An Overview of Quality of Service Routing Issues

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Abstract

The problem of Quality of Service routing poses several challenges that must be addressed within the service-provisioning framework. Quality of Service routing has associated two main components, one related to the metrics distribution mechanism and the other related to the path selection algorithm. In this paper we present the challenges inherent to these modules and describe the main proposals, including the association with scheduling and admission control algorithms. Quality of Service routing can impact the performance of best-effort traffic, leading to starvation. We present relevant research work that addresses this problem. The dynamic nature of Quality of Service routing algorithms can contribute to routing oscillations under heavy loads or bursty traffic. This situation can lead to network instability and overall performance degradation. We discuss the origins of this problem and present the main mechanisms that a Quality of Service routing strategy must have in order to avoid it. We also present the role of Quality if Service routing within the Traffic Engineering framework.

Keywords: Quality of Service Routing, Path Selection Algorithms, Stability.

1. Introduction

The best-effort service traditionally provided by the Internet has been unable to support new types of traffic with real-time characteristics, like videoconference and IP telephony. There have been several proposals of new services to support traffic with special Quality of Service (QoS) requirements on IP networks. Particularly, on the IETF[1], there are the Integrated Services and Differentiated Services frameworks [1, 2]. Both approaches aim at providing different levels of QoS according to traffic needs. Within Integrated Services there is resource reservation and traffic is differentiated at the flow level. In the Differentiated Services model traffic differentiation is done per class, and resources are not explicitly reserved for each flow.

Current routing protocols used on the Internet don't have the characteristics to contribute to the provision of QoS made by the emerging new services. These protocols use shortest path algorithms based on a single metric, such as number of hops and administrative configured costs. Thus, the paths selected don't take into consideration the dynamic state of the network and the QoS requirements of different types of traffic. This poses the challenge of integrating QoS capabilities on routing protocols.

QoS routing is an important component in the Integrated Services and Differentiated Services models. Specifically, in a network where there is resource reservation, QoS routing can contribute to the efficient establishment of reservations. In this case, the routing algorithm can produce a set of paths with the desired QoS characteristics where the reservation can be made.

The development and deployment of QoS routing rises several issues related to the distribution of routing information on the network and to the path selection algorithm. The former is associated with the nature of metrics to use, its distribution mechanism, the additional load that is introduced on the network by routing protocol messages and by the inaccuracy of the routing information maintained at the routers. The latter relates to the path selection algorithm computational complexity, instant of path computation (on-demand or pre-computed) and local of routing decision (source – path establishment ou hop-by-hop). Routing stability is a concern that involves both modules. In this paper we describe and analyze these challenges and main proposals, taking into consideration the corresponding traffic differentiation paradigm, that is, flow or class based.

This paper is organized as follows: in Section 2 we describe the major issues associated with QoS routing; the analysis of the main proposals for QoS routing in IP networks is presented in Section 3; in Section 4 are discussed some issues concerning QoS routing, including the impact of QoS routing on best-effort traffic performance, stability analysis, and the role of QoS routing within the traffic engineering framework; Section

[1] IETF - Internet Engineering Task Force.

5 contains the conclusion of this survey and some guidelines for the development of QoS routing schemes.

2. QoS Routing: Problem Statement

The main goal of QoS routing is to select, based on information about the state of the network, the path that is most suitable according to traffic requirements [3]. The maximization of network resource utilization is also an important goal of QoS routing. QoS routing schemes must present solutions for metrics distribution mechanisms and path selection algorithm. In this section we describe the main features of these issues related to intra-domain routing.

2.1. Metrics Distribution

The state of the network can be represented by a set of metrics, including available bandwidth, delay, jitter, and congestion level. Traffic requirements can be expressed in several ways, depending on the methodology used for traffic characterization. For instance, in the Integrated Services framework, this can be done using the QoS parameters associated with each data flow during resource reservation [4, 5]. In the Differentiated Services framework, traffic requirements are associated with each traffic class [6].

