Implementation & Evaluation of a Mobile Handover Protocol in Fairisle

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Abstract

Handovers for multi-media Wireless LANs (WLANs) have special requirements, unlike those in the public wireless networks. In this paper, the problems and challenges faced in a multi-media WLAN environment are presented and a multi-tier wireless cell clustering architecture is introduced. New design issues for multi-media handovers are specified and a fast, continuous and efficient hybrid handover protocol is proposed. A prototype of the proposed handover protocol is implemented into a Cambridge Fairisle ATM switch and the results are evaluated. We found that implementing transport mobility for a Wireless ATM environment is not practical as the cell re-routeing function is not scalable to increasing cell rate and to the number of mobile connections. It also changes the characteristics of the traffic. Instead, the data link layer mobility implementation is found to work well. The protocol provides symmetric data disruption to traffic flows in both directions and up to seventy five intra-cluster handovers can be supported in a second. Throughout the experiment, cells arrive in sequence with no cell loss observed during the handover, up to the capacity limit of the ATM switch.

1 Introduction

1.1 The Problems and Motivation

The fact that wireless cells have a limited coverage area means that a mobile host (MH) will be crossing through several wireless cells when it moves. This results in wireless cells switching. This switching is necessary to maintain connectivity to and the location tracking of the MH.

Handover is the process of passing the responsibility of communication connectivity from one base station (BS) to another. The resulting handover traffic is a function of many factors, such as the number of MHs, the size of wireless cells, the mobility profile of MHs, the desired channel capacity and the MH migration speed and direction. As the wireless cells size becomes smaller, signalling traffic as a result of handovers can be substantial. Hence, there is a need to reduce this handover traffic, so that more bandwidth can be devoted to data transfer. This calls for an efficient handover mechanism.

The wireless cells switching phenomenon tends to cause connectivity interruptions if the handover is not handled properly and quickly. In a wireless ATM (WATM) environment, multi-media services are to be provided to the MHs. Video and audio data are intolerant to delay and jitter and hence traffic interruptions as a result of the handover can be damaging. Therefore, other than an efficient way of providing handover, there is still a need to provide a continuous handover mechanism.

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The decreasing wireless cells size also results in the decrease of the wireless cells overlapping width. With the MH migrating at a certain speed and direction, there will come to a time when the handover mechanism cannot be completed within the time constraint imposed by the MH migration speed and the decreasing wireless cells overlapping width. Hence, a fast handover mechanism is required. The above therefore summarises the need for a fast, efficient and continuous handover mechanism.

1.2 Current Handover Schemes

A lot of work has been done on the mobility support for connectionless WLANs. An example is the IETF[1] Mobile IP[2] Group. One must not however rule out the possibility of a connection-oriented WLAN. If multi-media services are to be provided to MHs, one of the possibilities is to have a local wireless ATM (LWATM) [LM93] network.

Handovers can be initiated by the MH, the network or a combination of both. Several handover mechanisms have been suggested for MHs in a connection-oriented WLAN environment. They can be broadly classified under the full re-establishment, incremental re-establishment and multi-cast re-establishment based schemes.

The full re-establishment scheme requires a completely new connection to be setup from the source MH to the destination host. This is slow and inefficient. The incremental re-establishment scheme however requires only the establishment of a new partial path which connects to a portion of the original connection path and it also allows circuit reuse. Hence this scheme is fast and efficient. Finally, the multi-cast re-establishment scheme is fast but not necessarily efficient as the problems of ATM cell duplicates and the abundance of network bandwidth pre-allocation exist. The protocol proposed in this paper will be based on the incremental re-establishment scheme.

This section explains the need for a fast, efficient and continuous handover for multi-media WLANs and also highlights briefly the existing handover schemes. Section 2 presents a multi-tier wireless cells clustering architecture which exploits the advantage of locality and the concept of crossover switch discovery to provide fast and efficient handovers. The handover protocol design issues are listed in section 3, followed by a description of the proposed hybrid handover protocol in section 4. Section 5 presents the implementation details. Finally, section 6 presents the experimental results of the handover protocol. Issues regarding mobile location management and handovers between WLANs are outside the scope of this paper.

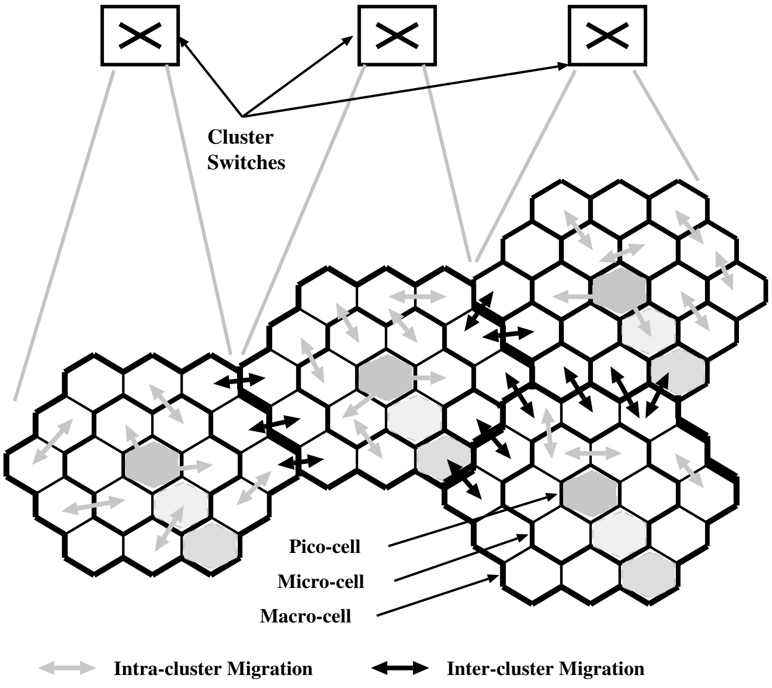
2 Multi-tier Wireless Cells Clustering Architecture

2.1 Principle

To exploit the advantage of locality, a multi-tier wireless cells clustering architecture is proposed. As shown in Figure 1, a cluster is a collection of BSs which are connected to a cluster switch. MHs migrations occurring under the coverage of the cluster switch are known as intra-cluster migrations, while those occurring between clusters are called inter-cluster migrations. The clustering of wireless cells and the grouping of BSs to cluster switches result in a distributed mobile handover management, location management and call admissions control architecture.

