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Technical Report

A Performance Evaluation Architecture for PNNI

Sandeep Bhat, Doug Niehaus, Victor Frost

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Abstract

As larger ATM networks are being installed, the performance issues relating to Private Network to Network Interface(PNNI) protocol, which provides link state based dynamic routing capability in an ATM network have assumed significance. The factors influencing the selection of topology of a network, the number of nodes in the network which share topology information(Peer Group size), the call setup times, link utilization, call rejection rates need to be evaluated. A comprehensive simulation tool for evaluating PNNI protocol is developed. The simulation tool is developed on a software architecture which has all the modules which are required to control an ATM switch, enabling its simulations closer to real network characteristics. Connection requests are generated using a comprehensive call generating tool. The factors influencing the peer group size and performance of a single peer group PNNI are addressed taking the topology convergence times, call setup times, bandwidth requirement of the PNNI topology messages, topology messages per call, source node failed calls, intermediate node failed calls and route computation times as metrics. The performance of the simulator to run sensible simulations is addressed.

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Chapter 1

Introduction

The Private Network to Network protocol(PNNI) is a comprehensive *routing* and *signaling protocol* architecture in a private Asynchronous Transfer Mode Network(ATM). It helps in exchanging the *routing* related topology information between ATM nodes. It also helps in selecting a *source_route* to the destination when a call connection is requested. PNNI uses the topology database it developed through flooding, to generate a source route to the destination required. The PNNI protocol is a very complex protocol to implement and it is even more difficult to predict its performance. The network behavior becomes unpredictable when controlling a big private network of ATM nodes(also known as switches), because connection requests will be coming from different host systems in the network, in unknown arrival patterns, with unexpected bandwidth requirements, and with different call connection durations. The PNNI protocol also contributes to this unpredictability by offering a wide range of parameters that may be manipulated.

One of the important issues of PNNI performance is its scalability. The PNNI protocol receives knowledge of the changing network through *topology updates* generated whenever there is a *significant change* in the topology information. These topology messages are broadcast to all the nodes in a network. In an expanding network, the *link delays*, the *flooding delays* due to *redundancy*, and the node *processing delays* impose a considerable delay before the information reaches all the intended network nodes. This could cause wrongly rejected calls due to false belief in lack of bandwidth in the network as well as wrongly accepted calls which will only be rejected later. Hence when the network service providers invest in installing an expensive ATM network, they seek to know about the performance of their network. Before deployment, it is of paramount importance to design a network for future extendibility. Testing a network's performance is a complex evaluation process as it is dependent on a number of parameters. To list some of them:

- the network topology.
- the connectivity density between the nodes.
- link bandwidth and link delays.
- call arrival rates.
- the call bandwidth requirements.
- the parameters of the PNNI protocol involved such as the *flooding_significance* and the *minimum_threshold* parameters for the topology information flooding.
- the switch port packet queue size and related packet losses,
- the difference in the relative processing capabilities of the nodes,
- the different routing policies that are used.

The list could be longer. This produces an *unbounded* problem which is beyond the reach of any *mathematical* solution. But nevertheless it is essential to have some type of performance prediction system, which could enable us to study the performance of the network.

The options to test the performance could be that the network providers have a *test network* of ATM nodes for testing purposes alone. But though such networks exist, they are only used for advanced network testing such as interoperability testing between two switch vendor's switches and a few basic sanity tests, and not for wide ranging performance evaluation test suites. Such test networks are also relatively small compared to an actual deployed network. These networks cannot be used for wide ranging performance tests because the setting up of such networks for the required experimentation is very time consuming, difficult, very expensive, and multiple such networks for simultaneous performance experimentation is not affordable. Succinctly, using real networks for all tests is not feasible, and since a great deal of effort is involved to get simplest of performance measures, this approach is not worthwhile.

The best alternative we find in such cases is either to *simulate* such networks or to *emulate* them in a distributed environment. While emulations scale to very large networks, simulations are very efficient for medium to large scale networks. While *emulation* is under advanced stages of development, *simulation* is used in this thesis for performance evaluation. Simulation is a *software process* which runs on a *single workstation*. It is configurable to simulate a required network with various network entities. It is also possible to specify the collection of various performance related data at different times during the experimentation. The simulations and emulations save time by offering simultaneous experimentation and are economically feasible.

The simulation is supported on the Bellcore's Q.port software. This software includes the UNI signaling messages, the data link Qsaal layer. GSMP off-board signaling agent capability is also added in the software which can control an ATM switch. Emulation support is also added to Q.port. The simulation model is built on this software with all necessary protocol stacks in the real ATM switch being used in the simulation to make it more real and accurate. The off-board signaling agent fabric, the emulation fabric, and the simulation model have about 98 % of their software in common.

The motivation to evaluate the performance of the PNNI protocol has led to developing a PNNI simulator as described in this thesis. The initiative to develop a simulator was taken up as there were no simulator tools available for PNNI performance testing which we required. At the time of developing this thesis, it was decided to use Naval Research Laboratory's(NRL) *Proust* simulator, but the *Proust* simulator did not support the call generation capabilities and it was primitive in some respects. *Nortel* (Northern Telecom) is working on a simulation tool which is in a development stage and not much is known about its capabilities. So simulator development was taken up which could help us test the performance of PNNI and extend our experimentation by expanding the tool's capability in a future perspective.

The simulator supports a *single peer group* version of the ATM forum PNNI specification. It is designed to an architecture which is convenient to be used, and which supports configuring and monitoring all the possible PNNI parameters of interest for experimentation. The *Q.port* software from Bellcore is used for the purpose of developing the simulator. Q.port's real time scheduling system is modified to support the *virtual time* oriented simulations. The Q.port software is upgraded to support an additional PNNI element, the *Designated Transition List*(DTL). The *DTL* contains the source node generated list of *nodal hops* to be traversed to reach the *destination* of the requested call. NRL's *Proust* PNNI architecture is interfaced in Q.port for providing the *PNNI routing subsystem* module. The most important finite state machine (FSM) in the PNNI protocol, the *Node Peer FSM* (NPFSM), the associated topology database interface, the *decoding* and *encoding* of the topology messages are developed for NRL by us which is reciprocated by the NRL in letting us use its software for the simulator. The *NPFSM* exchanges the topology information between the nodes and helps keep a database of all the topology information in each node. It interacts with the database to either seek topology information for broadcasting to other nodes or to insert new topology elements, it obtained from other nodes.

The simulator provides convenient usage of the tool by supporting a *user input script* language, which specifies

- The *duration* of the simulation.
- The network size in terms of the total number of nodes and links. *Generic node* characteristics and the individual node characteristics. Node characteristics include the *routing policies*, the PNNI protocol timer values, the *proportional multiplier* and *minimum threshold* values for effecting the significance of topology information change which leads to its flooding, and the number of ports.
- The *connectivity* between nodes, link bandwidth, queue size, *link delays*, and *queuing* delays.

- The generic and individual host characteristics, the different call arrival and duration distributions, prominently, *uniform*, *Poisson*, and *periodic* distributions. Multiple traffic sources with different destinations, *bandwidth requirements*, *QoS requirements*, and total number of calls to be attempted.

The user input script is designed in a manner to help users specify the minimum required parameters to run an experiment.

The tool supports the instrumentation of the following performance evaluation parameters:

- *Link utilization*.
- Call *setup times*.
- Initial PNNI topology *convergence time*.
- Call failure *causes*.
- The number of PNNI topology messages sent.
- The bandwidth consumed by PNNI messages.
- Call failures at the *source node* itself due to the knowledge of unavailability of network bandwidth.
- Call failures due to *non availability of bandwidth* in an intermediate link.
- Average *hop length* for each calls.
- Routing algorithm computation time.

The rest of this report is structured in the following manner. Chapter 2 explains the features of the PNNI protocol whose performance is studied under this thesis. Chapter 3 discusses the implementation aspects involved in the simulator. Chapter 4 explains the PNNI single peer group experiments conducted and the analysis of the performance obtained. The performance of the simulation tool regarding bigger network simulation is also discussed. Chapter 5 details the conclusions from the results and things learned from the thesis. It also explains the future enhanment of the simulator capabilities, providing the multiple peer group support and the specific performance issues of interest.

Chapter 2

Related Work

The Private Network to Network Interface protocol(PNNI) provides a scalable, dynamic routing architecture to support the ATM connection setup requests. In this chapter the basic ATM signaling connection setup sequences will be explained first. This will be followed with explanations on PNNI's specific features, hierarchical architecture, routing, and signaling information elements. Finally, the currently available research and commercial tools which support PNNI signaling will be presented.

2.1 ATM Connection Setup Sequence

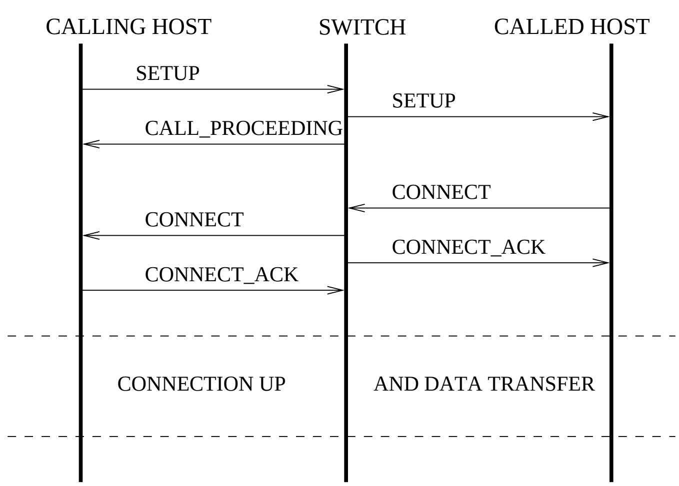


Figure 2.1: ATM Connection Setup Message Sequence

The flow of the ATM signaling sequences is illustrated in Figure 2.1. The *calling* *host* sends the *setup* message to the switch requesting a connection to the called host. The *switch* finds the route to the called host and forwards the *setup* message to the selected port connected to the called host. The *called host* receives the *setup* message and on deciding to accept the connection, sends the *connect* message to the switch. The *switch* receives the *connect* message and sends the *connect ack* message to the destination host which accepts it and prepares for data transfer. The switch sends a *connect* message to the *calling host*. The *calling host* receives the *connect* message and sends the *connect ack* message to the switch which accepts it. The connection is established. The calling and the called hosts exchange data.

2.2 PNNI Features

It is envisioned that ATM will grow and evolve into large networks consisting of a large number of switches connected by high-speed links. Many thousands of (Switched Virtual Circuit) SVC requests will be submitted to the network and the network will be expected to forward each request to the right destination, establish a path from calling to the called host, allocate resources and guarantee QoS. It will be a challenging task selecting the right path, one that optimizes network resources and guarantees QoS. The network itself may be made up of a mixture of ATM switches from different vendors. Different switches could set their own policies and procedures in the switch. PNNI is designed to support these challenging needs of a dynamic ATM network. Its features include:

- *Scalability:* It supports both small and very large networks of ATM switches.
- *Simple to install and configure:* As soon as the switches are connected, they exchange topology information and are able to route SVC requests with minimal configuration.
- *Dynamic routing mechanism:* PNNI supports dynamic routing of SVC requests through the network. In larger networks PNNI provides scalable hierarchical routing and support for multiple routing metrics and attributes. The best path

that will meet QoS objectives in the SVC request is computed and then the SVC request forwarded along that path. The routing is also responsive to changes in resource availability.

- *Source or transit policies support:* PNNI enables both *source or transit policies to be administered.* Different switch domains may have different policies based on security, usage, traffic types and other vendor specific issues.

- *Multi vendor:* PNNI supports a network of multi vendor switches and allows interoperability between them. The individual switches of different vendors could perform some specific functions such as route computation and Connection Admission Control(CAC) and others which suit their policy.

- *Interoperability :* PNNI supports interoperability with external routing domains, like Internet Protocol(IP) and others, not necessarily using PNNI. In Integrated PNNI the ATM switches exchange topology information with the IP routers to maintain routing database.

2.3 PNNI Topology

PNNI topology constitutes the PNNI routing hierarchy. These are terms associated with a PNNI topology. Please refer to Figure 2.2 along with explanation of the terms when required.

- *Peer Group (PG):* A peer group is a collection of nodes that shares the topology information generated by each node through topology information flooding. Members of a peer group discover their neighbors using a *hello* protocol. Physical peer groups consist of physical nodes. Logical peer groups are peer groups consisting of logical group nodes(which represent a low level peer group at the next higher level of hierarchy).

- *Peer Group Identifier :* Members of the same peer group are identified by a common peer group identifier. The peer group identifier consists of 14 bytes. The

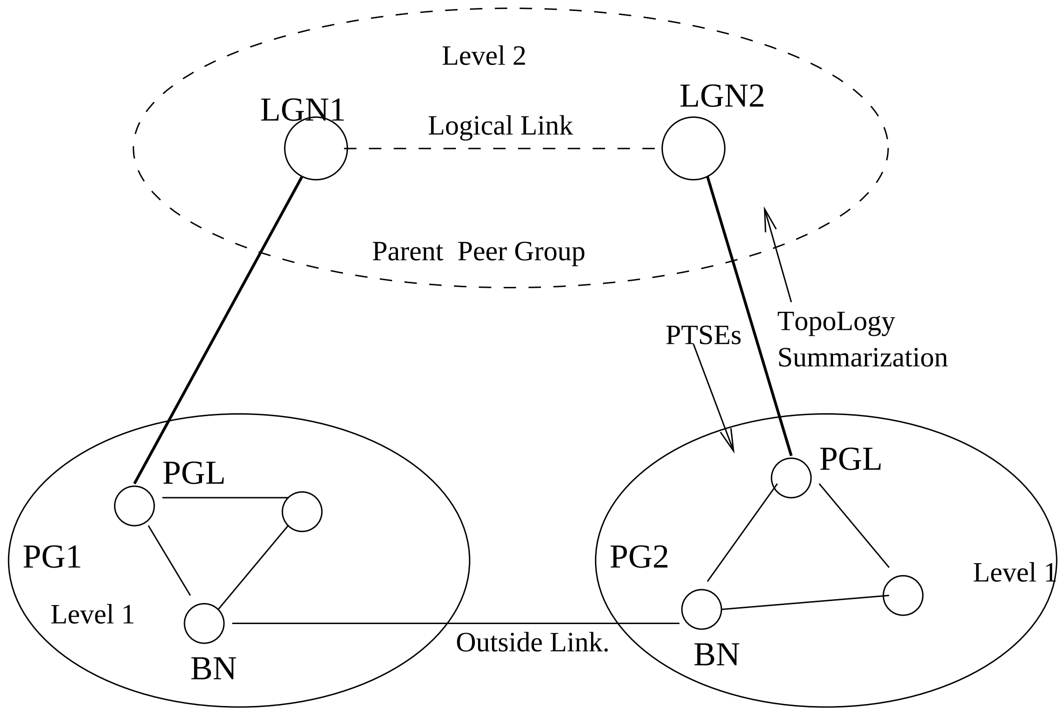


Figure 2.2: PNNI hierarchical architecture

most significant byte is a level indicator and specifies the bit mask. The next 13 bytes are derived from the 13 most significant bytes of the ATM address of the node in the peer group.

