A Scalable Wireless Virtual LAN

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Abstract

This paper presents a Wireless Virtual Local Area Network (WVLAN) to support mobility in IP-over-ATM networks. Mobility is handled by a joint ATM-layer handoff for in-session mobility and MAC-layer handoff for inter-session mobility, such that the effects of mobility are localized and transparent to the higher-layer protocols. Different functions, such Address Resolution Protocol (ARP), mobile location, and ATM connection admission are combined to reduce front-end delay for connectionless packet transmission in connection-oriented ATM networks. The proposed WVLAN, through the use of ATM technology, provides a scalable wireless virtual LAN solution for IP mobile hosts.

1 Introduction

Current shared media Local Area Networks (LANs) are experiencing performance bottlenecks and management difficulties. Asynchronous Transfer Mode (ATM) technology promises to alleviate these problems by supporting *Virtual LANs (VLANs)*. This will offer LAN users better performance, and also provide LAN administrators increased flexibility to move and locate hosts as needed.

ATM can be introduced in LANs by installing ATM interface cards in end hosts, and connecting these hosts to ATM switches. However, since not all end hosts can be immediately upgraded, it is important to support end hosts with non-ATM interfaces on these ATM-based VLANs. Since Internet Protocol (IP) networks and ethernet LANs are commonly used, three IP-over-ATM models, *LAN Emulation (LANE)*, *Classical IP-over-ATM*, and *Routing-Over-Large-Clouds (ROLC)*, have been proposed [1]. These networking solutions allow for the interconnection of legacy LANs, consisting of end hosts with ethernet or other non-ATM interfaces, with end hosts that have ATM interfaces. This is done by using routers (that convert IP packets to ATM cells and vice versa) or bridges (that convert MAC frames to ATM cells and vice versa).

In this paper, we consider *the problem of supporting wireless end hosts on IP-over-ATM networks.* Mobility management procedures are required to ensure that the network can handle mobile hosts. One solution is to extend the three IP-over-ATM models to provide this capability of handling mobile hosts. Given that Mobile IP [2] has been defined to handle mobility management at the IP layer, the IP-over-ATM models can be readily extended to handle wireless end hosts.

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There is an alternative to the above-stated approach of starting with the IP-over-ATM models, and extending these models to handle mobility at the IP layer. In this alternative, one can start with a wireless ATM networking solution, and add the capability of handling IP in such networks. In such an alternative, mobility will be handled at the ATM layer rather than at the IP layer. This approach has *two* advantages. *First,* packet delay performance will be better on a connection rerouted (due to a handoff) at the ATM layer instead of the IP layer. *Second,* if the ATM-layer handoff procedure can ensure sequenced cell delivery through a handoff, IP packets will not arrive out of sequence. This will improve the performance of TCP and other higher-layer protocols. We adopt this alternative approach for the problem of networking mobile (and fixed) end hosts using IP-over-ATM networks.

The wireless ATM networking solution we begin with is called Broadband Adaptive Homing ATM Architecture (BAHAMA) [3] [4]. BAHAMA is a wireless ATM LAN used to interconnect wired and wireless, fixed and mobile, end hosts *with ATM capability.* Figure 1 shows the BAHAMA LAN architecture. It consists of Portable Base Stations (PBSs) interconnected in an ad-hoc manner (using arbitrary topologies). A *PBS* is a network node that *combines radio-port functionality* of supporting air interfaces (radio or infrared) for wireless communication, along with *ATM switching functionality.* It also provides a mechanism to buffer ATM cells during handoffs to support mobility of end hosts that are engaged in active connections. This allows the BAHAMA network to ensure sequenced cell delivery through handoffs.

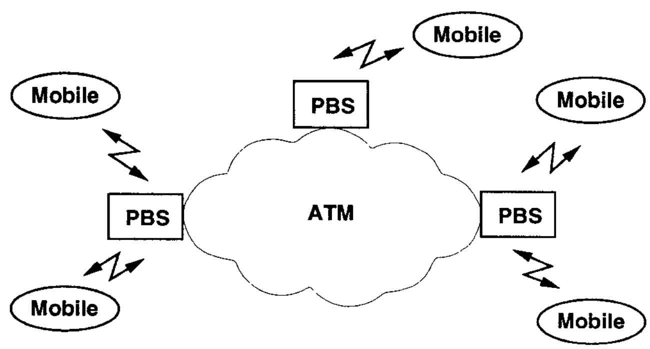

Figure 1: Network architecture of the BAHAMA LAN and the WVLAN.

In designing the networking algorithms of BAHAMA, we did not treat IP differently from any other native-mode application of ATM. However, to transport IP packets over ATM, specific problems need to be addressed. These include:

- the address resolution problem resulting from the different addressing formats used in IP networks and ATM networks;
- the difficulty in supporting broadcast communication required by Address Resolution Protocol (ARP) used to resolve IP addresses to MAC addresses; and
- the problem of having to set up and release ATM connections to transport "connectionless" IP packets.

In this paper, we provide a solution for these specific problems of IP-over-ATM, along with the mobility management problem of supporting wireless end hosts. Our solution is a modified version of BAHAMA, called the *Wireless Virtual LAN (WVLAN)*, designed to support mobile (or fixed) end hosts *without ATM capability*. The wireless hosts are assumed to have standard air interfaces, such as IEEE 802.11 [5], and the wired hosts are assumed to have ethernet interfaces. WVLAN thus overcomes a drawback of BAHAMA which requires that all mobile hosts have wireless ATM capability. WVLAN is a research prototyping network under development at Bell Labs.

WVLAN is a network of Portable Base Stations (PBSs) as shown in Fig. 1. A WVLAN PBS has IEEE 802.11 interface cards (instead of BAHAMA air interface cards) and an ATM switching fabric. It also provides proxy agent functionality on behalf of non-ATM end hosts for functions, such as ARP (Address Resolution Protocol), AAL (ATM Adaptation Layer), etc.

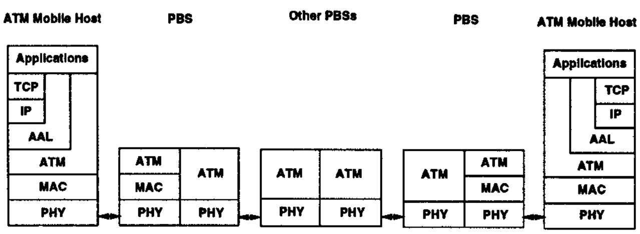

Figure 2: The protocol stack of the BAHAMA LAN.

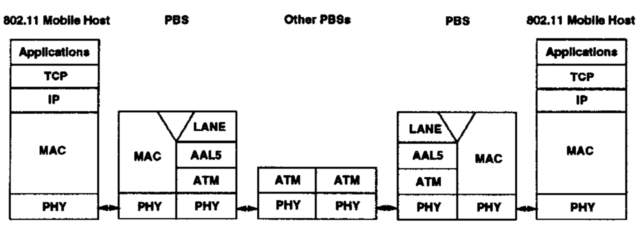

Figure 3: The protocol stack of the WVLAN.

