IPv6/ATM Integration:
A survey of the options, issues, and approaches

María Elena Villapol
Institute for Telecommunications Research,
University of South Australia, Mawson Lakes Adelaide 5095, Australia.

ABSTRACT
IPv6 is the new version of the Internet Protocol (IP). It is intended to be the most widely used protocol in the Internet in the future. Also, ATM offers several benefits including scalability, significantly higher speeds, and QoS provision, which are important features for supporting current and future applications such as real-time video and audio. Therefore, it is necessary that IPv6 and ATM work together. This paper describes the IPv6/ATM integration options, issues, and various approaches for supporting such integration. In addition, the proposals are compared in terms of the integration issues and options. The large number of these integration options, issues and approaches show the fundamental complexity of the task that is involved in interfacing IP over ATM. This paper also reflects the lack of an agreement between the standardization committees and individuals/Companies in adopting a proposal.

Keywords: IPv6/ATM integration, encapsulation, addressing, routing, Quality of Service, multicasting, flow.

1. INTRODUCTION
The Internet Engineering Task Force (IETF) has decided to develop a new version of IP; it is known as the Internet Protocol version 6 (IPv6) [20]. IPv6 solves the problem of supporting larger numbers of users in the Internet and incorporates and enhances other IPv4 (current version of IP) features, such as support for resource allocation and security mechanisms [25].

A major application of the Asynchronous Transfer Mode (ATM) technology is the support of TCP/IP traffic. Extensive work therefore has been carried out in implementing IPv4 over ATM [2]. There are several reasons for the integration of IP and ATM. For example, ATM offers scalability and significantly higher speeds (i.e. 155 Mbits per second, 622 Mbps, and higher) which are features required by the current and future IP-based networks and applications. In addition, the IETF has developed several protocols to incorporate real-time support into IP-based networks, such as the Internet. One of the most important features of ATM is the ability to provide virtual connections within a specified Quality of Service (QoS), so IP with real-time support may use the QoS properties of ATM. Also, IPv6 is intended to be the protocol which will dominate the Internet and other networks in the next few years, and thus it is important to focus on the integration of IPv6 and ATM.

The purpose of this paper is to provide a taxonomy of several options and issues for IPv6 over ATM and to describe various approaches for supporting the integration between IPv6 and ATM in these terms. In addition, this document considers only those approaches for supporting IPv6/ATM integration which have been standardized, or for which there is work in progress in the form of IETF’s Internet-Draft or an ATM Forum. Also, it considers approach specifications based on IPv4 when the core technology is extendible to IPv6 network layer protocol.

This paper is organized as follows. Section two describes the options and issues for IPv6 over ATM. Section three examines the various approaches for supporting the integration of IPv6 and ATM. Section four presents a comparison of the approaches in terms of the integration options and issues discussed in section three. Section five discusses the advantages and disadvantages of the IP over ATM options as well as some recommendations for the IPv6/ATM integration.

2. IPv6/ATM INTEGRATION ISSUES
In this section, various issues which should be considered in the integration of IPv6 and ATM will be described (also see [36]). The integration issues arise from the differences and similarities between both the protocols.

Encapsulation
The encapsulation methods allow the endpoints of a connection to be identified. The IETF has also defined two types of packet encapsulation and multiplexing over ATM Adaptation Layer (AAL5)[24]: the LLC/SNAP encapsulation and the Null encapsulation or VC-based Multiplexing. The LLC/SNAP encapsulation allows multiple protocols to be multiplexed on a single Virtual Connection (VC), so a LLC/SNAP header containing information about the identity of each protocol and VC endpoint is added to each packet. In the VC-based multiplexing, only one protocol entity is supported by a virtual connection. Any information about multiplexing or packet type is not carried in the packet, and the type of protocol may be negotiated during the call setup phase.

Other types of encapsulation have been proposed [17]. They eliminate largely or totally the IP header overhead, since single hop reachability between IP endpoints is assumed. For example, in the TCP and UDP over Lightweight IP (TULIP) model only the protocol and port information are carried in each packet, everything else is negotiated during the call establishment phase. Another example is the TCP and UDP over Nonexistent IP Connections (TUNIC) model in which everything is bound at call setup time; any information related to the network layer is not carried in the packet.

