
    D_lp=dlp(mean_handoff_rate); /* Generating the handoff inter-
arrival time*/

/* subtract D_lp from the contents of the queue and delete values <=
0.0 */
    p=front;
    while (p !=NULL)
      {
       p->PVC_Expiration_Time=p->PVC_Expiration_Time-D_lp;
       p=p->next;
      }

   p=front;
 while (p != NULL)
       {
             if (front->PVC_Expiration_Time > 0) p=NULL;
                else
                  {
                       PVC_Capacity=PVC_Capacity-1;
                       front=p->next;
                       delete (p);
                       p=front;
                  }
        }
```

```
 if (PVC_Capacity==PVC_BW)  N_B=N_B+1;

 if (PVC_Capacity < PVC_BW)
  {
/* calculating the PVC_Expiration_Time and insert it in the queue */
    PVC_Capacity=PVC_Capacity+1;
        Call_Holding_Time=TM (mean_holding_time);
    Call_Optimization_Time=TZ(mean_optimization_time);
        N=geometric (P_f);
    Total_Sojourn_Time=TR(N,mean_sojourn_time);
        p=new (list);
        p-
>PVC_Expiration_Time=min(Total_Sojourn_Time,Call_Holding_Time,
        Call_Optimization_Time);
        Sum_PVC_Holding_Time=Sum_PVC_Holding_Time+p-
>PVC_Expiration_Time;
    if (front==NULL)
            {
             p->next=NULL;
             front=p;
            }
           else
{

        if (p->PVC_Expiration_Time < front->PVC_Expiration_Time)
          {
           p->next=front;
           front=p;
          }
else{
           logic=1; p2=front;p1=p2->next;
           while (p1 != NULL) {
                        if (p->PVC_Expiration_Time < p1-
>PVC_Expiration_Time) {
                                  logic=0;
                                  p->next=p1;
                                  p2->next=p;p1=NULL;}
                             else { p2=p2->next;p1=p2->next; }
                            }
if (logic==1) {p->next=NULL; p2->next=p;}
    }

}


}
if (First_Run == 1) {

 if (MAX_Capacity < PVC_Capacity) MAX_Capacity=PVC_Capacity; }

}
```

```
P_f_Simulation=N_B*1.0/loop;


if (PVC_BW ==1) {printf ("PVC_BW=%d
                 Average PVC holding
time=%f\n",PVC_BW,Avg_PVC_Holding_Time)
                 ;return(0);}
if (First_Run==0) {

if (P_f_Simulation>P_f){printf("PVC_BW=%d
                      \n Average PVC  holding time=%f\n"
                       ,(PVC_BW+1), Avg_PVC_Holding_Time);
                        return(0);}
PVC_BW=PVC_BW-1;
Avg_PVC_Holding_Time=Sum_PVC_Holding_Time/loop;

}

if (First_Run==1) {
First_Run=0;
PVC_BW=MAX_Capacity;
}

}

// return(0);
}



double dlp (double lp1)
{
double rnd_lp;
r_seed1=fmod(A1*r_seed1,M);
rnd_lp=r_seed1*4.656612875e-10;
return -log(rnd_lp)/lp1;

}

double TM (double TM1)
{
double rnd_TM;
r_seed2=fmod(A2*r_seed2,M);
rnd_TM=r_seed2*4.656612875e-10;
return -log(rnd_TM)*TM1;

}

double TZ (double TZ1)
{
double rnd_TZ;
r_seed3=fmod(A3*r_seed3,M);
rnd_TZ=r_seed3*4.656612875e-10;
return -log(rnd_TZ)*TZ1;
```

```
}


double TR (int N1,double TR1)
{
double rnd_TR,T_R; int k;
T_R=0.0;
for (k=1;k<= N1; k++)
   { r_seed4=fmod(A4*r_seed4,M);
     rnd_TR=r_seed4*4.656612875e-10;
     T_R=T_R+(-log(rnd_TR)*TR1);
   }
return T_R;
}


int geometric (double P_f1)
{
double rnd_geo;
r_seed5=fmod(A5*r_seed5,M);
rnd_geo=r_seed5*4.656612875e-10;

return int ( ceil(log(rnd_geo)/log(1.0-P_f1)) );

}

double min(double TR,double TM,double TZ)
{
double minimum;

minimum=TR;
if (TM < minimum) minimum=TM;
if (TZ < minimum) minimum=TZ;
return minimum;
}
```

B.3:

