The Role of Inter-Controller Traffic in the Placement of Distributed SDN Controllers

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Abstract—We consider a distributed Software Defined Networking (SDN) architecture adopting a cluster of multiple controllers to improve network performance and reliability. Besides the Openflow control traffic exchanged between controllers and switches, we focus on the control traffic exchanged among the controllers in the cluster, needed to run coordination and consensus algorithms to keep the controllers synchronized. We estimate the effect of the inter-controller communications on the reaction time perceived by the switches depending on the data-ownership model adopted in the cluster. The model is accurately validated in an operational Software Defined WAN (SDWN). We advocate a careful placement of the controllers, that should take into account both the above kinds of control traffic. We evaluate, for some real ISP network topologies, the delay tradeoffs for the controllers placement problem and we propose a novel evolutionary algorithm to find the corresponding Pareto frontier.

Our work provides novel quantitative tools to optimize the planning and the design of the network supporting the control plane of SDN networks, especially when the network is very large and in-band control plane is adopted. We also show that for operational distributed controllers (e.g. OpenDaylight and ONOS), the location of the controller which acts as a leader in the consensus algorithm has a strong impact on the reactivity perceived by switches.

Keywords—Software Defined Networking, distributed SDN controllers, consistency data models.

I. INTRODUCTION

The centralized network control of the Software Defined Networking (SDN) paradigm, which enables the development of complex network applications, poses two main issues. First, a limited reliability, due to the single point-of-failure. Second, the control traffic between the switches and the controller concentrates on a single server, whose processing capability is limited, creating scalability issues. Distributed SDN controllers are designed to address the above issues, while preserving a logically centralized view of the network state necessary to ease the development of network applications. In a distributed architecture, multiple controllers are responsible of the interaction with the switches, with two beneficial effects. First, the processing load at each controller decreases, because the control traffic between the switches and the controllers is distributed, with a beneficial load balancing effect. Second, resilience mechanisms are implemented to improve network reliability in case of controller failures.

Distributed controllers adopt coordination protocols and algorithms to synchronize their shared data structures which define the network state and to enable a centralized view of the network state for the applications. The algorithms follow a consensus-based approach in which coordination information is exchanged among controllers to reach a common network state. This induces some delay that, as shown in Sec. III, can heavily affect the controller reactivity perceived at the switches. Indeed, any read/write of a shared data structure at a controller is directed to a possibly different “data owner” controller. In this case, the controller-to-controller delays must be added to the switch-to-controller delays when evaluating the controller’s reactivity perceived at the switches. Thus, the optimal placement of the controllers on the network topology must consider not only the delays between the switches and the controllers, but also the delays between controllers. As specified in Sec. VII most of the past literature concentrated on the Openflow-based interaction, thus considered the switch-to-controller delays only, and neglected the controller-to-controller delays, which are instead the focus of our work.

The adoption of the Software Defined Networking paradigm in Wide Area Networks (SDWANs), poses severe technical challenges. Indeed, the design of the network supporting the SDN control plane in WANs is more challenging than in data centers, where the limited physical distances between network devices permits the installation of a separated and dedicated network among the controllers (e.g., using Ethernet or InfiniBand connections), providing an out-of-band control plane. Furthermore, communication delays are typically negligible in data centers. Conversely, the problem of supporting a responsive controller-to-controller interaction becomes of paramount importance for SDWANs, due to their geographical extension. Furthermore, SDWANs are based on an in-band control plan: the control packets and data packets share the same network infrastructure. Separation mechanisms are normally used (e.g., by defining one dedicated VLAN for control traffic and/or possibly exploiting priorities) to run on the same physical infrastructure two logical networks, one for the data and one for the SDN control messages.

In this paper, we provide the following novel contributions:

1) we evaluate the reaction time perceived at the switches when interacting with the controllers, due to the inter-controller control traffic, and we prove the relevant role of the adopted data-ownership model;
2) we validate the previous findings with traffic measurements on an operational SDWAN;
3) we discuss Pareto-optimal controller placements considering controller-to-switch and controller-to-controller delays for WAN topologies adopted in some real ISP networks;
4) we propose a low-complexity algorithm to find the approximated Pareto frontier in large networks.