The information about the state of the network must be distributed, and kept updated, to all or some routers in the network. The distribution must be done more frequently than in traditional routing, to reflect the dynamic behavior of the network. However, if this frequency is too high, it will induce too much bandwidth consumption, and it is thus undesirable.

In these situations, it is advisable to achieve a compromise between the desired actuality of the state information and the overhead that this introduces. Some approaches to this problem include the distribution of quantified values, instead of instantaneous ones. Associated with this value quantification, triggers may be used to control the emission of updates and timers to force a minimum interval between the emission of updates (hold-down timers) [7].

A problem that relates to the frequency of the distribution of information pertaining to the state of the network is the inaccuracy that a lower frequency can introduce. Other sources of inaccuracy are the propagation delay of routing messages in large networks, the utilization of estimates, the impact of the metrics measurement mechanism used and information aggregation in hierarchical systems. The study of the impact of routing information inaccuracy on the performance of communication systems and the definition of the mechanisms to overcome its problems has been the subject of several research projects [8, 9, 10, 11].

2.2. Path Selection Algorithm

The path selection algorithm has a degree of complexity that depends on various factors. Since applications generate traffic with very diverse requirements in terms of QoS, the path selection algorithm must select paths that satisfy a set of restrictions. This is however, a problem with high computational complexity, depending on the rule of metrics composition.

The value of a metric along a path, based on its value in each hop, depends on the nature of the metric. There is additive, multiplicative and concave metrics. The rule for additive metrics composition is that the value of this metric over a path is the sum of the values of each hop (Equation 1). Delay and number of hops are examples of additive metrics. With a multiplicative metric, the value of the metric over a path is the product of its values in each hop, as it is the case of losses (Equation 2). The value of a concave metric over a path corresponds to the minimum value observed in all hops of that path (Equation 3). Bandwidth is a common example of a concave metric. In these equations, $m(l_i)$ is the value of a metric on link l, and $m(p)$ is the total metric value of the path composed of links l_1 to l_n.

$$m(p) = \sum_{i=1}^{n} m(l_i) \qquad (1)$$

$$m(p) = \prod_{i=1}^{n} m(l_i) \qquad (2)$$

$$m(p) = \min\left[m(l_i)\right] \qquad i = 1,2,\ldots,n \ (3) \qquad (3)$$

The problem of QoS routing when using two additive or multiplicative metrics, or one additive and one multiplicative metrics is a NP-complete problem [12]. This poses a challenge that must be addressed in order to conceive QoS routing strategies that are efficient and scalable. The major approaches for the solution of this problem are discussed in the following section.

3. Approaches for QoS Routing

QoS routing approaches can be characterized by several aspects, including the metrics, type of path selection algorithm, instant of application of the path selection algorithm and localization of the routing decision. In this paper we use as the main characterization feature, the metrics for path selection, because it is an attribute that determines most of the other aspects.

Bandwidth is widely used as a metric for QoS routing, alone or associated with other metrics, such as delay [4, 12] and number of hops [7]. It is usually coupled with systems where traffic differentiation is done at the flow level, with the specification of path QoS parameters.

When bandwidth is associated with other metrics, instead of solving an optimization problem with two or more restrictions, suitable paths are selected through the application of heuristics, in order to simplify the resolution of the problem. The resulting path is not the optimal path, but is able to satisfy traffic requirements without an excessive algorithm complexity.

The main heuristics used are the following:

- Metric ordering;
- Sequential filtering;
- Association with scheduling disciplines;
- Association with admission control mechanims.

3.1. Metric Ordering

Metric ordering requires the identification of the metric that has higher priority and the computation of the best paths according to this metric. Afterwards, the second metric is used, in case of a tie, to decide which is the best path. This is the case of shortest-widest path and widest-shortest path algorithms.