```
/*****************************************************************
 This program is used to simulate the handoff re-routing scheme
 explained in Chapter 6, flow chart Figure 6.3
 ****************************************************************/

# include <stdio.h>
# include <math.h>
# include <stdlib.h>

#define loop 1000000  /* Define the total number of handoff arrivals
*/
/* Initialization used for random number generating */
```

```
double  A1;
double  A2;
double  A3;
double  A4;
double  A5;
double  M ;
static double r_seed1;
static double r_seed2;
static double r_seed3;
static double r_seed4;
static double r_seed5;


main ()
{
FILE *fp; /* Definition of the External file*/

/* Definition of the time priority Queue */
struct list {double PVC_Expiration_Time; int tag; struct list
*next;}
*front,*p,*p1,*p2;

double dlp (double lp1); /* Function for handoff call inter-arrival
time*/
double TM (double TM1);  /* Function for call holding time */
double TR_1 (int N1, double TR1);/* Function for total residual time
where
                                    N=1*/
double TZ (double TZ1);         /* Function for call optimization
time*/
double min(double TR,double TM,double TZ);/*Function for
PVC_Expiration_Time*/

int geometric (double P_f1); /* Function for N cells to be visited
by a MT*/

int PVC_BW,        /* PVC bandwidth */
    PVC_Capacity, /* Instant PVC bandwidth */
    MAX_Capacity, /* Used to get approximate value of PVC_BW */
    First_Run,    /* Used to identify the First Run */
    N_B,          /* Number of handoff calls weer blocked */
    N_T,          /* Counter for number of handoff arrivals */
    N,            /* This variable is used to identify N visiting
cells */
    N_OB,         /* Number of handoff calls that has been blocked
from
                     optimization due to movement out of the cell */
    terminate; /* used to get an update External File to fit exact
PVC_BW*/


double mean_arrival_rate, /* Originating call arrival rate */
       mean_handoff_rate, /* Mean handoff arrival rate */
       mean_holding_time, /* Mean call holding time */
```

```
        mean_sojourn_time, /* Mean cell residual time of a call */
        mean_optimization_time, /* Mean call optimization time */
        Call_Holding_Time, /* Instant call holding time */
        Total_Sojourn_Time,/* Instant total sojourn time */
        Call_Optimization_Time, /* Instant call optimization time */
        D_lp, /* Instant handoff inter-arrival time */
        Sum_PVC_Holding_Time, /*Sum of PVC holding time*/
        Avg_PVC_Holding_Time, /* Average PVC holding Time*/
        Optimization_Blocking_Prob, /* The optimization blocking
probability due
                to movement outside the cell before the completion
ofoptimization */
        P_f,  /* Desired handoff blocking probability */
        P_f_Simulation, /* Simulation handoff blocking probability */
        P_o,            /* Originating call blocking probability*/
        logic, /* Used for re-ordering control of the contents of the
Queue*/
        lp_E1,
        lp_E2,
        Dlp_E, /* handoff inter_arrival time to be stored in External
File
                   and is equual to difference of lp_E1 and lp_E2  */
        time; /* The total handoff inter_arrival time */
        float temp; /* Used to change values that are variable in the
program*/

scanf ("%f",&temp);
mean_arrival_rate=temp;
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time=10.0;
P_o=0.01; P_f=0.001;

/* Choose the handoff rate depends on the calculation needs*/
mean_handoff_rate=(1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/

((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f);

//mean_handoff_rate=((1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/
//
((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f))/6.0;

//mean_handoff_rate=((1.0/mean_sojourn_time)*(1.0-
P_o)*mean_arrival_rate/
//
((1.0/mean_holding_time)+(1.0/mean_sojourn_time)*P_f))/3.0;


MAX_Capacity=1;
PVC_BW=1000;
First_Run=1;
```

```
terminate=0;

while (true)
{
fp=fopen ("External_File.res","w"); /*Open the External File for
writing */
/* initialization for generating independent streams of random
numbers */
  A1=   16801.0;
  A2=   16802.0;
  A3=   16803.0;
  A4=   16804.0;
  A5=   16805.0;
  M =  2147483647.0 ;
  r_seed1=1.0;
  r_seed2=2.0;
  r_seed3=3.0;
  r_seed4=4.0;
  r_seed5=5.0;

