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Research Article

An Overview on Inter-Domain Routing with Quality of Service*

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Abstract: This study discusses various problems of inter-domain routing with Quality of Service and gives an overview of the currently proposed solutions. The problem arises when the traffic must pass through different Autonomous Systems and therefore the quality of service requested cannot be guaranteed. Several studies and solutions have been made to improve the end-to-end quality of service. We classify these solutions in this study into two categories: theoretical and technical solutions. We present the main proposed solutions for each category and we show the performance and limitations of each solution.

Keywords: Inter-domain routing, path computation, pre-computation path algorithms, quality of service

INTRODUCTION

Today, one of complex challenges that Internet Service Providers (ISPs) are faced to, is to assure the Quality of Service (QoS) for Internet's user. That means to guarantee the same QoS parameters to the customer, knowing that their traffic across networks of another ISP.

Various studies have been conducted to solve the problem of inter-domain routing with QoS constraints. In this study, we present various aspects of this problem and also a several proposed solutions to date.

The proposed solutions can be classified into two main classes.

Theoretical (or analytical) solutions: Mainly based on algorithms for computing a path that satisfies the various constraints imposed by the different traversed domains. We present algorithms solving the problem of multiple-constraints routing, starting with the basic ones used in the intra-domain case and then, we present those used in inter-domain routing case.

Technical solutions: Are mainly extensions or improvements of existing technologies. Indeed, several solutions that have been proposed are based on operational technologies like Multi Protocol Label Switching (MPLS) (Rosen *et al.*, 2001) or Border Gateway Protocol (BGP) (Rekhter *et al.*, 2006).

The reminder of this study is an overview of the inter-domain multi-constraint routing problem and detailed description of the various solutions proposed to solve this problem.

ROUTING WITH QUALITY OF SERVICE AND INTER-DOMAIN ROUTING

Before discussing the various solutions proposed to ensure inter-domain routing with constraints of quality of service, it is more appropriate to recall routing with QoS and to define the notion of inter-domain routing.

Routing with quality of service: QoS is a set of techniques used by the ISP to guarantee to clients that their traffics will be delivered to destination in the appropriate conditions. It generally covers two aspects: the temporal aspect (delivery delay) and the semantic aspect (data loss), which are expressed by four parameters: bandwidth (rate), transfer delay, variation of this delay (jitter) and finally, the reliability (loss rate). QoS is generally based on those parameters that have a different nature and which are intended to clarify the user needs to service providers.

In summary, routing with QoS, or simply multi-constrained routing, is to find a path between two nodes that respects the QoS constraints assigned to the client's traffic. In what follows, we present the inter-domain routing.

Inter-domain routing: An Autonomous System (AS) corresponds to a routing domain under the control of a single administrative authority. The As's, forming Internet, have to exchange their accessibility information, this is the objective of inter-domain routing.

Thus, each of border routers of the two autonomous systems in Fig. 1, must firstly establish connectivity with its neighbor and then, provide its information

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Fig. 1: Connectivity of two autonomous systems

about networks that it is able to achieve. The border router in AS1 announces to the border router in AS2 (via an inter-domain routing protocol, EGP External Gateway Protocol) acquired information (by an intra-domain routing protocol, IGP Interior Gateway Protocol) about accessible networks via AS1. The border router in AS2 will diffuse this information via the IGP used in its domain.

To ensure QoS, the inter-domain routing protocol has to solve many specific problems. Each AS domain is under the responsibility of an operator. In practice, the cooperation between different operators is limited. Indeed, information concerning topology and available resources on the links, that are necessary for ensuring QoS, cannot be communicated between the various operators that are in competition. Another important issue related to inter-domain routing with QoS is the problem of scaling. In fact, the path computing that satisfies constraints, crossing a sequence of domains, is much more complex than path computing in intra-domain because the number of nodes involved in this computation is more important.

After introducing the two basic concepts related to this study, including routing with QoS and inter-domain routing, the objective of the next part is the presentation of theoretical solutions to solve the inter-domain multi-constraint routing problem.

THEORETICAL SOLUTIONS

To ensure inter-domain multi-constraint routing adopting an analytical approach, various solutions have been proposed. Before presenting some examples of these solutions, it is necessary to give the analytical formulation of the problem which is the basic of these solutions. We list then in the second subsection, some algorithms used for ensuring inter-domain multi-constraint routing. The last subsection is a presentation of two examples of theoretical solutions.

Analytical formulation of the problem: To better understand the problem related to inter-domain QoS routing, the paths are represented by a graph. Given a graph G (N, E), where N is the set of nodes and E is the set of links. Let be P a path belonging to P_{SD}, the set of paths from S to D in G (N, E).

Definitions: In this section we give definitions of certain characteristics of a path listed in Frikha *et al.* (2009):

- A path P is called feasible if and only if:

$$\forall i \in 1,....,k; \omega_i\left(P\right) \le C_i \tag{1}$$

where,

ω_i (P) = The cost of the path P for the metric i
C_i = The QoS constraint

- A path P is called non-dominated in the set of paths P_{SD}, if and only if, there is no path $P' \in P_{SD}$ that satisfy:

$$\forall i \in 1,....,k; \omega_i\left(P'\right) \le \omega_i(P) \tag{2}$$

and,

$$\exists i \in 1,....,k; such, \omega_j\left(P'\right) \prec \omega_j\left(P\right) \tag{3}$$

- The energy function L is the function that transforms the vector cost $\vec{\omega}_i$ of a path P in a scalar cost L (P).
- A path P is optimal for L in P_{SD}, if and only if, there is no path P' in P_{SD} that satisfy: $L\left(P'\right) \prec L\left(P\right)$.