Shortest-widest path algorithms first find paths with maximum available bandwidth. Next, if there are paths with the same amount of available bandwidth, it is selected the path that has the shortest number of hops. The main objective of this type of algorithm is to do load balancing, showing the best performance when the load in the network is light. However, this approach damages best-effort traffic performance because it contributes to resource consumption. This is due to the fact that usually, the path with a higher availability of bandwidth corresponds to a longer path, that is, a path with a larger number of hops [13].

Another type of shortest-widest path algorithm uses, as the second metric, instead of hop count, propagation delay. The corresponding path computation algorithms, based on distance-vector and link-state, are presented in [12].

Widest-shortest path algorithms select from the shortest paths with equal number of hops, the path that has higher bandwidth availability. In [5] it is presented an extension of the Bellman-Ford algorithm that computes widest-shortest paths. The Dijkstra algorithm can also be used to compute widest-shortest paths [13]. In this case are used two distance functions, the first concerning the number of hops and the second the maximum available bandwidth. At each iteration of the path computation algorithm it is selected the node with smaller number of hops. If more than one node has the same number of hops it is selected the node with maximum available bandwidth.

Although widest-shortest path algorithms have the objective of limiting resource consumption, they also allow for load balancing, because they avoid that the traffic load uses only one path. Since resource conservation is more important when the network is congested, and this type of algorithm contributes to resource conservation, it shows good results when the load is high. Widest-shortest path algorithms also show a good behavior when the routing decision is taken upon information of the state of the network that is inaccurate [13].

3.2. Sequential Filtering

The application of sequential filtering requires that the links of the graph that represents the network that don't have enough available bandwidth are excluded from the network graph before the application of the path selection algorithm. After the application of this "cut politic", it is computed the shortest path, based on the pruned graph.

The definition of the threshold that determines the exclusion of a link depends on the moment of application of the path selection algorithm, whether it is on-demand or pre-computed. When paths are computed on-demand, the desired value of bandwidth can be expressed on the request, for instance, on the messages of the resource reservation protocol, or in special messages of the routing protocol. If paths are pre-computed, bandwidth ranges must be established, originating network graphs that exclude links that don't satisfy the bandwidth values include in the specified ranges. On-demand path computation requires parameter specification. For path pre-computation it is necessary to compute and store several pre-computed paths that satisfy the defined range of bandwidth values.

In [12] it is presented a path selection algorithm that uses source routing for selecting paths subject to bandwidth and propagation delay constraints. The algorithm works as follows: first, all links of the network graph that do not satisfy the requested bandwidth are pruned; then it is applied the Dijkstra algorithm to find the minimum delay paths to nodes in the network. The algorithm terminates when the shortest path is found or if the maximum delay is reached.

Sequential filtering can also be used to find paths subject to more than two constraints. One such example is the cheapest-shortest-feasible path algorithm [9]. This source routing algorithm aims at finding feasible paths according to a bandwidth constraint, minimizing simultaneously cost and resource consumption. The cost function used reflects link utilization, and the number of hops determines resource consumption. In a first step all links that do not satisfy the requested bandwidth are pruned from the network graph. Next, the shortest paths are computed using the Dijkstra algorithm, based on the number of hops. Finally, it is selected the path with lower cost. This metric is used to distinguish among paths with the same length.

3.3. Association with Scheduling Disciplines

The problem of the complexity of path selection algorithms can be surpassed using the relationships among QoS parameters determined by the nature of scheduling disciplines. Particularly, if it is used a Weighted Fair Queuing (WFQ) scheduling mechanism, it is possible to use the relations between bandwidth, delay and jitter, to find a path, in polynomial time, subject to constraints of delay, jitter and bandwidth [13].