- *Logical Group Node(LGN) :* It is a node which represents peer group of the nodes in the next higher level.

- *Parent Peer Group :* A peer group which constitutes a LGN of a lower level peer group in the next higher level.

- *Peer Group Leader(PGL):* Within a peer group, a node is elected to represent this peer group in the next higher level. PGL summarizes the peer group information to the next level. It also passes higher level information obtained from the parent peer group to it's peer nodes.

- *Hello Protocol:* This is a standard link state procedure used by neighbor nodes to the discover the existence and identity of each other.

- *PNNI Topology State Element(PTSE):* This unit of information is used by nodes to build and synchronize a topology database within the same peer group. PTSEs are reliably flooded between nodes in a peer group and downward from an LGN into the peer group it represents. PTSEs contain topology information about the links and nodes in the peer group. A group of PTSEs are carried in PNNI topology state packets(PTSP). PTSPs are sent at regular intervals or are sent if an important change in topology occurs.

- *Logical link:* A logical link is a connection between 2 logical nodes. A logical link aggregates a group of links between the peer groups they represent at the lower level.

- *Border Nodes (BN):* A border node is a node in a peer group connecting to a node of another peer group. This is found by matching different peer group identifiers during hello protocol exchange. The link connecting border nodes is called the outside link.

- *Uplinks :* An uplink is a topology information advertised from a border node to a higher level LGN. The existence of the uplink is derived from an exchange of hello packets between the border nodes. These exchanges determine the higher hierarchical level where the two peer groups have ancestors in a common peer group. They advertise the the common level along with the address of the peer nodes in the common level in the uplinks information. These uplinks are flooded all the way up the hierarchy till they reach LGNs in the common higher level peer group. The LGNs which are neighbors try to establish logical link by using the address of the peer node specified in the uplink information.

- *Routing Control Channel(RCC):* The VPI =0, VCI = 18 which is reserved as the VC used to exchange PNNI topology information between physical nodes is called the PNNI RCC.

- *Topology aggregation:* This is the process of summarizing information at one peer group level to advertise into the next higher level peer group. Topology aggregation is performed by PGLs. Multiple links are aggregated into one link and a peer group of nodes is aggregated into one node LGN at the next higher level as explained earlier.

2.4 PNNI Routing

PNNI routing is used to distribute information about the topology of the ATM network among switches and groups of switches. This information is used by the switch connected to the *calling host* to compute a route to the *called host* that satisfies QoS requirements. PNNI supports a hierarchical routing structure that allows it to scale to large networks. PNNI makes use of several techniques that have been previously implemented in other inter-networking protocols. These techniques are:

- *Link-state* routing.
- *Hierarchical* routing.
- *Source* routing.

One choice for the routing data structure was the *distance vector* algorithm which is used in routing protocols such as Routing Information Protocol(RIP). This was dropped at the *ATM FORUM* because it is unscalable in larger networks and prone to routing loops. The other choice was *link-state* routing. This was chosen as it is scalable, converges quickly, generates less overhead traffic, and is extensible. Extensible means that information in addition to the status of links can be exchanged between nodes and incorporated into the topology database. This additional information could be topology QoS metrics and attributes. In link state routing, each switch exchanges updates with its neighbor switches on the state of links, state of resources on the switches and each other's identity. In each node this information is used to build the topology database of the entire network. The topology database is used while finding the destination routes.

The second technique PNNI uses for routing is *hierarchical routing*. In the hierarchical routing structure, the topology and addressing information about a group of nodes is summarized and presented as a single node abstraction in the next level up in the hierarchy. This serves the purpose of limiting the amount of information about a group of nodes that is advertised. The overall reduction in traffic due to this abstraction can be massive. This abstraction process is called *topology aggregation*. Though the degree of accuracy could be affected due to change in topology, it is compensated by the scalability in a big network.

The third PNNI routing technique is *source routing*. In source routing the node connected to the calling host computes the entire path to the destination. Since the QoS metrics of all the links are advertised in a PG, each node would be able to compute the entire path to the destination. The intermediate nodes through the destination just perform a CAC and forward the message to the next hop. The source routing avoids routing loops which can not be permitted in a SVC setup where minimal setup time is desired.

2.5 PNNI Metrics and Attributes

PNNI is a topology state protocol. Topology state parameters exchanged among network nodes are classified as *metrics* and *attributes*. A *metric* is a parameter whose value must be combined for all links and nodes in the SVC request path to determine if the path is acceptable. An *attribute* is a parameter that is considered individually at a switch to determine if a path is an acceptable candidate for an SVC request. The following are the metrics supported by PNNI:

- *Maximum Cell Transfer Delay(CTD):* Maximum delay through all the links in path. It must be less than or equal to the requested delay.

- *Cell Delay Variation(CDV):* Cell delay Variation is the variation in delay at each of the links than the fixed link delay to transmit a packet. CDV is relevant for CBR and VBR-rt traffic.

- *Administrative Weight(AW):* It is the Link or nodal-state parameter set by administrator to indicate a preference. This is a vendor specific parameter. It could be link distance for example.

The following are the attributes in PNNI:

- *Maximum Cell Rate(MCR):* Describes the maximum link or node capacity.
- *Available Cell Rate(ACR):* Measure of effective available bandwidth on the link.
- *Cell Loss Ratio(CLR) :* It is the ratio of the dropped cells to the transmitted cells. Describes the expected CLR at a node or link for Cell Loss Priority (CLP)=0,1 traffic.
- *Branching Flag :* Used to indicate if a node can branch point-to-multi point traffic.
- *Restricted Transit Flag:* Nodal-state parameter that indicates whether a node supports transit traffic or not. The transit traffic is the traffic which passes through an intermediate node in a connection. If a node does not want to act as an intermediate node for a SVC connection, it will set this flag. In this case it will accept only the connections which terminate at a called host connected to it.

2.6 PNNI Signaling

The signaling component of PNNI is used to forward the SVC request through the network of switches until it reaches its destination. It is based on UNI 4.0 signaling but has been enhanced with several extensions specific to the PNNI environment. Additionally, PNNI uses two other techniques, *designated transit lists (DTLs)* and *crank back* with alternate routing to successfully complete the SVC request and connection setup.

2.6.1 Designated Transit Lists

PNNI uses source routing to forward an SVC request across one or more groups in a PNNI routing hierarchy. The PNNI term for the source route vector is designated transit list (DTL). A DTL is a vector of information that defines a complete path from the source node to the destination node across a peer group in the routing hierarchy. A DTL is computed by the source node or first node in a peer group to receive an SVC request. Based on the source node's topology database available, it computes a path to the destination that will satisfy the QoS objectives of the request. Intermediate nodes obtain the next hop in the DTL and forward the SVC request through the network.

A DTL is implemented as an information element (IE) which is sent in the PNNI signaling *SETUP* message. The source node computes the DTL for the entire path to the destination across the peer groups. One DTL is computed for every peer group. While the source node provides an explicit DTL for its peer group, it gives the names of the other peer groups it has to traverse. When the request reaches an ingress node in new peer group, it removes the old DTL, and computes the new DTL to traverse its peer group. When the request reaches the destination peer group, the ingress node computes the route to the destination node.

2.6.2 Crankback and Alternate Routing

In PNNI, when finding the route to the destination, the route is computed using the topology database the DTL generating node has at the time of the connection request. In a big network the node's topology database may not be up to date due to long convergence times and propagation delays between the nodes. In such a case, it may not be possible at an intermediate node in the path to forward the connection request to the next hop node due to unavailability of bandwidth on the connecting link. The node where the DTL is blocked sends a release message to the preceding node and also includes an information element called the *crankback IE*. In the *crankback IE* it specifies the reason for failure of the connection setup and the blocked link. The DTL originator node, when it receives the release message with the crankback IE, eliminates the node with the blocked link and tries to obtain an alternate route to the destination. If it finds a route, then a fresh setup message with a new DTL is sent to the destination node along the alternate path. If no alternate path is available then the call is released. Crankback gives PNNI the flexibility to try alternate routes before giving up attempts at connection setup. The maximum number of crankback tries allowed for a connection attempt can be set as an attribute at individual nodes connected to calling hosts.

2.7 Performance Measurement Tools for PNNI

The performance issues in PNNI are many. The peer group size within a network is of particular interest. If the peer group grows bigger, then it would be very difficult to maintain identical topology databases at all the nodes in the peer group. The factors which could contribute to outdated topology information include the increased link delays between the nodes, queueing delays at individual nodes, and inter-arrival time of connection requests smaller than the time taken to distribute the topology messages amongst all the nodes in the network. Also the call setup times could be affected by long delays within the routing algorithms to obtain a path to the destination which satisfies all the QoS requirements. The effect of the PNNI topology update messages on call setup is crucial and should be monitored carefully. The factors affecting the utilization of the network must be controlled. Any possible bottleneck link should be avoided since it could significantly affect the call success rate. Different routing policies in the network could be used to control the network bandwidth utilization and obtain different call setup times. Some of the tools which are currently known include:

- *ATM Network Emulator:* This is a commercial product by Duet Technologies. It is an emulation tool supporting the PNNI stack. It has a CAC algorithm that resembles the equivalent bandwidth method. The current version supports a single peer group and one-level hierarchy. This tool is mainly developed for the interoperability testing with the ATM switch vendor's PNNI implementation. It does not support a logging mechanism for the research specific interests of PNNI.

- *ProuST:* This is a simulation tool, developed primarily by the Naval Research Lab. It is supposed to be public domain software in future and has interfaces for routing algorithms. At this time, since it is under development, it is not released for public use. It is aimed at providing emulation capability, call generation capability, and multiple level hierarchical PNNI architecture by December 1998. Our approach could substitute ProuST for Q.port.

- *SRI's simulation tool:* SRI has developed a simulation tool for its internal use.

This tool is supposed to have call generation and topology parameter setting abilities. SRI is experimenting with QoS based routing policies.

- *Siemens and Technical University of Munich:* The networking group at Siemens along with Technical University of Munich in Germany have built an emulation tool which is used for PNNI engineering. It has ability to set PNNI architectural variables, call generation, and built in CAC. It has no interface to routing algorithms.

The simulation tool which KU has developed is a part of a comprehensive architecture which supports a common interface for simulation, emulation and real ATM network experimentation. Since the simulation shares about 98 % of the real ATM switch controlling software, the results obtained are expected to closely match those obtained using the real network experiments. This is the single most advantageous feature of our tool over other simulation tools. The simulation has a user friendly input interface to configure the network for simulation. It supports instrumentation of many performance characteristics such as: initial convergence time which is the time taken by peer group nodes to synchronize on topology information, the calls failed at source nodes and at intermediate nodes, PNNI topology messages sent per node, the bandwidth required by these messages, redundant topology messages generated, the link utilization, the average number of hops taken by connection setups, call setup times, routing algorithms, percentage call rejection, and percentage traffic-wise bandwidth rejection. It also supports call arrival and duration distributions such as Poisson, uniform and periodic distributions, a range of destinations to make calls to, or explicitly specified destinations, the same host having traffic sources of different QoS requirements and percentage shares of these differing traffics in the total calls generated by a host. These features make it very convenient to generate real network traffic. This makes the simulation tool more comprehensive.

Chapter 3

Implementation

In this chapter first the design and implementation details of the PNNI simulator will be given. The additional Q.93B PNNI protocol information elements and their processing explanation is included. A brief explanation of the newly added PNNI router module is also given. Finally the host's call generator abilities and then the mechanism for collecting the performance evaluation logs will be explained.

3.1 Simulation Model

The Q.Port signaling software's scheduling architecture was modified to provide the simulator capability. In this architecture, all of the switch and host modules involved in the simulation register with one single instance of a *core-reactor* class as shown in the Figure 3.1. The functions the core reactor class offers are as follows.

- *Registering and dispatching multiple timer events:* The Reactor module holds a pointer to the timer manager. All the modules associated in a switch or host when request for registering a timer request the reactor through the *schedule-timer* interface it provides. The reactor forwards these requests to the *timer-manager* which it owns.