The following definitions are related to intra-domain QoS routing problems and are extended to inter-domain QoS routing.

A MCP problem: Multi-Constrained Path Problem, is to find a feasible path P between a source node N_S and destination node N_D.

A MCOP problem: Multi Constrained Optimal Path Problem, is to find an optimal path P between a source node N_S and destination node N_D, which minimizing all QoS constraints.

A MOOP problem: Multi-Objective Optimal Path, is to find all non-dominated paths P between a source node N_S and destination node N_D.

Concepts: Before defining the version of the MCP problem in inter-domain case, we cite the concepts used to solve the problems above.

The choice of energy function: There are two types of energy functions, linear and non-linear:

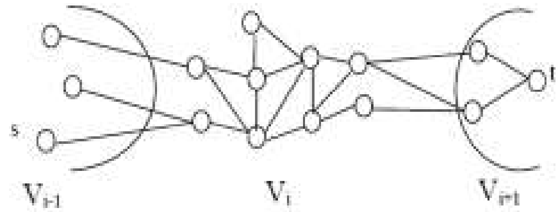

Fig. 2: Inter MCP problem

- Linear functions as Jaffe (1984) function expressed by Eq. (4) do not always solve the QoS routing problem MCP:

$$L(P) = \sum_{i=1}^{k} \left(d_i * \omega_i(P)\right) \quad (4)$$

where, d_i is a coefficient.

- Non-linear functions as expressed by Eq. (5) and which solve the MCP problem:

$$L_q(P) = \left(\sum_{i=1}^{k} \left(\frac{\omega_i(P)}{c_i} \right)^q \right)^{\frac{1}{q}} \quad (5)$$

The approach of the K shortest paths: Consists on storing in an intermediate node the k shortest paths not only one shortest path.

The non-dominance approach: Is to eliminate dominated paths from the search space for calculating the optimal path, so it reduces the computation time.

The look-ahead approach: Is a mechanism that is executed at the level of an intermediate node n to calculate the optimal path to the destination from the node n (and not the source), it reduces the search space.

Definition of inter-MCP problem: After defining the intra-domain routing problems and presenting the intra-domain routing problem MCP, we introduce the same problem to solve but this time in the case of inter-domain named inter-MCP.

An Inter-MCP problem (Fig. 2) is to find a feasible path between the node $s \in V_1$ and the node $t \in V_D$, through a sequence of domains $S = V_1, ..., V_D$.

A solution to Inter-MCP problem is to calculate a multi-constraints path from the source s in V_1 to at least one of nodes in V_1 which are connected to a node in V_2. This means that to solve the Inter-MCP problem, an NP-complete problem must be solved. Thus, the Inter-MCP problem is NP-complete (Garey and Johnson, 1979).

The following section presents algorithms for inter-domain multi-constraints routing.

Inter-domain multi-constraints routing algorithms: In this section we present first the basic algorithms most used for intra-domain multi-constraints routing SAMCRA and H_MCOP. Then we discuss the improvements that have been made to these algorithms to solve the inter-domain multi-constraint routing problem and we present different algorithms proposed to solve this problem.

SAMCRA and H_MCOP algorithms: SAMCRA (Self Adapting Multiple Constraints Routing Algorithm) is an exact algorithm for multi-constraints routing. It uses the following non-linear cost function:

$$L_\infty(P) = \max_{i \in 1,...,k} \left\{ \frac{\omega_i(P)}{c_i} \right\} \quad (6)$$

So to find the optimal path between a source node S and destination node D, it suffices to apply the algorithm for calculating the K shortest paths. The complexity of SAMCRA depends on the number of QoS constraints k and on the number of paths stored in an intermediate node.

H_MCOP (Heuristic Multi-Constrained Optimal Path) is a heuristic algorithm. This algorithm attempts to limit the non-linear cost functions. H_MCOP offers good performance to solve the MCOP problem and has a very low level of complexity because it runs Dijkstra (1959) algorithm (with minor modifications). Several changes have been proposed to improve H_MCOP as cited in Feng (2004).

Inter-domain MCP algorithm: The principles of SAMCRA and H_MCOP algorithms, which are used in intra-domain paths calculation, are adapted to the specific inter-domain path computation. The Inter-Domain-MCP (ID-MCP) algorithm (Bertrand, 2010), is a direct adaptation of these algorithms and it uses the same principles to reduce the search space and to present a solution to the Inter-MCP problem.

Unlike SAMCRA or H_MCOP, ID-MCP is able to calculate the inter-domain paths while preserving the confidentiality of topology and resources information.

Also, SAMCRA and H_MCOP cannot calculate a multi-constraints path from multiple sources to one destination. In particular, H_MCOP is designed to compute paths between two nodes only, i.e., the source and destination and SAMCRA can be used to compute paths from one source to multiple destinations. Thus, authors of ID-MCP have adapted SAMCRA by reversing the direction of his calculations. Therefore, ID-MCP calculates paths from the single considered destination back to the multiple sources, namely the edge nodes connected to the previous domain.