Figures 2 and 3 show the protocol stacks of the BAHAMA LAN and the WVLAN, respectively. In BAHAMA, end hosts communicate with end-to-end ATM. In WVLAN, end hosts communicate through hybrid paths consisting of IEEE 802.11 links and ATM connections. WVLAN supports the LANE model for transporting IP packets over ATM. Thus, MAC frames received from non-ATM hosts are segmented into ATM cells at an *origination PBS*, transmitted over an ATM connection within WVLAN, reassembled at a *destination PBS* into a MAC frame, and then sent over the shared medium air interface, where the MAC frame is received by the destination end host. Subsequent enhancements will be made to enable the WVLAN to support the ROLC and the Classical IP-over-ATM models. While WVLAN PBSs offer MAC-ATM bridging, we note that HIPERLAN 1 [6] provides a possible alternative solution with built-in forwarding at the MAC level. The relative advantages and disadvantages of WVLANs and HIPERLAN 1 will be addressed in a subsequent paper on this subject.

In general, implementations of wireless ATM networks should support both types of end hosts (with and without ATM capability). To accomplish this, both a BAHAMA PBS and a WVLAN PBS must coexist on the same network. However, for purposes of this paper, we describe how the mobility and connection management schemes proposed in BAHAMA are adopted for WVLAN, where a two-party end-to-end communication path consists of two non-ATM segments and an ATM connection extending between PBSs. Generalization of these schemes for communication paths between one ATM host and one non-ATM host, as would occur in network implementations supporting both BAHAMA and WVLAN end hosts, will be addressed in a later paper.

The basic networking concept and other preliminary information regarding WVLAN are described in Section 2. Section 3 describes our algorithms for handling address resolution, connection admission and release, bridging (packet forwarding), and mobility management for IP-over-ATM communications. Our conclusions from the work are presented in Section 4.

2 Preliminaries

In this section, we first explain how the WVLAN emulates "connectionless" networking using ATM, a feature originally designed for the BAHAMA LAN to simplify handoffs. Next, we describe how IEEE 802.11 MAC-ATM interworking is done in WVLAN. Finally, we list the data tables assumed in the PBSs, and the types of signaling channels used to transport mobility and connection management messages. The information presented in this section will be used in the descriptions of the WVLAN algorithms presented later in this paper.

2.1 Emulation of connectionless networking

ATM is a connection-oriented technology. In mobile networks, as endpoints move, segments of connections need to be torn down and reestablished. Different handoff schemes have been proposed for ATM networks [7]. Connectionless networks avoid this problem of having to tear down and set up segments as mobile hosts move. Instead, in connectionless networks, handoffs are accomplished by simply placing forwarding pointers for the mobiles as they move. Having observed this suitability of connectionless networking to support mobility, we developed the networking concept in

BAHAMA, which we have adopted in WVLAN, to emulate connectionless networks using ATM technology.

VPIs are assigned as addresses of network nodes (PBSs). All cells with a given VPI are routed to the same destination PBS. This is accomplished by pre-establishing VPI sink (destination-rooted) trees. Individual connections within a VPI tree are distinguished using VCIs. This type of networking emulates "connectionless" data transfer in that *no node-by-node connection setup is required prior to data exchange,* and packets are routed as per the destination address in the packet (cell) headers.

Figure 4 illustrates this networking concept in a network with nine PBSs. In this example, VPI 9a and VPI 9b are

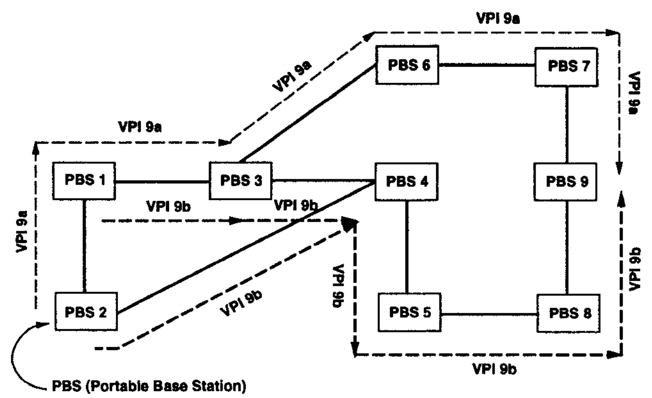

Figure 4: An example of provisioned VPI trees.

assigned to *PBS 9.* In other words, all cells with VPI 9a and VPI 9b are routed to the destination PBS, *PBS 9.* Associated with each VPI is a unique route through the network (from each source), thus forming a tree with the destination as the root. Cells from different connections are distinguished by the VCIs. Each PBS controls the assignment of VCIs associated with its VPIs (those rooted at that PBS). *VCIs are selected using an end-to-end handshake procedure* much like the procedure used to select ports while opening a TCP connection [8].

The VPI trees are maintained by a dynamic distributed Virtual Trees Routing Protocol (VTRP) [9]. As mobile hosts move and traffic conditions change, VTRP messages are exchanged to reroute the VPI trees through PBSs using the least-loaded links. This ensures that as connection admission requests arrive, the VPI trees are routed through links/nodes that have free resources, thus allowing the network to admit connections.

As shown in Fig. 3, in WVLAN, ATM connections (VCIs on selected VPI trees) extend between PBSs instead of between end hosts, and *they are unidirectional in WVLAN.* This works well in conjunction with the concept of destination-rooted trees. As we will show later, the recognition of unidirectional connections corresponding to destination end hosts is important for the design of various algorithms in the WVLAN.

2.2 MAC-ATM interworking

Figure 5 illustrates the interworking of IEEE 802.11 and ATM. *Each ATM connection terminated at a PBS corresponds to a mobile located at that PBS.* For example, Fig. 5 shows an ATM connection, VPI 2a, VCI 1, corresponding to *Mobile 2.* It is a unidirectional connection extending from *PBS 1* to *PBS 2* where *Mobile 2* is located. If *Mobile 1*

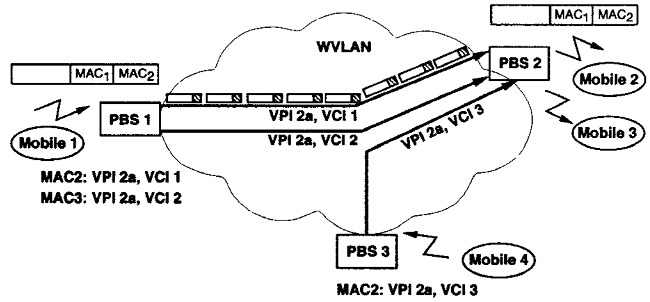

Figure 5: An example of unidirectional packet delivery (IEEE 802.11 MAC-ATM interworking).

sends MAC frames destined to *Mobile 2*, *PBS 1* segments these frames into ATM cells, and transmits them on VPI 2a, VCI 1. The received cells are reassembled at *PBS 2* into a MAC frame, which is then sent on the air interface of *PBS 2*, where it is received by *Mobile 2.*