Service Orientation
IP is a connectionless protocol, while ATM is connection-oriented. The operation of a connectionless protocol over a connection-oriented one is not common. Thus, IP may run on the top of ATM as follows:

• Hop-by-Hop IP Forwarding over ATM point-to-point links: IPv6 may remain connectionless and forward packets hop-by-hop as it usually does. In order to provide a
connectionless service, several ATM connections have been set up in advance between the IP routers attached to the ATM network. Therefore, it will provide a connectionless service which Cole et al. [17] refer to as a pure connectionless approach.

- **Hop-by-Hop IP Forwarding using ATM complex mechanisms**: IP packets will be delivered by ATM. The IP/ATM protocol will support the mechanisms necessary to manage the virtual connections for supporting IP flows. Therefore, it will provide an end-to-end connection-oriented service which Cole et al. [17] refer to as a pure connection-oriented approach.

- **Cell-by-cell switching based on IPv6 information**: IP packets may be directly switched cell-by-cell by the ATM switches within the network. The ATM forwarding and VC establishment are based on the results of the IP routing algorithms. The ATM-specific routing or addressing may not be needed. In addition, some packets may be forwarded hop-by-hop instead of being switched directly (i.e., selective hop-by-hop IP forwarding). Therefore, it will provide a service in the middle of the connectionless and connection-oriented service which Cole et al. [17] refer to as a middle ground approach.

- **ATM-based switching and routing**: ATM will provide switching and routing. Therefore, routers and switches within the network will run the same routing protocol (i.e., ATM-specific routing), and the data-link functions will be supported by ATM. Therefore, it will also provide an end-to-end connection-oriented service (i.e., pure connection-oriented approach [17]).

### Addressing

An addressing scheme defines the address structure used to identify the devices within a network, and how these addresses are assigned to these devices. There are two different models for the IP/ATM addressing integration:

- **Peer model**: ATM and IP could use the same address structures to identify routers, switches, and other devices. A variant of this model is described in [2] and [17]. It proposes a one-to-one algorithmic mapping between IP addresses and ATM addresses.

- **Overlay or subnetwork model**: this model proposes the use of independent addressing schemes. Thus an address resolution protocol for translating IP addresses into ATM addresses is needed.

### Routing

Both the IETF and ATM Forum have developed different protocols for routing packets within an IP-based network and Switched Virtual Connections (SVCs) within an ATM-based network. Thus two models have been proposed for integrating ATM and IP routing:

- **Integrated Routing**: this model proposes the use of the same protocol to route IP packets and ATM SVCs in switches and routers.

- **Layered Routing**: the ATM routing protocol will be independent of the IP routing protocols. IP routers will run IP routing protocols while the ATM switches will run ATM routing protocols.

### Multicasting

As in IPv4, IPv6 includes a multicast addressing capability [26]. IPv6 relies on the underlying data link protocol and routing protocols for the multicast packet delivery. The ATM UNI supports point-to-multipoint VCs. Thus, there are several ways to implement multicast service over ATM:

- **VC Mesh**: each source establishes a point-to-multipoint VC to the members of the multicast group.

- **ATM Multicast Server (MCS)**: the sources establish VCs to a multicast server which, in turn, establishes point-to-multipoint VCs for each multicast group. The leaves of a point-to-multipoint VC are the members of the group.

### ATM signaling

The ATM signaling functions include management [7], [8] (i.e., setup, release, and maintenance) of point-to-point and point-to-multipoint VCs, traffic and QoS negotiation, and signaling message routing.

When integrating IP and ATM, a duplication of functions arises. For example, in an ATM network, the switches and hosts attached to the network are identified by ATM addresses, while the routers and hosts attached to an IP network are identified by IP addresses. Several protocols have been developed for dealing with this duplication of functions, such as the address resolution protocol which maps ATM addresses into IP addresses. The approaches for supporting IP/ATM integration may be categorized into those which use the ATM signaling protocols and those which use IP signaling protocols to handle the packets belonging to the flow.

Flows between the same source and destination IP addresses and having the same TCP/UDP ports may be considered a flow.

- **QoS-based flow detection**: the flow label field in the IPv6 header may be used by a reservation protocol (e.g., Resource Reservation Protocol (RSVP) [13]) to identify a particular flow which for some resources have been allocated. The IP/ATM driver may use this field together with the source IP address and destination IP address (optional) to decide how to handle the packets belonging to the flow.

- **Host-address-based flow detection**: any sequence of packets flowing between the same source and destination IP addresses may be considered a flow.

- **Port-based flow detection**: any sequence of packets flowing between the same source and destination IP addresses and having the same TCP/UDP ports may be considered a flow.

