Toward Optimal Software-Defined Interdomain Routing

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1 Introduction

End-to-End control is the control acting between two applications that are communicating across one or more networks. End-to-end route control can delivers both the network and end-users benefits such as a better operational efficiency, reduced costs, and prevents Denial-of-service Attacks.

However, in the current internet format, it is difficult to achieve and requires a lot of experiments. In this article, we first discover the already existing solutions such as the Border Gateway Protocol (BGP), MIRO and ARROW Interdomain controls then it is a research work about finding an optimal solution for End-to-end control.

The goal is to reach an optimal End-to-End route control. This is mainly because of the current design of the Border Gateway Protocol. In the Border Gateway Protocol, each Autonomous System (AS) can make and execute its own policy to select routes to a destination prefix. It can export the different selected routes, in the matter of a path to its neighbor.

The problem is that it is not based on finding the shortest route from autonomous systems to its neighbors. Each owner can define beforehand the policy of their autonomous system. They will have a preset routes from that autonomous system to an other particular destination which may not be the shortest route.

Even if it is the current industry standard, it restrains network operators and end-users to achieve a flexible End-to-End control.

We will discuss about a new systematic formulation of the software undefined internet-working model. We will study on the optimal End-to-End route SDI routing problem which is NP-hard. We will focus on the Black-box Optimization algorithm, including its benefits and disadvantages.

2 Context and Related Work

2.1 Context

Routing traffic in communication networks has been studied for more than 40 years and is still an issue that can be improved with different techniques [1].

The internet is partitioned into a disjoint set of autonomous systems [2]. An autonomous system was a group of hosts and routers combined by running a single interior gateway protocol. After some years, this notion was synonymous with administrative domain. The routers and hosts were unified by a single administrative authority, and a set of interior gateway protocols [3].

In 1996, BGP was the new standard and is still today. It was already in its fourth version, that was used between all significant AS. BGP provides a mechanism to prevent routing loops between autonomous systems, and allows interconnections topologies between autonomous systems [1].

Today, BGP routers are only using a single and basic default path: when congested leads occur, we notice poor performances. The Border Gateway Protocol fails to react to congestion and chaos in traffic [4].

There is a lot of alternatives solutions or improvements that has been proposed through time. We could outsource the Routing Control Logic as a new model, and it would be used for inter-domain routing [5]. An other solution proposed was a multi-Path Inter-domain forwarding protocol (MIFO). Autonomous systems border routers allow to offload outbound traffic from a congested to an alternative path without touching the inter-domain route protocols: MIFO achieves multi-paths on data planes which differs to previously multi-path control planes [6].

2.2 Related Work

2.2.1 *Software-defined Networking*

There are multiple different SDN Software progressions made by companies such as Google, CISCO, Facebook and a few others focused on SDN Architecture. A few of the recent or most used [7] examples would be ODL [8], [9], [10] and ONOS [11].

2.2.1.1 **ONOS**: This control platform is mostly based on scalability and performance. Its affinity and focus with the Cloud Provider concepts makes it deeply bounded to scalability. Scalability is quite important since the number of Unique ASes follows an almost linear augmentation tendency since 1996 as shown with *fig. 2*.

Unfortunately, it has been exposed to security vulnerabilities issues, with the amount of public vulnerabilities recorded to 25 [12]. Theses bugs affect multiple components as well as the Ethernet VPN application (for the latest, *CVE-2019-16302*) to unauthenticated uses of websockets (declared by the *CVE-2017-1000080*).

2.2.1.2 **OpenDaylight**: Developed by the Linux Foundation, ODL is another control platform commonly compared to ONOS. Their focuses and architecture are slightly different. Experimentation on Mininet using Wireshark has shown that the performance results from the ODL controller was better than those from ONOS [13].