The grouping of BSs to a cluster switch results in fast handovers for MHs with intra-cluster migrations. This is so as the handover management entity resides in the cluster switch which is only a single hop away from the BS. Hence, a cluster of wireless cells is the region where fast handovers can be achieved and where handovers can occur most frequently.

[1] Internet Engineering Task Force
[2] Internet Protocol



1(b)

Figure 1: Concept of Intra and Inter-cluster Migration.

Inter-cluster handovers as a result of MHs migrations between macro-cells give rise to slower handovers, since the handover management entity is performed by a switch in the backbone network.

Compared to the clustering architecture mentioned in [I93], though the similar concept of micro-cells and macro-cells are being used, in our architecture, fast handovers occur when the MH crosses the micro-cells boundaries while slightly slower handovers occur for MHs crossing macro-cells boundaries. This is different from the idea of having high mobility users undergoing handovers over macro-cells boundaries and having lower mobility users undergoing handovers over micro-cells boundaries.

2.2 Crossover Switch Discovery

As mentioned in Section 1, the incremental re-establishment scheme allows the BS to setup a new partial path instead of a completely new path. The node where the convergence occurs (i.e. the point where the new partial path meets the old connection path) is called the crossover switch (CX). The purpose of the CX discovery mechanism is to derive a minimum-hop new partial path with reasonable circuit reuse efficiency by locating a suitable CX. Investigations into algorithms that govern the selection of a CX and the effects of network topology on CX discovery are currently in progress.

CX discovery is only invoked for inter-cluster handovers, where the CX is a switch in the backbone network. For intra-cluster handovers, the cluster switch is the CX, and hence no CX discovery needs to be invoked. The need to cater for both intra and inter-cluster handovers results in a hybrid handover protocol.

3 Handover Protocol Design Issues

The following is a list of the various important issues to be considered in a fast, efficient and continuous handover protocol design.

- Scalability
- Robustness of Protocol
- Cell Loss & Sequencing
- Exploitation of Locality
- Exploitation of Radio Hint
- Handover Requests Queueing
- Resource Reuse (Efficiency)
- Mutually Exclusive Handovers
- Exploitation of Personality
- Traffic Disruption Symmetry
- Consideration For Data Looping
- Mobile Quality of Service (QoS)
- Service Traffic Characteristics
- Service Disruption Time (Continuity)

4 Hybrid Handover Protocol

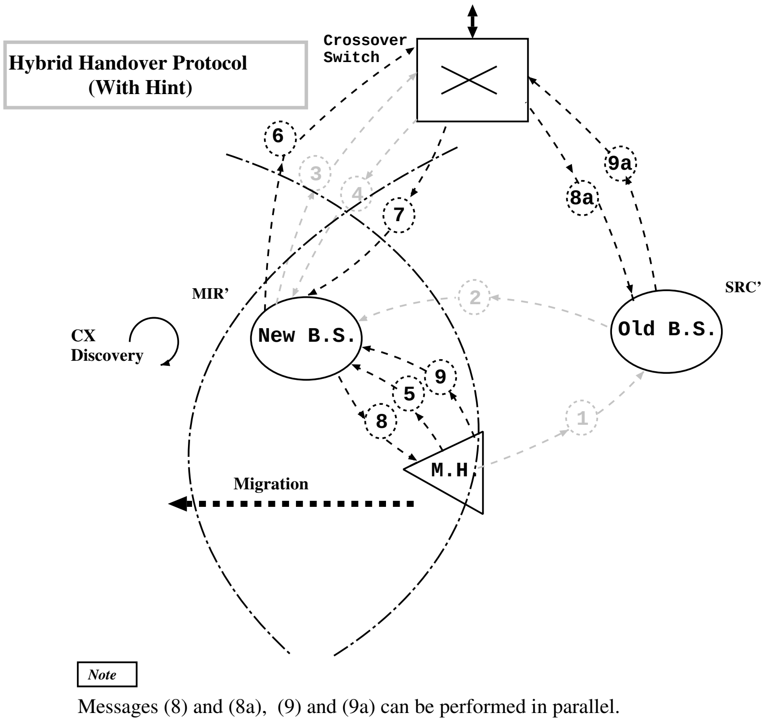
4.1 Handover With Radio Hint

4.1.1 Control Flow

Referring to Figure 2, the with-hint handover protocol allows advance set-up to be made. When the MH receives the beacons from the new BSs, after a certain signal threshold level, the MH sends a handover $hint_{(1)}$ message to the current BS (SRC). This results in the SRC sending a handover $invoke_{(2)}$ message , which contains the MH existing list of connections, to the target BS (MIR).

The MIR then determines if the handover is "intra" or "inter". For intra-cluster handovers, the cluster switch is the crossover switch (CX). No CX discovery needs to be invoked. However, if the next-cell beacon flag signifies an inter-cluster handover, the CX discovery process is invoked to compute the location of CX. New partial paths are then setup from the MIR to the CX. This is denoted by $set\text{-}up_{(3)}$ and $status_{(4)}$. Hence, by the time the MH enters well into the overlap region, the new partial paths have already been established.