WFQ is a rate proportional scheduling discipline that isolates each guaranteed session from the others, and that has delay bounds that can be mathematically determined. In this case, queuing delay and jitter are determined by the bandwidth to reserve and traffic characteristics, and buffer size is determined by bandwidth to reserve and hop count. Based on these relationships, and using adequate length functions, paths satisfying delay, buffer space and jitter constraints can be computed using the algorithms summarized in Table 1. The modified version of the Bellman-Ford algorithm proposed iterates over all values of links residual bandwidth, limiting path hop count to meet the jitter bound, and node hop count to satisfy the buffer space constraint.

	Bandwidth to reserve known	**Bandwidth to reserve unknown**	**Mixed bandwidth to reserve**
Delay constrained path	Shortest path	Iterative shortest path	Iterative shortest path
Delay, jitter constrained path	Bellman-Ford (limit on the number of hops)	Iterative Bellman-Ford (limit on the number of hops)	NP-complete
Delay, buffer constrained path	Bellman-Ford (limit on the number of hops)	Iterative Bellman-Ford (limit on the number of hops)	Bellman-Ford (limit on the number of hops)
Delay, jitter, buffer constrained path	Bellman-Ford (limit on the number of hops)	Iterative Bellman-Ford (limit on the number of hops)	NP-complete

Table 1- QoS routing algorithms based on WFQ scheduling properties.

3.4. Association with Admission Control

In some QoS architectures, the admission of new flows in the network is subject to a mechanism of admission control. This mechanism interacts closely with routing. For instance, the routing module can produce information about the state of the network that can help the admission control decision, increasing the likelihood that the new flow will be accepted [6].

Admission control and QoS routing are also tightly connected with resource reservation. The resource reservation protocol can express the flow QoS requirements that are used by the QoS routing protocol to compute suitable paths. The resource reservation protocol can then proceed to flow establishment on the paths produced by the QoS routing algorithm. If this establishment is successful, the flow is accepted; otherwise it is rejected.

The admission control module can produce information useful for path computation subject to QoS constraints. In [14] are presented path computation algorithms that take into consideration QoS requirements and admission control restrictions of multimedia traffic. The main algorithms analyzed and the corresponding metrics are depicted in Table 2.

Algorithm	**Metrics**
Shortest Path	Number of hops Delay – the minimum delay that can be guaranteed by the admission control module
Shortest Cost	Probability of the connection being rejected according to the admission control module
Modified Shortest Cost	Number of hops Probability of the connection being rejected according to the admission control module
Min Max Cost with Delay Bound	Probability of the connection being rejected according to the admission control module Delay

Table 2- QoS routing algorithms based on admission control.

These algorithms use information associated with the admission control module, namely, the minimum delay that can be guaranteed by the admission control module and the probability of the connection being rejected according to the admission control module. This information is used for pruning from the network graph the links that do not satisfy admission control restrictions. The remaining graph is then presented to the routing algorithm.

In this section we presented approaches for metrics manipulation in order to reduce the complexity of path computation algorithms. We also presented some heuristics that reduce path computation complexity, including the association of QoS routing with scheduling and admission control modules.

4. Issues on QoS Routing

In this section we present some relevant questions that arise when a QoS routing solution is considered. Particularly, the co-existence of QoS routing schemes and best-effort traffic, QoS routing stability issues and the role of QoS routing in a traffic engineering framework.

4.1. Co-existence with best-effort traffic

The main architectural proposals for traffic with QoS requirements include resource reservation and class based traffic differentiation. The QoS routing algorithms presented in the previous section aim at selecting adequate paths for traffic with QoS requirement. However, there is also the need to contemplate the performance of best-effort traffic. Thus, QoS routing mechanisms must take into consideration best-effort traffic, to avoid starvation. There is also the need to deploy mechanisms that contribute to fair and efficient resource utilization. The main proposals that access the co-existence of QoS sensitive and best-effort traffic combine scheduling and routing algorithms.

In networks where bandwidth is allocated according to the Max-min Fair Share paradigm it is possible to make routing decisions (best-effort) based on the state on the state of the network [15, 16].