During the operation of ID-MCP in each domain, the topology and link state of the considered domain and the state of connected link to this domain, must be known. The procedure for calculating the path segment in each domain is based on a queue that contains the stored paths. The elements of the queue are as follows: (node, predecessor, weight, color). The output of the calculations in each domain is a VSPT (Virtual Shortest Path Tree) tree containing one or more non-dominated virtual paths to the destination domain.

ID-MCP does not allow the calculation of parallel path segments in crossed domains, or pre-calculation of path segments. In addition, ID-MCP repeats the same calculations several times if multiple non-dominated paths are present in the VSPT for the same input. This makes ID-MCP slower and more complex. Algorithms presented in the rest of this section are ID-MCP improvements.

pID-MCP and kpID-MCP algorithms: The operation of *p*ID-MCP (Bertrand *et al*., 2010) is similar to ID-MCP (it is also based on the SAMCRA algorithm). The difference between the two may be noted in two specific situations:

- First, *p*ID-MCP performs comparisons of non-dominance depending on the destination of each element. Thus, in the worst case, at least one feasible non-dominated path by destination is stored for each intermediate node. Therefore, if a domain is connected to the next domain through many input nodes, a large number of paths must be memorized by *p*ID-MCP.
  However, in actual network configurations, the number of nodes linking two domains is quite limited.
- Second, *p*ID-MCP estimates the initial paths weights equal to zero; therefore, fewer paths can be detected as non-feasible within the end-to-end constraints. Compared with ID-MCP, *p*ID-MCP reduces the maximum number of paths stored in a node and thus provides a reduction of calculation complexity.

The *kp*ID-MCP algorithm is the heuristic of *p*ID-MCP; it is based on the TAMCRA algorithm (Tunable Accuracy Multiple Constraints Routing Algorithm) (Neve and Mieghem, 2000) (which is the SAMCRA heuristic). It can provide both an excellent performance against the quality of the computed path and a significant reduction in calculation complexity.

Distributed E2E QoS-based path computation algorithm over multiple inter-domain routes: This section presents a distributed inter-domain end-to-end QoS based algorithm (Djarallah *et al*., 2011) that computes inter-domain paths that satisfied QoS constraints and cross a set of domains, by considering multiple inter-domain routes.

The objective of this algorithm is to solve the MCP problem in the inter-domain case, named Inter-Domain Multi-Constrained Optimal Path over Multiple Domain Routes (ID-MCOP-MDR) problem. This problem is presented by the following equation:

$$\min_{\forall p \in P^*_{s,t}} Z\left(P^*_{s,t}\right) \tag{7}$$

Subject to,

$$\forall p \in P^*_{s,t}, W_{P,j} = \sum_{\forall e \in p, j=1}^{m} w_{e,j} \le C_j \tag{8}$$

where, Eq. (7) represents the selection of the optimal path from the set of non-dominated paths $P^*_{s,t}$ and Z ($P^*_{s,t}$) is the objective function.

And Eq. (8) represents the additive resource constraints on selected path segments within the different inter-domain routes, $w_{e,j}$ is an m-dimensional weight vector relative to *m* QoS constraints which characterize each path segment.

The main difference between this algorithm and the other algorithms is that it proposes a solution to the ID-MCOP-MDR problem through different inter-domain routes instead of only one pre-determined route. The algorithm is based on four main points:

- **Length function:** It is a non-linear length function represented by Eq. (9) and it is a combination of weights and constraints. After receiving a best path request the minimization of this function provides the optimal path:

$$l_\infty(p) = \max\left[\frac{w_1(p)}{C_1},......,\frac{w_m(p)}{C_m}\right] \tag{9}$$

  where,
  w_i (p) = A weight vector
  C_i = A constraints vector

- **k-shortest path storage:** The same principle as described above.
- **Non-dominance:** The same concept as explained above.
- **Path segmentation:** After computing the non-dominated paths within intermediate domains, instead of sending a full path, the computation units send abstract path or path segment, its QoS characteristics and the path cost. Once received, the path segments are concatenated to the domain graph.