- *Posting multiple Q.Port internal messages:* The Reactor supports the posting of the internal messaging between different Q.Port modules. When the Q.Port modules need to post messages, they call the *post ticket* interface of the reactor. The

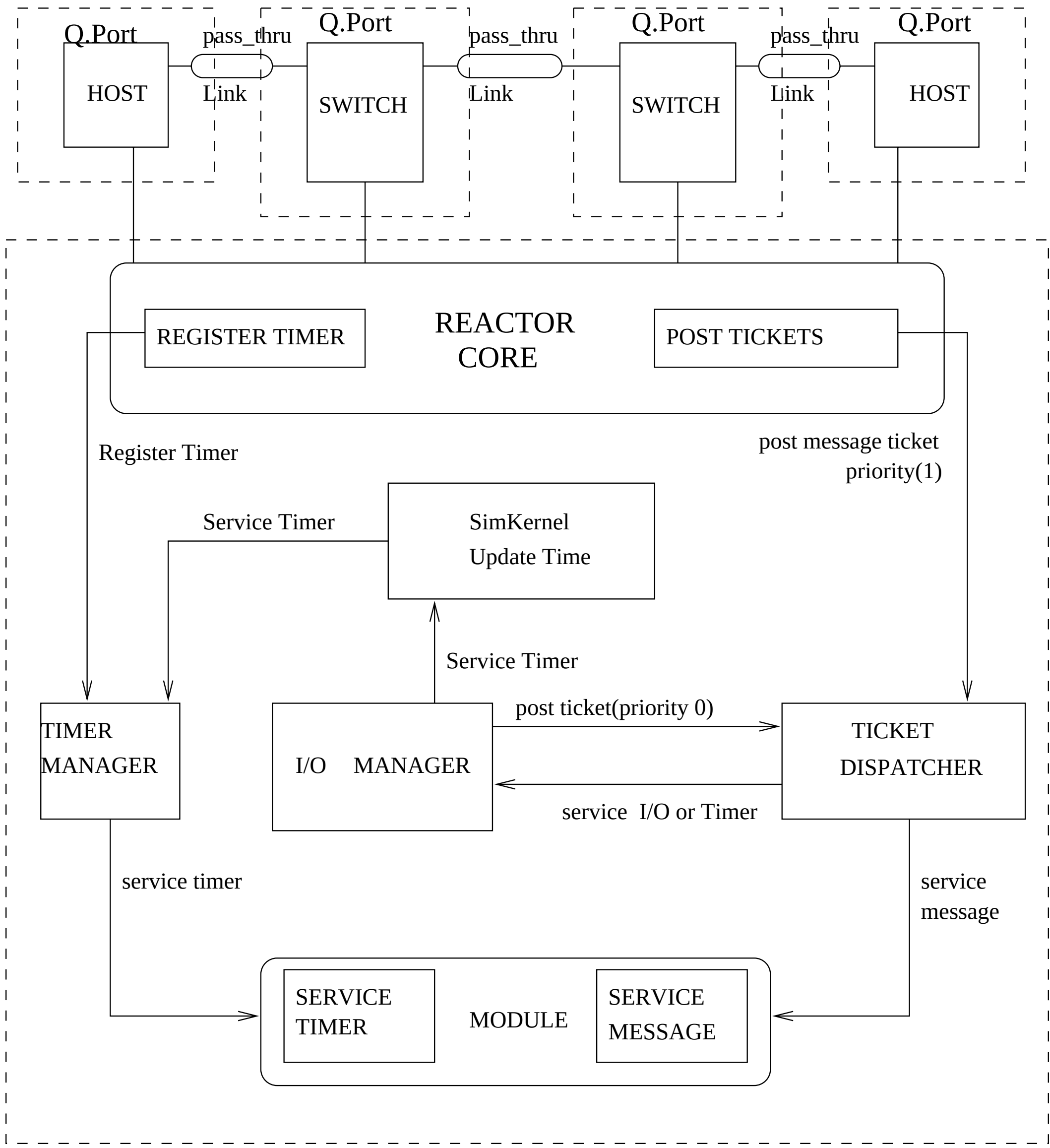


Figure 3.1: PNNI Simulator Model

reactor forwards this to the *ticket-dispatcher* which it owns.

Since all the Q.Port modules of different switches now report to one common reactor scheduler, Q.Port can support a single schedule oriented, discrete event simulator. In Figure 3.1 a new class *SimKernel* is added to scheduled the events to either a specified duration of time or until the simulation ends with no more events to be scheduled. The *SimKernel* class maintains virtual time which is updated whenever a timer event is scheduled. The ticket dispatcher is a class which schedules the tickets registered. The tickets are scheduled events which are either the timer events or the inter Q.Port module messaging events. The Input/Output (I/O) manager registers a ticket with the ticket dispatcher for scheduling timer events and the I/O events. Since in the simulation there is no interprocess communication involved, the I/O manager is modified to avoid checking for the input data from the other processes and all the I/O manager tickets are used to service the simulation timer events. The modifications are done to stop polling on the file descriptor changes using the UNIX *select* function during the simulations. The timer events are scheduled by the timer manager, which calls the *handle timeout* interface of the module which registered the timer. The message events are handled by the the *TicketDispatcher* which calls the *process* interface of the message ticket which was posted.

3.1.1 Simulation Kernel

A simulation kernel *SimKernel* is added which is used to schedule simulator events. It interacts with the timer manager for scheduling timer events. It maintains virtual time for the simulation. This virtual time is used by the other modules while registering new timer events. The *I/O Manager* class is interfaced with the class *SimKernel* to schedule timer events when the reactor is running in the *simulation* mode. The *SimKernel*'s service routine is used to schedule the timer events. It schedules the next event if the next event's scheduled virtual time is less than the duration of the simulation. It updates the current time to the time the next event is supposed to be scheduled. The pseudo code for the *service* routine is shown in Program 3.1.

Program 3.1 Pseudo-code for the Simulation Kernel Service Routine

```
void service()
{
   _next_sim_time = _timerManager.nextExpiration();
  if(_next_sim_time <= _sim_stop_time)
  {
    _sim_time = _next_sim_time;
    _timerManager.serviceNextEvent();
  }
  else
  {
    _stop_simulation = true;
    _sim_time = _sim_stop_time;
  }
}
```

3.1.2 Priority of Servicing

Two levels of priority are used for scheduling the events . They are,

- *Priority 1:* The events generated by inter Q.Port module messaging are assigned level 1 priority which is the highest priority. The messaging between the Q.Port modules Switch Call Control(SCC), PNNI Routing Service (PNNI RS), Static Router, and the Fabric are modified to suit this priority.

- *Priority 0:* This is the low level priority assigned to the servicing of the timer events.

With this priority setup, the tickets posted for messages are first serviced and then the queue for timers is serviced. This helps in processing an incoming message completely through different protocol stacks. Timer interrupts are secondary to processing a message in hand. There is provision for adding additional priorities if required.

3.1.3 Simulation of Link and Queueing Delays

The Simulation model includes simulation of links between the ports of nodes and hosts. Simulation of link delays, queueing delays, and queue length is also included.

3.1.3.1 Simulation of Links Between Ports

The ATM Adaptation Layer 5 (AAL5) module of the Q.Port is the lowest part of the signaling stack and represents the port which can be connected to the peer AAL5. This module is modified for the simulator to know before-hand the object pointer of the peer AAL5 object. To each AAL5, the peer AAL5 object pointer is specified during booting up of the configuration. When data needs to be transferred to the peer AAL5, the *SendToPeerAal5* method is called passing the data to the peer entity. This connectivity of links between simulator ports is labelled as *pass_thru* link as shown in the Figure 3.1. Figure 3.2 shows the stacks on ports of two different nodes. The Q.93B module passes the data to the datalink Qsaal module, which after adding appropriate headers, passes it to the AAL5 module. AAL5 module passes it to the peer AAL5 module by calling the *AcceptFromPeerAal* function of the peer AAL5 module along with the packet buffer pointer. The packet is subjected to adequate link delays and queuing delays before being taken up for processing. The pseudo code for transferring data between two ports is as given in 3.2. The name *_peerAal* indicates the peer Aal5 pointer which is set while configuring connectivity between the two Aal5 modules.

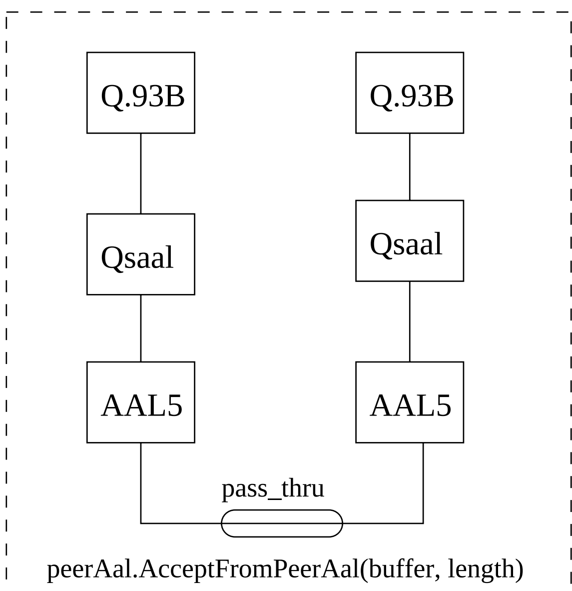


Figure 3.2: Q.93B port stack

Program 3.2 Pseudo-code for the Pass Thru link between simulation links

```
void  SendToPeerAal(char * data, int length)
{
  if(_peerAal)
    _peerAal.AcceptFromPeerAal(data, length);
}
```

3.1.3.2 LinkDelays and Queuing delays

The simulation model supports queuing of packets. These packets could be the Q.93b signaling packets encoded within the *Qsaal* PDUs or PNNI Route Control Channel(RCC) packets. The *AAL5* class has been modified to support a *queue length* which could be specified during configuration. Packets which arrive after the queue count exceeds the queue length are dropped. This accounts for losses in due to packet buffering in ports. The *queuing delay* on the packets is also supported. This is done by multiplying the *queue size* in the switch's ports at the time of arrival of this packet by the *mean processing delay* which could include the protocol processing delay and variable routing module delay. This *processing delay* can be configured. A measure of the processing delay is obtained by measuring the average time taken over processing of a large number of switch events. The link delay is added to the queuing delay, making the total delay before the packet is taken up for processing. This link delay is configurable and the AAL5 module is modified to include this information. Hence when a packet comes to the AAL5 module from the other side of the link these cumulative delays (Queuing delay and Link Delay) are calculated and a timer is started. When the timer expires, the AAL5 module takes up the packet for processing, giving it to the next stack in the protocol hierarchy. The pseudo code for including link and the Queuing delays is shown in the Program 3.3

3.2 Q93B PNNI Stack and DTL Processing

In Q.93B module, a new Information element class called *DTLElement* is added. This class provides the decoding and encoding abilities for the PNNI specific DTL Infor-

Program 3.3 Pseudo-code for Queuing and link delays

```
void  AcceptFromPeerAal(data, length)
{
  if(_queueCount == _queueLength)
  {
    delete data;
  }
  else
  {
    delay = linkDelay + QCount*processingDelay;
    startQtimer;
  }
}
void QtimerExpired()
{
  upperLayer.ProcessData(data, length);
   // The upper layer modules could be Q.93b or PNNI RCC modules
}
```

mation element. The format of this information element is shown in Table 3.1. In this format, *length of designated transit list contents* specifies the number of hops to be followed to the destination. *Current transit pointer* indicates the offset of the current node identifier in the list of the nodes. *Logical node identifier* gives the 22 byte node identifier. The *DTLElement* class also provides functions to manipulate its data structures uring processing of the information element in the *setup* message.

In the Q.93B module, another new class *Q93B_PNNI* is added. This class provides the Q.93b signaling stack support for PNNI signaling control channel communication between the ports of two switches. This class provides the ability to decode the mandatory DTL element from the setup message and store the DTL element object thus created in the setup message object which is provided to the *switch call control* for processing. In the outgoing *setup* message, it ensures the presence of the DTL element. It encodes this DTL element into the outgoing data stream. This class also takes care of the presence of the *connection identifier* IE in the *setup* or *call proceeding* or the *connect* messages. The *connection identifier* IE provides the information regarding the VPI and VCI pair to be used on the link for the connection establishment. A brief

8	7	6	5	4	3	2	1
1 ext	Coding standard		IE Instruction Field				
Length of designated transit list contents							
Length of designated transit list contents(continue)							
Current transit pointer							
Current transit pointer(continued)							
0	0	0	0	0	0	0	1
Logical node / Logical port indicator							
Logical node identifier							
Logical port identifier							

Table 3.1: Designated transition List

explanation is given for terms *master-node* and *slave-node* before looking into the rule to be followed for processing *connection-identifier*

Among two adjacent nodes in PNNI, the *master-node* is the one whose node identifier is numerically greater than the peer node's node identifier. The *slave-node* is the node whose node identifier is numerically less than its peer node's identifier. This information is obtained when the two nodes exchange *hello* messages through their route control channels before exchanging topology messages.

The rule to be followed while sending the *connection-identifier* is that the *master-node* is the node which allocates the connection identifier for the link between the two nodes. The following events which are supported in the *Q93B_PNNI* class ensure that the above rule is satisfied.

If the *master-node* receives the *setup* message from the slave, then the setup message does not include the *connection-identifier*. When the master node sends out *call-proceeding* or the *connect* message to the slave in reply to the *setup* message, the *connection identifier* is a mandatory element in the *connect* message if *call-proceeding* is not sent before it. Otherwise if the *call-proceeding* message is sent, the *connection-identifier* must be included in it.

If the *slave-node* obtains the *setup* message first, then the *connection-identifier* must be present in it. When the *slave-node* sends the response messages *call proceed-*

ing or the *connect*, the *connection-identifier* must be omitted.

3.3 Switch Call Control Support for PNNI

Changes have been made in the switch call control to accommodate the PNNI signaling and the routing. The changes could be listed as follows:

1. Support is provided to indicate if the destination host is connected to this node or not. This function compares the 13 byte destination ATM address with the 13 bytes of the node identifier. If they are the same, it is decided that destination host is connected to the same switch and a request is sent for the router table which stores the host's port number.

2. If Condition 1 fails then the destination address is compared with this node's peer group identifier mask and if it succeeds, then it is decided that the destination is present in the same peer group represented by this switch but not present on this switch. A request is sent to the PNNI routing module for seeking the source route to the destination.

3. If Condition 2 fails, then the destination is in another peer group and the call is terminated.

The routing in the switch call control is changed to seek the routing request in the following way.

- If the *setup* message is from a peer PNNI node, then the request for routing is sent to the newly implemented PNNI router. These are the parameters provided to the PNNI router whenever a routing request is made to the PNNI routing service.

  - The destination address.
  - The QoS requirements regarding PCR, SCR, CDV, CTD and CLR.
  - The designated transition list.

– Incoming port number

- If the *setup* is received from a peer host and destination host is connected to the same switch, the request is sent to the *router table*. Otherwise the request is sent to the PNNI routing service.

3.4 PNNI Routing Services (PNNI RS)

A new interface module called PNNI Routing Service is added in Q.Port. This interface provides interaction between the PNNI specific dynamic routing service and the Switch Call Control(SCC). It also provides interface to the AAL5 submodule for the purpose of Routing Call Control Channels. PNNI RS has a server-client relationship with the SCC. SCC is the client, requesting routing services from the server PNNI RS.