Separate ATM connections are established from an *origination PBS* to a *destination PBS* corresponding to different mobiles resident on the destination PBS. For example, Fig. 5 shows that connection denoted by VPI 2a, VCI 1 corresponds to *Mobile 2*, while the connection denoted by VPI 2a, VCI 2 corresponds to *Mobile 3*, which is also located at *PBS 2.* The reason for having such separate ATM connections between the same pair of PBSs is to support ATM-layer handoffs corresponding to individual mobiles. For example, in Fig. 5, if *Mobile 2* moves, the connection, VPI 2a, VCI 1 can be rerouted to its new *Local PBS* (the PBS in whose coverage area *Mobile 2* is located), without changing the ATM-layer connection, VPI 2a, VCI 2, corresponding to *Mobile 3* that remains at the original PBS, *PBS 2.*

It is also possible to have multiple VPI/VCI connections originating from different PBSs, which correspond to a same mobile. In Fig. 5, for example, the ATM connection denoted by VPI 2a, VCI 3, which extends from *PBS 3* to *PBS 2* also corresponds to the *Mobile 2.* When a mobile moves, its Local PBS determines the set of all VPI/VCIs corresponding to the mobile, and then performs ATM-layer handoffs on these connections. Thus, if *Mobile 2* moves, both ATM connections VPI 2a, VCI 1, and VPI 2a, VCI 3, need to be rerouted.

2.3 Data tables and signaling channels

Table 1 lists the data tables stored at each PBS. These tables are required to support the various networking algorithms and user-plane communication paths.

Figure 6 shows the *Registration Table* and the *IP-MAC Cache* at PBSs, *PBS 1* and *PBS 2.* Since *Mobile 1* and *Mobile 2* are registered at *PBS 1*, the *Registration Table* at *PBS 1* indicates the MAC addresses of these mobiles. The *IP-MAC Cache* at a PBS includes all the IP to MAC address bindings learned by the PBS. This includes the IP to MAC address bindings for all the mobiles registered at the PBS. In addition, the PBS may also store this information for mobiles registered at other PBSs. As shown in Fig. 6, *PBS 2*

Table 1: PBS data tables.

Data Table	Description
Registration Table	Stores MAC addresses of registered mobiles.
IP-MAC Cache	Maps IP addresses to MAC addresses.
Origination MAC-VPI/VCI Table	Maps MAC addresses of mobiles located on other PBSs to outgoing VPI/VCIs; Also stored in this table is the identifier of the destination PBS of the connection.
Destination MAC-VPI/VCI Table	Maps MAC addresses of mobiles located on the PBS to the incoming VPI/VCIs originating at other PBSs; Also stored in this table is the identifier of the origination PBS of the connection.
VPI/VCI Tables	Stores free and allocated VCIs and information about VPIs.

stores the IP to MAC bindings for its local mobiles, *Mobile 3* and *Mobile 4*. It also has the address binding for *Mobile 1* which it previously learned during a communication from one of its mobiles to *Mobile 1*.

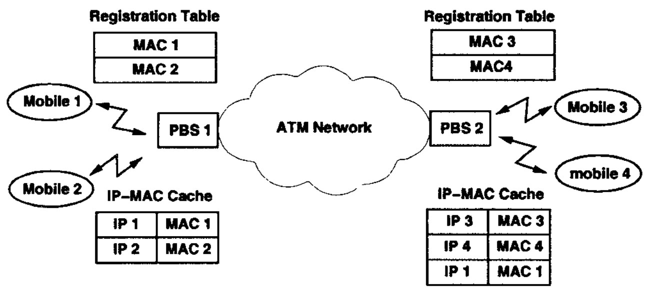

Figure 6: An example of Registration Tables and IP-MAC Caches at PBSs.

As described in Section 2.1, all ATM connections are unidirectional in WVLAN, and extend between PBSs. Furthermore, every ATM connection is associated with a mobile located at the destination PBS of the unidirectional connection. The mapping of the MAC address of the mobile to the VPI/VCI of the ATM connection extending from the origination PBS to the destination PBS of the mobile is maintained in the origination PBS. The table of these mappings is referred to as the *Origination MAC-VPI/VCI Table.* This table allows the origination PBS to segment MAC frames into ATM cells, and transmit them on the appropriate ATM connection.

Similarly, each PBS also maintains MAC address to VPI/VCI mapping for incoming VPI/VCIs. This table is referred to as the *Destination MAC-VPI/VCI Table.* This data table is not required for the function of delivering a MAC frame after its reassembly from the ATM cells received on a given VPI/VCI, since the MAC frames are self-identifying whereby the MAC address of the destination mobile can be determined from the reassembled MAC frame header. However, we maintain this data table at each PBS for its role during ATM-layer handoffs. As described in Section 2.2, if a mobile moves, its Local PBS must determine the identities of all the incoming VPI/VCIs that correspond to the mobile. These ATM connections will then be rerouted to the new Local PBS of the mobile.

Figure 7 shows the unidirectional ATM connections among PBSs, and the associated origination and desti-

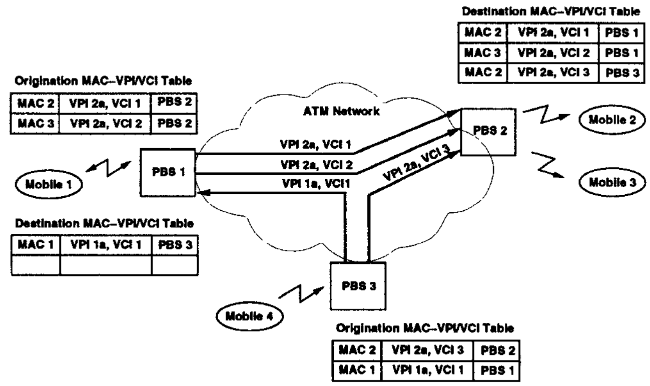

Figure 7: An example of Origination and Destination MAC-VPI/VCI Tables stored at PBSs.

nation MAC-VPI/VCI tables. For example, there are two open ATM connections from *PBS 1* to *PBS 2*. One ATM connection (VPI 2a, VCI 1) corresponds to *Mobile 2*, and the other (VPI 2a, VCI 2) corresponds to *Mobile 3*. In this case, the mappings MAC 2: VPI 2a, VCI 1 and MAC3: VPI 2a, VCI 2 are stored in the Origination MAC-VPI/VCI Table at *PBS 1* and in the Destination MAC-VPI/VCI Table at *PBS 2*. The identifier of the far end PBS on the connection is also maintained for each entry in the Origination and Destination MAC-VPI/VCI Tables.

Since unidirectional ATM connections are used for the transport of MAC frames, these connections might not be symmetric. In the example, there is only one ATM connection destined at *PBS 1* from *PBS 3*. The Destination MAC-VPI/VCI Table at *PBS 1* shows the data corresponding to this connection, MAC 1: VPI 1a, VCI 1.