Sum_PVC_Holding_Time=0.0;
PVC_Capacity=1;
p=new(list); /* Create a time priority Queue */
p->next=NULL;
p->PVC_Expiration_Time=0.0;
front=p;
N_B=0;
N_OB=0;
lp_E1=0.0;
time=0.0;
for (N_T=1;N_T<= loop;N_T++)
{
    D_lp=dlp(mean_handoff_rate); /* Generating the handoff inter-
arrival time*/
    time=time+D_lp;
/* subtract D_lp from the contents of the queue and delete values <=
0.0 */
    p=front;
    while (p !=NULL)
      {
       p->PVC_Expiration_Time=p->PVC_Expiration_Time-D_lp;
       p=p->next;
      }

   p=front;
 while (p != NULL)
       {
            if (front->PVC_Expiration_Time > 0) p=NULL;
               else
                 {
/* The "tag" is used to identify the handoff call which is moved out
from
  cell before optimization */
                       if (front->tag ==1) {
```

```
                        lp_E2=time+front->PVC_Expiration_Time;
                        Dlp_E=lp_E2-lp_E1;
                        fprintf(fp,"%f\n",Dlp_E);lp_E1=lp_E2;}
                        PVC_Capacity=PVC_Capacity-1;
                        front=p->next;
                        delete (p);
                        p=front;
                   }
         }


 if (PVC_Capacity==PVC_BW)  N_B=N_B+1;

 if (PVC_Capacity < PVC_BW)
  {
/* calculating the PVC_Expiration_Time and insert it in the queue */
    PVC_Capacity=PVC_Capacity+1;
         Call_Holding_Time=TM (mean_holding_time);
    Call_Optimization_Time=TZ(mean_optimization_time);
         N=geometric (P_f);
         N=1;
    Total_Sojourn_Time=TR_1(N,mean_sojourn_time);
         p=new (list);
         p->tag=0;
         if (( Total_Sojourn_Time < Call_Holding_Time) &&
             ( Total_Sojourn_Time < Call_Optimization_Time))

    { N_OB=N_OB+1;; p->tag=1;}
         p-
>PVC_Expiration_Time=min(Total_Sojourn_Time,Call_Holding_Time,
         Call_Optimization_Time);
         Sum_PVC_Holding_Time=Sum_PVC_Holding_Time+p-
>PVC_Expiration_Time;
    if (front==NULL)
             {
               p->next=NULL;
               front=p;
             }
           else
{

         if (p->PVC_Expiration_Time < front->PVC_Expiration_Time)
           {
             p->next=front;
             front=p;
            }
else{
           logic=1; p2=front;p1=p2->next;
           while (p1 != NULL) {
                        if (p->PVC_Expiration_Time < p1-
>PVC_Expiration_Time) {
                                      logic=0;
                                      p->next=p1;
```

```
                                p2->next=p;p1=NULL;}
                           else { p2=p2->next;p1=p2->next; }
                          }
if (logic==1) {p->next=NULL; p2->next=p;}
    }

}


}
if (First_Run == 1) {

 if (MAX_Capacity < PVC_Capacity) MAX_Capacity=PVC_Capacity; }

}


P_f_Simulation=N_B*1.0/loop;

/* Special case if MAX bandwidth=1 */
if (PVC_BW ==1) {printf ("PVC_BW=%d
                 Average PVC holding
time=%f\n",PVC_BW,Avg_PVC_Holding_Time);
                 printf ("Optimization Blocking Prob.=%f\n",
                 Optimization_Blocking_Prob);
                  ;return(0);}
if (First_Run==0) {
 if (terminate==1) return(0);
if (P_f_Simulation>P_f){printf("PVC_BW=%d
                      \n Average PVC  holding time=%f\n"
                       ,(PVC_BW+1), Avg_PVC_Holding_Time);
                        printf ("Optimization Blocking Prob.=%f\n",
                          Optimization_Blocking_Prob);
                         terminate=1;
                        }
if (terminate == 0) PVC_BW=PVC_BW-1;
if (terminate == 1) PVC_BW=PVC_BW+1;
Avg_PVC_Holding_Time=Sum_PVC_Holding_Time/loop;
Optimization_Blocking_Prob=N_OB*1.0/loop;
}

if (First_Run==1) {
First_Run=0;
PVC_BW=MAX_Capacity;
}
fclose (fp);
}

// return(0);
}


double dlp (double lp1)
```

```
{
double rnd_lp;
r_seed1=fmod(A1*r_seed1,M);
rnd_lp=r_seed1*4.656612875e-10;
return -log(rnd_lp)/lp1;