Similarly to the unfixed bugs recorded for *ONOS*, there are currently 17 CVE bugs records [14]. Particularly, one bug can lead to a Java Out of Memory Error (*cf. CVE-2017-1000359*). Getting this type of error is particularly serious, since a crash could allow an outside intruder to get into the system, and allows him to use the right elevation.

One of its interesting functions is that it supports REST API and the OSGi Framework.

2.2.2 Bayesian Optimization Algorithm

The Bayesian optimization (BOA) algorithm takes a population of candidate solutions as strings to a given problem and evolves by using Bayesian networks to model some promising solutions and generate new candidate solutions.
The first population of candidate solutions is generated randomly with uniform distribution but the initial population can be biased. Then the population is updated for a number of generations via four steps.
First, the best strings of the population are first selected using selection methods. Then, with the selected set of strings a Bayesian network is constructed. Then, a set of new strings is generated according to a joint distribution encoded by the previous constructed network. Finally, the new strings are mixed up with the original population. These steps are repeated until termination criteria are complete.
BOA can solve problems that can be decomposed into subproblems: the number of evaluations until convergence to its optimum has in a worst case a complexity of O(n^2). [15]

The advantages of Bayesian optimization are its sample-efficiency, low computational overheads and convergence to a global optimum. The disadvantage is that BO can not optimize a large number of parameters. The limit is 15 parameters for the most common form of Bayesian optimisation that uses Gaussian Process regression as a model for the objective function.
Bayesian optimization frameworks are born in order to solve many problems. For example in [16], they presented a Bayesian optimization framework for neural network compression that assist the accuracy and speed of the compression process.
In [17], they proposed a multi-fidelity Bayesian optimization method for the design application with both known and unknown constraints. It is build on a multi-level CoKriging method to predict the objective function.

3 Contribution

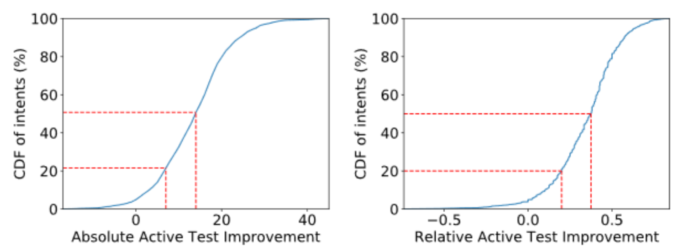
This article [18], which is still quite recent, brings contributions that could be one day change the current standard of End-to-End route control such as a "base stone" for future progressions and researches.

First, the authors of this article provide the first systematic formulation of the software defined internet-working Model. Their work is basically based on an extension of an Intra-Domain SDN towards a Generic Inter-Domain SDN. SDI maximizes network autonomy by allowing a network to maintain the control of its interdomain export policies in order to avoid violations such as valley routing for example. This particular application differs from intradomain SDN that cannot do it.

On the other hand, they systematically study the optimal End-to-End SDI routing problem, and they prove that the problem is strongly NP-hard. To achieve the NP-hardness proof, they first needed to consider another problem: the shortest Policy Compliant AS-Path Problem.
This is basically a simplified version of the optimal end-to-end SDI routing problem. It is also an NP-hard problem. They prove this problem with a reduction to 3-SAT problem, which directly proves that the optimal End-to-End SDI routing problem is a strong NP-Hard.

The major contribution, which integrates Bayesian optimization theory and some important properties in interdomain routing algebra, is that they develop a Black-Box Optimization algorithm. This algorithm is used to efficiently find near-optimal End-to-End route with a small number of route samplings. Bayesian optimization is a sequential model-based approach. It is a very powerful framework that can optimize objective functions: the evaluation of these functions are really expensive.

Finally they implemented a prototype of a Black-box Optimization. They measure its performances with extensive experiments using real-world topology. They compute a first estimation of its searching efficiency and effectiveness compared to SPE. Provided by the figures 3.a and 3.b, we can see an improvement in most of the cases. We can observe a deterioration of its performance for a relatively small percentage of cases.