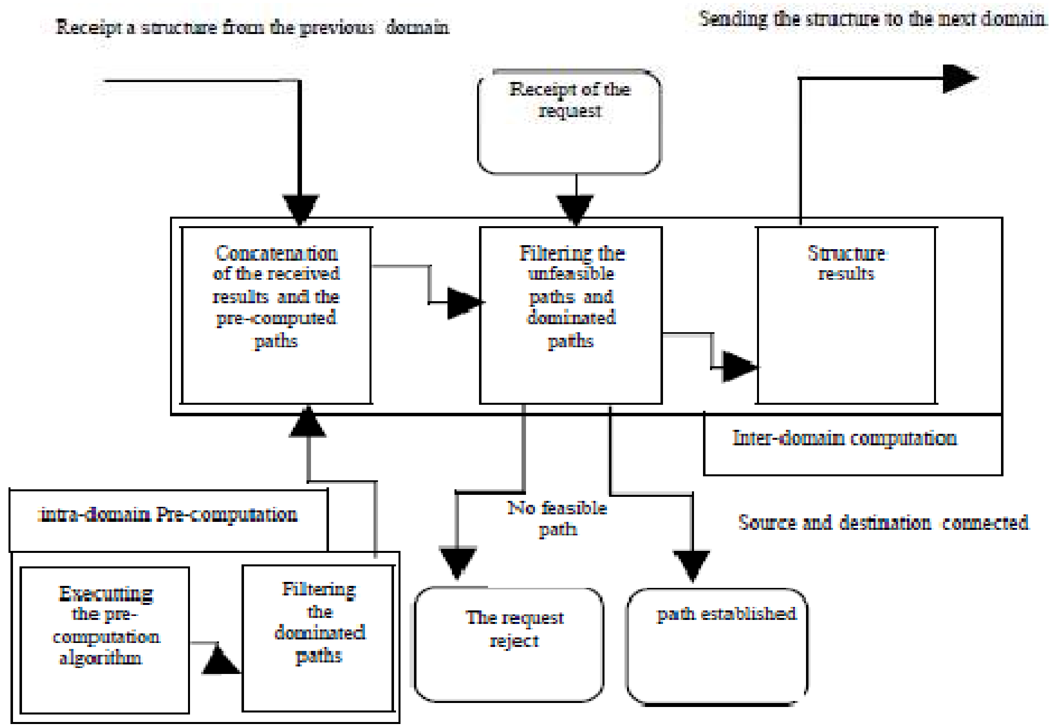

Fig. 3: Functional blocks of the architecture (Frikha *et al*., 2009)

The ID-MCOP-MDR algorithm allows increasing the success rate to find an inter-domain QoS path by exploring a set of inter-domain routes and not one route. However, the algorithm presents some limitations, concerning prevention of inter-domain loops and also the increase observed in the execution time.

The following sections are devoted to the presentation of three new analytical solutions that propose new architectures and also implement new algorithms to solve the problem of inter-domain multi-constraints. The first solution is proposed in Frikha *et al*. (2009) and it concerns the pre-computation of inter-domain multi-constraints path, the second is the one proposed in Frikha *et al*. (2013) and it proposes an hybrid architecture and algorithm to solve the inter-MCP problem and the third presents a reliable routing with QoS guarantees for multi-domain IP/MPLS Networks (Sprintson *et al*., 2007).

The pre-computation of inter-domain multi-constraints path: Figure 3 shows the architecture proposed in Frikha *et al*. (2009).

The proposed architecture is mainly formed by two blocks of pre-computation, one for the intra-domain and the other for inter-domain pre-computation.

The intra-domain pre-computation block: At this block, the pre-computation algorithm is executed for finding paths connecting the edge nodes to domain's internal nodes and then filtering dominated paths.

Several algorithms can be implemented at this block like the ID-MEFPA (Inter-Domain-MEFPA) MEFP algorithm described in Cui *et al*. (2003), the ID-PPPA (Primary Path based Pre-computation Algorithm) algorithm described in Frikha *et al*. (2009) and also pID-MCP and kpID-MCP algorithms already presented in the previous section.

The inter-domain pre-computation block: It allows the communication between the domains via pre-computed paths. The calculation starts at the block upon the QoS request reception, the calculation result is either the establishment of the path between the source and destination in the case of a feasible path, or the request rejection otherwise. It is formed by three sub-blocks:

- **The first:** Is responsible for concatenating the results of intra-domain pre-computation and those received from the domain above.
- **The second:** Is responsible for filtering non-feasible and dominated paths.
- **The third:** Is responsible for structuring results and sending them to the domain below.

For the calculation of inter-domain paths (which is the function of this block), the PCE architecture (Farrel *et al*., 2006a) (Path Computation Element) is used. The PCE is a path computation entity from a graph representing the network, taking into account the QoS constraints.

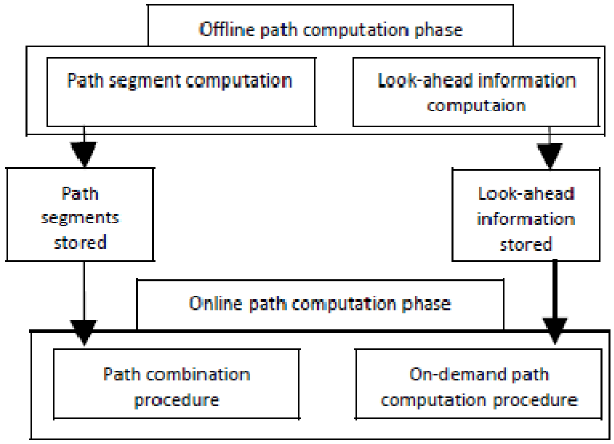

Fig. 4: The hybrid architecture blocks (Frikha *et al*., 2013)

The proposed solution will meet some operator's objectives. Indeed, the principle of the path pre-computation and the new algorithms reduce the response time for the computation paths requests and at the same time respect the privacy and autonomy constraints imposed by the operators.

However, the paths pre-computation can lead to several problems. Specifically, the stored paths are calculated based on the instantaneous state of the network taken before the QoS request reception. Therefore, after a possible change of network status, pre-computed paths do not necessarily satisfy the QoS constraints. So, this plan requires a periodic update of network status information. In addition, a pre-computation system cannot anticipate every possible QoS request. It also creates instability of the pre-computation algorithms in the case of a dynamic change of the network's links status.

Hybrid solution:

Hybrid architecture: To meet limitations of the paths pre-computation solution, a new architecture was proposed in Frikha *et al*. (2013). This architecture combines the calculation at the request and paths pre-computation. It proceeds in two phases.

Like the pre-computation model, the first phase is to prepare in advance paths or path segments. And the second phase is to start the computation after paths request reception, if the paths pre-computed in the first phase do not respond to the received request.

The proposed architecture is as follows in Fig. 4.