The paper is organized as follows. In Sec. [II] we provide
an overview of distributed SDN architectures. We describe the interaction in the control plane, highlighting the role of the controller-to-controller communications. In Sec. III we define the data-ownership models and the controller placement problem. We propose an analytical model to evaluate the reaction time for the different data-ownership models and, to show its wide applicability, we apply it to a specific forwarding application in OpenDaylight. The model is experimentally validated in Sec. IV. In Sec. V we discuss the controller placement problem and present the numerical results obtained by optimizing the controller placement in realistic ISP topologies. To solve the optimal placement problem in large networks, in Sec. VI we propose an evolutionary algorithm and investigate its performance. In Sec. VII we discuss the related work. Finally, in Sec. VIII we draw our conclusions.

II. DISTRIBUTED SDN CONTROLLERS

Many architectures have been proposed to support distributed SDN controllers, to improve the performance and scalability of SDN networks and/or to ensure reliability. We concentrate on some specific architectural aspects only. For more details, the reader can refer to the bibliography cited in [1]. In distributed controllers, two control planes can be identified. First, the switch-to-controller plane, denoted as Sw-Ctr plane, supports the interaction between any switch and its controller (denoted as master controller) through the controller’s “southbound” interface. This interaction is usually devoted to issue data plane commands (e.g., through the OpenFlow (OF) protocol) and to configure and manage network switches (e.g. through OF-CONFIG or OVSDB protocols). Second, the controller-to-controller plane, denoted as Ctr-Ctr plane, permits the direct interaction among the controllers through the controller’s “east-west” interface. Indeed, the controllers exchange heart-beat messages to ensure liveness and to support resilience mechanisms. Controllers need also to synchronize the shared data structures to guarantee a consistent global network view.

Instead, the traffic in the Sw-Ctr plane mainly depends on the network application running on the controller. For example, for a reactive application, a packet-in message with a copy of the first packet of a new flow is sent from the switch to the controller, which replies usually with a flow-mod to install a flow-specific forwarding rule. After such reply, the following packets of the same flow can be directly forwarded by the switch to the destined port without interaction with the controller. As a consequence, the reactivity of the controller, defined as the latency perceived by the switch to install the forwarding rule for a new flow, is lower bounded by the round trip time between the switch and its master controller.

A. Data consistency models

The traffic on the Ctr-Ctr plane is instead crucial for the interactions occurring in the Sw-Ctr plane, and the controller reactivity as perceived by a switch depends on the local availability of the data necessary for the controller. We can identity two distinct operative models.

In a single data-ownership (SDO) model, a single controller (denoted as “data owner”) is responsible for the actual update of the data structure, and any read/write operations on the data structures performed by any controller must be forwarded to the data owner. In this case, the Ctr-Ctr plane plays a crucial role for the interactions occurring in the Sw-Ctr plane,
because some Sw-Ctr request messages (e.g., packet-in) trigger transactions with the data owner on the Ctr-Ctr plane. Thus, the perceived controller reactivity is also affected by the delay in the Ctr-Ctr plane. As discussed in Sec. II-A, this data-ownership model is currently adopted in ODL and ONOS, for all the strong-consistent data structures managed by Raft algorithm: a local copy of the main data structures is stored at each controller, but any read/write operation is always forwarded to the leader. With this centralized approach, data consistency is easily managed and the distributed nature of the data structures is exploited only during failures.

In a multiple data-ownership (MDO) model, each controller has a local copy of the data and can run locally read/write operations. A consensus algorithm distributes local updates to all the other controllers. This model has the advantage of decoupling the interaction in the Sw-Ctr plane from the one occurring in the Ctr-Ctr plane, thus improving the reactivity perceived by the switch. The main disadvantage is the introduction of possible update conflicts that must be solved with ad-hoc solutions and of possible temporary data state inconsistencies leading to network anomalies (e.g., forwarding loops) [4]. Thus, the model applies to generic eventual consistent data structures, as the ones managed by the anti-entropy algorithm in ONOS.

We now derive the reactivity for the two data-ownership models. For simplicity, we consider only the propagation delays of the physical links, and neglect all the processing times and the queuing delays due to network congestion.

A. Reactivity model for MDO model

In a MDO scenario, a generic event occurring at the switch (e.g. a miss in the flow table) generates a message (e.g., a packet-in) to its master controller, which processes the message locally and eventually sends back a control message to the switch (e.g., flow-mod or packet-out message). In the meanwhile, in an asynchronous way, the master controller advertises the update to all the other controllers. Thus, the reaction time of the controller perceived by the switch, defined as $T_R^{(m)}$, can be evaluated as follows:

Property 1: In a MDO scenario for distributed SDN controllers, the reaction time perceived at the switch is:

$$T_R^{(m)} = 2d_{sw-ctr}$$

being $d_{sw-ctr}$ the delay from the switch to its master controller.