The MH will now command the MIR to initiate a handover via the $greet_{(5)}$ message. This causes the MIR to send a connection $redirection_{(6)}$ message to the CX, so that the ATM cells can now be re-routed over the new path. This mechanism avoids the "sudden withdrawal" problem of the MH, i.e. if the MH suddenly withdraws from entering the new cell, time-outs will abolish all the newly created partial paths. Once the CX has performed the redirection, it informs the SRC to disconnect the old partial paths. If the SRC does not receive the $disconnect_{(8a)}$ message from the



(b)

Figure 2: With-Hint Handover Protocol

CX, it will time-out. Likewise, if the MIR does not receive the $greet_{(5)}$ message from the MH, it will time-out and the handover process is aborted. If the cell redirection operation is successful, an $acknowledgement_{(7)}$ message is returned to the MIR. MIR then informs the MH (via *greet-ack*$_{(8)}$), giving the service parameters of the newly created partial connection. This facility allows the provision of QoS - where the MH is informed about the connection status and quality so that the appropriate actions can be taken (such as degradation of QoS) by the mobile application.

Finally, the MH returns a $done_{(9)}$ message to the MIR, indicating that it is now ready to receive and transmit data via the new BS. Due to the advance set-up and the use of buffering at the BSs and CX, handovers can now be done quickly and seamlessly.

4.1.2 Data Flow

A connection is a bi-directional path for the transfer of information between two end communicating entities. During a handover, both the upstream and downstream data flows are affected. The data flow is analysed below, with reference to Figure 3.

Considering the upstream data flow, before a handover, the MH transmits data via the SRC and CX to the destination host. Upon a handover, the $greet_{(5)}$ message is sent and the MH starts to queue the transmitting data in its upstream buffer, until the MIR responds with an $acknowledgment_{(8)}$ message. This is the upstream traffic disruption period. Thereafter, the upstream data flow resumes over the new wired and wireless segment.[3]

For the downstream case, prior to the handover, the downstream data flows from the destination host through the CX and SRC to the MH. During a handover, the downstream data flow is

[3]The mobile application needs not re-create a socket during handover. The same mobile VCI is used. The new wired segment mentioned here still supports the original source-destination connection.

Hybrid Handover Protocol With Radio Hint

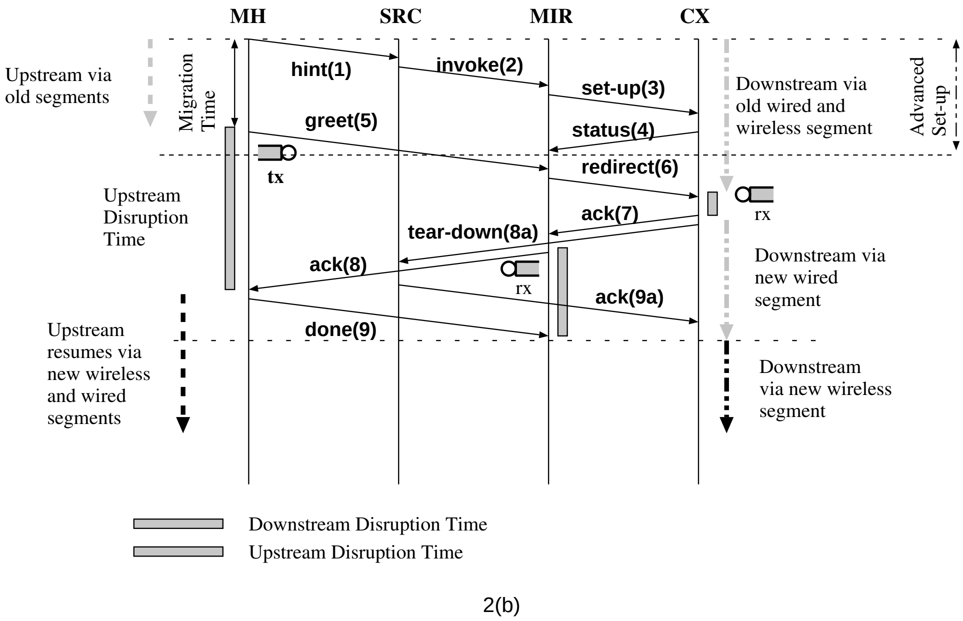


Figure 3: With-Hint Protocol Data Flow Diagram

disrupted at the point when the $redirect_{(6)}$ message is received at the CX. Once the cell redirection is successful, the downstream data flow resumes through the new wired segment and is buffered at the MIR until it receives a $done_{(9)}$ message from the MH (this is the downstream disruption experienced by the MH). Thereafter, the MIR flushes its downstream buffer and the data now flows through the new wireless segment.