3.4.1 Interaction between PNNI RS and SCC

The message interaction between PNNI RS and SCC is as shown in the Figure 3.3

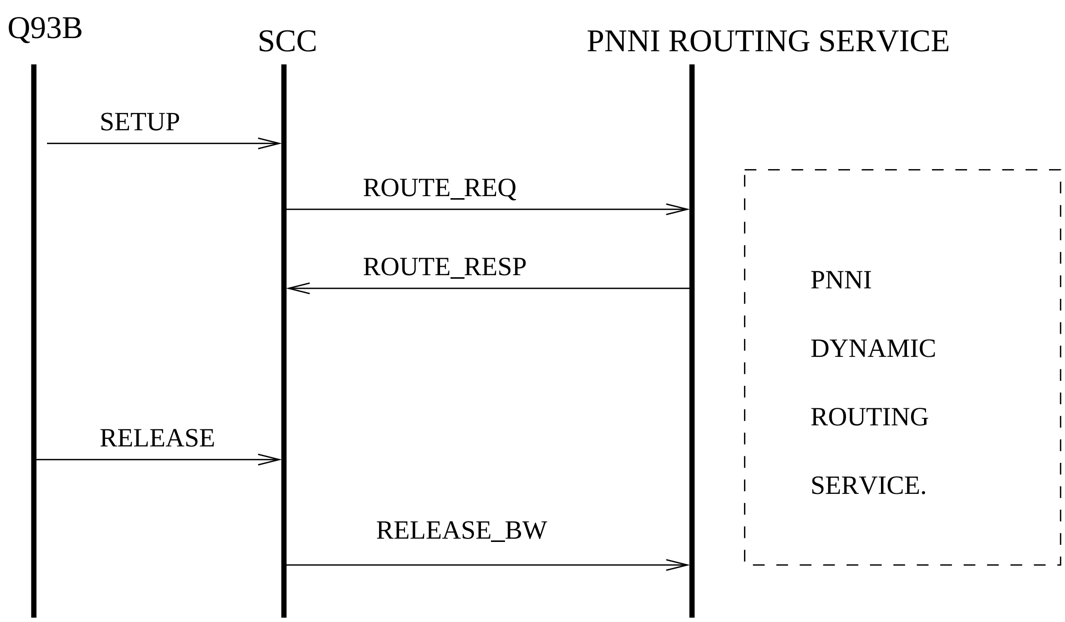


Figure 3.3: Interaction between SCC and PNNI RS Modules

The messages are described below:

- *route_req message*: This message is a routing service request from the SCC to the PNNI RS. There could be two categories of routing requests. They are:
  - *dtl_request*: This request is issued by the SCC when a *setup* message is received from a host machine and the destination is not connected to this switch. The PNNI RS will obtain the whole route to the destination which satisfies the QoS, and then provides the DTL to the SCC.
  - *dtl_parsing_request*: This request is issued by the SCC when a *setup* message comes from a peer PNNI node which will have DTL in it. The PNNI RS will check if the top of the DTL stack is this node itself. If so, it obtains the output *portnumber* for the next hop.
- *route_resp message*: This message is a response from the PNNI RS to a route request message from the SCC. There could be five categories of responses in this message which are:
  - *destination_in_same_switch :* This indicates that the request has been found to satisfy QoS requirements for the input port so the call can be accepted. It also indicates that the destination is in the same switch. When the SCC finds this response, it requests the destination port from the local *router_table*.
  - *call_routed :* This indicates that a path to the destination has been found and the DTL is included for the path. It also provides the output *portnumber* to which the SCC forwards the call.
  - *no_bandwidth_on_incoming_port :* This indicates that the route request failed due to unavailability of bandwidth on the incoming link and hence the call cannot be routed.
  - *no_bandwidth_on_outgoing_port :* This indicates that the there is no bandwidth available on the outgoing port to support the requested bandwidth and hence the call request is rejected.
  - *no_route_available :* This indicates that no single path could be found which satisfied all the QoS requirements all the way to the destination. Hence the call request is rejected.

- *release_bw message*: This message is sent by the SCC when a release message is obtained from one of the parties involved in the call. The PNNI RS, releases the resources specified for this call and if required sends out topology messages to the other nodes.

3.4.2 Interaction Between the PNNI RS and the AAL5 module

PNNI RS interacts with the AAL5 module for sending and receiving the PNNI RCC messages. PNNI RCC messages use the VPI 0 and VCI 18. They carry the *Hello FSM's* and the *Node Peer FSM's* packets.

Hello FSM: Hello FSM is the initial hand shake protocol between two PNNI nodes. It runs when the physical link comes up.

- It obtains the peer group identifier of the peer node which helps to know if the remote node is in the same peer group.
- It obtains the node identifier of the peer node.
- When it is synchronized with the above two items and knows that the peer node also knows about its identity, it initiates the exchange of the topology information between the two nodes, using the Node Peer FSM.

The Figure 3.4 shows the packet flow between two node's Hello FSMs, the Node Peer FSMs. It also shows the topology database where the exchanged topology information is stored.

Node Peer FSM: This manages dynamic topology exchange information protocol in PNNI. It is the core protocol upon which the PNNI concept is based. It exchanges the following packets with the remote node:

- *Database Summary packets (DS pkts):* These are the first series of packets which are exchanged. These packets give the summary of the topology database in a node.
- *Request Packets (REQ pkts):* These are sent to request a set of topology elements from the remote data base which were advertised in the DS pkts of the remote

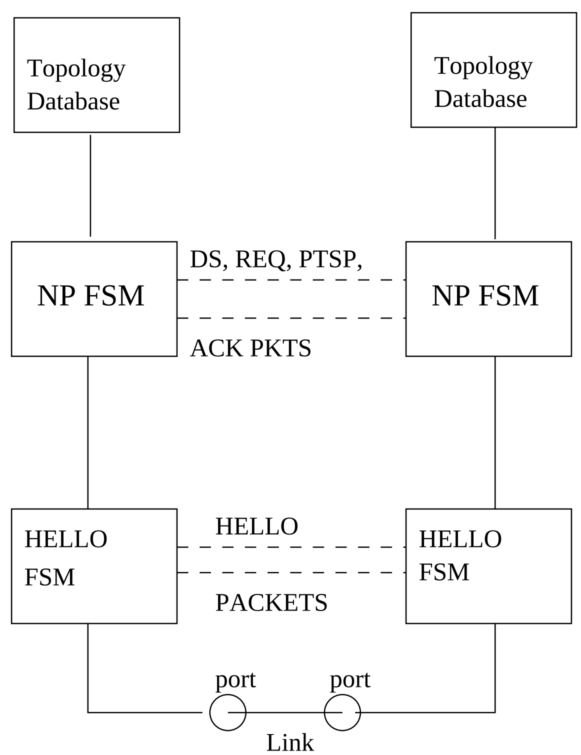


Figure 3.4: Hello and Node Peer FSMs

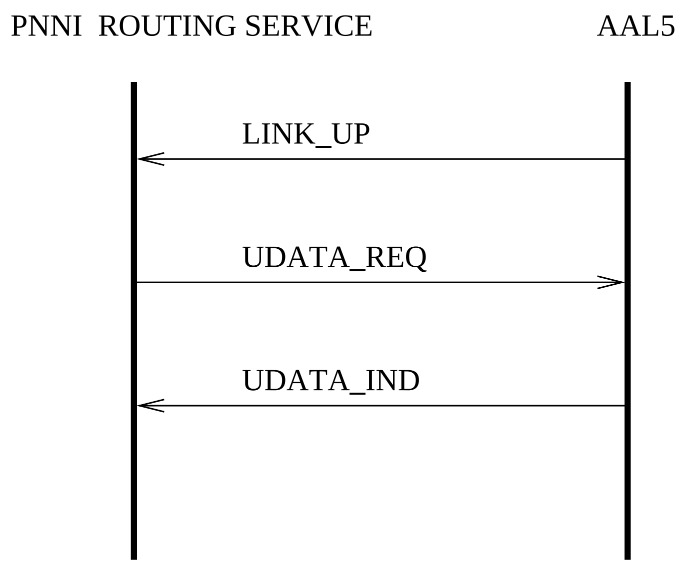


Figure 3.5: Messaging between PNNI RS and AAL5

node.

- *PTSP packets (PTSP pkts):* These are the topology information carrying packets. They are sent out when a request is made by the peer node for specific topology information or periodically when significant topology changes occur.

- *Ack Packets (ACK pkts):* These are the acknowledgements to the topology packets sent by the peer node.

The interface between the AAL5 and the PNNI RS module is shown in Figure 3.5 These messages are explained below.

- *Linkup message*: When the AAL5 module establishes the TCP connection with the remote node, it sends the *Linkup* message to the PNNI service indicating that the physical link is up and ready for data transfer.

- *udata_req*: When the PNNI RS wants to send out any RCC packet stream to to the remote node, it sends the *udata_req* message to the remote node with a pointer to the packet data stream.

- *udata_ind*. When the AAL5 obtains packet data stream from the remote node, it sends *udata_ind* message to the PNNI RS.

3.4.3 PNNI Routing Module's Functionalities

The PNNI routing module is based on the PNNI routing software called *ProuST* developed by the the Naval Research Laboratory. This software, when interfaced with the Q.Port signaling software, needed to be changed significantly first in order to get the ProuST architecture fit over the Q.Port architecture and later to have the additional functionalities to support PNNI single peer group experimentation. A summary of the changes is explained here.

Part of the architectural changes included were discussed in the form of the PNNI Routing service interface provided between the Q.Port modules SCC, AAL5 and the PNNI routing modules in the Section 3.4. In addition to these changes, the timers in the routing modules were changed to make use of the Q.Port supported timers. The timer handling of the modules is changed to use the Q.Port style of timer handling. All the modules were detached from the ProuST kernel support and were registered to the Q.Port *reactor* scheduling and underlying *passMT* module. Most of the underlying *Design Pattern Frame Work* of Proust software is retained for the intra-ProuST module communication. In bringing up the PNNI routing module, some of the modules which were redundant in case of the Q.Port architecture are eliminated. Important amongst them are the Q93B signaling stack and associated information elements, queues, and the modules simulating the links between switches. These are replaced by appropriate Q.Port modules in the unified architecture. One of the important changes made was in the routing of the data from the *PNNI Routing Service* to the *Control modules* of the ProuST architecture. The complex inter-module routing facility which is present in ProuST for provide the abilities a switch requires, is simplified to just providing the routing service in the context of Q.Port.

The following additional functions were provided in the PNNI routing service.

- *Convergence Time*: Convergence time is the time taken by all the nodes in a peer group to initially exchange the topology information and to be synchronized with it. It helps to know about the arrival rates of the connection requests the network could sustain sensibly. Also it could help in learning about the peer group size. In the *Database* module of the PNNI routing architecture, support for finding the convergence time is implemented. All the nodes involved in the experimentation are configured with the number of initial topology information elements present in the peer group. When the topology exchange is started the time is noted. When the database has all the topology information present in the peer group through exchange of information with other nodes, the convergence time is noted. The effective convergence time is calculated as the time it took for the last node in the peer group to achieve convergence.

- *Topology Update Messages*: The topology update messages give the number of topology messages sent by a node either during initialization or due to change in topology significance or aging. The number of topology floods due either to a significant change in topology information or to the process of aging is very helpful in measuring the PNNI RCC overhead on the call setup times and the blocking rate. In the *Database* module, the ability is provided to keep account of total flooded topology information as it is from this database that the flooding occurs.

- *Utilization*: The utilization is the amount of the link bandwidth utilized at a given time. In the PNNI router module a facility is provided to request for utilization periodically.

- *Reorigination Ability*: Reorigination is the flooding of the PNNI topology information in a node either when there is a significant change in the topology information or to prevent the aging of the element. An implementation of the reorigination policy provided in the PNNI specification is supported. Also the ability to specify the *proportionality_constant* and the *minimum_threshold* is provided. These constants can be dynamically changed for experimentation purposes.

- *Call-Packing and Load-Balancing*: Call packing is a policy used to select a next hop link amongst multiple alternative links as the link which has the minimum bandwidth. *Load-balancing* is a policy used to select a next hop link which has the maximum bandwidth at that time amongst a set of available links, thus balancing the load. Ability to specify these policies and run the specified policies is implemented.

- *Selective routing policy*: Using Dijkstra's shortest path algorithm, the ability to specify the cost function is provided.

  The three policies based on the cost functions are,

  - *minimum_hop policy*: This is a distance vector policy where all the links have the same cost associated with them.
  - *maximum_bandwidth policy*: This is a policy where the links are provided with costs based on the amount of available bandwidth they have. The higher the available bandwidth, the lower is the cost to traverse the link.
  - *minimum_time policy*: This is a policy where the links have cost based on the link delay. The smaller the link delay the lower is the cost to traverse the link.

3.5 Results and Logging Format

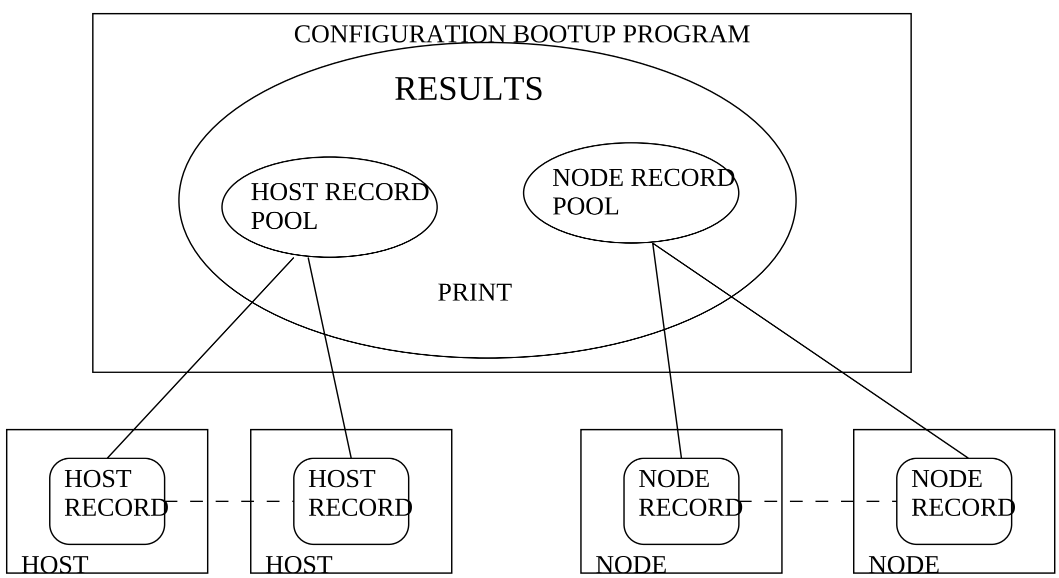


Figure 3.6: Logging mechanism for results

For logging the results, a hierarchical mechanism of storing the objects is followed.