Finally, data pertaining to the VPI trees on which a PBS is a transit node or a root node is also maintained. A list of free VCIs is stored at each destination PBS. The reader is referred to [4] for details regarding these VPI/VCI Tables.

Two types of *signaling channels* are used in WVLAN: *out-of-band signaling channels* and *broadcast signaling channels.* Most signaling messages exchanged between PBSs are sent on the out-of-band (VCI 5) channel of a VPI rooted at the destination node of the message [4]. Messages destined to all PBSs are sent on the broadcast signaling channels. These are source-rooted trees pre-established for the purposes of broadcast signaling. For example, the mobile location procedure sends broadcast signaling messages to all PBSs while trying to locate a mobile. Such messages are transported over these pre-established broadcast signaling channels. It is assumed that these source-rooted broadcast trees are maintained by some off-line management-plane procedure, or a protocol, such as VTRP [9].

3 Algorithms

The functions for which procedures need to be defined are first identified. In the IP-over-ATM LANE model for wired networks, three steps are required prior to data exchange:

- *IP to MAC address resolution* (henceforth referred to as *IP-ARP*),
- *MAC address to ATM address resolution* (called *LE-ARP* for LAN Emulation ARP), and
- *connection setup.*

Finally, a *connection release* procedure is required to release ATM connections. In mobile networks, there are three additional functions:

- to *track mobiles*,
- to *locate mobiles* for incoming call or packet delivery, and
- to *perform handoffs.*

In WVLAN, we require all of these functions, except LE-ARP. LE-ARP is required in standard LAN Emulation networks because connection setup signaling (Q.2931 [10]) uses ATM addresses. Thus, the MAC address of the destination mobile (or its bridge, if the mobile is non-ATM) needs to be translated to an ATM address. In WVLAN, the connection admission procedure (consisting of the end-to-end handshake as described in Section 2.1) is never performed in isolation. It is combined with either an IP-ARP procedure (where only the IP address of the mobile is known), or a mobile location procedure (where the MAC address of the mobile is known). Thus, in both cases, the ATM address of the PBS (since mobiles are non-ATM in WVLAN, we can only talk about ATM addresses of the PBSs which serve as bridges) is not used in the procedure, thus eliminating the need for LE-ARP.

We provide an outline for this section of algorithms by defining how some of the functions listed above have been combined for optimization reasons. First, we describe the algorithm for the two location management functions of *mobile tracking* and *mobile locating* in Section 3.1. Mobile tracking is done independent of user data exchange. It only depends on user movement. On the other hand, the mobile locating procedure is typically executed prior to delivering a service (such as delivery of an incoming MAC frame) to a mobile. It is thus combined with the different procedures associated with data exchange. These include the handling of IP-ARP requests, or the actual forwarding of MAC frames. If the sending host does not know the MAC address of the destination host, it sends an IP-ARP request. On the other hand, if the sending host knows the IP address to MAC address mapping for the destination host, it directly sends a MAC frame to a PBS without going through an IP-ARP phase. The procedures for handling these two cases are described in Section 3.2 and Section 3.3, respectively. As mentioned earlier, mobile location and connection admission are combined with these two procedures, if needed.

The remaining two sections, Section 3.4 and Section 3.5, describe the algorithms for performing handoffs and releasing ATM connections, respectively.

3.1 Location management

In a wireless network, there are basically two aspects to the location management problem: *tracking* and *locating. Tracking* is the procedure used by the network to track the location of mobiles. This is typically done by having base stations in the network emit periodic *beacons* (e.g., using IEEE 802.11 *Beacon* frames). As mobiles power on, power off, or change base stations (detected at the mobile by the new base station identifier in the received beacon), they send messages to the network notifying it of their current location. *Locating* is the procedure used to determine the current location of a mobile in order to deliver services, such as incoming connection requests or packets, to the mobile. If the tracking procedure tracks the exact base station on which a mobile is located, and this location is stored in a centralized database, then the locating procedure simply consists of a database lookup. On the other hand, the mobile tracking procedure may only track the "zone" (cluster of cells) in which a mobile is located. In this case, the locating procedure will require a "page" to be sent out to all the base stations within that zone, each of which then broadcasts a page on its air interface.

In WVLAN, the *tracking* procedure is designed to avoid the administrative overhead incurred by using centralized data bases, such as the cellular network Home Location Registers (HLRs). It also avoids having to page for mobiles on the wireless links, thus saving valuable air interface resources. In this approach, each mobile notifies its PBS as it powers on (using IEEE 802.11 *Association Request* frames), powers off (using IEEE 802.11 *Disassociation* frames), or moves in to a new coverage area (using IEEE 802.11 *Reassociation Request* frames). This procedure allows each PBS to record the identifiers of the mobiles (both IP and MAC addresses) located at that PBS. Unlike in cellular networks, where an HLR is "statically" associated with each mobile [11], there is no static "Home" binding between a mobile and any network node in WVLAN. Thus, the only network node that knows the location of a mobile is its current Local PBS. Since there is no centralized statically-bound "Home" node to which a PBS can send a request to determine the location of a mobile, an alternate mobile locating procedure is needed.

The *locating* procedure used in WVLAN is a broadcast mechanism. The location of a mobile typically needs to be determined for delivering incoming packets to the mobile. In WVLAN, when a PBS receives a MAC frame destined to a mobile, it sends a broadcast message (*Broadcast locate*) to all the PBSs in the network. The PBS at which the called mobile is located responds to the broadcast. If the called mobile is not registered with any PBS (i.e., it is not powered-on, or is outside the range of the WVLAN), the broadcast-sending PBS will time out and assume that the called mobile is unreachable. Note that since each PBS stores information about the mobiles located in its coverage area, this *Broadcast-locate* procedure does not require paging on the air interfaces and thus saves valuable wireless bandwidth.

Figure 8 shows an example of the tracking procedure. Originally, *Mobile 1* and *Mobile 2* are registered with *PBS 1*, and *Mobile 3* is registered with *PBS 2*. Thus, *PBS 1* is the Local PBS for *Mobile 1* and *Mobile 2*. It stores *Mobile 1* and *Mobile 2's* MAC addresses, MAC_1 and MAC_2, in its Registration Table. Similarly, *PBS 2* is the Local PBS for

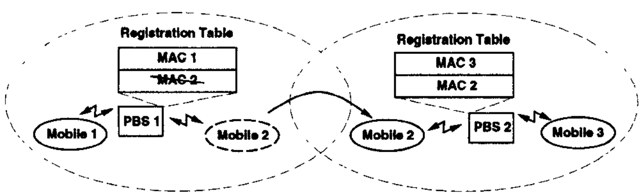

Figure 8: An illustration of the mobile tracking procedure.

Mobile 3 and it stores *Mobile 3's* MAC address, MAC_3, in its Registration Table. When *Mobile 2* moves to the coverage area of *PBS 2*, the latter stores the address MAC_2 in its Registration Table during the Reassociation procedure. It notifies *PBS 1* that *Mobile 2* has moved. This causes *PBS 1* to remove *Mobile 2's* MAC address, MAC_2, from in its Registration Table.