### Service Models

Several Working Groups (WGs) of the IETF are working on developing some standards and/or proposals for extending the original TC/IPI protocol stack to support real-time applications as well as the traditional best-effort applications over networks such as the Internet (e.g., the Integrated Services Model in the Internet Architecture [13]). Also, the ATM Forum has

In addition, when a flow is detected, a node may choose to create a new ATM VC or to use an existing one. The existing mechanisms for flow detection may be categorized as follows:

- **QoS-based flow detection**: the flow label field in the IPv6 header may be used by a reservation protocol (e.g., Resource Reservation Protocol (RSVP) [13]) to identify a particular flow for which some resources have been allocated. The IP/ATM driver may use this field together with the source IP address and destination IP address (optional) to decide how to handle the packets belonging to the flow.

- **Host-address-based flow detection**: any sequence of packets flowing between the same source and destination IP addresses may be considered a flow.

- **Port-based flow detection**: any sequence of packets flowing between the same source and destination IP addresses and having the same TCP/UDP ports may be considered a flow.
developed an unified service model [21] which includes the specification of the traffic and congestion control mechanisms, the quality of services parameters, the service categories, and the signaling protocols for resource reservation and connection management.

There are several problems which arise from the differences between the IETF and ATM Service Architecture [12]. In this paper, four alternative models for the integrated service IP-over-ATM are proposed:

- **IETF-integrated-service-based model:** several approaches for running IP over ATM propose the use of the ATM as a fast switch. They largely or totally eliminate the ATM signaling protocol. These approaches may rely on either the IETF resource reservation protocols or their own resource reservation protocol for providing QoS.

- **ATM-service-based model:** some approaches for integrating IP and ATM may not consider the use of any IETF Integrated Service implementation including RSVP. They therefore rely on ATM for QoS provision.

- **IETF-and-ATM-service-based model:** it might be desirable that an IP-based network supporting the IETF integrated service model is integrated to an ATM network in which the signaling and traffic management protocols are employed. The complex task of implementing this model involves: mapping the IETF service classes into ATM service categories, translating the IETF traffic parameters to the ATM Connection Traffic Descriptor parameters, integration of the IETF's reservation protocols (e.g. RSVP) and the ATM signaling protocols, and determination of how the ATM traffic management functions could be used to control the IP traffic [18].

- **Integrated Model:** the Integrated Model proposes the use of a QoS Architecture (e.g. see [16]) which will provide a framework for the QoS provision in distributed systems.

### 3. OVERVIEW OF THE PROPOSED INTEGRATION APPROACHES

The aim of this section is to outline the approaches for supporting IPv6/ATM integration (see also [36]).

#### Next Hop Routing Protocol

The Next Hop Routing Protocol (NHRP) is an IETF's proposal [29] for communicating stations (i.e. hosts or routers) over Non-Broadcast Multi-access Networks (NBMA) such as an ATM network. NHRP is intended to extend the functionality of the Address Resolution Protocol specified in [28] by allowing end stations to set up shortcuts towards other stations attached to the same link-layer cloud or NBMA subnetwork. A shortcut may be defined as a NBMA VC which directly connects two IP endpoints which may be separated by one or more routers.

There are two types of NHRP logical components: the Next Hop Server (NHS) and the Next Hop Client (NHC). A NHS is a protocol entity which provides address resolution information in response to an address resolution request from a NHC. A NHC is a protocol entity which cannot answer address resolution requests, but it interacts with the NHSs to request the NBMA address of a particular destination. Both the NHSs and NHCs maintain caches that contain mapping information between the internetwork addresses, such as IPv6 addresses and ATM addresses.

#### Multiprotocol Label Switching

The IETF's Multiprotocol Label Switching (MPLS) WG is working on a proposal which integrates the network routing and the label swapping forwarding paradigm. In other words, the packet forwarding is performed based on a short, fixed length label carried in the packet. The information contained in the routing tables is used for label binding and distribution. The proposed technology is called Multiprotocol Label Switching (MPLS), and it is described in [15]. The initial effort of MPLS WG has been focused on IPv4 and IPv6.

In [15], a label is defined as a short fixed length piece of data which has local scope, and is used to simplify the packet forwarding. It should also have clear semantics and support various levels of aggregation. The length of a label depends on how the streams of data can be associated with the labels.

A label may be carried in the Virtual Path Identifier (VPI) and/or Virtual Channel Identifier (VCI) fields of an ATM cell.