5 Prototype Implementation

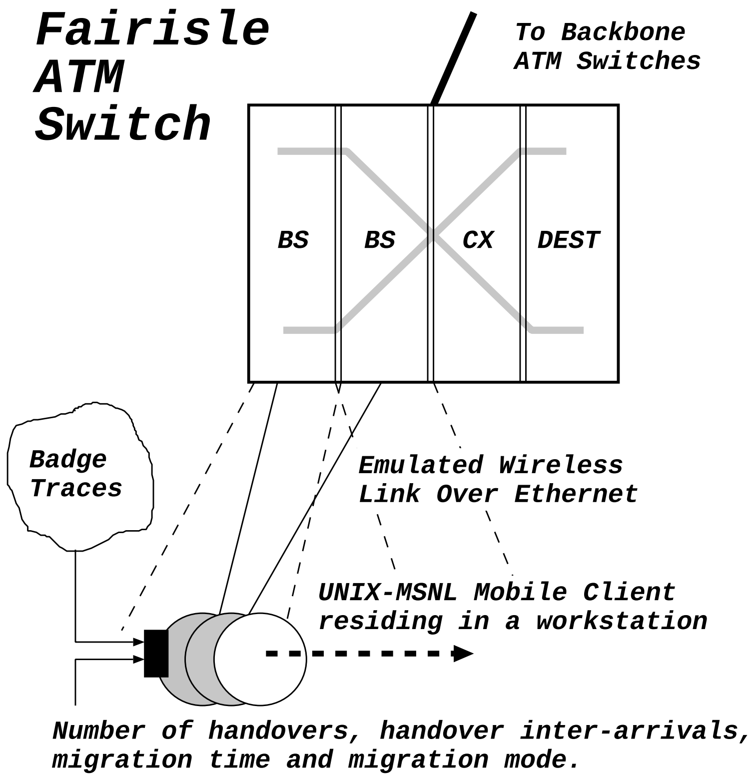
5.1 Experimental Environment

A prototype of the proposed with-hint handover protocol is implemented into a Cambridge Fairisle ATM switch. The switch has an eight-by-eight crossbar fabric, eight port controllers with TAXI[4] transmission interfaces and an Ethernet gateway. The port controllers (PCs) each runs Wanda [M.J92], a micro-kernel developed to support multi-media. The protocol stack used to support inter-process communication is based on Multi-Service Network Architecture (MSNA) [McA90]. MSNA defines MSNL and MSDL[5] protocols. Console outputs of individual PCs can be observed via serial link interfaces. The ARM 3 processor used in the PC is clocked at 25 MHz and the fabric is clocked at 18 MHz. Further details about the switch construction is found in [Gro94].

5.2 Prototype Model

The mobile network prototype model is shown in Figure 4. Mobility software for the SRC, MIR, CX and DEST are respectively downloaded into separate PCs of the ATM switch, along with a complete copy of Wanda and the signalling code. When the PC boots, the BSs, DEST and CX

[4]Transparent Asynchronous XCVR Interface
[5]MSNL - Multi-Service Network Layer; MSDL - Multi-Service Data-Link Layer



5(a)

Figure 4: The Mobile Network Prototype Model

mobility software are executed. A MH is a UNIX-MSNL client. This is so because we want to have control over when the handover should occur and the frequency at which they occur. This also allows the feeding of the Active Badge System [WH92] mobility traces of individual badge wearer to the mobile client. This emulate realistic occurrence of handovers. The prototype supports two modes of experimentation, namely upstream and downstream modes. This will be elaborated in Section 7.

5.3 The Mobility Software

5.3.1 Mobile Protocol Stack

In the mobile protocol stack, the mobile connection management is supported by the wired ATM connection management. The mobile connection manager hides the mobility functions from the application via a mobile communications interface. The mobile connection manager supports both end-to-end and partial connections and handover management. Note that the BSs, CX and MH mobility software are different. In particular, the CX software has the capability to perform cell re-routeing.

5.3.2 Cell Redirection (CR) Module

The essential element of the handover entity is the CR module. It resides in the CX and is responsible for ATM cells re-routeing from the old SRC-CX path to the new MIR-CX path during handovers. Here, we have implemented the CR module in both the transport and the data link layers and its performance at these layers is evaluated.

- **Single Thread Suck-Spit CR Module**

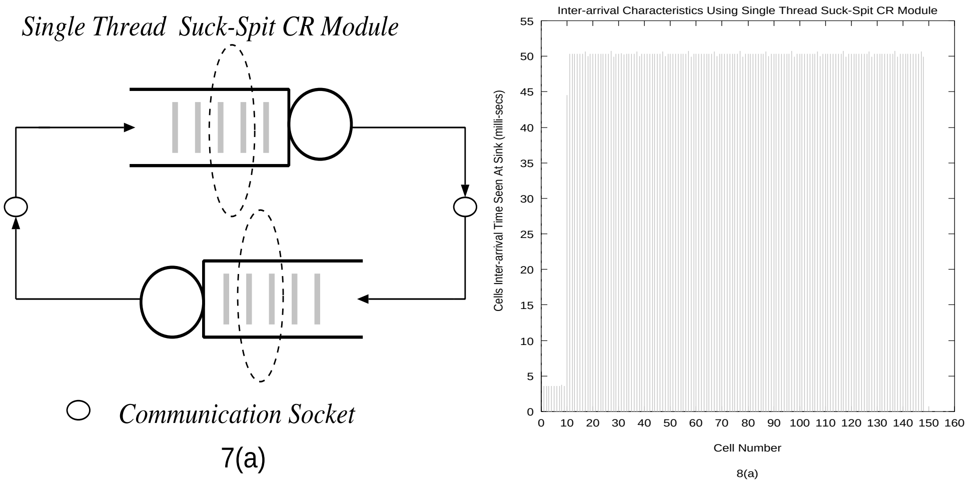


Figure 5: Single Thread Cell Redirection (CR) Module and Its Effects on Cell Inter-arrivals

The single thread CR module shown in Figure 5a is implemented to receive incoming cells from one socket and to resend them over another. To avoid copying the cell into user space, only the cell buffer handler is stored. The cell inter-arrivals at the sink are shown in Figure 5b, with the source transmitting ATM cells at 50 msecs interval. The initial low inter-arrival times are due to cells arriving before the redirection thread gets activated. Once the thread gets its time slice, it flushes the cell buffer, one cell after the other. It then starts to receive and send cells at regular intervals, with characteristics similar to that of the traffic source. However, with increasing cell rate, it comes to a point where the "suck-spit" thread fails to keep in pace with the cell arrivals, resulting in the kernel running out of IO buffers. This causes the cell forwarding (CF) process to halt.

