# QoS-Policy based Routing in Public Heterogeneous Broadband Networks

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**ABSTRACT**

As telecom providers introduce new and more sophisticated services the necessity of a global, unified view of the network infrastructure becomes demanding. Today, heterogeneous backbone networks are interconnected in order to provide global connectivity. Due to technological impairments the cost of network operation, the maintenance complexity and the overuse of resources are extremely high under the goal of supporting the diverting customer QoS requirements.

In order for a network to guarantee customers' QoS requirements, it should be able to reserve resources and exercise network control functionality at different time-scales. In connection-oriented networks, the transfer of information between two end-users is accomplished by network functions that select and allocate network resources along an acceptable path. Routing is a call-level network control mechanism through which a path is derived for establishing communication between a source and a destination in a network.

In this paper we propose a QoS-Policy based routing management architecture appropriate for heterogeneous, multi-domain, multi-technology networks. This architecture is appropriate for inter-network communication between Public Network Operators (PNOs) each of which might support several sub-networks of different technologies. Every autonomous network provider supports a QoS Manager able to manage local network resources and able to interact with the QoS Managers of neighbouring network providers for information exchange and maintenance. The key idea behind the QoS Manager is that it is able to take routing decisions with the sole objective to increase resource utilisation for the network under its supervision while at the same time cooperate with its peers in order to guarantee the end-to-end QoS requirements of the customer requests. According to the customer traffic characteristics and QoS requirements, the QoS Manager is able to find a route to support the connection, that optimises users' and networks' profits while satisfying their requirements.

**KEYWORDS:**

QOS, POLICIES, ROUTING MANAGEMENT ARCHITECTURE, HIERARCHICAL, HETEROGENEOUS, MULTI-TECHNOLOGY, ATM, SDH, NETWORK PROVIDERS.

## 1. INTRODUCTION

In today's telecommunications world the networks used for data, telephone, video-conferencing and other services are still based on different technologies. These networks run in part or whole over the same infrastructure and use discrete management systems that do not currently collaborate. This implies extremely high costs and complexity in use and management. For this reason increasing efforts are being made to integrate all telecommunications services into one network, optimising resource allocation. The biggest challenge of this integration is the support of the different quality of service requirements of legacy services. Furthermore new compound services that start to appear, i.e., multiparty collaborative working sessions, have to be provided with the required total QoS in attractive prices, in order to create demand and subsequently increase optimised network usage. The heterogeneity of the telecommunication equipment together with the plethora of the organisations involved in service provision adds to the complexity of the problem.

In order for a network to guarantee customers' QoS requirements, it should be able to reserve resources and exercise network control functionality at different time-scales. In connection-oriented networks, the transfer of information between two end-users is accomplished by network functions that select and allocate network resources along an acceptable path. Routing is a call-level network control mechanism through which a path is derived for establishing communication between a source and a destination in a network. In this paper we propose a QoS-Policy based routing management architecture appropriate for heterogeneous, multi-domain, multi-technology networks.

Several architectures have been proposed in the literature [3-10] for QoS guarantees of multimedia applications over ATM networks. ATM technology that plays a central role in the integration challenge, highly relies on the statistical multiplexing discipline. The conditions under which statistical multiplexing can work efficiently in an ATM network are an active area of research and experimentation in both academia and industry [5, 6]. Several research organisations and standards committees [1, 2, 11, 19], are actively investigating how to best benefit from statistical multiplexing. Link bandwidth in an ATM network should be utilised efficiently, and the quality of service requirements of delay and loss for different types of real time and non-real time as well as bursty and constant bit rate traffic should also be satisfied during periods of congestion. Nevertheless, all the above studies concern local area ATM networks.

Furthermore routing is typically formulated as a shortest path optimisation problem, i.e., determine a series of network links connecting the source and destination such that a particular objective function is minimised. The objective function may be the number of hops, cost, delay or some other metric that corresponds to a numeric sum of the individual link parameters along the selected path. Efficient algorithms for computing shortest paths have been proposed in [27] (e.g., Dijkstra, Bellman-Ford). However, in the context of satisfying diverse QoS requirements, the computation becomes difficult as constraints are introduced in the optimisation problem. Specifically path constraints (e.g., the end-to-end delay of a path should not exceed a certain threshold value) make the routing problem intractable. It has been proved in [25] that the problem of finding a path subject to multiple constraints is NP-complete. Several studies on routing addressing QoS issues can be found in the literature. An overview and relevant references can be found in [28]. Nevertheless, neither inter-domain nor scalability issues have been thoroughly investigated.