The hybrid ID-MCP algorithm: The Hybrid ID-MCP (HID-MCP) (Frikha *et al*., 2013) algorithm is based on the previous architecture, so it also proceeds in two phases.

Phase 1: Offline path computation: The Offline path computation is to calculate in advance a set of intra-domain paths subject to multiple predetermined QoS constraints and also to calculate the look-ahead information at the entrance of each domain's edge node.

Phase 2: On-line path computation phase: The on-line computation path procedure is to find a feasible end-to-end path, using the pre-computed paths and taking advantage of the look-ahead information calculated in phase 1.

The main advantage of the hybrid approach is that it offers a high QoS requests acceptance rate, thanks to the on demand path computation procedure which succeeds in finding feasible paths satisfying QoS constraints when the pre-computation cannot do it. However, in some cases especially in large sizes and complex networks, this may cause a relatively high response time which can reduce the performance of this approach.

Reliable routing with QoS guarantees for multi-domain IP/MPLS networks: The approach presented in Sprintson *et al*. (2007), used the PCE architecture and proposes an Aggregated Representation (AR) for a multi-domain network used by the PCE units for computing optimal disjoint QoS paths across multiple domains, this AR is used also for introducing a new distributed routing algorithm that compute a disjoint QoS path in a multi-domain IP/MPLS environment.

Multi-domain network aggregated representation: The goal of the AR is to permit to the source PCE to find two disjoint paths of minimum weights by summarizing the traversal properties of each routing domain.

The AR is based on the disjoint paths algorithm, which permits to the source PCE to compute efficiently the minimum weight of disjoint paths.

Consider the AR A_i of D_i, where D_i (V_i, E_i) is the routing domain and B_i the set of border nodes on V_i.

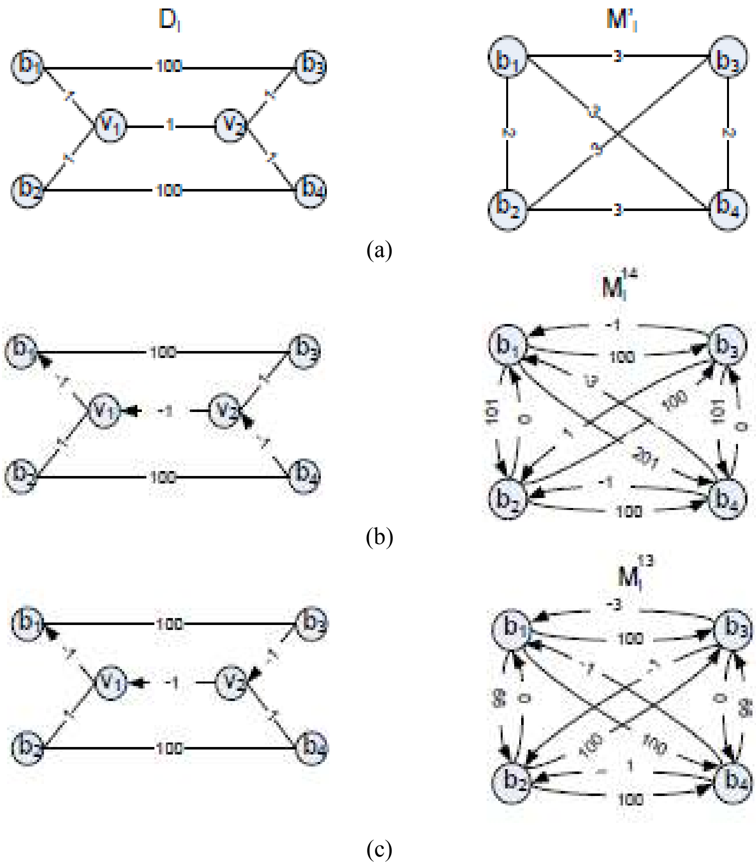

Fig. 5: The graphic presentation of "aggregated representation" (Sprintson *et al*., 2007)

The A_i is divided in two parts: in the first part the PCE computes a shortest path P1 *s* and the destination node *t* and in the second part the source PCE computes the second path P2.

Also, the first part of A_i consists of the matrix M_i^l which includes for each two border nodes b_j and b_l of Di, the minimum weight of a path between b_j and b_l and the second parts of A_i consists of a set of $|B_i|$ ($|B_i|$-1) matrices $\{M_i^{j,l}|\ b_j \in B_i,\ b_l \in B_i,\ b_j \neq b_l\}$ each matrix contains $|B_i|$ ($|B_i|$-1) elements.

Figure 5 is a graphic representation of the A_i.

Disjoint path algorithm: The disjoint algorithm is based on two main phases.

The first phase: consist in computing the AR using an algorithm named FINDAR. For each pair of border nodes b_j, b_l of D_i, the algorithm computes a shortest path $P_i^{j,l}$ between b_j and b_l, then the results is stored in the matrix M_i^l. After the computation, the algorithm reverses all links forming $P_i^{j,l}$, eliminates their weights and computes then a minimum weight path between any pair of border nodes in the resulting graph.

The second phase: Consist in computing the minimum weight of shortest paths. The computation is performed by the PCE according to the FIND2DP algorithm. The algorithm consists in three operations: 1-to construct an auxiliary graph G' (V', E') that, for each domain D_i, consists in the complete graph that passes over the border nodes of D_i., also G' includes the source domain D_s and a set of inter-domain links E_{inter}, 2-to compute the shortest path P1 between *s* and *t*, 3-to compute the second path P2 between *s* and *t*.