#### IPv6 over ATM Networks

IETF's Internetworking over NBMA (ION) WG is working on IPv6 over NBMA networks [4], [5]. It is intended to support the Neighbor Discovery protocol for IPv6 [30] over NBMA networks, such as an ATM network: Neighbor Discovery (ND) uses a multicast service for distributing some messages; so any data link layer technology below IPv6 should provide this service. The Multicast Address Resolution Server (MARS) [3] therefore is intended to provide the required multicast service over ATM.

In IPv6, those nodes attached to the same link over which it can communicate at the data-link layer (e.g. ATM, Frame Relay, and Ethernet) by an interface are considered neighbors. In addition, a logical link (LL) is defined as an administrative group which is made up of several hosts managed by a single MARS [3]. Thus, Armitage et al. [4] make a distinction between IPv6-over-ATM ND operation within a LL (intra-LL) and the operation outside a LL (inter-LL). In the intra-LL mode, MARS is used to forward the ND multicast messages. Inter-LL is the result of a redirection [30]. NHRP is therefore used to resolve the mapping between IP addresses and ATM addresses.

#### LAN Emulation Version 2.0

**LAN Emulation (LANE)** is an ATM Forum standard. The first version was released in 1995 and the most current version (i.e. version 2.0) in 1997 [11]. LANE is a layer 2 protocol which emulates some functions of LANs such as connectionless service, multicast services and MAC station interfaces. It therefore can provide the same services to the higher layer protocols, such as IPv6, that are provided by a legacy LAN (e.g. Ethernet and Token Ring). LANE only emulates Ethernet and Token Ring networks and does not specify the communication between two or more Emulated LANs (ELANs). Furthermore, LANE allows not only ATM-attached devices to communicate but also ATM-attached LANs to exchange packets.

Like other proposals, LANE is based on a client/server model, so there are two components: LANE clients (LECs) and servers. The latter ones are the LANE Configuration Server (LECSs), the LANE Servers (LESS) and the Broadcast and Unknown Servers (BUSs). Also, LANE defines a LANE Emulation Service as a set of one or more LECs, one or more LESs, and one or more BUSs. A LEC performs data forwarding and address...
resolution, and other control functions. Multiple LEC instances may run over an ATM end system (e.g. ATM bridge and ATM-attached host). A LEC is identified by an unique ATM address and interacts with the LANE Service via the LANE User Network Interface (LUNI) [11]. A LES provides an address resolution service that resolves unicast and multicast LAN MAC addresses to ATM addresses. A BUS distributes broadcast, multicast and unknown traffic (i.e. multicast or unicast MAC addresses which have not been resolved) which is sent by the LECs. A LECs assigns individual LANE clients to ELANs by directing them to the LES that correspond to the ELAN.

Multiprotocol over ATM

Multiprotocol over ATM (MPOA) is a specification from the ATM Forum [10], which is based on existing ATM Forum and IETF standards. MPOA uses LANE, NHRP, and UNI services to provide both bridging and routing capabilities. It is not only capable to forward packets based on the MAC address as LANE does but also to transfer unicast data between subnets (inter-subnets).

The MPOA components are as follows. A MPOA client (MPC) interacts with the MPOA Servers (MPSs) in the Router Servers in order to set up and release shortcuts. The MPCs may forward packets but they do not run any internetwork layer routing. A MPS provides internetwork layer information to the MPCs. A MPS is the component which allows MPOA to use NHRP services, so it has a NHS component.

Integrated PNNI

The Private Network-Network Interface (PNNI) has been developed by the ATM Forum [7] for use within private ATM networks. PNNI consists of two protocols, the signaling protocol used for virtual connections management, and the protocol for distributing topology information used to compute path through the network.

The Integrated-PNNI (I-PNNI) protocol is an extension of PNNI; however it is at an early stage [9]. In an I-PNNI-based network, there may be ATM switches and IP routers. In the I-PNNI proposal, it is expected that PNNI is the only protocol running on routers and ATM switches in the network. For example, an IPv6 router could run PNNI instead of the traditional IP routing protocols, such as OSPF. It may also run other routing protocols if it will interact with other non-I-PNNI networks. I-PNNI also supports hosts running multiple protocols and attached to the ATM network via protocols, such as LANE and MPOA.

IP Switching

IP Switching is the alternative proposed by Ipsilon Networks to run IP on the top of ATM [33]. ATM is only used to switch IP packets based on IP flow and routing information. Any ATM signaling and routing components are removed.