- **Double Threads Suck-Spit CR Module**

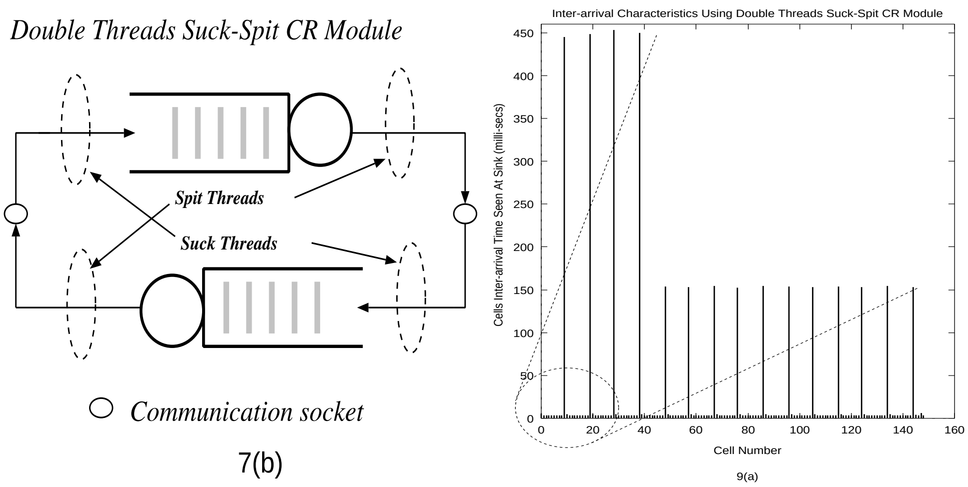


Figure 6: Double Threads Cell Redirection (CR) Module and Its Effects on Cell Inter-arrivals

Earlier work on mobile handovers and connection management using this redirection module in an ATM environment was performed by [Bis94]. Here, we investigate further the practicality of this CR mechanism.

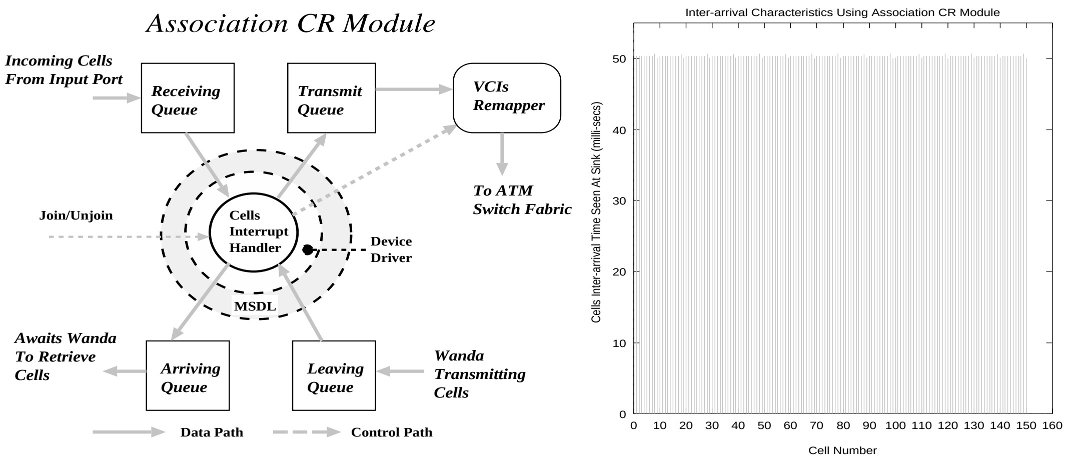
As shown in Figure 6a, one thread is used to receive incoming cells from one socket and place the cell buffer handler into a queue while another thread extracts the handler from the queue and sends the cell out on another socket. Again, a 50 msecs ATM cell transmission interval is used and the cell inter-arrivals are measured. The result in Figure 6b shows that a long lapse exists between cell arrivals, i.e. cells now arrive in bursts.

This can be explained as follows. When the "suck" thread is active, cells are accumulated in the kernel buffer and when the "spit" thread becomes active (the "suck" thread inactive), all the cells accumulated are now transmitted back-to-back, explaining the burst of low cell inter-arrivals. When the "suck" thread gets active again, the process repeats. With increasing cell rate, the effect of the threads switching [Tan94] is less obvious but again, it comes to a point where the CR threads can no longer keep in pace with the increasing cell arrivals, causing the CF process to fail. Hence, the results show that implementing CR module using double threads suck-spit buffers changes traffic characteristics and is unacceptable. Furthermore, this CR mechanism does not scale well with an increasing number of mobile connections[6]. The CF process also fails on increasing cell rate. Given these encounters, we implemented the CR mechanism at the data link layer (i.e. ATM Layer), where the ATM cells are now re-routed at fabric speed (since cells in the switch queues now are serviced via fast CPU interrupts).

- **Associations Join/Unjoin CR Module**

To achieve practical CR and CF operations, the wired ATM connection management code residing in the Wanda kernel is modified so that these operations can occur at the data link layer. Here,

[6]Four threads are required for each mobile connection.



10(a) 10(b)

Figure 7: Association Cell Redirection (CR) Module and Its Effects on Cell Inter-arrivals

the re-routeing latency is only once per handover, not for every cell in the “suck-spit” case. This implementation allows the mobile signalling manager to invoke the “join” and “un-join” operations of two data link associations during a handover. The “unjoin-join” operation causes the cells from one receiving queue to be forwarded to the appropriate outgoing queue, with VCIs remapping performed (see Figure 7a). The binding of the earlier pair of associations at the CX is now unchained and the outgoing association is now re-chained with the new incoming association formed by the new MIR-CX partial connection.