The approach presents an optimal solution for computing two disjoint QoS paths across the multi-domain IP/MPLS environment. However, the approach may involve some issues concerning its large scale implementation.

After presenting the analytical approaches and solutions that have been proposed to ensure inter-domain routing with QoS, the second part of this study discusses some technical approaches developed by searchers to respond to this objective.

TECHNICAL SOLUTIONS

As mentioned above, solutions that have been proposed to solve the inter-domain multi-constraints routing problem can be classified into two main categories: theoretical solutions those we presented in the previous section and technical solutions those are this section's objective. These solutions can be described as technical solutions because they are based on technologies that are implemented and already operational on networks like MPLS, BGP and DiffServ (Blake *et al*., 1998). In this context, various studies and several solutions have been proposed to ensure QoS in inter-domain. Each solution suggests a specific approach to treat the problem. Among these solutions, we choose to present in the first subsection the inter-domain MPLS Traffic Engineering (Farrel *et al*., 2006a), in the second subsection a BGP extension presented in Weisser (2007), in the third subsection MESCAL project (Howarth *et al*., 2006), in the fourth subsection a framework for selling inter-domain path (Misseri *et al*., 2013) and in the last subsection a new mechanism for inter-domain QoS management that we have proposed in Bakkali *et al*. (2014).

Inter-domain MPLS traffic engineering: Inter-domain MPLS traffic engineering is an extension of MPLS in multi-domain environment. Its objective is to extend all MPLS services in inter-domain including QoS. That means it ensures inter-domain QoS. This solution has been published in RFC 4726.

This solution is mainly a set of techniques used for establishing Traffic Engineered (TE) Label Switched Paths (LSPs) across multiple domains. These techniques can be classified into three categories: Techniques for distributing reach-ability and TE information, Techniques for computing paths of LSPs and Techniques for signaling the LSPs.

Techniques for distributing reach ability and TE information: TE information is collected and stored in a database named TED (Traffic Engineering Database). Path computation algorithms operate on this database. TE information is distributed within domains via IGPs.

A TE information distribution mechanism is necessary for delivering TE information corresponding to the inter-domain links to the corresponding domains.

This technique allows a better path computation and reduces crank-backs related to TE on inter-domain links.

Techniques for computing paths of LSPs: Various techniques are used for path computation. We describe briefly the principle of these techniques.

Head-end computation: In this technique the end-to-end path computation is assured by the ingress LSRs (Label Switching Routers). Depending on the visibility and the TE information available in the ingress, the computation is assured according three options.

Multi-domain visibility computation: Used if sufficient visibility of the topology and TE information concerning all domains that the LSP crosses to its destination, are available.

Partial visibility computation: Used if only information about domains connectivity and the TE resources availability are available, but not a global visibility of all domains topology.

Local domain visibility computation: Used if only visibility within the current domain is available.

Domain boundary computation: The boundary LSR of each domain adds path information to the path message, this information must be sufficient to allow the path message to arrive at least to the next domain boundary.

Path computation element: In this technique the LSRs are not responsible for path computation. This function is ensured by a PCE (Path Computation Element) that can be appointed by a static configuration or by a dynamic discovery. Across the network or within a domain, one centralized PCE or multiple PCEs can be appointed. More information about the PCE technique is available in Farrel *et al*. (2006b).

Techniques for signaling the LSPs: For signaling inter-domain LSPs three different methods are defined.

LSP nesting: is a technique which allows transmission of one TE LSP within another. Nested LSPs can be advertised as TE links and can create a tunnel that transports multiple TE LSPs which have a common part of their paths. However, nested LSPs cannot be advertised as TE links that enclose domains. We note that during the establishment of a nested LSP the specific path objects named SENDER_TEMPLATE and SESSION are unchanged throughout the length of the nested LSP. We note also that the routing protocols do not use the nested LSPs as support for exchange routing messages.

Contiguous LSP: For a single signaling exchange a single contiguous LSP is established. The contiguous LSP keeps the same SESSION object and LSP ID value throughout the entire path.

LSP stitching: The LSP stitching principal consists in establishing a distinct TE LSP segments, these segments will be stitched together for creating a single end-to-end LSP.

The choice of the signaling techniques depends on multiple parameters including the used path computation technique, the network's topology and also the application's type.

The inter-domain MPLS TE is an improvement of MPLS adapted to inter-domain networks. Thus, it allows ensuring inter-domain QoS. However, it's mainly based on bandwidth reservation using an enhanced version of resource Reservation Protocol

(RSVP) (Braden *et al*., 1997) named RSVP-TE (Farrel *et al*., 2008). The use of RSVP may be a significant inconvenient because of the delay caused by the resource reservation procedure and also the unavailability of resources in some cases.

A BGP extension using the blind exploration algorithm: The solution proposed in Weisser (2007) introduces a new algorithm for inter-domain path research named the blind exploration algorithm. It is based on sending a sensor messages on the network. It is based on BGP, because it uses only information stored in BGP routing tables.

The algorithm description: The blind exploration algorithm is a distributed heuristic algorithm. Its objective is to ensure the establishment of multi-constraint path between domains. The algorithm's operation is based on sending two types of messages.