3.2 Address resolution (with mobile location and connection admission)

If a mobile does not have the MAC address of the destination host to which it needs to send an IP packet, it generates an IP-ARP request. *Two cases* are possible:

- *Case 1:* the requesting host's Local PBS has the IP to MAC binding for the destination host.
- *Case 2:* the requesting host's Local PBS does not have the IP to MAC binding for the destination host.

In *Case 1*, the Local PBS of the IP-ARP requesting host will find the IP-MAC binding for the destination host in its IP-MAC Cache. The host whose IP address is being resolved (referred to as *target* host) may or may not be in the coverage area of the same PBS. If it is in the coverage area of the same PBS, then an issue arises as whether the PBS or the target host itself should respond. In IEEE 802.11, the MAC frame header specifies whether the frame is a peer-to-peer frame or one that should be received by the Access Point (role played by the PBS). Since the IP-ARP requesting host cannot be sure whether the destination host is located at the same PBS or not, the IP-ARP query should be targeted at the Local PBS. Using this approach, whether or not the target host is registered at the PBS, if the PBS has the IP to MAC binding, it responds.

An example is shown in Fig. 9. In this example, *Mobile 1* with MAC address MAC_1 (and IP address IP_1) is registered with *PBS 1*, *Mobile 2* with MAC address MAC_2 (and IP address IP_2) is registered with *PBS 2*, and *Mobile 3* with MAC address MAC_3 (and IP address IP_3) is registered with *PBS 9*. When *Mobile 1* sends an IP-ARP request for *Mobile 3's* MAC address, *PBS 1* finds the binding in its IP-MAC cache (assuming it learned the binding previously), it sends an IP-ARP reply with this binding on its air interface. On the other hand, when *Mobile 2* sends an IP-ARP request for *Mobile 3's* MAC address, *PBS 2* does not find the binding in its IP-MAC cache. This is an example of *Case 2*.

In *Case 2*, the Local PBS receiving the IP-ARP query does not have the IP to MAC binding for the target host. It requests the help of other PBSs to perform this address resolution. Since each PBS stores at least the IP-MAC bindings

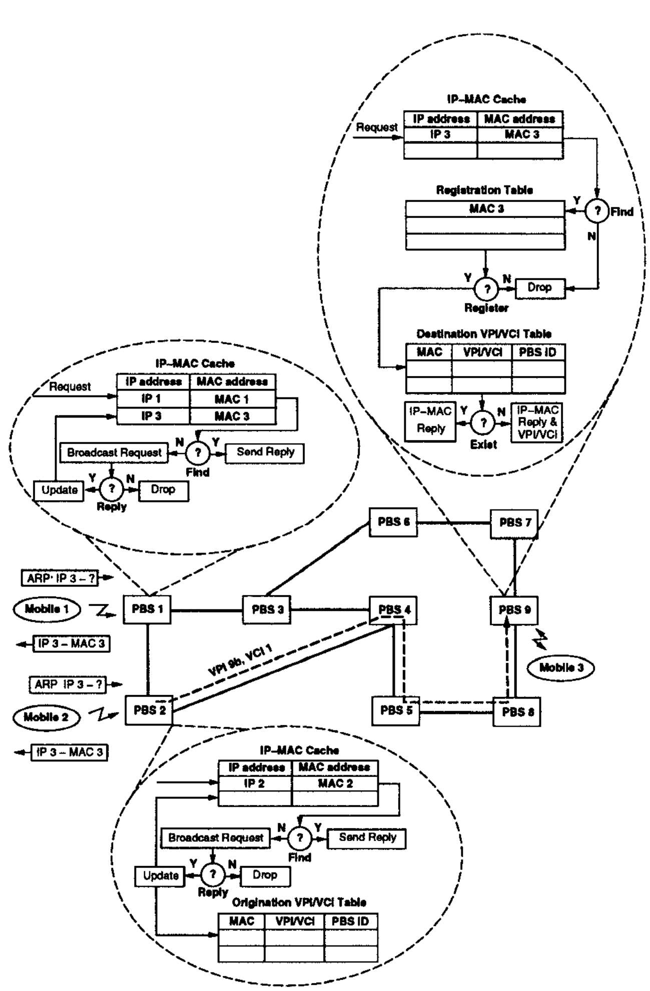

Figure 9: An example of distributed IP-ARP.

of all the mobiles registered at the PBS (Section 2.3), PBSs can act as proxy agents for their mobiles, and thus help resolve the IP address. If a mobile is registered, the target IP-MAC mapping is available in some PBS of the network. Due to the distributed nature of this data, the Local PBS of the IP-ARP requesting host must send a broadcast request to all the PBSs in the network, asking for this resolution. Fortunately, broadcast signaling channels are available in WVLAN (see Section 2.3) for use in the mobile location procedure (see also Section 3.1). This allows the Local PBS of the IP-ARP requesting host to send a broadcast message (*Broadcast ARP request*) to all the PBSs in the WVLAN.

Upon receiving this message, all the PBSs perform the first of three checks:

- *Check 1*: Check if the target IP to MAC binding is in the local IP-MAC Cache; if so,
- *Check 2*: Verify whether the target host is registered at the PBS; if so,
- *Check 3*: Check whether an ATM connection terminated at the PBS exists for the target host.

Check 1 is done to determine if a PBS knows the requested binding, given that these bindings are distributed among all the PBSs in the WVLAN. All PBSs perform this check. Only those that find the requested binding perform *Check 2*. This check is done by consulting the Registration Table for the resolved MAC address of the target host. Only the Local PBS of the target host can respond to the *Broadcast ARP request*. The reason for this policy is to avoid duplicate responses which may occur since PBSs learn the IP-MAC bindings of even non-local hosts, and store them in their IP-MAC Caches. Thus, if a PBS knows the IP to MAC binding for the target host, but finds that it is currently not registered locally, it simply drops the IP-ARP request. Note that the mobile location procedure is implicitly completed by adopting this policy. If any PBS was allowed to respond to the *Broadcast ARP request*, a separate *Broadcast locate* would be required to determine the mobile location following the address resolution. Furthermore, by having PBSs store IP-MAC bindings for their local hosts, IP-ARP broadcasts are not required from all the PBSs on their wireless links, thus saving valuable air interface resources.

In the example, the IP-ARP request generated by *Mobile 2* for *Mobile 3*, is resolved by *PBS 9*. Since *Mobile 3* is registered at *PBS 9*, it will finds entries for the mobile in both its IP-MAC Cache and its Registration Table. Hence, *PBS 9* sends a reply to the *Broadcast ARP request* generated by *PBS 2*.

Check 3 is done on the assumption that when an address resolution request for a destination host is generated by a sending host, the latter typically intends to send a MAC frame to the destination host. Recall that the WVLAN networking solution requires a separate unidirectional ATM connection extending from the Local PBS of the sending host to the Local PBS of the destination host corresponding to each destination host (Section 2.2). By performing the third check, a separate connection admission procedure following address resolution, is avoided.