The cell inter-arrivals in Figure 7b clearly show that the “join” operation is independent of the threads scheduling and the cell arrivals characteristic resembles that of the source. More importantly, with increasing cell rate, the CF mechanism does not fail until the capacity limit of the switch has been reached.

6 Results & Observations

Various performance parameters associated with mobile handovers were evaluated. They included cell loss and sequencing, traffic disruption time, buffer size, cell redirection time, backbone protocol signalling time, connection establishment time and connection release time. The upstream and downstream experimental set-up is shown in Figure 8.

The sections below describe each of these parameters obtained for unidirectional handovers experiments using constant bit rate (CBR) traffic at 73.28 Mbs [7]. A hundred handovers (with an inter-arrival of one second) for a single mobile with a single connection were performed before the results were recorded. “Zig-zag” handovers were also performed to evaluate the robustness and correctness of the protocol.

[7] In terms of data portion of the ATM cell only. A lower data rate can be used. However, the purpose here is to emulate a heavily loaded mobile environment, where BSs are busily serving multiple MHs. This also provides an appropriate environment to evaluate cell loss during handovers.

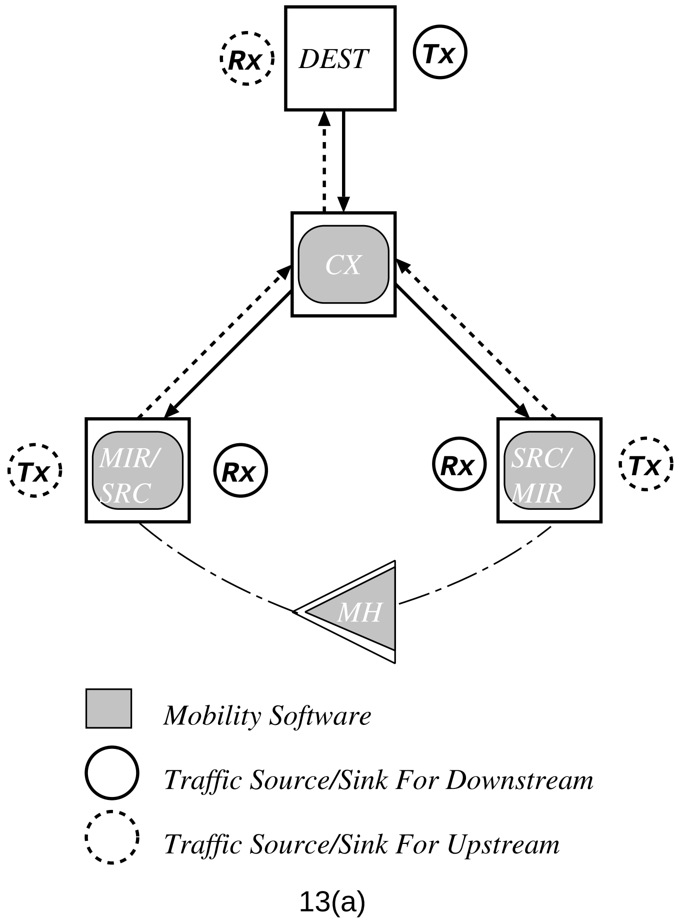


Figure 8: Upstream & Downstream Experimental Set-up.

6.1 Unidirectional Handovers

6.1.1 Upstream Mode

In the upstream mode, the MH issues the $hint_{(1)}$ message to the SRC to invoke the SRC handover protocol state machine. The SRC traffic generator is also triggered, which starts sending ATM cells of a unique data value to the DEST via the CX. The SRC then sends an $invoke_{(2)}$ message to the MIR, causing the MIR protocol state machine to be invoked. After some migration time, the MH issues a $greet_{(5)}$ message to the MIR, causing the MIR traffic generator to start sending ATM cells of a different data value to the DEST. This enables the DEST to discriminate the origin of the arriving cells.

- **Upstream Disruption Time At MH**

The upstream disruption time experienced by the MH was measured. This is also the MH transmit hold time. To maintain data consistency, a hundred unidirectional upstream handovers were performed, with the timings measured at the UNIX-MSNL mobile client at low Ethernet traffic.

Let T_{upmh} and T_{updest} be the upstream disruption experienced by the MH and the DEST respectively. Let T_{hold} be the MH upstream data transmit hold time, $T_{greet_{(5)}}$ be the time when the MH sends the greet message and $T_{ack_{(8)}}$ be the time when the MH receives the acknowledgement

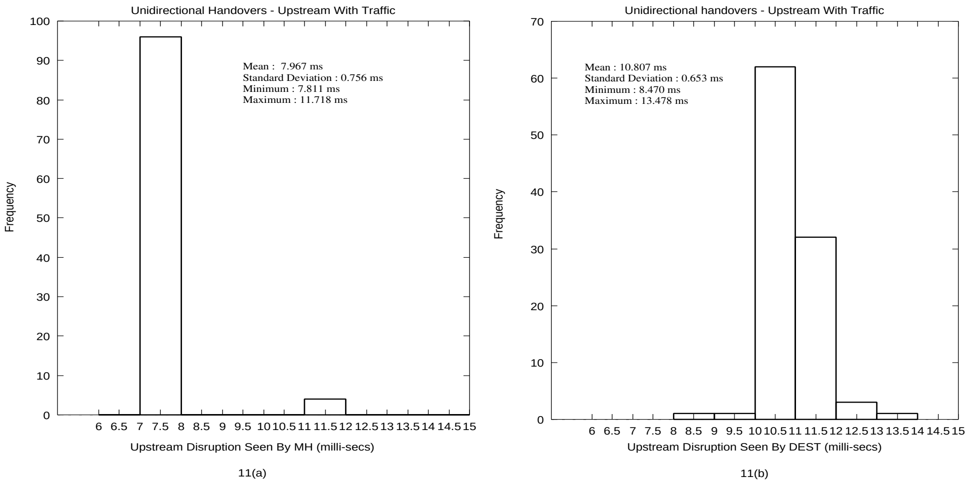


Figure 9: Upstream Traffic Disruption Experienced by the MH and the DEST Port Controllers.