In this type of network, available bandwidth can be determined from the *max-min fair rate*. The mixed approach of routing and fair allocation of bandwidth according to the max-min fair share model is suitable for connection-oriented networks, such as ATM, in particular, the ABR traffic class, that will transport several types of best-effort traffic. In [17] it is presented a QoS routing algorithm associated with a scheduling algorithm that guarantees bandwidth requirements for QoS flows associated with a max-min fair based routing algorithm for best-effort traffic.

The impact of QoS traffic on best-effort traffic can also be controlled, if the maximum reservable bandwidth for QoS flows is limited. Also, resource utilization may be maximized if unused bandwidth by QoS flows can be allocated to best-effort traffic by the scheduler [18].

Another approach that aims at avoiding starvation for best-effort traffic is presented in [19]. This routing algorithm allows for the dynamic sharing of link resources among multiple traffic classes. Specifically, the algorithm deviates QoS flows from links that are congested with best-effort traffic. In order to achieve this goal it is used a link cost function that takes into consideration the congestion level of best-effort traffic, the *virtual residual bandwidth*.

4.2. QoS Routing Stability Analysis

Some QoS routing proposals compute shortest paths based on a metric that represents the congestion state of the network. The usage of a single shortest path may induce instability under heavy loads or bursty traffic. When congestion increases in one path, all traffic tends to shift to another path, with lower load. In the next iteration of the path computation algorithm, the inverse path change may occur, creating oscillations. Oscillations originate network instability and contribute to congestion under dynamic routing protocols, since there is the need to distribute the updates corresponding to the state change of the network.

A common approach to avoid instability in networks where it is deployed dynamic routing is the advertisement of metrics that are quantified in some manner, instead of advertising instantaneous values. The quantification can be done using a simple average [20], or using a hysteresis mechanism [5].

Another methodology to avoid routing oscillations is to use load-balancing techniques, allowing for the utilization of multiple-paths for the same destination [5, 21]. If alternate paths exist and if they are used, load will be distributed over the network and the oscillation of the total amount of traffic between two paths is avoided.

Routing stability can be achieved using some other mechanisms, like route pinning and doing load sensitive routing at the flow level [22]. However these approaches are not suitable for a situation where routing is done hop-by-hop and there is not connection establishment.

4.3. Association with Traffic Engineering

Traffic engineering is an important piece for the control of network performance, and encloses three levels of action: network planning, capacity management, and traffic management [23]. Network planning concerns the issues associated with node and transport planning in order to support future traffic growth. This component is deployed at a monthly and yearly scale. Capacity management is responsible for ensuring that the network can meet performance objectives while keeping the costs as low as possible. Traffic management is the module that aims at maximizing network performance under all working conditions, including load conditions and failures. This is done at a finer time scale, ranging from seconds to minutes. The implementation of these functions requires performance evaluation and optimizations tools.

Constraint based routing is a powerful tool for traffic engineering at the traffic management module, since paths are selected according to the availability of network resources, using QoS routing protocols, and also subject to politics constraints, as for instance is the case of pricing. Other aspect of QoS routing presented in this paper that is extremely relevant to traffic engineering is the ability for an efficient inter-class resource sharing.

The approaches used for traffic engineering include the Differentiated Services model and Multi Protocol Label Switching (MPLS) [24]. In the first case traffic management is done on a per-hop basis. MPLS is a path-oriented technology that supports explicit, constrained-based routing.

5. Conclusion

QoS routing is a main component of a QoS framework. In this paper we presented the major issues associated with QoS routing and some of the approaches to handle them. We described several metrics that represent the state of the network, and presented the compromise that must exist between communication overhead introduced by the frequent distribution of information about the state of the network and the accuracy of this information. The rules for metrics composition were presented in association with the problem of path selection subject to multiple constraints. The main approaches for this problem were described. Mechanisms for the co-existence of QoS routing with best-effort traffic and stability control of QoS routing strategies were exposed. The contribution of QoS routing for Traffic Engineering was also presented.

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