We propose a QoS-Policy based routing management architecture for on-demand services supporting QoS requirements over heterogeneous networks. Hetetogeneity of networks is basically expressed in terms of technology and administrative policy impairments. Our architecture is appropriate for inter-network communication between Public Network Operators (PNOs) each of which might support several sub-networks of different technologies. There is no interaction with any control level routing protocol. Our approach could be used stand-alone in order to select a path that guarantees the QoS characteristics of a requested connection while making efficient use of network resources. Our architecture supports point-to-point connections. Its extension for point-to-multipoint connections is under study. Future scheduling of connections is under study as well.
In the following section we present the QoS requirements in a heterogeneous network

environment. In section 3 we introduce our assumptions concerning the network environment under study. In section 4 we introduce the quality of service framework and in section 5 we propose the routing strategy supported by our management architecture. In section 6 we present a hierarchical multilevel management scheme supporting our QoS-Policy based routing management architecture. In section 7 we initiate a discussion on efficiency, scalability and performance issues of our approach. We conclude by elaborating on the value added by this work and the interesting open issues that come next.

## 2. QOS REQUIREMENTS OF PUBLIC HETEROGENEOUS BROADBAND NETWORKS

In the deregulated telecoms market the QoS issue is important since it is a prerequisite for the development of advanced broadband services. Customers are asking for more flexibility and the possibility to choose between a variety of services. Service providers especially, need to negotiate the QoS with network providers on behalf of their users/customers.

A customer' s request for a compound service is interpreted to a set of end-to-end connection requests with guaranteed QoS, to be provided over international broadband networks. Such connections may cross several heterogeneous domains owned by autonomous service or network providers, heterogeneous in terms of network technology and administrative policy. Network providers have to communicate to each other exchanging and maintaining appropriate information in order to be able to support customers' requests with the following objectives: customers have special QoS requirements that providers have to fulfil, within a matter of seconds, as well as providers require efficient use of network resources. These are conflicting requirements since customers always try to get the best QoS, in other words increase the amount of resources allocated to their service while network providers try to achieve high level resource utilisation.

Further more in an integrated multi-technology, multi-domain environment an end-to-end connection could be accommodated over physical networks that adopt different transport infrastructure (e.g. ATM, SDH, PDH, photonic networks). An end-to-end connection could be split in several segments switching from one technology to another. This segmentation should be totally transparent to the customer using the connection, and should not affect its end-to-end QoS requirements.

In other words QoS management is concerned with identifying appropriate characteristics and reserving the corresponding resources which are necessary to achieve the required functionality of a given service and to optimise the overall system performance. Such objective in heterogeneous environments is a problem of increased complexity due to impairments that result from different network infrastructure and incompatibilities in network management and control methods adopted by different providers.

We approach the QoS management problem by designing a routing management mechanism adequate to a multi-domain, multi-technology environment supporting multi-class services. Our approach is based on the existence of a manager named QoS Manager. Every autonomous network provider supports a QoS Manager able to manage local network resources and able to interact with the QoS Managers of neighbouring network providers for information exchange and maintenance. The configuration of each individual network provider is given in Figure 1 and is explained in the following sections. The key idea behind the QoS Manager is that it is able to take routing decisions with the objective to increase resource utilisation for the network under its supervision while at the same time cooperate with its peers in order to guarantee the end-to-end QoS requirements of the customer requests. According to the customer traffic characteristics and QoS requirements, the QoS Manager is able to find a route to support the connection, that optimises users' and networks' profits satisfying their requirements. The QoS Manager supplies the selected path to the Configuration Manager that is able to configure the switching devices under its supervision according to the decisions taken. Configuration of the switching devices consists of routing table set-up and configuration of the resource reservation controller of every switching device. We operate in the management plane overcoming any signaling impairments due to different network infrastructure.