message from the MIR. Let "$\rightsquigarrow$" represent the time span from one event to another. Therefore,

$$T_{upmh} = T_{hold} = \left\{T_{greet_{(5)}} \rightsquigarrow T_{ack_{(8)}}\right\} \tag{1}$$

Figure 9a shows that T_{upmh} has an average value of 7.967 msecs.

- **Upstream Disruption Time At DEST**

T_{updest} is defined as the time difference between the last cell (from the SRC) and the first cell (from the MIR) arriving at the DEST.

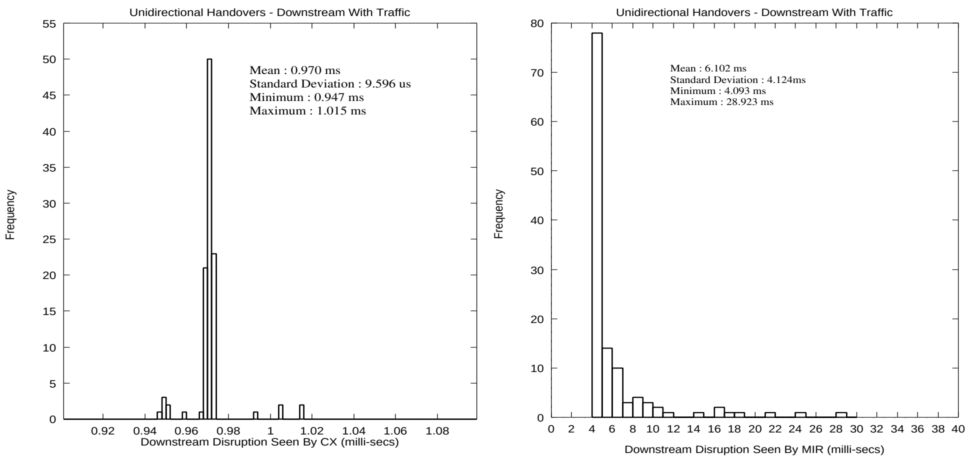
Figure 9b shows that T_{updest} has an average value of 10.807 msecs. T_{updest} is observed to be greater than T_{upmh}. This is due to the latencies associated with the transmission over the links, the overhead in discriminating the cells, the dependency on the data rate and the delay incurred in the transmission of an explicit signal to stop the SRC traffic generator when the MH switches between wireless cells. Currently, the DEST is two hop away from the traffic generators and data are transmitted at 73.28 Mbs. Beyond this cell rate, little time will be available to any Wanda processes [RBM94].

6.1.2 Downstream Mode

In this mode, the traffic sink and source components were interchanged. After the MH, SRC, MIR and DEST had established both the signalling and mobile connections, the DEST PC began to transmit ATM cells to the SRC PC via the CX. Upon a handover, ATM cells were re-routed to the MIR PC.

- **Cell Loss & Sequencing**

The cell arrival sequence for both upstream and downstream cases were observed (at the SRC, MIR and DEST PCs) by sending ATM cells with an incremental data value. Cell loss here refers to the loss of cells arriving at the MIR (downstream case) and the DEST (upstream case) after the handover CR operation. Cell loss as a result of delay in the radio transmission and reception links cannot be evaluated here. Throughout the experiment, cells arrived in sequence, with no cell loss observed, up to the capacity limit of the ATM switch.



(a) 12(b)

Figure 10: Downstream Traffic Disruption Experienced by the CX and the MIR Port Controllers.

- **Downstream Disruption Time**

Since there was no global clock associated with the PCs, the downstream disruption time could not be measured by the time difference between the last cell arriving at the SRC and the first cell arriving at the MIR. Instead, the disruption time seen at the CX and the MIR PCs were measured individually (see Figure 10). The summation of these two measurements then gives the downstream disruption time. Let T_{downmh}, T_{downcx} and $T_{downmir}$ be the downstream disruption time experienced by the MH, CX and MIR respectively. From Figure 3, we deduce that :

$$T_{downmh} \simeq T_{downcx} + T_{downmir} \tag{2}$$

From Figure 10a and 10b, T_{downmh} has an average value of 7.036 msecs. This time is quite close to T_{upmh}. To verify that our protocol provides data disruption symmetry for both upstream and downstream traffic, we present below a simple numerical analysis. Let $T_{greet(5)}$, $T_{redirect(6)}$, $T_{ack(7)}$, $T_{ack(8)}$, and $T_{done(9)}$ be the time required to send out the respective signalling messages. Referring back to Figure 3, we deduce that :

$$\begin{aligned} T_{upmh} &= T_{greet(5)} + T_{redirect(6)} \\ &\quad + T_{redirect(6)} \rightsquigarrow T_{ack(7)} \\ &\quad + T_{ack(7)} + T_{ack(8)} \end{aligned} \tag{3}$$

$$\begin{aligned} T_{downmh} &= T_{redirect(6)} \rightsquigarrow T_{ack(7)} \\ &\quad + T_{ack(7)} + T_{ack(8)} \\ &\quad + T_{done(9)} \end{aligned} \tag{4}$$

Therefore $T_{upmh} - T_{downmh} = T_{redirect(6)}$[8] , i.e. the time difference is a messaging time component over the high speed wired link. This explains why T_{upmh} is slightly greater than T_{downmh} and it also infers data disruption symmetry, as compared to the highly asymmetric handover protocol implementation in [Bis94].