Sensor messages: Used to find a path between the source and the destination which satisfy the QoS constraints and then request the resource reservation. The sensor message is transmitted from a domain to another until reaching the destination or abandoning the search. The sensor message contains the following fields:

- The request description (source, destination, the set of the constraints)
- The current path (within the current domain)
- The current path weight for each constraint
- The list of the previous domain already visited
- A logical variable indicating if the sensor message progresses in the network or not

Acknowledgment messages: Used for the path request validation or rejection. If the validation is accorded then the resources reservation becomes a permanent resources allocation. If the path request is rejected the all resources reservation is canceled.

Number of exchanged messages: As mentioned before, the algorithm is distributed which means that its complexity lies in the number of the exchanged messages.

Considering a specific request, the sensor message creates a tree by browsing through the graph. The size of this tree and its depth are limited by the nodes number specified in the parameter N_{hop}.
The algorithm stops in two cases:

- The number of vertices that are allowed to visit (N_{hop}) is exhausted. In this case, a negative ACK message is sent.
- The sensor message reaches the destination via a path respecting imposed constraints. In this case, a positive ACK message is sent.

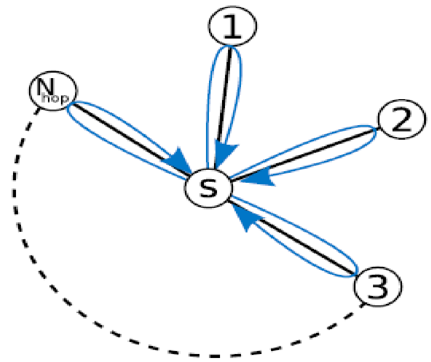

Fig. 6: Number of exchanged messages in the blind exploration algorithm

In both cases, the total number of exchanged messages is equal to twice the number of vertices that makes up the tree. The number of the ACK message is comprised between 1 and N_{hop}. The number of sensor messages exchanged it is between 1 and $2N_{hop}$ (Fig. 6).

Advantages and limitations: The approach presents many advantages that can be resumed in the following points:

- The main advantage of this approach is that it is implemented in parallel with BGP, thus it can be easily adopted in networks and do not need an overall changing in the networks.
- Another important advantage is that the domain takes a decision about available resources after receiving the sensor message. This allows to the domains a better control of the resources attributed to a specific request and also limits information diffusion.
- Also, the algorithm do not need or use a global knowledge of the inter-domain network and do not use either any prior knowledge of resources proposed by domains. Then it preserves certain domains independence.

However, the approach presents also some limitations:

- The main limitation is that the proposed algorithm needs to be integrated into a mechanism for inter-domain domain path reservation. The path reservation can reduce significantly the network performances especially in term of delay.
- Also, the topology used to simulate the algorithm and to prove its efficiency is relatively a small topology. Thus, the efficiency and the stability of the algorithm in large-scale are not proved yet.

The MESCAL project: One of the major contributions related on ensuring inter-domain QoS is the MESCAL (Management of End-to-end QoS across the internet At

Large) project (Howarth *et al*., 2006). The project was created by multiple industrials and academics partners and it ran from November 2002 to August 2005. The main objective of MESCAL is to propose solutions ensuring QoS across the Internet network.

In the context of this project, various studies has been published and standardized. In this study we studied works published in Howarth *et al*. (2006), the rest of this section is a brief presentation of these works.

The MESCAL QoS models: The MESCAL architecture is based on two QoS models.

Business model: The business defines relationships between the different network entities. Thus, the network is formed by customer that requests QoS-based services (Atkinson and Floyd, 2004) from its provider or INP (IP Network Provider) and by INPs that offer these services according to the SLA (Service Level Agreement) established with customer (Fig. 7).

In the SLA customers define their traffics needs in term of QoS constraints and agree to comply and not exceed these constraints limits, also in the SLA providers assume to provide to customers traffic the QoS constraints that they need.

Details of all services constraints values are defined in the SLS (Service Level Specification) which is a part of the SLA.

Cascaded inter-domain QoS peering model: Various models has been proposed for defining interconnection between providers for ensuring QoS services across domains, such as hub, centralized, cascaded and hybrid (Asgari *et al*., 2004) models. The MESCAL project uses a hop-by-hop cascaded model for managing the interactions between INPs. The cascaded model is based on establishing a peer SLS (pSLS) contracts between the direct adjacent INPs. Thus, the QoS peering agreements are between the "one hop" adjacent neighbors.

The MESCAL functional architecture: The MESCAL approach proposes an architecture that describes all functions required for ensuring inter-domain QoS services. The principal functions are the following.

Service planning and QoS capabilities exchange: The planning includes the business activities that define the services offered by an INP and the QoS capabilities exchange allowed the customers and INPs to know the offered services.

Network planning and provisioning: The offline process is that defines the type, quality and geographical location of the physical resources requested by the INPs.

Offline traffic engineering: Includes two processes inter-domain and intra-domain traffic engineering. The inter-domain process is responsible for QoS class mapping and binding and the intra-domain process is responsible for the intra-domain network configuration computing that ensures the estimated traffic demand.

Dynamic traffic engineering: Includes two dynamic processes inter-domain and intra-domain traffic engineering. The dynamic inter-domain traffic engineering is the function that ensures the inter-domain routing and also the load balancing between paths selected with the offline inter-domain traffic engineering. The dynamic intra-domain traffic engineering (Trimintzios *et al*., 2001) combines functions for intra-domain routing, for load balancing and for a dynamic bandwidth allocation.