This check is facilitated by the presence of the Destination MAC-VPI/VCI Table, as described in Section 2.3. This allows the Local PBS of the target host, which passes the first two checks to consult its Destination MAC-VPI/VCI Table to determine if an incoming connection already exists for the target host from the Local PBS of the IP-ARP requesting host. This is possible if some other host located on the same PBS as the IP-ARP requesting host recently sent data to the same destination host. In this case, an ATM connection will already exist from the origination PBS to the destination PBS corresponding to the target host. If this is so, the Local PBS of the target host replies to the *Broadcast ARP request* with simply the MAC address of the target host.

On the other hand, if there is no MAC-VPI/VCI entry for the target host, the PBS requires an ATM connection to be admitted. This procedure is facilitated by the fact that VCIs are selected on VPI trees by the destination PBS (root of the VPI tree), as described in Section 2.1. Upon selecting the VPI/VCI, the PBS replies to the *Broadcast ARP request* with both the MAC address of the target host, and the VPI/VCI of the corresponding ATM connection.

The Local PBS of the IP-ARP requesting host updates its IP-MAC Cache (and Origination MAC-VPI/VCI Table if the VPI/VCI data is present), and then sends an *ARP reply* with the MAC address of the target host on its air interface.

In the example, after *PBS 9* finds the entries for *Mobile 3* in both its IP-MAC cache and its Registration Table, it further checks its Destination MAC-VPI/VCI Table for incoming ATM connection from *PBS 2* for the target host, *Mobile 3*. Since this ATM connection is not found in its Destination MAC-VPI/VCI Table, it selects VPI 9b, VCI 1, for the ATM connection, makes an entry in its Destination MAC-VPI/VCI Table, and then replies to the *Broadcast ARP request* to *PBS 2* with both $IP_3 - MAC_3$ and VPI 9b, VCI 1. Upon receiving this combined reply, *PBS 2* updates both its IP-MAC Cache and Origination MAC-VPI/VCI Table, and then sends an *ARP reply* with MAC address MAC_3 on its air interface.

If a mobile is not registered at any PBS, then no response will be generated to the *Broadcast ARP request*. The origination PBS will time out, and so will the ARP unit at the requesting host.

Thus, as mentioned at the start of Section 3, *mobile location and connection admission are combined with the address resolution procedure*. This is unlike the current LANE model where there are no such schemes to reduce performance overhead. Furthermore, the WVLAN solution for handling IP-ARP is a distributed solution, unlike the LANE standards approach, which requires centralized multicast servers [12].

3.3 Packet forwarding (with mobile location and connection admission)

As described at the start of Section 3, if the origination host has the IP address to MAC address mapping for the destination host, it simply sends the MAC frame without sending an IP-ARP request. The procedure executed at a PBS receiving such a MAC frame is discussed in this section.

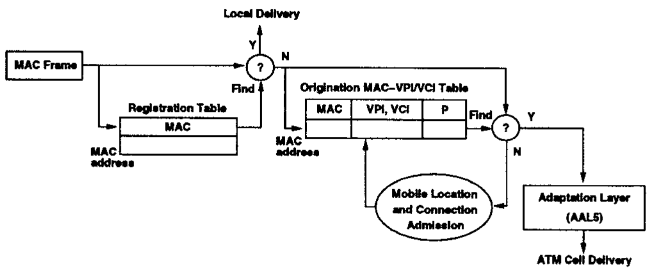

Figure 10: Packet forwarding operation at origination host's Local PBS.

When a PBS receives a MAC frame from one of its mobiles, it checks its Registration Table (as shown in Fig. 10) to determine whether the *destination mobile is registered locally*. If the mobile is registered locally, the Local PBS either does nothing (if the lower layer of the WVLAN air interface allows for peer-to-peer communication), or sends the packet within the local coverage area (if the lower layer of the WVLAN operates such that communication is via a PBS). For example, in the IEEE 802.11 standard, a sending mobile specifies in the MAC frame header whether the communication is peer-to-peer or through an Access Point (PBS). This allows the Local PBS to act accordingly.

However, if the *destination mobile is not registered locally*, the origination PBS consults its Origination MAC-VPI/VCI Table with the destination mobile's MAC address. If an entry is found, i.e., *an ATM connection exists from the origination PBS to the destination PBS cor-*

responding to the destination mobile, then the Local PBS invokes the AAL functionality, and forwards the resulting ATM cells over the open VPI/VCI connection to the Local PBS of the destination mobile, which performs reassembly before transmitting the MAC frame over its air interface, as described in Section 2.2.

If an entry is not found in the Origination MAC-VPI/VCI Table, this implies that *no ATM connection exists from the origination PBS to the destination PBS corresponding to the destination mobile.* In this case, the origination PBS needs to first determine the location of the mobile (the PBS on which it is located), and then perform connection admission to obtain a VPI/VCI selection.

The operations of locating a mobile and selecting a VPI/VCI (connection admission) are combined into a single operation. As described in Section 3.1, the origination PBS uses the broadcast mechanism to locate a mobile by generating a *Broadcast-locate* message to all the PBSs in the network. The PBS on which the mobile is located responds to this location search. Instead of simply providing the destination PBS identifier in this response which will necessitate a further connection admission procedure, the destination PBS selects a VCI on one of its VPI trees for the ATM connection. The selected VPI/VCI is stored in the Destination MAC-VPI/VCI Table at the destination PBS, and also included in the response to the *Broadcast-locate* message. The origination PBS stores the MAC-VPI/VCI mapping in its Origination MAC-VPI/VCI Table allowing packet forwarding to commence. The corresponding far end PBS identifiers are also stored in the two MAC-VPI/VCI tables at the two PBSs (see Table 1 in Section 2.3).

3.4 Handoffs

As mentioned in Section 3.1, when a mobile moves to a new Local PBS, it sends a *Reassociation Request* frame to the new Local PBS. Upon receiving this frame, the new Local PBS contacts the old Local PBS to initiate a handoff procedure. Two cases are possible:

- *Case 1:* There is no ATM connection destined at the old Local PBS corresponding to the moving mobile. This case is handled simply by changing entries in the Registration Tables of the new and the old Local PBSs. We refer to this case as a "MAC-layer handoff" or "Idle handoff."
- *Case 2:* There is at least one ATM connection destined at the old Local PBS corresponding to the moving mobile. In this case, the open ATM connections need to be rerouted to the new Local PBS. We refer to this case as an "ATM-layer handoff" or "Active handoff."

The existence of ATM connections destined at the old Local PBS corresponding to the moving mobile is determined by consulting the Destination MAC-VPI/VCI Table at the old Local PBS.

An example of a Case 1 handoff is shown in Fig. 8 in Section 3.1. It is described as part of the mobile tracking procedure since it is the mechanism by which the WVLAN tracks the PBS locations of mobiles. In WVLAN, we assume that the mobiles are non-ATM, and hence have no knowledge of any ATM connections setup in the network on their behalf. Thus, both *idle handoffs* and *active handoffs* are perceived by the mobiles in the same manner.