An IP Switch has two main hardware components, the ATM switch and the IP controller. The ATM switch performs the ATM-layer and AAL functions. The IP controller runs both the IP software and switching software components. The IP switching software components are: the Ipsilon Flow Management Protocol (IFMP) [33] which maps IP flows into ATM VCs; the General Switch Management Protocol (GSMP) [33] which allows the communication between the switch and the controller; and the flow classifier which decides whether a flow can be switched or not.

Tag Switching

Tag Switching has been developed by Cisco and is specified in [34]. It combines the Network Layer routing with the tag switching model which is known as tag (label) swapping. Tag swapping is a type of forwarding method which uses short, fixed length labels (or tags) that identify a sequence of packets belonging to a particular flow to determine how to deliver these packets. Tags therefore are assigned based on the network layer routing information, and labeled packets are forwarded using the information in their tags.

When ATM is used as a Tag Switching Router (TSR), the ATM control components are not needed, since tag switching has its own control component. In addition, the tag is carried on the VPI/VCI fields of an ATM cell. Also, an ATM Tag Switching Router (ATM-TSR) should run one or more network layer routing algorithms.

Cell Switch Router

Katsube et al. [27] from Toshiba propose a network model based on Cell Switch Routers (CSRs). A CSR integrates cell switching capabilities and IP routing functions. An IP packet therefore may be either switched by ATM or forwarded hop-by-hop by IP.

The ATM VCs connect adjacent CSRs or a CSR and an ATM-attached node (e.g. host/router). Multiple concatenated VCs form an ATM-bypass-pipe. The ingress and egress nodes of a bypass-pipe should be bypass-capable nodes, since they should support a bypass-control protocol. The intermediate CSRs of the bypass-pipe should incorporate both the ATM cell switching capabilities and the bypass control protocol. Two types of ATM VCs are defined: the default VCs and the dedicated VCs. The default VCs are set up between routers and used for hop-by-hop forwarding. Dedicated VCs are the components of the ATM bypass-pipes and support specific IP flows.

Aggregate Route-Based IP Switching

Viswanathan et al. [35] from IBM have proposed a model which integrates routing protocols, such as OSPF and RIP, and switching protocols such as ATM. The Aggregate Route-Based IP Switching (ARIS) protocol provides the mechanism to manage switched paths based on routing information. A device which has the above mentioned functionality is called Integrated Switch Router (ISR). ATM may be used as the switch component of an ISR, and the switched paths may be created over the ATM virtual connections.

A switched path may be defined as a routed path identified by an egress identifier. ARIS supports several types of egress identifiers [35] such as the IP destination prefix, the IP address, the OSPF Router ID, and the explicit route. It may be noted that the flow label and priority fields in the IPv6 header together with the source and/or destination addresses, and/or the port identification may be also used as an egress identifier, since the specification leaves the possibility to use other types of flow identifiers open.
IP Switching Over Fast ATM Cell Transport

IP Switching Over Fast ATM Cell Transport (IPSOFACTO) is the NEC's proposal for integrating IP and ATM [1]. It defines a method for mapping IP flows into ATM switched paths. The switch also runs IP routing protocols and a control component. ATM signaling component therefore is not needed.

In an IPSOFACCTO-based network, a switch is composed of a controller and the ATM component. While ATM forwards IP packets cell-by-cell, the controller performs IPSOFACCTO functions.

### Table 1: The encapsulation methods used by the different approaches.

<table>
<thead>
<tr>
<th>Encapsulation Methods</th>
<th>VC-based multiplexing or Null Encapsulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLC/SNAP</td>
<td>LANE</td>
</tr>
<tr>
<td>MPLS</td>
<td>MPOA</td>
</tr>
<tr>
<td>IPv6 over ATM Networks</td>
<td>IP Switching</td>
</tr>
<tr>
<td>LANE</td>
<td>Tag switching</td>
</tr>
<tr>
<td>MPOA</td>
<td>CSR</td>
</tr>
<tr>
<td>IP Switching</td>
<td>ARIS</td>
</tr>
<tr>
<td>Tag Switching</td>
<td>IPSOFACTO</td>
</tr>
</tbody>
</table>

**Table 2: A taxonomy of the approaches based on the service orientation models and options.**

<table>
<thead>
<tr>
<th>Service Orientation</th>
<th>Connection Oriented</th>
<th>Middle Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Hop-by-hop IP forwarding using ATM complex mechanisms</td>
<td>ATM-based switching and routing</td>
</tr>
<tr>
<td>Approach</td>
<td>NHRP IPv6 over ATM networks</td>
<td>LANE MPOA</td>
</tr>
</tbody>
</table>

* It also supports selective hop-by-hop IP forwarding.