SLS management: This function includes two steps: the first function establishes contracts between INPs peers and the second reserves resources before the traffic admission.

Data plane functions: Includes functions for traffic conditioning and QoS classes enforcement, these functions are responsible for packet classification, policing and traffic shaping and marking.

Options for the architecture implementation: In the previous section we presented the MESCAL project general architecture and its main functions, in this section we present three approaches that respect this architecture and provide mechanisms for ensuring these functions. Each approach ensures a different level of QoS.

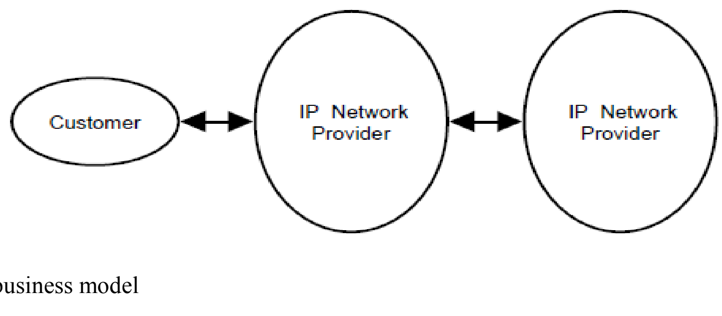

Fig. 7: Number MESCAL business model

The first approach: Named "Loose guarantees solution", it proposes a set of parallel QoS planes. In each plane two concepts are adopted: the meta-QoS-classes and an enhanced version of BGP.

The second approach: Named "Statistical guarantees solution", used for customer traffics that have a higher QoS needs than those offered by "Loose guarantees" approach. In this approach the pSLS specifies destination address prefixes and maps the requested QoS to these prefixes.

The third approach: Named "Hard guarantees solution", used for customer traffics that request the highest QoS constraints. It is based on the use of inter-domain MPLS TE tunnels and an enhanced version of BGP that supports QoS named qBGP and it uses also the PCE mechanism.

The MESCAL project proposes a global model for ensuring inter-domain QoS. It includes several mechanisms and approaches to respond to this objective.

However, the MESCAL approach focuses more on the management of business relationships between customers and providers or between providers and do not gives a specific mechanism for inter-domain routing and inter-domain path computing.

A new service to provide multi-path inter-domain: The auction-type framework for selling inter-domain paths is an approach proposed in Misseri *et al*. (2013) in order to ensure inter-domain QoS. This approach allows the providers to sell paths to their neighbors. It is mainly based on a process that performs a path allocation based on auctions.

The path allocation mechanism proceeds in two phases: the first one is pricing paths; the second phase is matching these paths to interested neighboring domains.

The approach is interesting since it proposes a new mechanism to manage inter-domain relationship between ISPs and provides inter-domain path by an innovative way.

However, this framework does not provide a complete architecture for ensuring inter-domain QoS and inter-domain multi-constraints routing.

A new method for managing inter-domain QoS: The last solution that we present in this section is a recent method proposed in Bakkali *et al*. (2014). The main objective of this method is to ensure continuity of QoS constraints offered to the client even after the transition to other domains.

Definition of the method principal: The basic idea in this approach is to designate in each domain a server responsible on the management of the different classes of service, named the Class Manager (CM). On this server a table is defined, named Class Table (CT) that contains all information concerning the different classes defined in this domain (such as bandwidth, loss rate, delay, etc.). Once the CM of each domain filled its CT, it sends it to the neighboring domain. In this way, each CM has all the information about its neighbor's classes of services.

The main functions: The method operation is based on the following points.

Sending information from routers to CM server: The intra-domain routers create classes of service for classifying the customer's traffic according to intra-domain QoS model and send characteristics of these classes to the CM.

Creating the CT table: In each domain the CM creates the CT, this table comprises various fields that represent the main QoS constraints. The CT entries represent the characteristics of classes defined within the current domain.

Exchanging tables between CM servers: After enabling the CT, each CM exchanges its CT with the neighbor's CM.

Establishing agreements between domains: Before implementing this approach, establishing an agreement between all domains that participate on the mechanism is a necessary point. This agreement defines the management of the CT exchange between domains and also the business relationship between the domain's owners.

This approach introduces an interesting and innovating mechanism for ensuring inter-domain QoS. The main advantage of this method is that it allows to the clients traffics to keep the QoS constraint attributed in the source domain in the neighboring domain which ensures to the traffic to cross the neighboring domain in the same routing conditions. Also, the implementation of this method does not require a total change of the architecture and network equipments, which makes it easy to implement in networks that are already operational.

However, the new method may present some limitations especially concerning the cost of the tables exchange between CM servers and also the security vulnerabilities at the communications between the edge routers and the CM servers and between the CM servers themselves.

Several other solutions have been proposed to solve the inter-domain QoS problem, as those presented in Jasinska *et al*. (2014), Shah *et al*. (2013) and Amigo *et al*. (2012).

CONCLUSION

In this document we have presented an overview of the inter-domain with QoS constraints routing solutions. We have classified these solutions into two main categories: analytical solutions and technical solutions. We have presented the analytical definition of the inter-domain routing with multiple QoS constraints problem and described three examples of analytical solutions. Then, we presented technical solutions that treat the inter-domain QoS problem.

Even if many of the presented solutions and several other solutions look promising, there are still many other issues related on implementing inter-domain QoS, that's why until today, no solution has been standardized and implemented in the Internet.

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