The configuration boot up program has the main *results* object of the *Results* class. This class has pools of objects of two other classes, which are,

- *Host-Call-Record*: which is used to store the host related call generation logs. A unique HostCallRecord for a host also has an array of call records. The pseudo code of this log record is given in Program 3.4. Each call record for a call has details to show the status of the call which could be *failed* or *successful*, the type of call(CBR, ABR, VBR, UBR), the start time , the setup time, the bandwidth used and the cause of failure if the call failed.

- *Node-Record*: The *NodeCallRecord* is unique to a node and it stores a node's logs. The pseudo code of this log record is given in Program 3.5. The *hops* stores the average number of hops taken by calls generated at this node. The *route computation time* indicates the average time taken in running routing algorithms. The *utilization* provides the utilization logs of the network at different times. The *convergence* gives the time taken for achieving convergence at this node. The *floods* provide the number of topology floods that were generated.

Program 3.4 Pseudo code for the host call record

```
class HostCallRecord
{
   array of CallRecords;
}
class CallRecord
{
  StateOfCall{ success, failure};
  Calltype { cbr, rtvbr, nrtvbr, abr, ubr};
  startTime;
  setupTime;
  call bandwidth request;
  call failure cause;
}
```

As shown in Figure 3.6 the *boot up program* has an object pointer to a unique *results* object. When it creates the individual hosts, it creates a *HostCallRecords* object and passes it to the corresponding host. When it creates the individual nodes, it creates

Program 3.5 Pseudo code for the node call record

```
class NodeRecord
{
   number of hops;
   route computation time;
   link utilization;
   convergence time;
   number of floods;
}
```

a *NodeRecords* object and passes it to the corresponding node. During the experimentation, each of the hosts and nodes collect the logs they created into their respective logging objects. When the experimentation is complete, the boot-up program which has the object pointer to all the host's and node's logging records, prints them for the user.

3.6 User Input Interface

The *simulator* is provided with a user input script interface. Using this script interface, the network of interest could be specified along with the experimentation logs to be collected. The design for this utility is as shown in Figure 3.7

When the user specifies the network, a PNNI parser is used to parse the input and store the input data into a data structure. There may be some default parameters left out by the user and these are filled in the *complete user input* function. When the input configuration is complete, the data structure is given to a simulation boot-up program, which sets up the simulation.

3.7 Call Generator Changes

The simulator uses a *Call Generator* module to make call connection requests with the nodes. The call generator is designed to request the connections in specified arrival and duration distributions. The call generator parameters can be specified in a user input script during experimentation. Thus the call generator is a very comprehensive

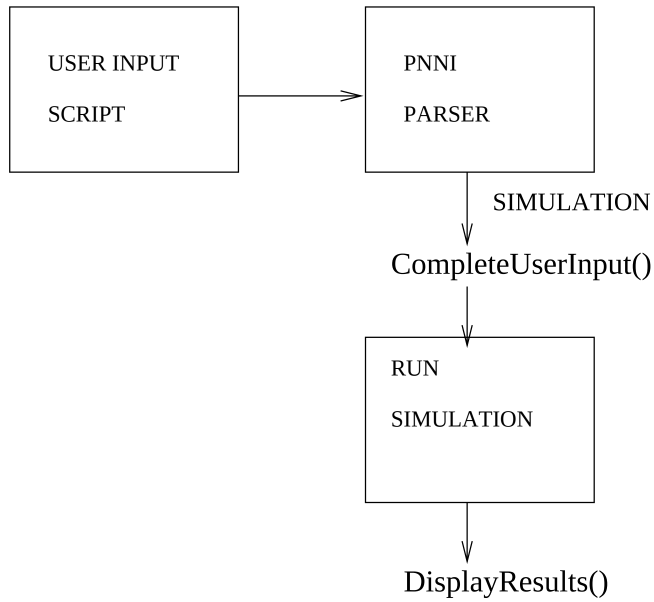


Figure 3.7: Design of common interface to simulator and emulator

and is extended to generate realistic traffic in a big ATM network. The call generator is provided with these capabilities.

The following call *arrival distributions* are supported:

- Poisson Distribution.
- Uniform Distribution.
- Periodic Distribution.

The following additional call arrival types are supported:

- Tear Down type: In this type of calls, when a call connection is established, it is immediately torn down and the the next call is attempted.
- Burst Type: In this type calls, when a call connection is established, immediately next call is attempted.

The following call *duration distributions* are supported:

- Poisson distribution.

- Uniform distribution.
- Periodic distribution.

The following call *traffic types* are supported:

- CBR: Constant Bit Rate.
- ABR: Available Bit Rate.
- RTVBR: Real time Variable Bit Rate.
- NRTVBR: Non Real time Variable bit rate.
- UBR: Unspecified bit rate.

The following *QoS parameters* for connection request are supported:

- pcr : peak cell rate.
- scr : sustainable cell rate.
- ctd : Minimum cell transfer delay.
- cdv : cell delay variation.
- clr : cell loss ratio.

The call connections can be made to the following types of *destinations*.

- A *single* specified destination. Ex: destination1
- A *range* of destinations. Ex: destination1 to desitination10.
- *Explicitly specified* destinations. Ex: destination1 destination2 destination3

When the calls are generated to more than one destination, the destinations are selected uniformally over the available destinations.

The call generator also supports *multiple traffic sources* with different QoS requirements being part of the total number of the calls generated. Here QoS requirements are specified for individual sources. The number of calls generated of each traffic can be specified as percent share of total calls generated. When multiple traffic sources are available, the calls are made with a single arrival distribution, while the duration distribution for each of the traffic sources can be different.

Chapter 4

Evaluation

This chapter evaluates the work done to study the performance of a single peer group PNNI protocol. It also evaluates the capacity of the simulator to simulate large scale networks. The evaluation is done in the following 2 sections.

- *Experiments with abstract topologies:* Abstract topologies like *ring*, *chain* and the *mesh* topologies are used in these experiments. The experiments regarding the basic *topology convergence time* with these topologies is explained.

- *Experiments with realistic topologies:* Realistic edge-core topologies are used in these experiments. Experiments regarding, PNNI proportional_multiplier for significant topology information change, call setup times, utilization, and topology scaling are explained. The simulator's performance study is also explained in this section.

4.1 Experiments With Abstract Topologies

Sample *chain*, *ring* and the *mesh* topologies are shown in Figure 4.1. Some of the features of these topologies are as follows: The *chain* topology has a higher *diameter* than the *ring* topology. Here note that *diameter* is the maximum of the minimum distances between all the two node pairs in the topology. Hence for the chain topology shown in the figure, the *diameter* is 5 and for the ring topology it is 3. For the 9 node mesh topology the *diameter* is 4. The mesh topology has nodes connected with

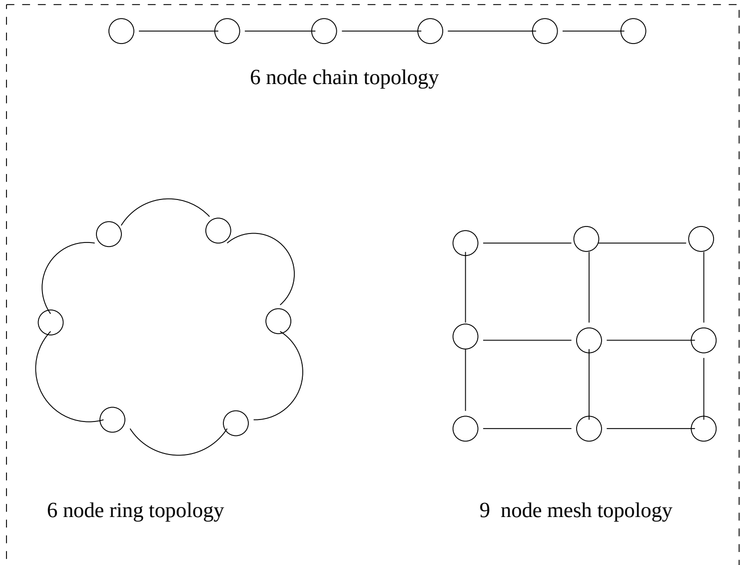


Figure 4.1: Chain, Ring and Mesh topologies

different number of links with maximum number of links connected to a node being 4 and minimum 2. The experiments on *convergence time* and the *topology update messages* generated for each of the topologies is explained in this section.

4.1.1 Topology Convergence Time

The topology convergence time is the time it takes for all the nodes in the network to synchronize with initial topology information generated by each of the participating nodes. The initial topology information generated by each node includes:

- *Nodal Information*: which gives information about the node identifier and peer group of the node along with some node specific characteristics such as leadership priority and others.
- *Horizontal Link Information*: This contains link information regarding bandwidth, delay, and others. Each node advertises all the links to neighboring nodes.

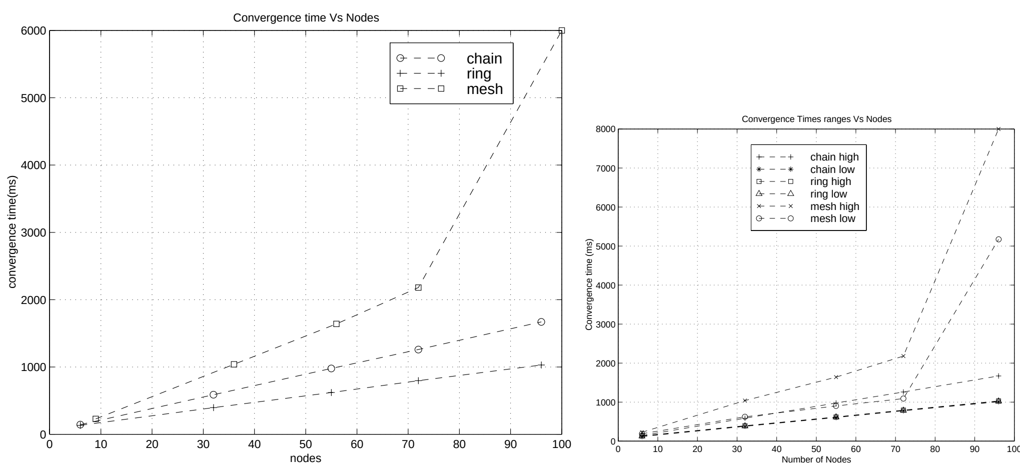
These primary topology information elements are sufficient for routing a call connection request to any other node in the peer group.

Convergence time is an important performance metric as it lets us know how quickly topology information which is flooded could get through the different nodes in the network and help all the nodes in the network have a common view of the network. The convergence time depends upon the following factors:

- The *size* of the network.
- The *connectivity density* of the links between the nodes, which is number of links between the nodes in a network.
- The *processing* capabilities of the nodes in the network.
- The *link delay* between the nodes in the network.

Following sections describe the convergence time experiments with each of the above parameters.

4.1.1.1 Convergence Time With Increasing Number of Nodes



(a) Convergence time with nodes (b) Differing Convergence times

Figure 4.2: Topology Convergence time related plots

Convergence time with increasing number of nodes for the *ring*, *chain* and the *mesh* topologies is as shown in the Figure 4.2(a). With each topology, five sizes of networks with the number of nodes ranging between 9 and 100 are used. From the figure we can see that the *mesh* topology has a convergence time which is very high compared to the other two topologies. This is mainly because of the greater *connectivity* between nodes in this topology than the other two. Also we can see that the mesh topology has an exponential rise in convergence time when the number of nodes increase. This is because in larger sized mesh networks most of the nodes will have connectivity to four other nodes and whenever topology information is obtained from one node, it is flooded to all the other nodes. This creates an extremely high number of redundant topology messages which greatly increases the topology convergence time. Thus the mesh topology is not a realistic topology with bigger networks. The convergence times of the chain and ring topologies show that they are linearly increasing with the number of nodes. The ring topology has a slightly smaller convergence time than the chain topology because of the fact that the maximum shortest distance between any two nodes in the ring network is half that of the chain topology. This helps in reducing the convergence time in topology message flooding.

4.1.1.2 Differing Convergence Times Among Nodes

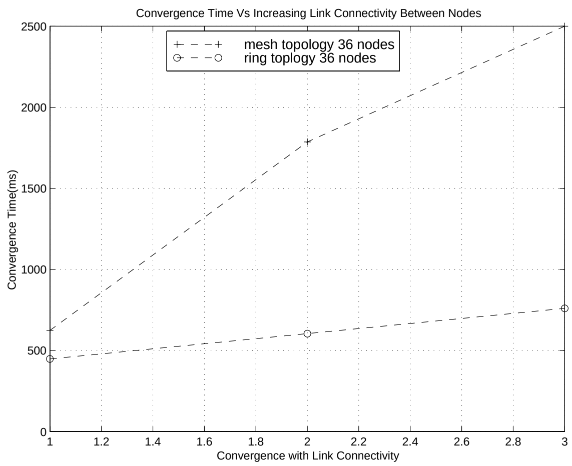
Different nodes in a topology could converge to the correct view of the network at different times. Though this could be unavoidable because of a perticular network topology, a large difference between the convergence times of the node which attends it first and the one which attends it last in the network is undesirable. This is because it leads to an inconsistant view of the network amongst the nodes, affecting the events of the network in terms of call success rate, call setup times and network utilization. Figure 4.2(b) shows a plot of *differing convergence time* with increasing number of nodes for the mesh, chain, and ring topology. Note that *differing convergence time* is the difference between the convergence time of the last node which achieved it and the one which achieved it the first in the network. For the mesh topology, we can see that the difference in convergence is about 50 percent of the highest convergence time. At small convergence times this difference could be affordable, but as the convergence time gets higher, the difference could be very perceptible in terms of asymmetry in network view. For example, in the mesh topology with 100 nodes, the difference in convergence time is about 3 seconds. If the average call interarrival time of the network is less than 3 seconds, then the calls could be routed or rejected by the source nodes with outdated topology information leading to inefficient use of network resources which is undesirable. If we compare the ring and chain topology in the Figure 4.2(b) it is observed that the ring topology will form a better PNNI network topology than the chain network, not only because its convergence time is small, but also the difference in the convergence time amongst the participating nodes is less.