B. Reactivity model for SDO model

In a SDO scenario, we assume the exchange of messages coherent with the detailed description of Raft algorithm available in [7] and devise a model to evaluate the reactivity of the controller as perceived by the switch. This analytical model, here obtained in a speculative way, will be later tailored to a specific ODL network application in Sec. III-C and experimentally validated in a real SDN WAN networking running ODL (see Sec. IV).

According to Raft implementation in ODL, the controller can operate as either unique leader or as one of the followers, for a specific data store (denoted “shard” in the following). As an example, Fig. 3 shows a general message exchange sequence in a cluster with 3 controllers (one leader and two followers), when an update event (e.g. packet-in message) for the shard is generated at some switch (S1 in the figure), which receives a response message from its controller due to the update (e.g. packet-out message). The arrows show the exchange of messages in both Sw-Ctr and Ctr-Ctr planes triggered by the update event; the number associated to each arrow shows the temporal sequence of each packet. We have now two cases.
In the first case, S1’s master controller is a follower for the shard (as depicted in Fig. 3). Thus, the switch sends the update event (message 1) to the master controller, which asks the leader to update the shard through a “Raft request” (message 2). Now the leader sends a “log replication” message to all its followers (message 3) and waits for the acknowledge from the majority of them (“log reply” in messages 4). Only at this point, the update is committed through a “log commit” (message 5) sent to all the followers. Thus, after receiving the commit message, S1’s master controller can process the update on the shard and generate the response event (message 6) to the switch.

In the second case, S1’s master controller is the leader for the shard. This case is identical to the previous one except for the “Raft request” message 2, now missing.

For both cases, the controller reaction time perceived by switch S1 is given by the time between the update event and the response event messages. Let \( d_{sw-ctr} \) be the communication delay between the switch and its master controller and \( d_{ctr-leader} \) the communication delay from the master controller and the leader (being null whenever the master is also leader). Assume a cluster of \( C \) controllers. Because of the majority-based selection, let \( d_{ctr*-leader} \) be the communication delay between the leader and the farthest follower belonging to the majority (i.e., corresponding to the \( \lceil (C/2) + 1 \rceil \)-th closest follower). Observing Fig. 3 the reaction time is obtained by summing twice \( d_{sw-ctr} \), twice \( d_{ctr-leader} \) (only in the first of the above cases) and twice \( d_{ctr*-leader} \). Thus, we can claim:

**Property 2:** In a SDO scenario (e.g., adopting Raft consensus algorithm) for distributed SDN controllers, the reaction time \( T_R^{(s)} \) perceived at the switch is:

\[
T_R^{(s)} = 2d_{sw-ctr} + 2d_{ctr-leader} + 2d_{ctr*-leader}
\]  

(2)

Thus, the reaction time is identical to the one for MDO model plus either 2 or 4 times the RTT between the controllers, when the master controller is either leader or follower of the shard, respectively. Notably, the delays between controllers may be dominant for large networks as SDWAN, as shown experimentally in Sec. IV.

**C. Reaction time for reactive forwarding in ODL**

To show the wide applicability of the SDO model devised in Sec. III-B and its practical relevance, we apply Property 2 to compute the flow setup time for the specific layer-2 forwarding application called “l2-switch” available in ODL, deployed on a generic topology. Notably, even if this analytical model is derived in a speculative way, in Sec. IV we will show that it is very accurate from experimental point of view, and thus its relevance is practical. The same methodology can be applied to analyze other applications, given the knowledge of their detailed behavior.

L2-switch application provides the default reactive forwarding capabilities and mimics the learning/forwarding mechanism at layer 2 of standard Ethernet switches. Anytime a new flow enters the first switch of the network, the corresponding ARP-request is flooded to the destination, and only when the ARP-reply is generated, the controller installs a forwarding rule at MAC layer in all the switches involved in the path from the source to the destination, and vice versa. The association of a MAC address to the switch port, needed for the learning phase, is distributed to the other controllers using Raft algorithm.