(a) Absolute Improvement **(b)** Relative Improvement

Fig. 3: CDF of Active Test Improvement

4 Discussion

4.1 Black-Box Optimization

The first thing to consider about this paper is that the optimization protocol used is **Black-box Optimization**. This method only implies a naive optimization of the subject from this paper. Moreover, Black-Box Optimization executes an optimization routines only on the possible input and does not adapt according to the behavior of the intern structure. Meanwhile this type of optimization can be useful for companies, who do not need to know the content of the following domain in order to implements it. It does not provide an efficient optimization method.

By using this type of optimization, users do not know what is happening with precision, as with *Machine Learning*, inside their Inter-domain Routing. This also implies a less flexible and transparent protocol, and even harder to debug.

A Black-box optimization is non-deterministic (*ie.* for a fixed input, the output will not always be the same). This means that an input can leads to the best routes with the lowest cost, but also that the same input can randomly lead to a deadlock. Using a Black-box and having no views on the algorithm processing means that there is no direct way to fix it, except by using external analysis tools.

4.1.1 Analysis of the Black-Box Optimization Algorithm

In this algorithm (*ie. Algorithm 2: Black-box Optimization Algorithm [19]*), we can see multiple points which are quite blurred. First of all, the while loop (line 11) implies two conditions. First of all, a counter t_{global} going on until it is lesser or equal to T_{Global}. There is no mention, in the paper of the meaning of this variable where we will have to iterates on. The other point, still on the same line, is the size of the set R_q.

Finally, in this loop, the first if...else statement brings us to either a call of the *getGlobalCandidates* method, which has not been described in term of cost or code in this paper. Otherwise, in the case where we enter the else clause, a call to the method *getLocalCandidates* (*cf. Algorithm 3* [20]) is made. Its worst complexity can be evaluated to $\mathcal{O}(n^2 * n \log n)$, which is quite significant, particularly with a large set of data, since we are already inside a loop.

As stated by the writers of this article, it can happens that the black-box optimization is not able to find a route before testing a large number of routes. Even if this case has a low probability of occurrence, it is still quite important to maintains a $\mathcal{O}$-cost as low as possible. The internet, either local or the world-wide web is manipulating an incredible number of requests per second, this amount will increase over time.

4.1.2 Possible Improvements

This kind of optimization problem, due to the iterative and non-optimized algorithm could probably be improved by using a Gray-Box Optimization [21], [22], or even a White-Box Optimization [23], [24]. Since the produced software will be deeply bound to the system, it would allow a more efficient implementation of this problem, to the cost of a less adaptable Inter-domain Routing.

From the below schema, we understand that the two other types of modelling (*ie.* White and Gray-Box Modelling) have their pros and cons.

4.1.2.1 White-box Modelling: It will exclusively use mathematical equations to represent the routing software. It will provide us one of the best costs and a deterministic model, but it will not be easily adapted to other models.

4.1.2.2 Gray-box Modelling: It will use information and mathematical equations that could be used to make a white-box model to makes the black-box model more efficient. It could be compared to a mixture of supervised and unsupervised learning. Meanwhile the black-box would only be unsupervised and white-box exclusively supervised. This combination of methods can lead to either a deterministic model (*ie.* there ares no random components), or to a stochastic model (*ie.* contains random components). In this paper, the NP-hardness of the problem has been proved