The transmission, since the route is calculated for the ATM connection, and the packets are switched based on the ATM VCI/VPI fields. A route is calculated for a connection rather than for each IP packet. Third, the resources can be allocated for the connection duration, the congestion control is simplified. For example, NHRP is used to obtain the ATM address of an IP destination address which may benefit from a shortcut. Shortcuts optimize the forwarding path, since they are direct connections established between parties.

4. ANALYSIS OF THE APPROACHES

In this section, the approaches for integrating IPv6 and ATM will be compared in terms of the integration options and issues. It is also based on the study in [36].

**Packet encapsulation**

Table 1 shows the encapsulation methods used by the integration approaches. In the LLC/SNAP encapsulation, a single virtual connection may be used for more than one protocol. Transporting and multiplexing multiple types of packets over the same ATM reduce the connection setup latency and save connection resources. In addition, LLC/SNAP is a convenient option for those approaches which are intended to support multiple network-layer protocols, such as MPLS and MPOA.

On the other hand, those approaches which are intended to support only the IP protocol, such as IP Switching, use or would use VC-based multiplexing. This method has the advantage that no header is added to the IP packet. However, an ATM connection can only carry single-protocol packets. Also, since some approaches do not use the ATM signaling, VC multiplexing information must be negotiated by means of another protocol; for example, Tag Switching's TDP (Tag Distribution Protocol) is used to negotiate this multiplexing information.

TULIP and TUNIP encapsulations are not used by any of the approaches. The main disadvantage of these methods is that they minimize the use of the network protocol, such as IPv6, since they are intended to support application or transport protocols running directly over ATM.

**Service orientation**

Table 2 shows a mapping between the models for running a connectionless protocol on the top of a connection-oriented one. Several proposals provide a connection-oriented service. Some advantages are claimed by the connection-oriented approaches. First, there will be a low switching delay during the transmission, since the route is calculated for the ATM connection, and the packets are switched based on the ATM VCI/VPI fields. Second, a route is calculated for a connection rather than for each IP packet. Third, since the resources can be allocated for the connection duration, the congestion control is simplified. For example, NHRP is used to obtain the ATM address of an IP destination address which may benefit from a shortcut. Shortcuts optimize the forwarding path, since they are direct connections established between parties.

However, the connection-oriented approaches incur a setup delay (i.e. connection setup latency). But the setup delay may be reduced by multiplexing traffic from multiple sources on a single VC. Also, some approaches reduce the impact of the connection setup latency by means of other alternatives such as the use of default routed paths. For example, in MPOA, while awaiting an address resolution reply, the MPC may send the packet by the default route. Another drawback is that the VCs which share a failed link or switch must be released and reestablished. In addition, a connection may be refused if there is not sufficient resource availability.

At the other end of the spectrum, the approaches may be highly connectionless. Although the approaches studied here do not implement a connectionless model, some portions of the IPv6/ATM network may provide a full connectionless service. For example, communication between ELANs may be supported by IP routers attached to an ATM network. An advantage of this model is that it does not incur a connection setup delay. In addition, since ATM connections have been previously established between the IP routers, the system may not refuse the entry of a packet in the event of congestion. Also, the packets are routed independently which gives robustness in the case of congestion or link failures, and it may rely on ATM traffic management functions for congestion control. On the other hand, the network resources must be pre-allocated over the ATM connections, which connect IP routers, that may lead to a waste of resources. However, the network resources may be allocated over SVCs based on the traffic measurement, so the network could release a SVC and open a new one with the new traffic characteristics.

Furthermore, there are several approaches which provide a service which combines the features of the connectionless and connection-oriented models. First, they do not incur in a long setup delay; for example, in IP switching, the IP packets are always forwarded hop-by-hop until a switched path is built. Second, each packet has a label (e.g., ATM VPI/VCI fields).
which is used to deliver it along the route from the source to the destination. Third, the routers and/or switches maintain the state of the switched paths; however this information may be refreshed after a period of time as in the soft-state model; for example, in MPLS, a label has a time of life associated, if it is not refreshed after the time out, the label and corresponding binding are released. And fifth, if a node or link along the route fails, the packet could be forwarded hop-by-hop using IP; for example, IP switching use the default VCs for forwarding non-classified flows.

The middle ground model has also some disadvantages. For example, some approaches which follow this model discard the use of the ATM signaling, such as Tag Switching, and hence ATM QoS provision and resource reservation mechanisms cannot be used. Also, additional space is required for allocating the tables containing a mapping between IP flows and labels.