Assume a generic topology as shown in Fig. 4 connecting source host H1 to destination host H2, with every switch \( s \) attached to its master controller (denoted as \( c(s) \)) which can be either a follower or a leader (denoted as \( L \)) within the cluster. We assume initially empty flow tables in all the switches. At the beginning, the first ARP-request corresponding to a new flow from H1 is flooded in the whole network (avoiding loops.
by precomputing a spanning tree on the topology). Anytime the ARP packet is received at a switch, a packet-in is generated and the association (MAC source address, ingress port, switch identifier) is stored in the shared data store, in order to mimic the standard learning process. This means that at each switch, along the path from the source to the destination, a latency is experienced according to (2) of Property 3. When the ARP-request reaches the destination, H2 sends back an ARP-reply which generates a packet-in from the last switch (denoted as s′) to the controller. This event generates another update since the controller learns the port of s′ at which H2 is connected. Only at this point, the controller installs a flow rule across all the switches in the source-destination path and then the ARP-reply is switched back to the source. Thus the flow setup time can be evaluated as ARP reaction time \( t_{c,ARP} \), defined as the time between the sent ARP-request and the received ARP-reply, both evaluated at the source host. Let \( d_{i,j} \) be the propagation delay between nodes \( i \) and \( j \). Let \( P \) be the list of all the nodes involved in routing path from \( H_1 \) to \( H_2 \), in which the last switch \( s' \) appears twice. Thus, the total number of updates within a flow is |\( P \)|. We can claim:

**Property 3:** In OpenDaylight (ODL) running l2-switch application, the flow setup time (ARP reaction time) can be computed as

\[
t_{c,ARP} = 2d_{H1,H2} + \sum_{s \in P} (2d_{s,c(s)} + 2d_{c(s),L}) + 2|\mathcal{P}|d_{cmt-follower} + |\mathcal{P}|t_c \tag{3}
\]

Indeed, the first term in (3) represents the delay to send the ARP request and reply along the routing path, the second term represents the delay occurring for all the switches along the path (the final switch \( s' \) is double counted) due to the packet-in and the packet-out/flow-mod \( (2d_{s,c(s)} + 2d_{c(s),L}) \) and the Raft-log commit \( 2d_{c(s),L} \), the third term represents the delay to get the acknowledgement from the majority for each of the updates, and the fourth term represents the computation time for each update at the controller (assuming to be constant and equal to \( t_c \)).

IV. EXPERIMENTAL VALIDATION OF THE SINGLE DATA-OWNERSHIP (SDO) MODEL

We validated the analytical model proposed in Sec. III-B on a real and operational network. Specifically, we run a cluster of OpenDaylight (Helium SR3 release) controllers running the default Simple Forwarding Application. We run our experiments in the JOLNet, which is an experimental SDN network deployed by Telecom Italia Mobile (the major telecom operator in Italy). JOLNet is an Openflow-based SDWAN, with 7 nodes spread across the whole Italy, covering Turin, Milan, Trento, Venice, Pisa and Catania. Each node is equipped with an OF switch and a compute node. The compute node is a server deploying virtual machines (VMs), orchestrated by OpenStack. Network virtualization is achieved through FlowVisor and the logical topology among the OF switches is fully connected.

**A. Methodology for the validation**

Due to the limited number of nodes in the JOLNet and the limited flexibility in terms of topology, we augmented the topology with an emulated network running on Mininet.

In one available compute node. We adopted the linear network topology of Fig. 5 with a variable number of nodes (from 3 to 36) and with one host attached at each switch. We generated ICMP traffic using the ping command among the different hosts. We run a single controller cluster with multiple ODL instances running in different nodes of the JOLNet, in order to distribute geographically the controllers across Italy. The controllers instances and Mininet run individually on single VMs for a flexible placement across the nodes. Thanks to the large physical extension of the network, we could experiment a large variety of scenarios, e.g. with large Sw-Ctr delays (when the VM of the master controller was located in a far compute node from the switch node) and/or large Ctr-Ctr delays (when the VMs of the controller instances were located in nodes far one from each other). By selecting the master controller of the switches, we were able to change the data owner of the shared data structure within the cluster. We evaluated the flow setup time in ODL of the Simple Forwarding Application in a cluster of 3 controllers.

We measured the flow setup time \( t_c \) as defined in Sec. III-C. As a reminder, it is the delay perceived by a flow at the first switch, namely the latency between the time when the first switch sends the packet-in message to the controller and the time it receives back the packet-out/flow-mod messages. This latency was measured by comparing the timestamps of the packets obtained by using Wireshark as network sniffer at the Mininet interface towards the controllers.