}

double TM (double TM1)
{
double rnd_TM;
r_seed2=fmod(A2*r_seed2,M);
rnd_TM=r_seed2*4.656612875e-10;
return -log(rnd_TM)*TM1;

}

double TZ (double TZ1)
{
double rnd_TZ;
r_seed3=fmod(A3*r_seed3,M);
rnd_TZ=r_seed3*4.656612875e-10;
return -log(rnd_TZ)*TZ1;

}


double TR_1 (int N1,double TR1)
{
double rnd_TR,T_R; int k;
T_R=0.0;
for (k=1;k<= N1; k++)
   { r_seed4=fmod(A4*r_seed4,M);
     rnd_TR=r_seed4*4.656612875e-10;
     T_R=T_R+(-log(rnd_TR)*TR1);
   }
return T_R;
}


int geometric (double P_f1)
{
double rnd_geo;
r_seed5=fmod(A5*r_seed5,M);
rnd_geo=r_seed5*4.656612875e-10;

return int ( ceil(log(rnd_geo)/log(1.0-P_f1)) );

}

double min(double TR,double TM,double TZ)
{
double minimum;
```

```
minimum=TR;
if (TM < minimum) minimum=TM;
if (TZ < minimum) minimum=TZ;
return minimum;
}
```

B.4:

```
/***************************************************************
 This program is used to simulate the handoff re-routing scheme
 explained in Chapter 6, flow chart Figure 6.4
 ***************************************************************/

# include <stdio.h>
# include <math.h>
# include <stdlib.h>


/* Initialization used for random number generating */
double  A1;
double  A2;
double  A3;
double  A4;
double  A5;
double  M ;
static double r_seed1;
static double r_seed2;
static double r_seed3;
static double r_seed4;
static double r_seed5;


main ()
{

/* Definition of the external File */
FILE *fp;
/* Definition of the time priority Queue */
struct list {double PVC_Expiration_Time; struct list *next;}
*front,*p,*p1,*p2;


double TM (double TM1);  /* Function for call holding time */
double TR (int N1, double TR1); /* Function for total residual time
*/
double TZ (double TZ1);         /* Function for call optimization
time*/
double min(double TR,double TM,double TZ);/*Function for
PVC_Expiration_Time*/
```

```
int geometric (double P_f1); /* Function for N cells to be visited
by a MT*/

int PVC_BW,        /* PVC bandwidth */
    PVC_Capacity, /* Instant PVC bandwidth */
    MAX_Capacity, /* Used to get approximate value of PVC_BW */
    First_Run,    /* Used to identify the First Run */
    N_B,          /* Number of handoff calls weer blocked */
    N_T,          /* Counter for number of handoff arrivals */
    N;            /* This variable is used to identify N visiting
cells */


double mean_holding_time, /* Mean call holding time */
       mean_sojourn_time, /* Mean cell residual time of a call */
       mean_optimization_time, /* Mean call optimization time */
       Call_Holding_Time, /* Instant call holding time */
       Total_Sojourn_Time,/* Instant total sojourn time */
       Call_Optimization_Time, /* Instant call optimization time */
       Sum_PVC_Holding_Time, /*Sum of PVC holding time*/
       Avg_PVC_Holding_Time, /* Average PVC holding Time*/
       P_f,  /* Desired handoff blocking probability */
       P_f_Simulation, /* Simulation handoff blocking probability */
       P_o,            /* Originating call blocking probability*/
       logic; /* Used for re-ordering control of the contents of the
Queue*/

       float temp;/* Used to change values that are variable in the
program*/
       float D_lp; /* Instant handoff inter-arrival time */

scanf ("%f",&temp);
mean_holding_time=240.0;
mean_sojourn_time=240.0;
mean_optimization_time=temp;
P_o=0.01; P_f=0.001;


MAX_Capacity=1;
PVC_BW=1000;
First_Run=1;


while (true)
{

fp=fopen("External_File.res","r");
/* initialization for generating independent streams of random
numbers */
  A1=   16801.0;
  A2=   16802.0;
  A3=   16803.0;
  A4=   16804.0;
```

```
  A5=   16805.0;
  M =  2147483647.0 ;
  r_seed1=1.0;
  r_seed2=2.0;
  r_seed3=3.0;
  r_seed4=4.0;
  r_seed5=5.0;

Sum_PVC_Holding_Time=0.0;