4.1.1.3 Convergence Time With Varying Connectivity Density

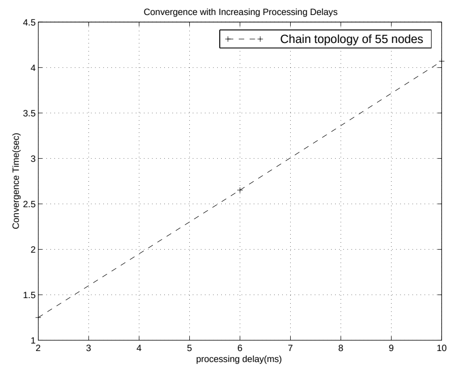
The convergence time also increases with the connectivity density between the nodes. The connectivity density experiments were conducted with one, two, and three links between any two nodes in the networks. Mesh and ring topologies, both with 36 nodes, were used for the experiments. Figure 4.3(a) shows that the for mesh and ring topologies the convergence time increased linearly with the increasing connectivity densities. Since for each link there are two topology messages originated, one by each side of the link, adding new links causes additional topology messages in the network and hence increased convergence time. It is undesirable to have a higher convergence time for this sake. This shows that it would be better to have fewer links with more bandwidth than the other way around. This is the concept which is used in multiple peer group PNNI by aggregating links between the peer groups to reduce the topology information flooding.

4.1.1.4 Convergence Time With Varying Processing Delays

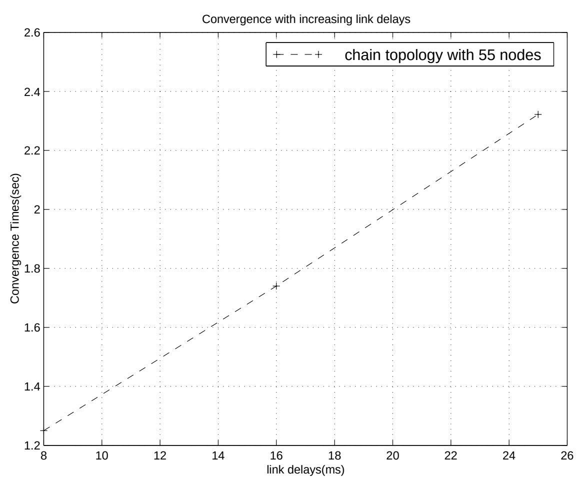
This is an attempt to see how the convergence time could be affected with different message processing delays for the nodes. Processing delays of 2ms, 6ms and 10ms were tried on a chain topology of 55 nodes. Figure 4.3(b) shows that we get a linear rise in convergence time with the increasing processing delays. This is an interesting issue as in a network we could have nodes with different processing delays. Some network providers offer two types of switches which differ in processor capabilities by a factor



(a) Convergence time with link connectivity density



(b) Convergence time with processing delays



(c) Convergence time with link delays

Figure 4.3: Topology Convergence time related plots

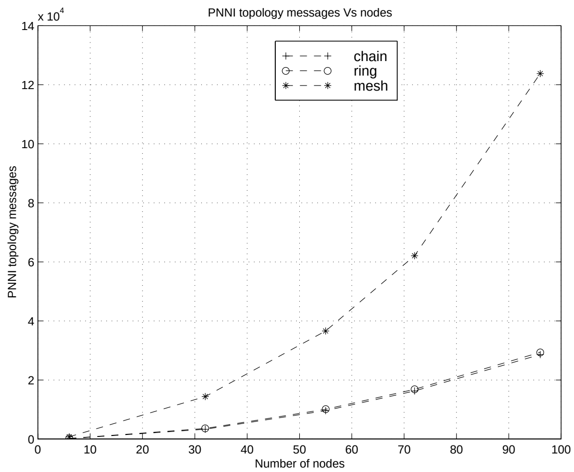
of five. If we have such switches in the same network, then the convergence times they achieve could differ and lead to some inconsistencies in terms of the network behavior. Hence it is better to avoid having two different nodes exposed to similar network traffic with differing processing capabilities. At the same time, a core node supporting many edge nodes could benefit form higher processing capability.

4.1.1.5 Convergence Time with Varying Link Delays

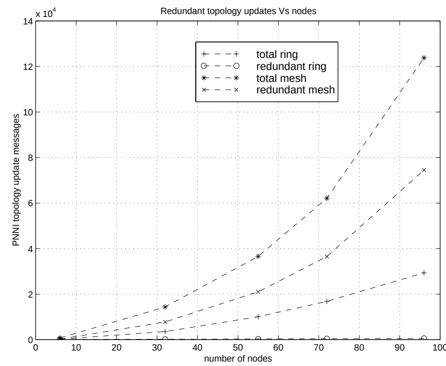
The convergence time changes with increasing link delays. Link delays of 8, 16 and 26 ms were tried between the links in a 55 node chain topology. Figure 4.3(c) shows that the convergence time increases linearly with increasing link delay. Bigger link delays signify bigger networks and so the network should be carefully designed to limit the peer group size when convergence times become large.

4.1.2 Topology Updates With Different Network Topologies

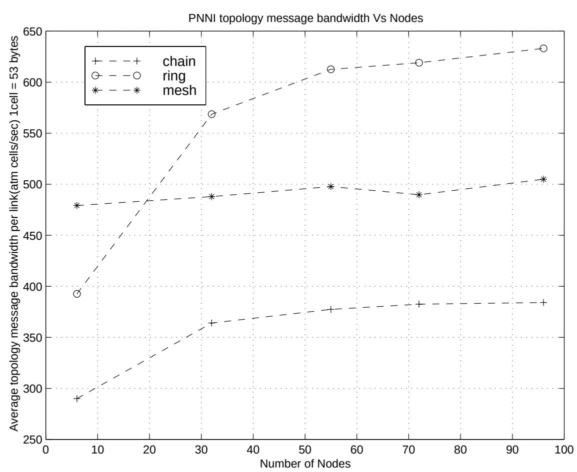
The simulation tool can be instrumented to log the number of PNNI topology update messages sent by each node during topology synchronization. Figure 4.4(a) shows the topology update messages for the ring, chain, and the mesh topologies during convergence. From the figure it is apparent that the update messages increase linearly for the ring and chain topologies with increasing nodes. For the mesh topology, the number of update messages becomes extremely high with the increasing nodes. This is because the redundancy of flooded messages increases in the mesh topology where most of the nodes are connected to four other nodes. In ring and chain topology, each node is connected to only two other nodes. In the mesh topology, nodes flood information amongst themselves, increasing the redundantly flooded messages. This can be seen in Figure 4.4(b). For the mesh topology, it is observed that more than half of the messages are redundant messages. More interconnectivity between nodes helps reduce the convergence time of the network. But having half of the messages being redundantly flooded, the performance of a mesh network decreases with increasing network size. The average link bandwidth consumed during topology convergence is shown in 4.4(c). It can be observed from the figure that the ring topology has a higher band-



(a) Topology messages



(b) Redundant messages



(c) Bandwidth occupied by topology messages

Figure 4.4: Topology message flooding related plots

width consumption than the mesh topology. This is because in the ring topology the links to nodes ratio is equal, which is not true of the mesh topology. In the mesh topology, because of higher connectivity density, more links share the topology messages reducing the per link bandwidth. The ring topology has higher topology bandwidth per link than the chain topology because of the redundant messages. This is reflected in a smaller convergence time for the ring topology than the chain topology. In a chain topology there are no wasted messages. Figure 4.4(b) shows the redundant messages for the ring topology. In the ring topology we can see that the redundant messages are a very small fraction of the total topology messages. But the ring topology performs better compared to chain topology by reducing the convergence time to half that of the chain topology.

4.2 Experiments With Realistic Topologies

The popular Edge-Core topology which is mostly used in setting up a private ATM network is used. The model topology used is explained in section 4.2.1. The experiments with this topology are based on the following studies:

- The study regarding *proportionality_multiplier* which is used to calculate the significant changes in the topology information before flooding them.
- *Link utilization* improvement study.
- Different *routing policy* study.
- The performance of the PNNI protocol with the *expanding* networks.
- Performance of the simulator.

4.2.1 Topology description

For experimentation purposes an edge-core topology of 45 nodes is considered as shown in Figure 4.5. This will be labelled as the *Model topology*. In this topology, core nodes are connected to other core nodes. Each core node connects to 2 edge nodes.

Each edge node connects to a host which generates the calls. Depending upon the density of connectivity of the core nodes with the other core nodes, they are divided into three categories.

- A *Large range* node which connects to other larger nodes to support the long distance traffic.
- A *middle range* node which connects to other middle range nodes to support medium range traffic.
- A *small range* node which depends upon the adjacent long and the middle range nodes for long and medium range traffic.

These three categories of nodes are identified by the letter L for Large range node, M for Middle range node, and S for small range node. The edge nodes are denoted with the letter E and the hosts are denoted with the letter H. In the topology each of the core nodes is connected to 2 edge nodes and each edge node is connected to a host node. In the figure, multiple edge nodes and hosts are avoided for simplicity. The numbers on each of the links specify the link delays in milliseconds.

The link delays between core nodes are chosen so that large scale nodes are preferred for long distance connections and middle scale nodes for middle distance connections, though it may not happen this way necessarily depending upon the traffic and network conditions. The topology supports a maximum round trip time of about 45 milliseconds. The link bandwidth between different nodes and hosts is shown in

Link	bandwidth(Mbps)
core to core	155
edge to core	2000
edge to host	2000

Table 4.1: Link bandwidths for different links

The host to edge node and the edge node to core node link bandwidths are kept at very high values to avoid bottleneck bandwidths at these links and thus helping to exploit the core bandwidth in the network. Note that the bandwidth in the links

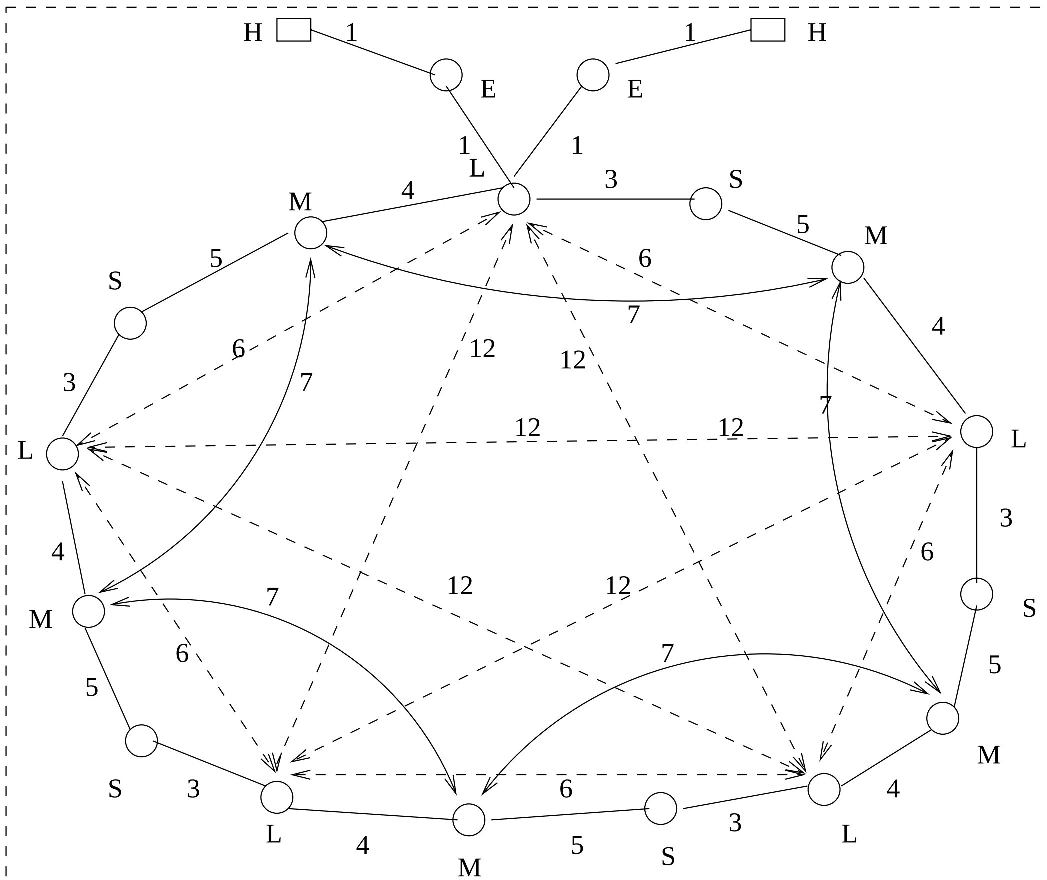


Figure 4.5: Edge core topology of 45 nodes

between edge node and core nodes and the links between the edge node and a host is chosen to be very high which is not realistic, but it helps avoiding congestion at the edge itself which could have limited the scope of the this experimentation to the edge of the network. The call generation related arrival distributions, the duration distributions and QoS parameters for the calls are given in Table 4.2. Multiple traffic types are used during call generations to ensure a variety in bandwidth requirements. All the hosts generate calls to all the other hosts in the network with the destinations being selected in uniform distribution from the whole range of the hosts. All the hosts use different random number seeds to generate the call connection requests, select the destinations and select the call duration times, ensuring different traffic patterns from different hosts. The total number of calls generated per experimentation are about 6000 calls with different call arrival rates with Poisson mean of 5sec and 2sec for each host. This gets the average network call arrival rates of 6 and 15 calls / sec respectively. These measures and capabilities help simulate a traffic which is close to that in a real ATM network. These parameters are used with all the experiments under this section.