As first step to validate Property 3 we evaluated the RTT among each pair of nodes in JOLNet and thus we were able to compute the delay between any pair of nodes \( i \) and \( j \) as \( d_{i,j} = \text{RTT}_{i,j}/2 \), required to apply (3). The experiments reported in the following refer to the scenarios using 3 JOLNet nodes, namely Turin, Milan and Pisa, to deploy the VMs. The RTT between these nodes are shown in Fig. 6.

As second step, in order to effectively validate Property 3, we performed multiple measurements (typically, 100) by clearing the whole forwarding tables and restarting the controllers at each run. We evaluated the 95% confidence intervals of the measurements. The accuracy of the measurements were computed according to the formula: \( \lambda = I_{95}/(2\mu) \) where \( I_{95} \)
TABLE I: Placement of the VMs for the experimented scenarios. “L”: leader controller. “F1”, “F2”: follower controllers. “Net”: Mininet.

| Scenario | Turin VMs | Milan VMs | Pisa VMs |
|----------|-----------|-----------|----------|
| TT       | Net, L, F1, F2 | - | - |
| TMC      | Net, F1 | L, F2 | - |
| TMF      | Net | L, F1, F2 | - |
| TPC      | Net, F1 | - | L, F2 |
| TPF      | Net | - | L, F1, F2 |

TABLE II: Input parameters for the model, accuracy of measurements and relative error of the model

| Scenario | $d_{sw-cr}$ | $d_{ctr-ctr}$ | $t_c$ | Experimental accuracy ($\lambda$) | Model error ($\delta$) |
|----------|-------------|---------------|-------|---------------------------------|------------------------|
| TT       | 0.25 ms     | 0.25 ms       | 20 ms | 1.2% - 2.7%                     | 3.2%                   |
| TMC      | 0.25 ms     | 2.0 ms        | 20 ms | 0.7% - 3.9%                     | 5.2%                   |
| TMF      | 2.0 ms      | 0.25 ms       | 20 ms | 0.6% - 3.6%                     | 5.1%                   |
| TPC      | 0.25 ms     | 66 ms         | 20 ms | 0.3% - 1.3%                     | 9.2%                   |
| TPF      | 66 ms       | 0.25 ms       | 20 ms | 0.6% - 2.3%                     | 0.5%                   |

represents the width of the 95% confidence interval and $\bar{\mu}$ the average measure. For each scenario and topology, the relative error of the model was computed as: $\delta = |\bar{M_i} - \bar{T_i}|/|\bar{T_i}|$ where $\bar{M_i}$ is the average flow setup time according to the experiments and $\bar{T_i}$ is the flow setup time according to Property 3.

We considered different scenarios, depending on the placement of the controllers and of Mininet across the different JOLNet nodes. We refer to the physical distance between the network nodes (emulated with Mininet) and the controllers (followers and leader) as “close” when the corresponding VMs are running in the same node, and “far” on remote nodes. Table I lists all the experimented scenarios, discussed in the following section. In our cluster of 3 ODL controllers, the leader controller is denoted as “L” and the two followers are denoted as “F1” and “F2”. Controller F1 is set to be master controller for all the switches in Mininet network. “Net” represents Mininet emulated network.

B. Experimental results

Table II summarizes the input parameters that have been used in (3), and shows also the final experimental results in terms of the accuracy of the measured values and the model error. The input parameters have been obtained either by the measurements in Fig. 6 when the VMs were located in different nodes, or by following the steps explained below. In more detail:

- **Scenario TT (Turin-Turin):** We run the VMs of all the controllers and of Mininet in the same node, in order to evaluate the baseline latency due to the controller processing time and to the communication overhead (through the local virtual interfaces). First, we measured the communication delay between VMs, due to the local hypervisor running the different VMs, using ping command. We measured 0.5 ms, thus the delay between the network and the controller, and between controllers was assumed to be 0.25 ms. By running Mininet and measuring the flow setup time, we estimated an average processing latency of 20 ms, used as reference for all the other experiments. We run many experiments varying $n_{sw}$ in the interval [3, 36] and observed an average relative error 3.2% of the model expressed by (3) with respect to experimental data.

- **Scenario TMC (Turin-Milan-Close):** In this scenario, leader L and Follower F2 of the cluster are located in Milan, whereas follower F1 is co-located with the network in Turin node, thus all OF switches are close to their master controllers.