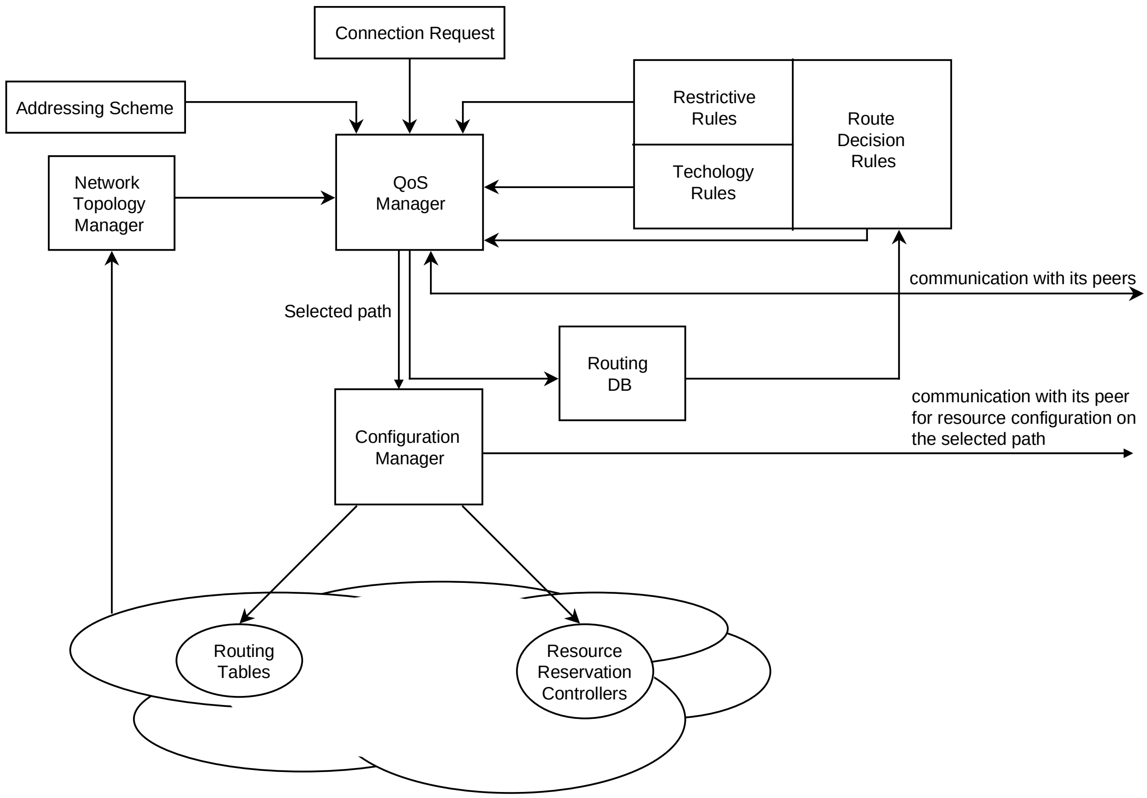


**Figure 1. Autonomous network provider's configuration**

We still assume that call set-up is handled by control plane functions, and according to the decisions taken by the QoS Manager. Call set-up is then handled in a segment by segment basis that is feasible since no interactions needed between incompatible network infrastructures.

Summarising this section we claim that our QoS Manager implements a QoS-Policy based routing management protocol suitable for routing end-to-end connections over heterogeneous network environments. Compared to other QoS routing protocols, like PNNI for ATM, the advantage of our scheme is that it supports this heterogeinity.

## 3. ASSUMPTIONS ON THE NETWORK ENVIRONMENT

We assume that our network environment consists of multiple interconnected heterogeneous sub-networks offering switched, on-demand services. The heterogeneity of the environment lays on differences in the network technology or the administrative authority. The network environment is composed of different interconnected *administrative domains* $AD_i$s. Every administrative domain corresponds to an autonomous network provider. Every $AD_i$ consists of more than one sub-networks of different technology. The sub-networks within an administrative domain could be even of the same technology and are split into different sub-networks for further management or administrative reasons (see Figure 2). The sub-networks $D_i$s within an AD are called *domains*. It is assumed that domains offer *potential connectivity* from any node of the domain to any other.

Each connection from a source to a destination may spread in more than one domain. Connections that spread beyond the boundaries of an administrative domain are called *inter-domain connections*. Connections that remain within the boundaries of a single administrative domain are called *intra-domain connections.* Connections that remain within the space of a sub-network are called *sub-network connections*. Both inter/intra-domain connections crossing multiple domains are split in interconnected *connection segments.* For example a connection segment$_i$ could either correspond to the part of the connection that crosses domain $D_i$ or represent the part of the connection that crosses administrative domain