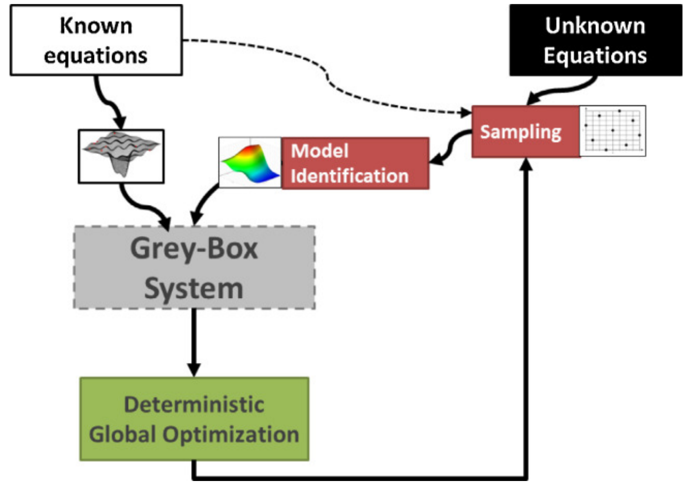
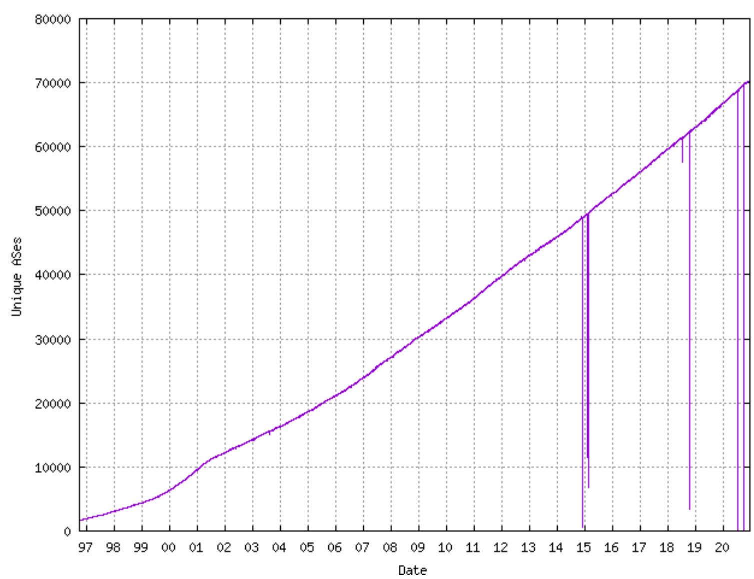


Fig. 1: Comparison of Modelling type

by doing a reduction of the SAT-problem. Consequently, we could use these equations to set up and to exploit a Gray-box Optimization. By doing so, the Optimization Model will be more efficient than the black-box's one, and requires less work to adapt this model to new systems.

4.2 Test Sample



Date range: 30-Sep-1996 to 13-Dec-2020

Fig. 2: Number of Unique ASes over time

These tests has been carried out using real-world data without taking into consideration the increasing tendency in numbers of ASes and AS-level links. The CIDR Report of the 13 December, 2020 [25] states that the number of AS has already reached 70000 ASes (using IPv4), which represents an increase of 7.7% compared to the tests sample used on this article [18].

As stated in *fig.* 2 provided by the CIDR Report [25] on the evolution of the numbers of Unique Autonomous Systems, we can assert that we observe a constant increasing evolution of the number of ASes. Consequently, the contribution of the article on this part is relative and would require further testing and analysis to prove its potential.

5 Conclusion

In conclusion, this article has provided us with an opening on a way to define Software Defined Network mixing both efficiency and adaptability between systems deploying it. The concepts and ideas proposed in this article could be used in a way to achieve an Optimal SDN. Such an optimal SDN would be technology allowing the End-User to control its own export policies and return the optimal route defined on them. Based on the content produced and explained in this paper, the optimal route could not be found in the best time by the usage of a Black-Box Optimization due to its randomness, nevertheless it offers a good compromise between efficiency and simplicity with the cost of the deployment of a stochastic method, and, consequently of a robust debuggable process. This research could significantly improve the actual End-to-End control in order to find an optimal solution, and the shortest routes. In contrast, the 1989 BGP solution has major issues. As an example, BGP is not capable of finding the shortest route and enabling congestion in the traffic. Technological progress in order to replace BGP is really important today to replace outdated routing protocols.

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