[8] We assume that the messaging time of each of the messages over the respective wireless or the wired network to be the same.

Buffer Size (Kbits) :	Min	Mean	Max
CX	0.363	0.372	0.389
MIR	1.572	2.329	9.389
MH	2.999	3.059	4.499

Table 1: Buffering Requirements at MH, CX and BS.

Parameters	Time (Average)
Suck	23.019 msecs
Spit	20.718 msecs
Join	175 μsecs
Unjoin	492 μsecs
Partial Path Set-up	5.785 msecs
Partial Path Tear-down	1.768 msecs
Backbone Signalling at SRC	13.277 msecs
Backbone Signalling at MIR	16.374 msecs

Table 2: Common Parameters

6.2 Common Parameters

The parameters stated in Tables 1 and 2 are common to both upstream and downstream handover modes. We will analyse them individually.

- **Buffer Size**

The buffering requirements at the CX, BS and MH during a handover can be computed from the following relationships :

$$\begin{aligned} Buffer\ Size\ (CX) &= T_{downcx} * Data\ \ Rate \\ Buffer\ Size\ (MIR) &= T_{downmir} * Data\ \ Rate \\ Buffer\ Size\ (MH) &= T_{hold} * Data\ \ Rate \end{aligned}$$

For a compressed video stream of 384 Kbs [Ray93], the buffering requirements will be that in Table 1. Due to latencies associated with the wireless links, the buffer size for the MIR and the MH are larger than that for the CX.

- **Cell Redirection Time**

For comparison purpose, the average "double threads suck-spit" time was included, which was observed to be much slower when compared to the "join-unjoin" time of 667 μsecs. The "unjoin" time was larger since it was implemented as a IOCTL call to the Wanda kernel, unlike the IPC system call in the "join" case. As expected, the "suck" and "spit" times revealed that they were affected by the thread scheduler, with characteristics similar to that in Figure 6b.

- **Partial Path Set-up & Tear-down Time**

The average time required to perform a single hop partial path set-up (T_{setup}) is 5.785 msecs while the average tear-down time (T_{tear}) is only 1.768 msecs. This shows that the setting up of a new path requires significant time and hence CX discovery is needed to compute the optimised path (least hops) so that this set-up time can be kept low.

- **Backbone Signalling Time**

The backbone signalling time indicates how fast the backbone network can perform the handover. At the SRC, $T_{srcback}$ is the time when the $hint_{(1)}$ message is received till the time when the old partial path is disconnected by the SRC. $T_{srcback}$ has an average value of 13.277 msecs, which can be verified by the relationship : $T_{srcback} \simeq T_{mhup} + T_{setup}$. Hence, about 75 intra-cluster handovers can be supported in a second. At the MIR, $T_{mirback}$ is the time span between receiving the $invoke_{(2)}$ and the $done_{(9)}$ messages. $T_{mirback}$ has an average value of 16.374 msecs, which can be verified by the relationship : $T_{mirback} \simeq T_{downmh} + T_{setup} + T_{migration}$[9].

6.3 Zig-Zag Handovers

"Zig-zag" handovers were performed to evaluate the robustness and correctness of the handover protocol under the conditions of random mobile movements, such as when the MHs moved in a forward and backward fashion over the wireless cells overlapping zone. "Zig-zag" handovers caused the BSs to invoke the appropriate SRC or MIR protocol state machine to support the handover. Throughout the experiment, "zig-zag" handovers could be performed without failures.

7 Conclusion

In this paper, the problems and challenges faced in a connection-oriented Wireless LAN environment are presented. In particular, there is a need for a fast, efficient and continuous handover mechanism. To cater for both high and low mobility and to exploit the advantage of locality, a multi-tier wireless cells clustering architecture is proposed. To support fast, efficient and continuous handover, a hybrid handover protocol based on the incremental re-establishment scheme and the concept of crossover switch discovery is introduced.

The hybrid handover protocol is designed to exploit the advantage of radio hint, with considerations given to circuit reuse efficiency, quality of service, scalability, traffic continuity, traffic disruption symmetry, cell loss and sequencing, data looping, robustness, and radio link failures. The results obtained from the prototype implementation of the with-hint handover protocol reveal that implementing cell redirection mechanism at the transport layer using suck-spit buffers is not feasible, as it changes the traffic characteristics and fails at higher data rates. The data link layer implementation however does not change the traffic characteristics and is able to perform cell forwarding and re-routeing operations up to the capacity limit of the ATM switch.

From the results of the upstream and downstream handover experiments, traffic disruption symmetry is observed. No cell loss is discovered and cells arrive in sequence after the handover. Based on the traffic disruption present at the mobile host, the crossover switch and the base stations, the buffering requirements at these nodes are derived and are found to be within implementation limits. In addition, "zig-zag" handovers can be performed without any failures.

Further work include implementing the protocol in a Wireless ATM environment (so that the advantage of radio hint can be realised) and on a ATM backbone network of reasonable size (so that inter-cluster handovers and crossover switch discovery can be evaluated). In addition, QoS issues during handovers require further investigation.

[9]The MH migration time here refers to the time when the $hint_{(1)}$ message is sent to the SRC till the time when the $greet_{(5)}$ message is sent to the MIR and this must be $\geq T_{setup}$.

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