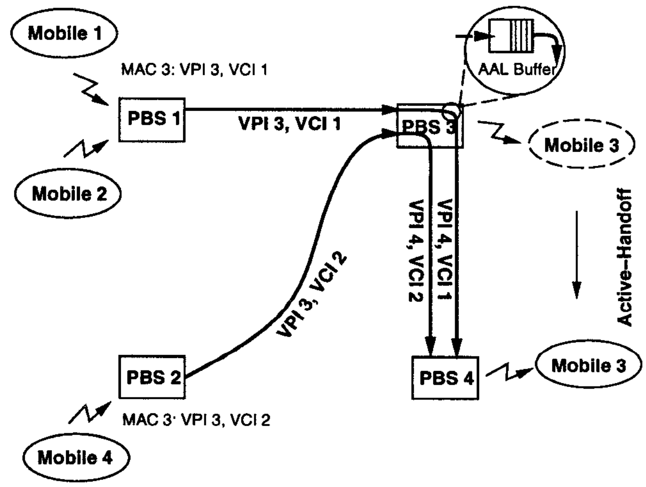

Figure 11: Phase 1 of Case 2 Handoff: Forwarding phase.

Figures 11 and 12 show an example of a Case 2 handoff. In this example, *Mobile 3* moves from *PBS 3* to *PBS 4*. *PBS 3* has two incoming ATM connections corresponding to *Mobile 3*, one from *PBS 1*, and the other from *PBS 2*. *PBS 3* determines this by consulting its Destination MAC-VPI/VCI Table.

The Case 2 handoff proceeds in two phases:

- *Phase 1:* A *forwarding pointer is placed* in the old Local PBS to effect the forwarding of ATM cells received at the old Local PBS to the new PBS (while operating in this mode, the old Local PBS is referred to as the *Home PBS* for the connection); and
- *Phase 2:* A *Home update* is performed in order to use a more optimally-routed VPI tree for the ATM connection.

Phase 1 consists of several steps executed at the moving mobile's old Local PBS and the new Local PBS. *The old Local PBS* first stops its AAL from sending any reassembled MAC frames destined for the moving mobile. Next, it removes entries corresponding to the moving mobile from its Registration Table and its Destination MAC-VPI/VCI Table. It continues buffering cells received on the ATM connections corresponding to the moving mobile in the AAL reassembly queues. In the example, *PBS 3* will continue buffering cells received on ATM connections VPI 3, VCI 1, and VPI 3, VCI 2 without transmitting any reassembled MAC frames. The old Local PBS then communicates with the new Local PBS of the moving mobile in order to obtain VCIs on VPI trees extending from the old Local PBS to the new Local PBS. The old Local PBS then sets the forwarding pointers for these connections. In the example, cells received on VPI 3, VCI 1 will be forwarded to VPI 4, VCI 1, and cells received on VPI 3, VCI 2 will be forwarded to VPI 4, VCI 2. Finally, the old Local PBS sends cells currently queued in the AAL reassembly queues to the new PBS. When these queues are empty, the cell forwarding action commences, and there is no more buffering at the old Local PBS.

Actions in the *new Local PBS* corresponding to *Phase 1* are as follows. When asked by the old Local PBS for the

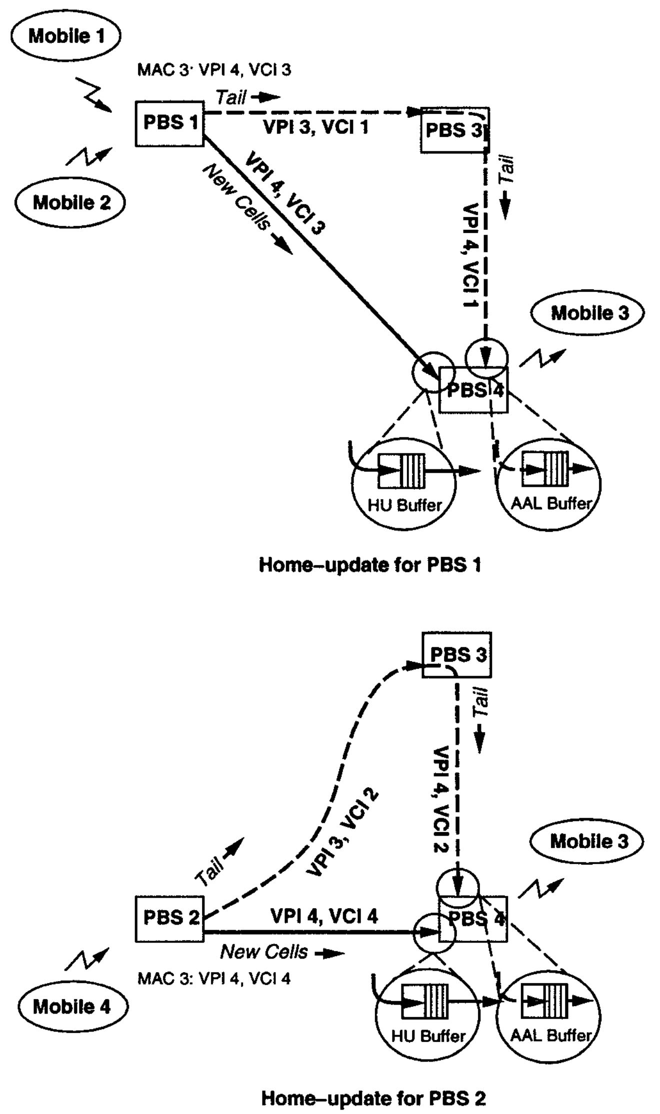

Figure 12: Phase 2 of Case 2 Handoff: Home-update phase.

VPI/VCIs of the ATM segments extending from the old Local PBS to the new Local PBS, the new Local PBS selects VCIs, one for each connection being handed-off, on its destination-rooted VPI trees (recall the connection admission procedure described in Section 2.1). The new Local PBS then stores entries in its Destination MAC-VPI/VCI Table and its Registration Table. It starts receiving cells sent by the old Local PBS, and places them in AAL reassembly queues, one for each connection corresponding to the newly arrived mobile. It reassembles ATM cells into MAC frames and sends these frames on its air interface to be picked up by the mobile.

As soon as the new Local PBS is ready to receive cells on the ATM connections from the old Local PBS (i.e., Phase 1 is complete), it initiates *Phase 2* of the handoff procedure. This phase is equivalent to the "route optimization" step in mobile IP [13]. In typical connection-oriented ATM networks, any route optimization step will require the teardown and setup of new segments. However, since WVLAN emulates connectionless networking, no such segment release and setup is required. Instead, an end-to-end handshake asking the far end PBS to start using an alternate VPI, one that is rooted at the new Local PBS, suffices to accomplish route optimization. This makes this step very similar to route optimization in mobile-IP networks. We refer to this step as a "Home update" to avoid the connotation of segment release and setup required while optimizing routes in connection-oriented networks.