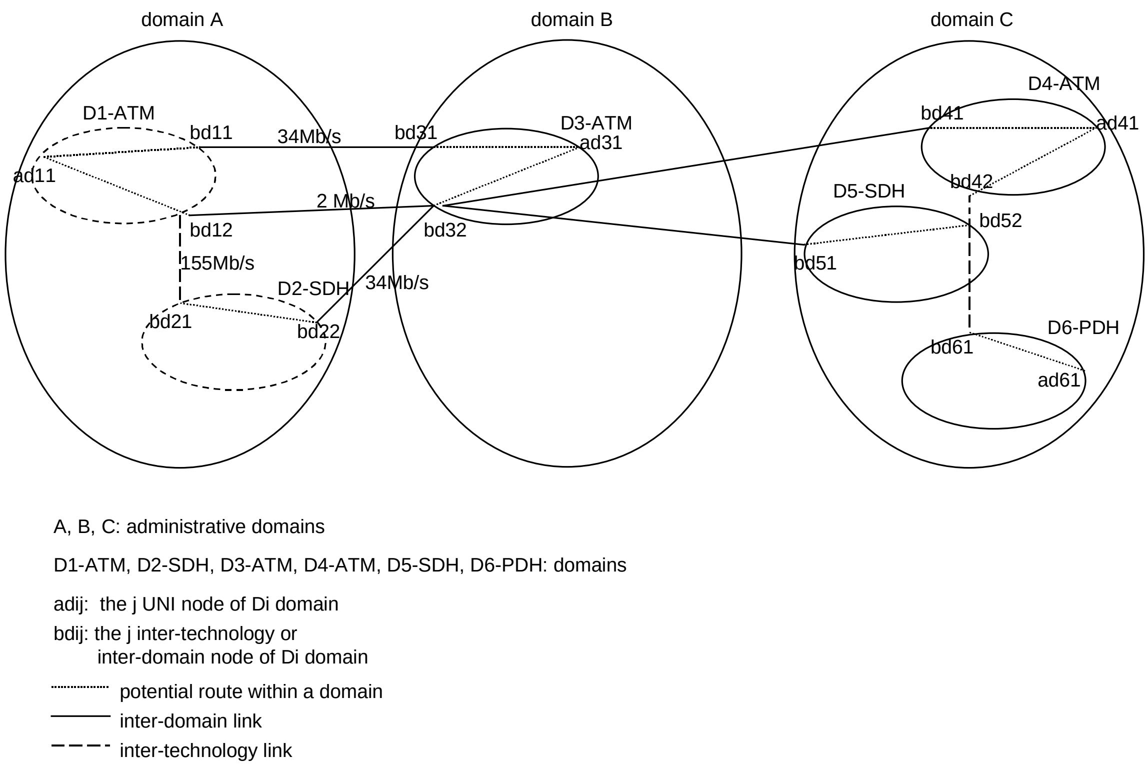


**Figure 2. Multi-domain, multi-technology network environment**

$AD_i$. Connection segments are interconnected with *link connections* crossing physical links, either *inter-technology* links or *inter-domain* links. Inter-technology links interconnect different $D_i$s within an AD. Inter-domain links interconnect different administrative domains $AD_i$s. Summarising, a connection is represented as a sequence of connection segments inter-connected with link connections.

Connection segments are instantiated over *segments*. Actually segments represent parts of the *route* the actual connection is traversing, from the source to the destination. A segment corresponds either to the part of the route that crosses domain $D_i$ or to the part of the route crossing administrative domain $AD_i$. Segments may correspond to more than one physical paths interconnecting the end-points of the segment. A *route* from a source to a destination corresponds to a physical path from the source to the destination. A route is represented by a sequence of segments inter-connected with physical links.

Customers are attached to the network via nodes called *UNI nodes*. Nodes that are the end-points of inter-domain links are called *inter-domain nodes*. Nodes that are the end-points of inter-technology links are called *inter-technology nodes*. The physical network consists of switching devices (e.g. ATM switches or A/D multiplexers etc.) as well as physical links. Each switching device is able either to be polled or to announce its spare resource capabilities (actually its capabilities on every outgoing link), in terms of upper or lower bounds of a set of traffic and QoS parameters. We define a generic set of traffic specification and QoS parameters to be bandwidth, delay, jitter, loss rate. Further details are given in the following sections.

## 4. QUALITY OF SERVICE FRAMEWORK

ITU-T defines Quality of Service as "the collective effect of service performances which determine the degree of satisfaction of a user of the service". In other words QoS deals with the perceived characteristics of a service from the user's point of view. Representative proposals of QoS frameworks and architectures can be found in [3-10].

We define a QoS framework that supports the requirements of our environment in which QoS is specified as a set of constraints. Two general classes of constraints are specified. The first class is a description of the type of service requested by the user. We assume that a service request corresponds to a single point to point connection request. A connection is characterised by a number of attributes like whether it is protected or not, time-scheduling of the connection, cost, its type of service and traffic characteristics like throughput as well as its network performance requirements like delay, jitter etc.

Since ATM is the most powerful technology intended to support a wide variety of services, we are motivated to assume that connectivity requirements coming from either customers or end-users are going to adopt the *ATM Service Architecture* proposed by *ATM Forum UNI 3.1* [1] and *ATM Forum Traffic Management Specification 4.0* [2]. Due to the diverse nature of the different Service Categories [2], their QoS and traffic characteristics are different as well. Therefore, different sets of QoS and traffic parameters defined in [2] as well, are used to characterise each type of Service Category.