**Addressing**

Table 3 shows a taxonomy of the approaches based on the addressing options. Most of the approaches which follow the overlay model rely on a server to translate IP addresses into ATM addresses. For example, in MPOA and NHRP, the NHSs provide address resolution information. Centralized servers therefore simplify the address resolution procedures; however, the servers represent potential bottlenecks for the network, since they may receive address resolution requests from multiple clients. The use of caching reduces this problem because the client may cache address resolution information. In addition, a server may only serve the clients within a subnetwork. For example, a NHS serves the client within a NBMA subnetwork (e.g. an ATM subnetwork).

Furthermore, the overlay model allows the ATM and IP addressing scheme to develop independently of the others. However, since IPv6 and ATM require their own addressing schemes, there is a duplication of functions such as system address administration and routing.

On the other hand, the approaches listed in table 3 use a variants of the peer model. They do not require any address resolution protocol to resolve internetworking addresses into ATM addresses, since the IP addresses are employed for route calculation and the ATM VPI/VCI fields (i.e. the label) are used for packet switching. The peer model also simplifies the system address administration and routing functions. However, by using only IP addressing and routing, these approaches cannot benefit from the ATM scalability and QoS provision.

**Routing**

Table 4 shows a categorization of the approaches in terms of the integrated and layered models. The layered model decouples the routing functions into ATM routing and IP routing. The goal of this model is to take advantage not only the routing in ATM but also the multiple existing IP routing protocols, such as OSPF and RIP. For example, IPv6 over ATM networks and MPOA use IP routing protocols for hop-by-hop IP forwarding and ATM signaling for shortcut establishment.

However, under the layered model, an ATM connection is established for every IP packet flow even though the flow could benefit from the hop-by-hop IP forwarding based on routing protocol information. For example, once MPOA detects a flow and a shortcut is established, and the packets belonging to this flow are forwarding over this connection. In addition, a duplication of routing protocols arises from using the layered model, and hence a duplication of maintenance and management functions.

The integrated model, on the other hand, proposes the use of one routing protocol. Several approaches use the IP routing protocols and discard the ATM signaling protocol, such as IP Switching and Tag Switching. In addition, I-PNNI is intended to use PNNI as the protocol running on routers and switches. The use of a unique routing protocol eliminates the duplication of the maintenance and management functions. Also, only single routing-protocol information must be maintained in the routers.

**Multicasting**

Table 5 shows a mapping between the approaches and the different ways of providing multicast support over ATM. For the approaches which do not use the ATM signaling protocol (e.g. IP Switching), the solution to the problem of transporting IP multicast packets over ATM is straightforward; they directly support IP multicast. However, these approaches rely on the multicasting capability of the ATM switches for multicast cell forwarding, and not all of the existing hardware supports this capability. Also, a large number of labels may need to be allocated for supporting multicast trees, as these approaches implement a variant of the VC mesh model.

In the VC mesh model, since each source originates its own point-to-multipoint VC to the members of the multicast group, it may lead a significant resource consumption and impose a heavy load on the ATM signaling protocol. However, this model minimizes the end-to-end latencies for each point-to-multipoint VC from the source because the path length of the connection set up between the source and the destinations may be optimized by the ATM signaling protocol.

Alternatively, the multicast server approach reduces the number of point-to-multipoint connections which have to be established to support multicast IP forwarding, when compared to the VC mesh approach, and hence the resource consumption and signaling load. For example, in IPv6 over ATM networks, each node sets up a point-to-point VC to the MARS, which in
Discarding the ATM signaling component has the disadvantage of using their own setup protocols, which are outlined in [36]. ATM Signaling overcomes this problem.

However, a multicast server is a potential point of congestion and a single point of failure. Some approaches, such as LANE v 2.0, may support multiple BUSs within a Emulated LAN to overcome this problem.

ATM Signaling
MPLS, IP Switching, Tag Switching, ARIS, and IPSOFACTO use their own setup protocols, which are outlined in [36]. Discarding the ATM signaling component has the disadvantage that ATM cannot provide any QoS guarantees. Also, the communication parameters must be negotiated by means of other protocols. For example, Tag Switching Routers negotiate VC-based multiplexing information using TDP. In addition, the approaches must rely on other reservation protocols for resource allocation along the path to the destinations.