Phase 2 consists of the new Local PBS of the just-moved mobile sending a signaling message to the far-end PBS notifying it of a *Home update*. Given that PBSs store the identity of the far-end PBS for each of its connections (in the Origination and Destination MAC-VPI/VCI Tables as shown in Section 2.3), the old Local PBS passes on the identity of the far-end PBS for each of the handed-off ATM connections to the new Local PBS during Phase 1. The new Local PBS selects VCIs on VPIs (rooted at the new PBS) that the far-end PBS can use for the directly routed connection. These identifiers are communicated in a *Home-update* signaling message sent from the new PBS to the far-end PBS. The far-end PBS sets entries in its Origination VPI-VCI Table, sends a "Tail" signal down the old path, and then commences sending ATM cells destined for the just-moved mobile on the new direct path to the new Local PBS. The purpose of the "Tail" signal is to notify the old Local PBS that no more ATM cells will be sent on the old path, as well as to help the new Local PBS maintain cell sequence. Upon receiving the *Tail* signal, the old Local PBS clears out the forwarding pointers. The example shown in Fig. 12 illustrates Phase 2 for the two connections handed-off in Phase 1. The connections following the handoff Phase 1 are shown in dashed lines, and the connections following the Home-update phase (handoff Phase 2) are shown in solid lines. *PBS 1* and *PBS 2* are the far-end PBSs of the two ATM connections, respectively. They send the *Tail* signals after the last data cells are sent on the old paths, and then start sending new ATM cells on the new direct paths to *PBS 4*.

Phase 2 actions at the new Local PBS consist of setting entries in its Destination MAC-VPI/VCI Table for the direct connection from the far-end PBS, and buffering cells received on the new path until the *Tail* signal is received on the old path. This allows it to maintain cell sequence. Fig. 12 shows how the new Local PBS, *PBS 4*, buffers cells received on the new path in a "Home-update buffer". Cells received on the old path are collected in the AAL reassembly buffer. After receiving the Tail signal on the old path, PBS 4 will move cells from the Home-update buffer to the AAL reassembly buffer without any threat of out-of-sequence cells. Subsequent cells received on the new path are directed to the AAL reassembly buffer. The Home-update buffer resources are released. This completes the two-phase active handoff procedure.

Note that the procedure described above is used to handoff only ATM connections destined to the Local PBS of the moving host. On the other hand, since there is no unique relation between a source mobile and an ATM connection, no ATM-layer handoffs are required for connections origination from the Local PBS of a moving host. In the example, MAC frames sent by both *Mobile 1* and *Mobile 2* resident at *PBS 1*, destined to *Mobile 3*, are transmitted on the same ATM connection VPI 3, VCI 1 to *PBS 3*. If either *Mobile 1* or *Mobile 2* move, this ATM connection should still remain to enable the non-moving mobile (as well as other mobiles) located at *PBS 1* to continue sending MAC frames destined to *Mobile 3*. Thus, the origination MAC-VPI/VCI Table is not consulted during handoffs, since no outgoing ATM connections from a PBS need to be rerouted when a mobile moves.

3.5 Connection release

In the standard IP-over-ATM solution, Q.2931 signaling is used to release connections using either a *Delayed-release* or an *Immediate-release* scheme. *Delayed release* implies that a connection is held for some period of time after a MAC frame is sent on a given ATM connection. This minimizes signaling and processing overhead. *Immediate release*, on the other hand, implies that an ATM connection is released after every MAC frame transmission. In both cases, connection release is performed hop-by-hop through all the switches in the connection.

In WVLAN, since VPI trees are provisioned as described in Section 2.1, connection "release" consists of simply deleting the corresponding entries in the Origination and Destination MAC-VPI/VCI Tables. No actions are required at the transit PBSs since the destination-rooted VPI trees remain provisioned.

We adopt the delayed-release scheme, and use a timeout procedure for deleting the Origination and Destination MAC-VPI/VCI Table entries. A timer is associated with each MAC-VPI/VCI entry in the Origination MAC-VPI/VCI Table at the origination PBS. The timer is reset each time the MAC-VPI/VCI entry is accessed for packet forwarding. When the timer expires, a simple end-to-end handshake procedure is performed to remove the MAC-VPI/VCI entries in both origination and destination PBSs. Details have been worked out to avoid race conditions between the two end PBSs.

4 Conclusions

In this paper, we presented WVLAN (Wireless Virtual LAN) to support mobility on IP-over-ATM networks. The proposed WVLAN provides a scalable wireless virtual LAN solution for supporting a large number of mobiles and over a large geographical area. It supports mobility at the ATM layer, rather than at the IP layer. This has the advantage of localizing the effects of mobility to the virtual LAN, where the virtual LAN, through the use of ATM, is a scalable network. Three aspects of mobility management were considered: mobile location tracking, locating a mobile for incoming packet delivery, and handoffs.

We draw *four conclusions* from this study, which will be useful in defining wireless ATM architectures and algorithms. *First, the concept of virtual paths* is very useful in wireless ATM networks. It allows us to effectively emulate connectionless networking, a feature that is most useful for performing handoffs. Handoffs are simplified to placing forwarding pointers rather than tearing down and setting up segments of connections, as would be required in a connection-oriented network.

Second, the provision of a simple *switching capability at the base station* (even realizable on a single bidirectional ATM interface), and the *capability of buffering cells at the base station*, will greatly help the handoff procedure. These two features can be used to ensure sequenced cell delivery even through handoffs. In the wireless ATM model of terminating ATM connections at base stations, and using any wireless protocol, such as IEEE 802.11, on the air interface, base stations will have the ability to buffer ATM cells for AAL reassembly. While performing handoffs, cells can continue to be buffered, thus avoiding any cell loss.

Third, it is important to *combine different functions* required in wireless IP-over-ATM wherever possible. For example, the current LANE model requires an IP-ARP, LE-ARP, and connection setup. In wireless networks, an added mobile location function is needed. Performing each function in a separate phase, each of which requires messaging, could prove very costly from a performance standpoint. We combine these functions to minimize the overhead required to carry IP packets over ATM networks, especially in a wireless context.

Finally, we propose a *broadcast scheme for mobile location* in wireless IP-over-ATM networks to enable it to be easily combined with the IP-ARP (Address Resolution Protocol) function, which uses a broadcast scheme. Drawing from the cellular model, most of the current proposals for mobile location management are based on the use of centralized databases to store mobile location information, even for LANs. The alternative is to use a broadcast scheme for determining mobile location. This may not be feasible if broadcasts are to reach all the mobiles. However, schemes in which network nodes act as proxy agents for mobiles, can be considered in conjunction with broadcasts. This is similar to bridges acting as proxy agents for the ARP function. Given that some IP-over-ATM networks will need to support ARP, designing the mobile location scheme using the broadcast approach, will enable us to make performance optimizations by combining mobile location and ARP functions.

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