An *end-to-end connection specification* for a given (s-d) pair (source - destination pair is expressed in the form of a *Connection Profile*. An example of the *Connection Profile* adapted to the GBCM (Global Broadband Connectivity Management) Service currently under development by the ACTS project MISA, can be found in [13]. A general format for the *Connection Profile* carries information like the following:

- Connection Characteristics
  protection, time scheduling, cost, integrity

- Service Category
  Constant Bit Rate (CBR), real-time Variable Bit Rate (rt-VBR), non-real time VBR (nrt-VBR), Unspecified Bit Rate (UBR), Available Bit Rate (ABR)

- Traffic Specification
  Peak Cell Rate (PCR), Sustainable Cell Rate (SCR), Cell Delay Variation Tolerance (CDVT)

- Quality of Service parameters
  Cell Loss Ratio (CLR), maximum Cell Transfer Delay (maxCTD), peak-to-peakCDV

In other words an end-to-end connection specification, $c_{ee}$ is a vector of values of Connection Characteristics (*CC*), Service Category (*SC*) and a set of QoS constraints (*QoSconstraints*) expressed as upper or lower bounds on the set of Traffic Specification and Quality of Service parameters, $c_{ee} = < CC, SC, QoS\ constraints >$.

The second class of constraints includes the policies applied by a network provider. Policies are expressed as a set of rules. Policy rules are a number of inference rules. Some of these rules could be statically defined, and some others could be dynamically updated. Based on prior knowledge, real-time network state information and by using reasoning models, the dynamically updated set of rules could become better and better as the system evolves over time. In the current version we have statically defined rules and we are currently investigating the upgrade to some dynamic update way. We define for our purposes two clusters of rules:

1. *Domain specific policy rules*
   Rules statically defined by the local administrator of some specific domain. They are further subdivided into two categories:

   *a) Restrictive policy rules*
   They represent constraints on network resources (e.g., links). Constraints could be of the form “link *x* is not allowed to be used for CBR type of connections” or “connections with destination address *d* are not allowed to be routed through administrative domain *ADi*”. They could refer to either inter-domain or intra-domain constraints. They effectively influence the routing decisions since they control the availability of network resources.

   *b) Technology dependant policy rules*
   Intuitively not all network technologies are able to support the same Service Categories. That is why our management system has to be enriched with the knowledge of mapping between the Service Categories and network technologies. A possible mapping, in case of an ATM, SDH mixed environment, could be defined, as follows: if the underlying technology uses ATM as the transport protocol then it supports all the Service Categories, namely CBR, rt-VBR, nrt-VBR, ABR, UBR. On the contrary, if the transport protocol is SDH then only CBR is supported. Such mappings are investigated for several network technologies. Furthermore rules of

thump are defined for taking decisions. For example:

- CBR services are preferably supported by SDH pipes. In case of non-available SDH pipes, ATM VPs can be used.
- Rt-VBR and nrt-VBR services are preferably served through ATM VPs. This is because they could benefit from statistical multiplexing. In case there is a need to use SDH pipes, VBR services are treated as CBR.
- ABR services are preferably served through ATM VPs. In case of ATM VPs unavailability, SDH pipes are used and ABR services are treated as if they were CBR.
- UBR is best served through ATM VPs. UBR service is treated as CBR in case that SDH pipes need to be used.
- Protection requirement is better satisfied by SDH.

2. *Route decision policy rules*
   This is the dynamically updated part. Based on past experience and real-time network state information concerning availability of resources, network planning and status, a set of rules is derived that influences the routing decision procedure. In the next section we elaborate more on this issue.

The QoS framework defined in this section, should be supported by each autonomous network provider, as clearly demonstrated in Figure 1. All network providers should be aware of the connection profile structure. Policy rules though, are defined individually by each network provider and it is information that is locally kept to each administrative domain.

## 5. ROUTING FRAMEWORK

In this section we define a routing framework suitable to support the divergent QoS requirements imposed by end-users as well as network providers in a multi-technology, multi-domain network environment. In section 4 we identified that the QoS requirements imposed by the users are expressed in terms of a connection profile and QoS requirements imposed by network providers are expressed in terms of policy rules.

The routing problem in such a network environment becomes extremely complex. Several frameworks have been proposed in the literature [28]. Nevertheless the related work proposes routing solutions for isolated case studies. For example there are several proposals for policy based routing appropriate for inter-domain communication without taking into account QoS requirements. On the other hand several QoS based routing algorithms and heuristics have been proposed that do not take into account policies or inter-domain routing issues. Further more most of the work available applies to homogeneous network environments. Our framework supports QoS and policy based routing appropriate for inter-domain communication in heterogeneous network environments.