SOURCE	BANDWIDTH	DURATION(sec)	PERCENTAGE OF CALLS
CBR1	2Mbps	uniform[10, 40]	40
CBR2	4Mbps	uniform[20, 50]	40
CBR3	8Mbps	fixed 50	20

Table 4.2: Call sources and QoS requirements

4.3 Call Generation Experiments Related To Proportional Multiplier

The Proportional multiplier is a parameter which is used to determine the significance of change of link bandwidth with respect to the previously available bandwidth on the link. It helps in obtaining a lower and higher bound for the next available bandwidth. If the new call request or the released call, forces the link available bandwidth to cross any of the two bounds, the change is considered significant and the horizontal link information is flooded amongst the other nodes. The algorithm for finding the significance is given in PNNI specification [3]

4.3.1 PNNI Topology Update Messages

Figure 4.6 shows the PNNI topology update messages generated at different core nodes in the network. From the figure it can be seen that the maximum number of messages are generated in the *large range* core nodes and next in the *middle range* nodes and finally in the *small range* nodes. The wasted messages generated are also shown respectively at each of the nodes. This confirms that the traffic pattern in the large, middle range, and the small range nodes is on the expected lines.

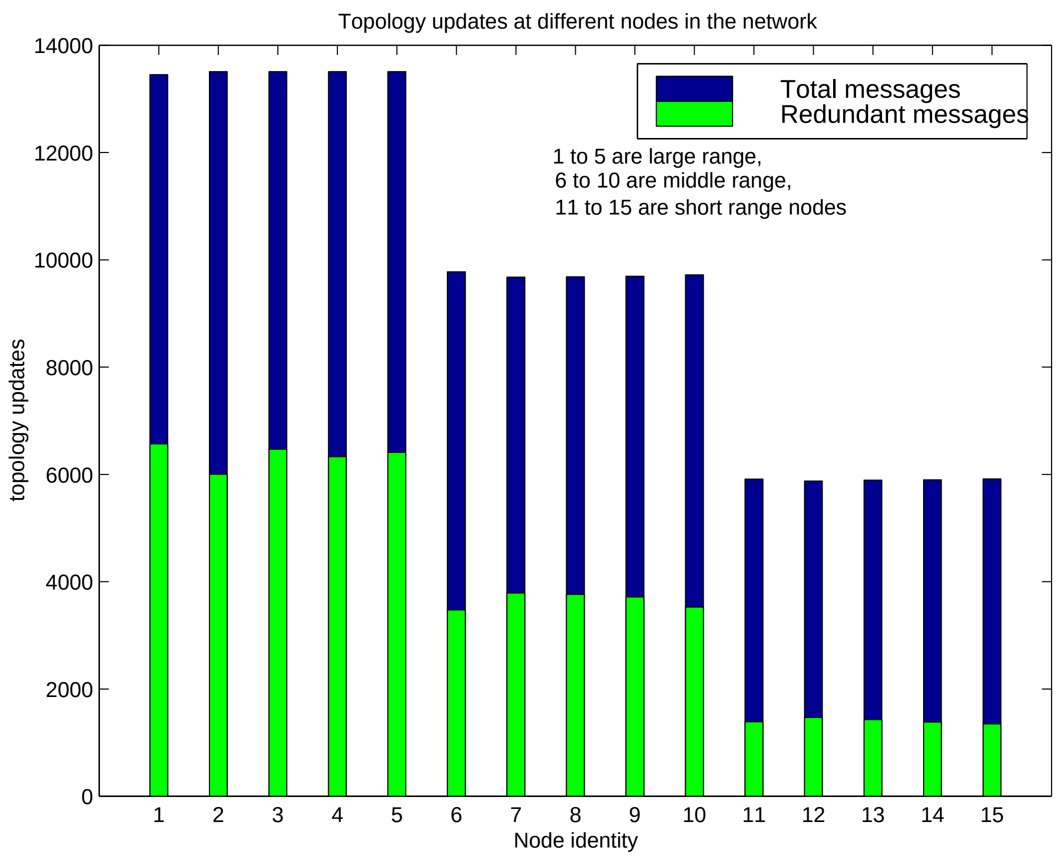


Figure 4.6: Topology update messages

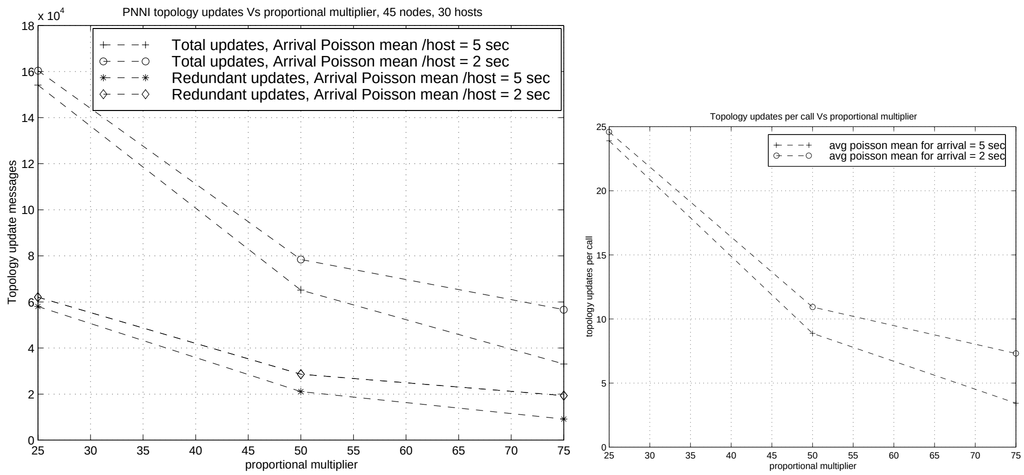
4.3.2 PNNI Topology Messages With the Different Proportional Multiplier Values

Proportional multiplier(prop_mult) values of 25, 50 and 75 are used to calculate the significant changes in the topology information. Figure 4.7(a) shows the total topology flood messages generated. We can see that with the decreasing proportionality multiplier, we have increasing numbers of topology messages. At prop_mult of 25 we can see three times more messages generated than with the prop_mult of 75. This is because of the lower significance of change of information crieteria for flooding the topology information at a lower proportional multiplier. More updates will lead to frequent convergence amongst the nodes in the network and this is helpful if the inter-call arrival time is less than the time it takes topology information originated in a node to reach all the other nodes in the network. Figure 4.7(a) also shows the topology updates generated at a Poisson mean of 2sec per host. More topology updates are observed here because at 2sec/call, with 30 hosts, the average call arrival rate for the network is around 15calls/sec and this results in some of the core links getting fully utilized during high traffic conditions and resulting in increased floods. Note that when the links get utilized to a higher extent, a small change in link bandwidth leads to a significance change, resulting in flooding of the topology information.

Figure 4.7(b) shows the average topology updates per call with respect to different prop_mult values. We can observe that, as expected with a lesser prop_mult, value, more updates per call are generated than at a higher prop_mult value. Also, with a mean Poisson call arrival of two we find slightly more updates per call than at Poisson mean of five, which is as expected. More topology updates per call could lead to higher call setup times.

4.3.2.1 Average Call Setup Times

Figure 4.8(a) shows the average call setup times with three different values for prop_mult. There are two plots showing the mean Poisson call arrivals means at 5sec and 2 sec per host. While comparing the call-setup times at call arrival rates with a Poisson mean of 2sec, for different values of prop_mult we can see that at prop_mult = 25 we get the



(a) Topology messages with changing proportional multiplier

(b) Topology update messages per call

Figure 4.7: Topology message flooding related plots in Model topology

highest average call setup time of about 120ms compared to the lowest average call setup time of 90ms for the prop_mult = 75. This is because of the larger number of topology updates generated with prop_mult 25 than with prop_mult 75, affecting the call-setup times. When comparing call setup times at different call arrival rates, we can see that with a Poisson mean of 5sec the call setup times scale down to about 50% of the setup times at Poisson mean of 2sec. This is because of the cumulative effect of increased interleaving among the calls requests, and also due to the resultant topology floods generated.

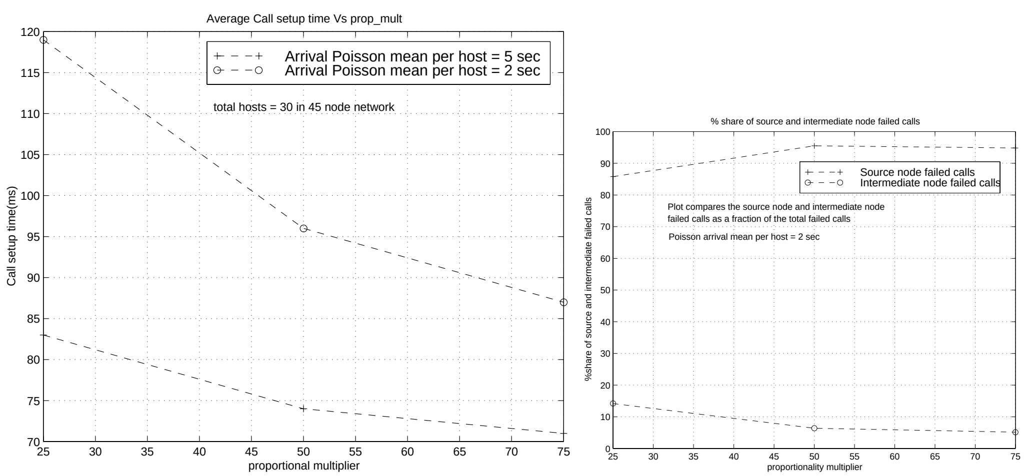
4.3.2.2 Failed Calls Amongst the Calls Generated

The type of failed calls will let us know if there is a convergent view in the network. Failed calls are distinguished as:

- Source node failed calls(*SFCs*): These are the calls which failed at the source node itself due to non-availability of the route which satisfies the bandwidth requirements of the call.

- Intermediate node failed calls(*IFCs*): These are the calls which failed at an intermediate node due to non-availability of the bandwidth for the call.

This is an important distinction because a larger percentage of SFCs in the failed calls indicates that the nodes have converged so that the source node knows the unavailability of the bandwidth for the call. Larger percentage of IFCs in the calls indicates non convergence, as the source nodes accept the call and send it to a destination only to have an intermediate node reject it. This is an important metric to limit the network size for a single peer group. Figure 4.8(b) shows the failed calls in the experimentation with regards to the Poisson arrival mean of 2 sec per host. From the figure, it can be seen that about 90% of the failed calls are SFCs. This indicates that this topology of 45 nodes is *convergent* and can be used for a single peer group network.



(a) Avg Call-setup times

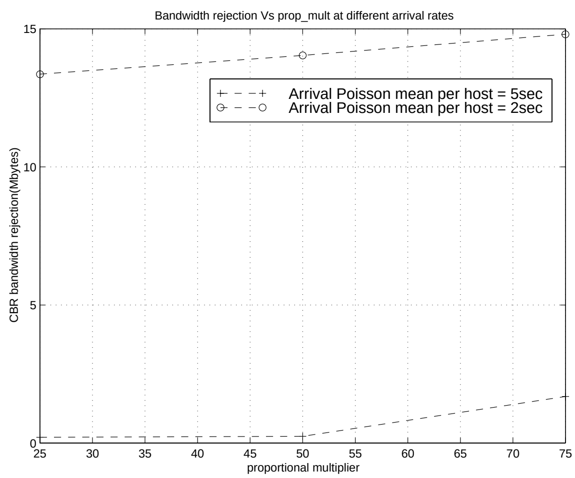
(b) Failed calls

Figure 4.8: Call setup time and Call failure plots

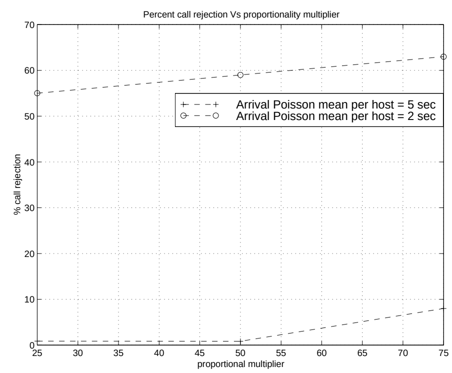
4.3.2.3 Bandwidth Rejection of The Calls

With the simulation tool, we can also log the amount of the bandwidth rejected. Percentage bandwidth rejected could be different from the percentage of rejected as calls could request different bandwidths. The call bandwidth rejected is shown in Figure

4.9(a). From the figure it is observed that at Poisson arrival rates of 2sec per host about 64 % of the bandwidth is rejected at a prop_mult of 75. This is because there were about 15 bottleneck links which were occupied to the full bandwidth during some time or other during the simulation. The percentage call rejection is shown in Figure 4.9(b). From the experiments, it is observed that using prop_mult at 25, though the network creates more topology messages, it maintains better synchronization because of the quick convergence. Hence, 25 is a better suited value for prop_mult. Using the value of 25 for prop_mult has a higher value of average call setup time, but better percent call success.