I-PNNI uses the PNNI protocol. Even though the PNNI protocol is a scalable protocol which use QoS and reachability information for route calculation, it has high processing requirements and large latencies. Also, the I-PNNI specification is at an early stage, and there are significant remaining open issues related to I-PNNI operation.

The most complete solutions are provided by the approaches which attempt to keep ATM and IP unchanged: IPv6 over ATM networks, MPOA, LANE, and CSR. They may benefit from the ATM capabilities such as QoS provision and traffic management, however they use more complex mechanisms for dealing with the duplication of functionality.

Flow detection
Table 6 shows the flow detection models and some fields which are or may be part of a flow identification in the different approaches studied here.

Most of the approaches use the source and destination IP addresses as part of the flow ID, and a sequence of packets is considered a flow if they are flowing between the same source and destination addresses. For example, in MPOA, once a threshold (i.e. number of packets for a single Internetwork Layer address in a fixed period of time on the ingress side) is exceeded, the MPC can place a call to establish a shortcut. Therefore, this view of a flow adapts well to the concept of best-effort traffic. In addition, most network applications today do not expect to receive, and do not request, any guaranteed QoS from the underlying technologies. Consequently, in the integration of IP and ATM, the initial effort has been put into providing a best-effort service.

The host-based and port-based flow detection mechanisms therefore are not suitable for networks which are intended to support applications with QoS guarantees. As an alternative, the QoS-based flow detection mechanism may be used if the IP/ATM network is intended to support applications with guaranteed QoS. The flow label and/or priority fields in the IPv6 header may play an important role in how the packets belonging to a flow may be handled by the IP routers along the path towards the destinations. Few approaches have considered QoS for flow detection. For example, the MPLS specification proposes a label assignment method based on the control traffic generated by protocols, such as RSVP.

Service Models
As mentioned above, most of the current applications do not expect to receive any QoS guarantees from the underlying network. So the best-effort service, and hence the ATM Unspecified Bit Rate (UBR) and Available Cell Rate (ABR) service classes [2], [21] is the default option supported by most of the approaches, such as IP over ATM networks, LANE, and MPOA.

The proposals which discard the use of the ATM signaling protocols, such as MPLS, IP Switching, Tag switching, ARIS, and IPSOFACTO, cannot use the services offered by ATM, for example QoS provision. These approaches may support the IETF Integrated Service and Reservation Protocols (i.e. they follow the IETF-integrated-service-based model). However, it could become clear that one of the most attractive feature of ATM is the QoS provision.

The approaches which support the full capabilities of ATM (i.e. IPv6 over ATM networks, LANE, MPOA, I-PNNI, and CSR) may benefit from the services offered by this technology, which include the QoS provision, multiple service categories, traffic and congestion control. They may follow the ATM-service model. However the default service provides by all of these approaches is the best-effort packet transport. In addition, some of these approaches such as LANE and MPOA could also support both the IETF and ATM service models (i.e. follow the IETF-and-ATM service model).
In addition, I-PNNI developers may consider a QoS architecture which can provide a framework for QoS provision in the network. This architecture may include the definition of several layers. Each layer may guarantee the requested QoS to the highest layer and demand QoS from the next lower layer.

5. CONCLUSIONS

Perhaps the major contribution of the integration approaches studied here has been the large number of proposed options to solve the integration problems. These options represent important technological contributions which may play an important role in the development of the future technologies. However, the diverse proposals for interfacing IP over ATM have not been jointly developed or adopted by the standardization committees and the individuals/companies. Thus it may be desirable that these committees work toward merging these approaches as far as possible and exploit their compatibility.

Also, the large number of integration options, issues and approaches reflect the fundamental complexity of the task that is involved in interfacing IP over ATM. The evolution to an IPv6/ATM network will be complex and require sophisticated protocols such as the ones described in this paper.

This paper explains how the integration technologies work without reaching a final judgement about which technology is the best for a particular environment. The author believes that considerable additional work is required to arrive to a decision. Additional studies may include the analysis of the performance measurements of the IPv6 over ATM.

The problems of the IPv4/ATM integration are similar to those which arise from interfacing IPv6 over ATM. However, some of the changes from IPv4 to IPv6 simplify the IPv6/ATM integration. For example, the IPv6 flow label field enable the labeling of packets which need special handling, such as the traffic with requested QoS.

The foregoing discussion in this study indicates that a new integration technology could arise soon. For example, it would solve most of the internetworking problems outlined in this paper. It would be also integrated easily into existing networks. In addition, it would be simple and avoid the duplication of functions found in the IP/ATM integration process.

6. REFERENCES