### 5.1 BASIC DEFINITIONS

An *end-to-end connection request* is a tuple ($s$, $d$, $c_{ee}$), where $s$ is the source of the connection, $d$ is the destination of the connection and $c_{ee}$ is an end-to-end connection specification as defined in the section 4.
A *route* for a given (s-d) pair corresponds to a physical path from $s$ to $d$. A route is characterised by its source node, destination, a set of QoS constraints expressed as upper or lower bounds on a set of traffic specification and QoS parameters as well as a value (weight) on a parameter called *BestFit* (see bellow). We define a generic set of traffic specification and QoS parameters to be bandwidth, delay, jitter, loss rate. A route, as defined in section 3, is a sequence of segments inter-connected with physical links. If we assume that a route consists of $i$ segments, then the number of interconnection links are $i-1$. Segments are characterised by their source, destination and by the set of routes from the source to the destination node of the segment.

*BestFit function*: *BestFit* is a benefit function. It takes as input a set of technology dependant rules, a set of route decision rules, the connection characteristics, service category values of a requested $c_{ee}$ (refer to the definition in section 4) and a route and evaluates it with a weight called *BestFit*. The physical interpretation of the *BestFit* is towards the benefit of the network provider. The highest the value of the *BestFit* the better the route from the network providerís point of view, taking into account the kind of the requested connection.

*QoSsignificant*: Each Service Category [1, 2] is mostly sensible to one QoS parameter called *QoSsignificant.* For example CBR Service Category as well as rt-VBR is vulnerable to delay or jitter, while nrt-VBR is vulnerable to cell-loss rate. The UBR Service Category is a best-effort service so no guarantees are requested from the network and the *QoSsignificant* parameter for ABR services is bandwidth.

## 5.2 QoS ON DEMAND SOURCE ROUTING STRATEGY

The route calculation process can be divided into to two main parts. A route computation algorithm being able to compute routes upon a connection request and a route selection algorithm able to select routes among the computed ones according to some selection criteria. The result of the route calculation process is expected to be a route from a source to a destination that satisfies the QoS requirements specified by the user and give the network provider high level of resource utilisation.

For route computation we propose a centralised on demand source routing algorithm. It is based on the source routing algorithm proposed in section III.B in [25]. Given a network topology, a source and a destination node, a constraint on bandwidth and a constraint on one of the QoS parameters (preferably on the *QoSsignificant* of the connection request), the algorithm computes all possible routes and their end-to-end capabilities that satisfy both constraints. The end-to-end capabilities of the routes are given as a set of QoS constraints defining upper or lower bounds on a set of QoS parameters (e.g., bandwidth, delay, jitter, loss rate) and BestFit value. Several approaches for calculating end-to-end capabilities in terms of bandwidth, delay, jitter, losses exist in the literature [20-24]. The end-to-end characteristics of a route are calculated from the characteristics of the routes corresponding to its segments and the characteristics of its interconnecting physical links. Let us assume that a route *r* consists of *m* segments and *m-1* interconnecting links *(ils).* Let us define $R^i$ to be the set of routes corresponding to the $i^{th}$ segment of route *r* and $r^i_k$ is the $k^{th}$ element of the set $R^i$.

Then the simplified mathematical formulas [8, 18], presented bellow, are applied:

$$bandwidth(r) = \min(bandwidth(r_k^i), bandwidth(il_j)),$$
$$where\,1 \le i \le m, 1 \le j \le m-1$$
$$delay(r) = \sum_{i=1}^{m} delay(r_k^i) + \sum_{j=1}^{m-1} delay(il_j)$$
$$jitter(r) = \sum_{i=1}^{m} jitter(r_k^i) + \sum_{j=1}^{m-1} jitter(il_j),$$
$$\log(1 - lossrate(r) = \sum_{i=1,\, j=1}^{i \le m,\, j \le m-1} \log(1 - lossrate(r_k^i) - lossrate(il_j))$$
$$BestFit(r) = \sum_{i=1}^{m} BestFit(r_k^i)$$

The output of the route computation algorithm is the set of all possible routes for the given (s-d) pair with calculated QoS constraints and *BestFit* satisfying the constraint on bandwidth and *QoSsignificant* QoS parameter. We investigate the replacement of the simplified mathematical formulas presented bellow with more accurate approximations of the end-to-end capabilities of the routes as those proposed in [20-24].

The route selection algorithm takes as input a set of routes with calculated their end-to-end characteristics and a set of QoS constraints and eliminates all routes that do not satisfy at least one QoS constraint. To those routes left it applies an optimisation function with respect to the *QoSsignificant* and *BestFit*. The output of the route selection algorithm is the set of *Best Routes*, if any, that give the best performance with respect to *QoSsignificant* and the highest benefit to the network provider for the given connection request without violating any of the QoS constraints. If the set of *Best Routes* is not a singleton, heuristics can be used. For example, “choose the route with the best constraint on the *QoSsignificant* parameter” favours the user; while “choose the route with the highest BestFit value” favours the network provider.