(a) Call bandwidth rejection

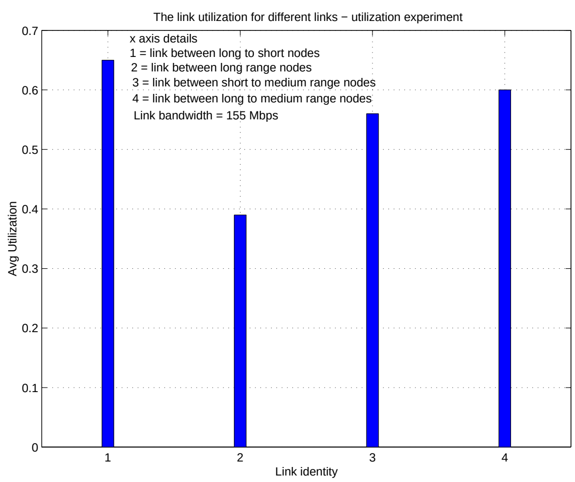


(b) Percent call rejection

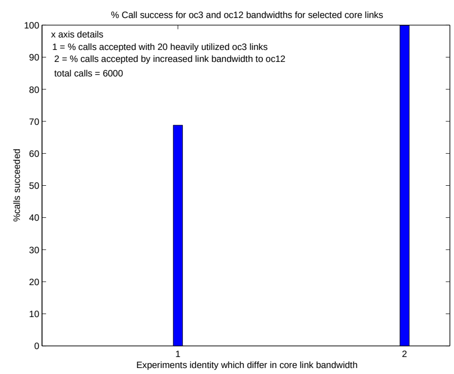
Figure 4.9: Call Rejection and Bandwidth Rejection Plots

4.4 Improvement In Percent Call Success Rate

Figure 4.10(a) shows the average utilization on some of the links. We can see that the links connecting the short range and long range nodes are more utilized than any other links. The links between the long range to long range nodes are the least utilized. When the simulations were run with a call arrival rate with a Poisson mean of 5sec it was found that about 20 links which are mainly connecting the short to long range nodes with delay of 3ms(refer to Figure 4.5), connecting the short to middle range nodes with delay of 5ms, or connecting the long to middle range nodes with delays of 4ms were found to be fully utilized at sometime during the simulations, causing call rejections. This was producing a call success rate of about 70 % . Then, in the next run of the simulation these identified bottleneck links were given a bandwidth of *oc12* instead of *oc3*. With the increased bandwidth, a 100 % call success rate was achieved as shown in Figure 4.10(b).



(a) Utilization



(b) Call Success Improvement

Figure 4.10: Utilization and Call success improvement

4.5 Routing with Different Routing Policies

Using the simulation tool, different routing policies can be selected to route a call. The experiments were run for 15000 calls with Poisson arrival mean of 5sec per host. The following policies were used.

- *minimum_time*: Link delay is used as the cost function in calculating the route. The higher the link delay, the higher the cost.

- *maximum_bandwidth*: Maximum available bandwidth is used as the cost function. The higher the bandwidth the lesser the cost.

- *minimum_hops*: Minimum available bandwidth is used as the cost function. All the links are allocated a fixed value of 1 for the cost of the link.

- *minimum_bandwidth*: Minimum bandwidth is used as a cost function. The lesser the available bandwidth, the lesser the cost.

Figure 4.11 shows the Call success rates in the policies used. The minimum-time and the maximum bandwidth policies performed the best with about 90% call success. Minimum-hop policy and the minimum-bandwidth policies didn't perform well. The minimum- hop policy performs badly because it always selects the same shortest path which could lead creating a bottleneck link. Minimum-bandwidth performs the worst with 70 % call success.

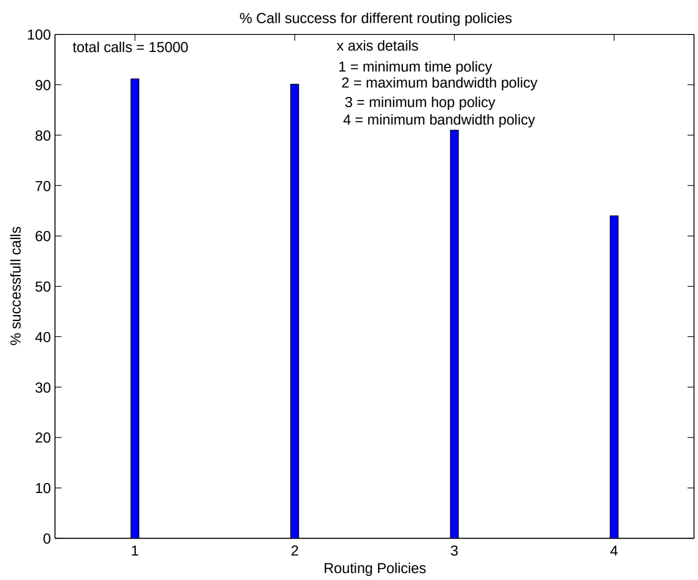


Figure 4.11: Call Success with different routing policies

4.6 The Performance of the PNNI Protocol with Expanding Networks

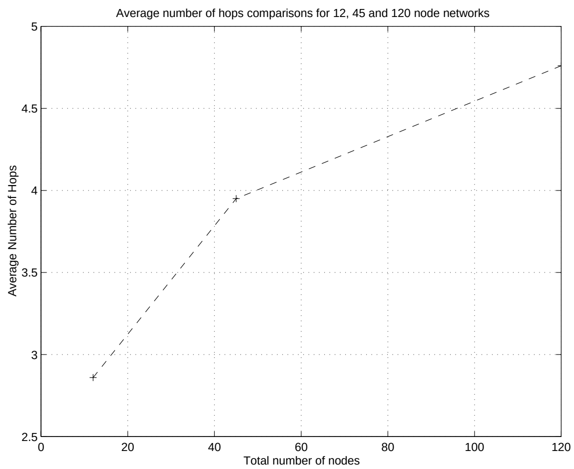
To compare the performance of the single peer group PNNI network with an expanding network size, three different sizes of core edge network topology are chosen. They are of the sizes:

- *12 nodes:* 4 core, 8 edge nodes, 8 hosts.
- *45 nodes:* 15 core, 30 edge nodes, and 30 hosts.
- *120 nodes:* 40 core, 80 edge nodes, and 80 hosts.

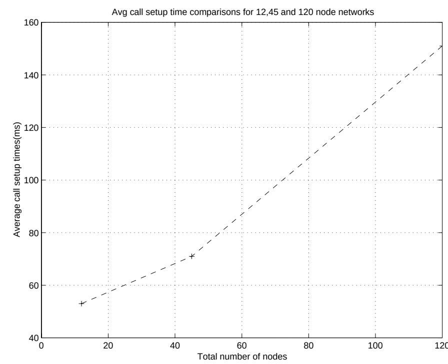
Figure 4.12(a) shows the average number of hops of a connection with respect to the total nodes. The average hops in a 45 node network is about 4 hops and that for a 120 node network is about 5.5. This shows that though the networks get bigger, they are interconnected in such a way that the average number of hops does not increase linearly, thus reducing the call setup time. For the edge core topology tested, the average number of hops obtained seem appropriate. Figure 4.12(b) shows the call setup time. This shows the tendency of a 120 node network to have larger setup times.

Figure 4.13(a) shows the percentage of the calls failed in the intermediate hops in the network. There is a marked difference between the 120 node topology and the other two. In the 120 node topology, about 70 percent of the failed calls are failing at the intermediate nodes indicating a non-convergence amongst the nodes. A convergence time for the 120 node network is shown in the Figure 4.13(b). The convergence time of about 8 secondsconfirms the fact that it takes longer for the network to converge the with the topology information. At Poisson arrival rates of 5 sec per host it could generate many topology elements resulting in continuously changing the network topology information. Thus a 120 node network seems to be unsuitable for a single peer group topology. This is a very important result in terms of deciding the topology size.

Figure 4.14(a) shows the average route computation time for the different networks. It is seen that in 12 and 45 node networks, the route computation time makes

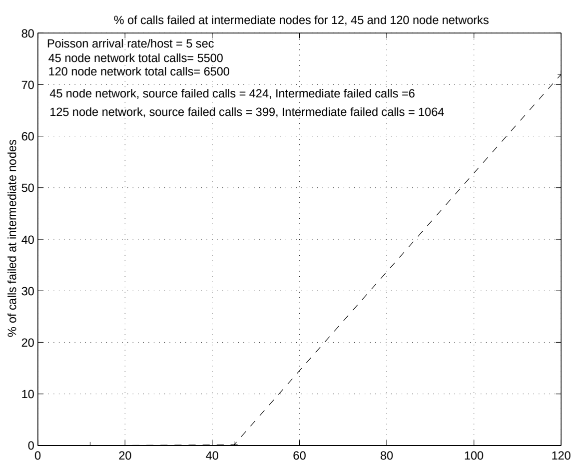


(a) Average Hops

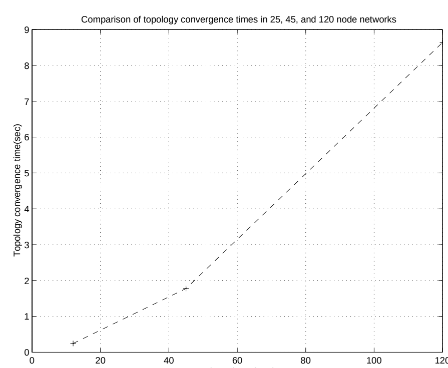


(b) Average Setup times

Figure 4.12: Average hops and Call setup plots



(a) Failed calls



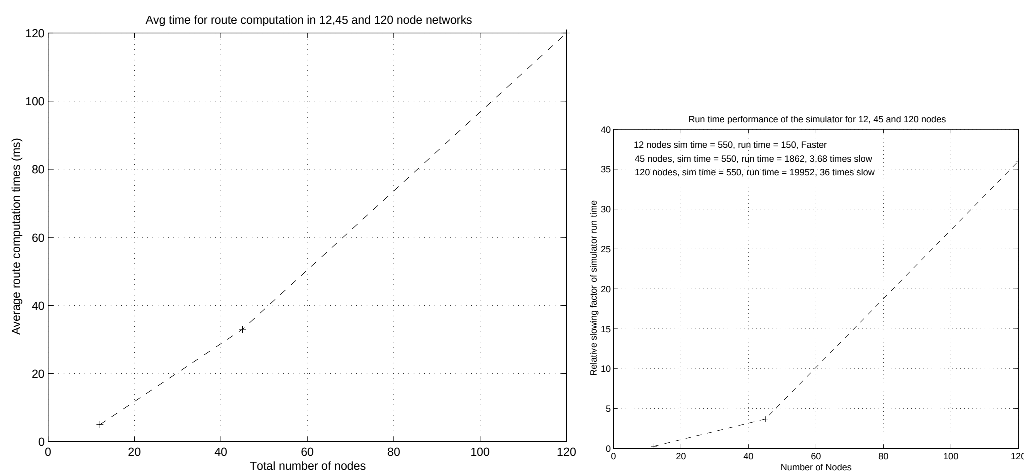
(b) Convergence time

Figure 4.13: Failed Calls and Convergence Time plots

up a small part of the call setup time. Whereas in 120 node network, the route computation time is about 120ms - comparable to the call setup time. This is due to the time required to cull through a graph of about 120 nodes and all the associated links. This could be easily avoided by providing smaller peer group sizes. This is another reason for believeing that a 120 node network is not suitable for a single peer group.

4.7 Performance of Simulator

The Figure 4.14(b) shows the slow down factor of the simulation at 12, 45 and 120 nodes. While at 12 nodes, the simulation runs faster than the real time, it slows down by about four times at 45 nodes and about 35 times at 120 nodes. Slow down with the larger networks is due to the size of the simulation network itself. Another important reason for slowing down of the simulation is because of the increased PNNI topology updates in bigger networks. These topology updates give much smaller simulation time increment though a lot of them are processed. Considering the slow down factor of about 35 for a network of about 120 nodes is supposed to be good, we can simulate such a network.



(a) Route computation time

(b) Simulation performance

Figure 4.14: Route Computation time and Simulation performance plots

Chapter 5

Conclusions and Future Work

The simulation tool which is developed provides a reliable platform for performance evaluation of the PNNI protocol. Since the tool is based on the real ATM switch software, the findings of the simulations are mostly assumption free. The user interface helps user provide minimum required inputs to setup a topology and run the simulation. From the experimentation on abstract topologies like the ring, chain and the mesh topologies, we tested some of the known facts to check the simulations for correctness. As expected the chain topology converged faster than the ring topology and the mesh topology had the highest convergence time. The redundant topology messages also showed that though they are result of increased cross connectivity for enabling faster convergence, they could increase the processing load on the nodes, downgrading their performance. The PNNI topology message bandwidth per link showed us that the ring topology had higher bandwidth consumption per link than the mesh and chain topologies. This is because when compared to the mesh topology, the ring topology has smaller link to node ratio increasing the topology message overhead per each link. When compared with the chain topology, in the ring topology the links carried additional redundant messages increasing the bandwidth requirement.

For the real networks the edge-core topology was chosen, as it is the most widely used network topology. The connectivity between the nodes were chosen to carefully distribute the traffic. Poisson arrival rates at each of the hosts, with calls generated to all other destination hosts in the network created the real network traffic scenario. With

45 node network, experiments were conducted with the PNNI parameter affecting the significant change in the bandwidth, the proportional_multiplier(prop_mult) fixed at 25, 50 and 75. It was found that with prop_mult 25, though the call setup times were a little higher,it provided the best call success rates. The prop_mult with 75 performed the worst. Hence the prop_mult value should be decided based on the call connection bandwidth requirement, topology size and call arrival rates. For our edge-core network topology of 45 nodes, the prop_mult value 25 seemed to be most suitable.

The experiments also showed that the bottleneck links can be identified and eliminated resulting in better call success rates. Using different cost considerations for links in the route computation we obtained varied performance regarding percentage call success. The minimum_time and maximum_bandwidth costs performed better than the minimum_hop and minimum_bandwidth costs.

By distinguishing the failed calls as source failed calls(SFCs) and the intermediate failed calls(IFCs) we could best distinguish the performance of an expanding network. A higher number of IFCs indicates poor convergence of the network as in these cases, the source nodes forward the connection request assuming bandwidth availability all along the entire path, only to be rejected later at an intermediate node. In 12 and 45 node, network we find majority of the calls failed being SFCs where as in 120 node network we find them to be IFCs. Hence in 120 node network, the nodes, do not posses a common view of the network making it unsuitable to be a single peer group.

Finally the simulator showed the capability to run simulations of a network of 120 nodes in a realistic edge-core network. The simulations seemed to be slower at higher network sizes. This is mainly because, of the increased PNNI topology messages which increase with more nodes in a network and they provide very less increase in the simulation time.

5.1 Future Work

The following are the issues for future consideration:

- Crank-back and Multiple peer group implementation, for performance evaluation of multiple peer group PNNI.

- Validating the simulation experiments with the emulations, which are run in real time speed.
- Plugging in Different Routing algorithms: for example a price based routing algorithm.
- Pre computed paths at periodic intervals help reduce call setup times.
- Different topology aggregation schemes in the multiple peer group implementation.

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