PVC_Capacity=1;
p=new(list); /* Create a time priority Queue */
p->next=NULL;
p->PVC_Expiration_Time=0.0;
front=p;
N_B=0;
N_T=0;
while (fscanf(fp,"%f",&D_lp) != EOF)
{

N_T=N_T+1;

/* subtract D_lp from the contents of the queue and delete values <=
0.0 */
    p=front;
    while (p !=NULL)
      {
     p->PVC_Expiration_Time=p->PVC_Expiration_Time-D_lp;
       p=p->next;
      }

   p=front;
 while (p != NULL)
       {
            if (front->PVC_Expiration_Time > 0) p=NULL;
               else
                 {
                      PVC_Capacity=PVC_Capacity-1;
                      front=p->next;
                      delete (p);
                      p=front;
                 }
        }


 if (PVC_Capacity==PVC_BW)  N_B=N_B+1;

 if (PVC_Capacity < PVC_BW)
  {
/* calculating the PVC_Expiration_Time and insert it in the queue */
   PVC_Capacity=PVC_Capacity+1;
        Call_Holding_Time=TM (mean_holding_time);
   Call_Optimization_Time=TZ(mean_optimization_time);
```

```
        N=geometric (P_f);
    Total_Sojourn_Time=TR(N,mean_sojourn_time);
        p=new (list);
        p-
>PVC_Expiration_Time=min(Total_Sojourn_Time,Call_Holding_Time,
        Call_Optimization_Time);
        Sum_PVC_Holding_Time=Sum_PVC_Holding_Time+p-
>PVC_Expiration_Time;
    if (front==NULL)
            {
             p->next=NULL;
             front=p;
            }
          else
{

        if (p->PVC_Expiration_Time < front->PVC_Expiration_Time)
          {
            p->next=front;
            front=p;
           }
else{
          logic=1; p2=front;p1=p2->next;
          while (p1 != NULL) {
                       if (p->PVC_Expiration_Time < p1-
>PVC_Expiration_Time) {
                                    logic=0;
                                    p->next=p1;
                                    p2->next=p;p1=NULL;}
                               else { p2=p2->next;p1=p2->next; }
                               }
if (logic==1) {p->next=NULL; p2->next=p;}
    }

}


}
if (First_Run == 1) {

 if (MAX_Capacity < PVC_Capacity) MAX_Capacity=PVC_Capacity; }

}


P_f_Simulation=N_B*1.0/N_T;


if (PVC_BW ==1) {printf ("PVC_BW=%d
                 Average PVC holding
time=%f\n",PVC_BW,Avg_PVC_Holding_Time)
                  ;return(0);}
if (First_Run==0) {
```

```
if (P_f_Simulation>P_f){printf("PVC_BW=%d
                        \n Average PVC  holding time=%f\n"
                         ,(PVC_BW+1), Avg_PVC_Holding_Time);
                          return(0);}
PVC_BW=PVC_BW-1;
Avg_PVC_Holding_Time=Sum_PVC_Holding_Time/N_T;

}

if (First_Run==1) {
First_Run=0;
PVC_BW=MAX_Capacity;
}

}

// return(0);
}




double TM (double TM1)
{
double rnd_TM;
r_seed2=fmod(A2*r_seed2,M);
rnd_TM=r_seed2*4.656612875e-10;
return -log(rnd_TM)*TM1;

}

double TZ (double TZ1)
{
double rnd_TZ;
r_seed3=fmod(A3*r_seed3,M);
rnd_TZ=r_seed3*4.656612875e-10;
return -log(rnd_TZ)*TZ1;

}


double TR (int N1,double TR1)
{
double rnd_TR,T_R; int k;
T_R=0.0;
for (k=1;k<= N1; k++)
   { r_seed4=fmod(A4*r_seed4,M);
     rnd_TR=r_seed4*4.656612875e-10;
     T_R=T_R+(-log(rnd_TR)*TR1);
   }
return T_R;
}
```

```
int geometric (double P_f1)
{
double rnd_geo;
r_seed5=fmod(A5*r_seed5,M);
rnd_geo=r_seed5*4.656612875e-10;

return int ( ceil(log(rnd_geo)/log(1.0-P_f1)) );

}

double min(double TR,double TM,double TZ)
{
double minimum;

minimum=TR;
if (TM < minimum) minimum=TM;
if (TZ < minimum) minimum=TZ;
return minimum;
}
```

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