## 6. HIERARCHICAL QOS-POLICY BASED ROUTING MANAGEMENT ARCHITECTURE

As discussed in section 3, our network environment is structured hierarchically in terms of domains.

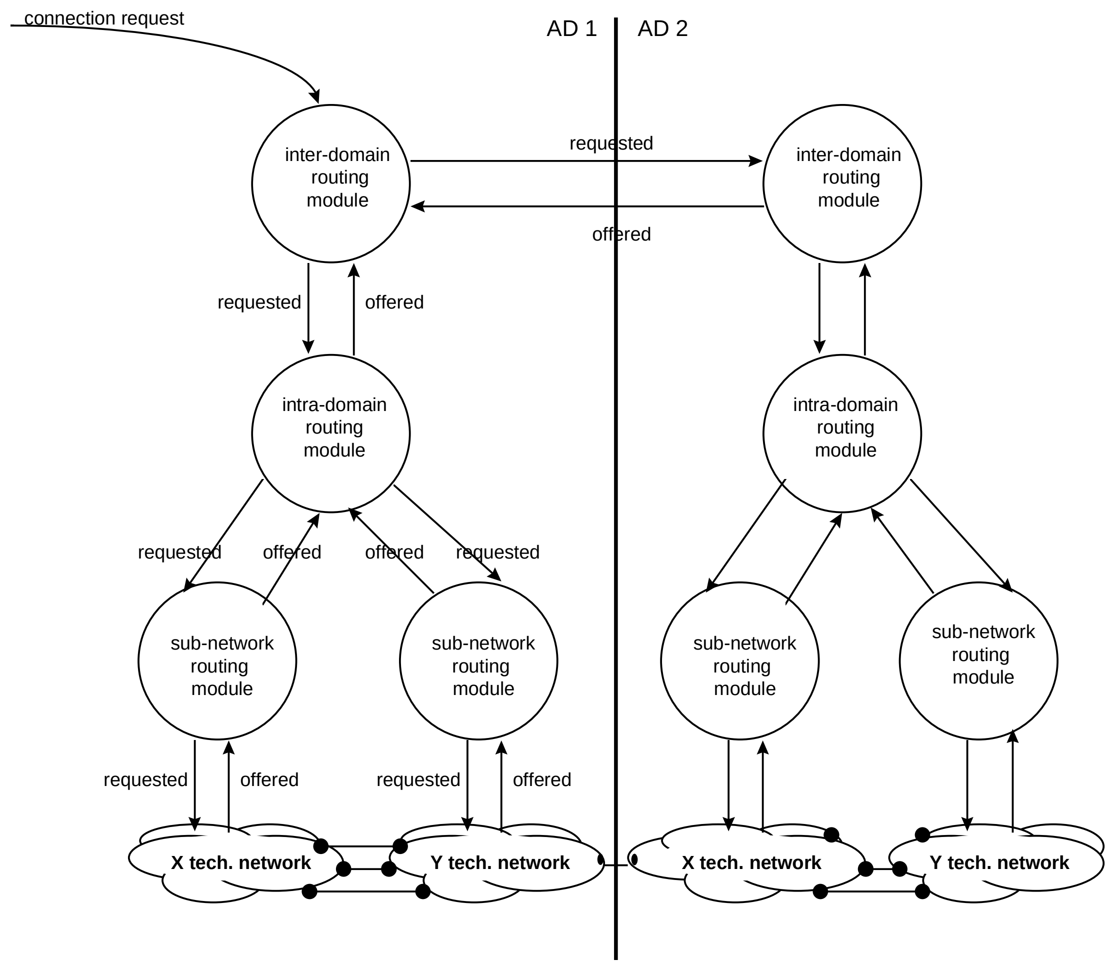


**Figure 3. Hierarchical QoS-Policy based routing management architecture**

Domains provide a means of abstraction as well as of grouping of the network resources. There are 3 levels of the domain hierarchy. The administrative domain level, the sub-networks domain level and the node level. Network topology information of interest is different at each level of the domain hierarchy. At the administrative domain level, interesting network information consists of the immediate neighbouring administrative domains as well as their physical connectivity to the local administrative domain (i.e., inter-domain nodes and inter-domain links). At the sub-networks domain level, interesting network information consists of the different domains and their interconnections (i.e., inter-technology nodes and inter-technology links). At the node level view the network topology view consists of the nodes and links belonging to each domain of different technology. A convenient scheme should be selected in order to be able to represent the network for each level of the hierarchy.

It is straightforward that a multi-level hierarchical scheme would be most convenient to support our routing management architecture as shown in Figure 3. So our architecture consist of 3 levels of hierarchy. The inter-domain level, the intra-domain level and the sub-network level. At each level of hierarchy there is a routing module implementing the routing algorithms defined in section 5.2. Specifically at the inter-domain level there is a routing module responsible for inter-domain routing. At the intra-domain level there is a routing module able to calculate routes within the boundaries of a single administrative domain. At the sub-network level there is one routing module per domain of different technology, able to calculate routes within the boundaries of a single domain. Each routing module operates on a different level of abstraction of network topology information. As it is expected the inter-domain routing module operates on the administrative domain network topology view, the intra-domain routing module operates on the sub-networks domain network topology view and the sub-network routing modules operate on the node level network topology view.

Our architecture is based on the idea that the routing modules are able to inter-work using the manager-agent model. A routing module in a manager's role asks the appropriate agent routing modules of the routes they are able to offer in order to satisfy a specific connection request. The agent routing modules calculate the routes that are able to offer and reply them back to the calling routing module. As soon as all agents reply back the offered routes, the manager acting as an agent for its caller, calculates all routes it can offer and replies them back to its caller.
In the following sections we will briefly sketch the functionality of our multilevel QoS-Policy based routing strategy.

## 6.1 INTER-DOMAIN ROUTING

Assume that a connection request arrives at the QoS manager of an administrative domain. The QoS manager is able to identify whether the destination address of the request belongs to the local administrative domain or to a remote one. This is accomplished by the aid of an addressing scheme available to the administrative domain as shown in Figure 1. The intra-domain connection case is explained in section 6.2. In case of an inter-domain connection request the inter-domain routing module creates the set of *potential routes* from the source to the destination of the connection request. Every potential route consists of a segment laying within the local administrative domain, an inter-domain link to a neighbouring domain and a segment from that neighbouring domain to the destination. In general, a potential route has the following properties:

1. Does not violate any restrictive policy rule and
2. The inter-domain link that participates to the potential route does not violate any of the QoS constraints of the initial connection request.

The inter-domain routing module propagates appropriate connection requests to every neighbouring administrative domain that participates to any of the potential routes. Further more it propagates connection requests to its intra-domain routing module. It is evident that at this stage the QoS characteristics of the potential routes are unknown. But they are going to be calculated from the replies from the agent routing modules. The replies consist of the *Best Routes* offered by the requested agents. This set of routes corresponds to the set $R^i$ defined in section 5.2. Then for every potential route the routing module calculates all possible routes with their end to end characteristics by applying the algorithms presented in 5.2. The result is the set of *Best Routes* offered for the initial connection request.

## 6.2 INTRA-DOMAIN ROUTING

The intra-domain routing module is able to calculate the set of *Best Routes* within the boundaries of a single administrative domain. The domains that host the source and destination address of the request are known thanks to the addressing scheme available to every administrative domain. Once more, the set of *potential routes* from source to destination are computed in the same way as in the inter-domain case. In the intra-domain case, potential routes consist of segments laying within different sub-network domains inter-connected with inter-technology links. Connection requests are propagated to the appropriate agent sub-network routing modules. The replies, as in the inter-domain case, consist of the set of the *Best Routes* offered by each sub-network. Then for every potential route the routing module calculates all possible routes with their end to end characteristics by applying the algorithms presented in 5.2. The result is the set of *Best Routes* offered by the local administrative domain.

## 6.3 SUB-NETWORK ROUTING

The sub-network routing module calculates the set of *Best Routes* within the boundaries of a sub-network. It simply applies the routing algorithms of section 5.2 and report back to their calling intra-domain routing module.

## 7. DISCUSSION

In this paper we presented a multilevel hierarchical management architecture supporting a QoS policy based routing strategy, appropriate for inter-network communication between public network operators. We investigate important issues like the efficiency, performance and storage requirements of the routing strategy. Our approach is an on demand approach that computes the best routes satisfying users' and providers' requirements for a connection request with specific QoS characteristics. Our architecture can support either on-demand or calculation-in-advance routing. Scalability issues have been heavily considered in the design of our architecture. An analysis of the above issues is the subject of a forthcoming paper.

The proposed QoS-Policy based routing management architecture is TMN compliant, and its design and realisation is currently underway in a mixed CORBA, CMISE environment. The work is in progress and it is complemented by an architecture for an intelligent distributed Java/CORBA based negotiation and provision of service management. Prototype implementations of service management systems are used to validate the proposed solutions in Intranet environments like in [15].

## ACKNOWLEDGEMENTS

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