Fig. 6: The average RTT between the JOLNet nodes relevant for the experiments

Fig. 7: Experimental results with the VMs running either in Turin or Milan

Fig. 8: Experimental results with the VMs running either in Turin or Pisa
The dominant term in \( \delta \) is the delay between controllers, equal to 4/2 = 2 ms. Fig. 7 shows the average flow setup time computed according to \( \delta \) and the one measured. According to Table I, the experimental results were quite stable for the different values of nodes. The measured value was quite close to the theoretical one, with a relative error 5.2%. Interestingly, the flow setup time in absolute values is always larger than 100 ms and can reach also 1.2 s when the network is quite large. Notably, this is mainly due to the interaction between the master controller and the leader controller.

- **Scenario TMF (Turin-Milan-Far):** All the controllers are located in Milan, thus all OF switches are far from their master controller. Thus, now the dominant term in \( \delta \) is the delay from the switch to the controller (2 ms). Fig. 7 compares the measured flow setup time with the theoretical ones. Now the relative error of the model is 5.1%. As in the previous case, the theoretical flow setup time in absolute values is always larger than 100 ms and can reach also 1.2 s when the network is quite large. Notably, this is mainly due to the interaction between the master controller and the leader controller.

- **Scenario TPC (Turin-Pisa-Close):** All OF switches and their master controller F1 are located in Turin, whereas the leader controller and the other controller are located in Pisa. The dominant term is the delay between controllers (132/2 = 66 ms). As shown in Fig. 8, the measured value approaches the theoretical value with a relative error of 9.2%. The measured delays can range from 2 to 12 s as we vary the number of switches. These surprising huge delays are due to the interaction between leader L and follower F1.

- **Scenario TPF (Turin-Pisa-Far):** All the controllers are located in Pisa with the network still in Turin. Due to the large delay between Turin and Pisa (66 ms), the dominant term in \( \delta \) is the delay between follower F1 and the network. In all the results shown in Fig. 8, the relative error (0.5%) of the model with respect to the theoretical value is very small. Also in this case, the flow setup time is huge in absolute terms (up to 6 s), due to the large delay between the network and the controllers.

In summary, our experimental results show clearly that the delays introduced by inter-controller communications can be very large and the great accuracy of our model with respect to experimental data shows exactly the reason for it (i.e. the interaction between controllers due to the RAFT consensus algorithm).

V. THE CONTROLLER PLACEMENT PROBLEM

The Sw-Ctr delays (between the switches and their master controller) and Ctr-Ctr delays (between controllers) have a direct impact on the reactivity of the controller perceived at switch level, as highlighted in Properties [12]. This observation is particularly relevant for large networks, where propagation delays are not negligible. Thus the placement of the controllers in the network is of paramount importance and implies different tradeoffs between Sw-Ctr delays and Ctr-Ctr delays.

Let \( N \) be the total number of switches in the network and \( C \) be the total number of controllers to place in the topology. The output of any placement algorithm can be represented by the vector denoted as placement configuration:

\[
\pi = [\pi_c]_{c=1}^C
\]

where \( \pi_c \in \{1, \ldots, N\} \) identifies the switch at which controller \( c \) is connected to. We assume that all the controllers are connected to distinct switches (equivalently, two controllers cannot be connected to the same switch), i.e. \( \pi_c \neq \pi_{c'} \) for any \( c \neq c' \). Let \( \Omega \subset \{1, 2, \ldots, N\}^C \) be the set of all placement configurations; thus, the total number of possible placements is

\[
|\Omega| = \binom{N}{C} \quad (5)
\]

The optimal controller placement problem consists of finding \( \pi \in \Omega \) such that some cost function (e.g. the maximum or average Sw-Ctr delay) is minimized and it is in general a NP-hard problem for a generic graph, as discussed in [13].

A. Results on the placement of controllers in ISP networks

To explore all the possible tradeoffs on the Sw-Ctr and Ctr-Ctr planes, we adopt an optimal algorithm (denoted EXA-PLACE) to enumerate exhaustively all possible controller placements and get all Pareto-optimal placements \( x^* \) and thus the corresponding Pareto-optimal frontier. For small/moderate values of network nodes \( N \) and number of controllers \( C \), as considered in this section, the number of possible placements, evaluated in [5], is not so large and thus EXA-PLACE is computationally feasible. In Sec. VII we will instead devise an approximated algorithm to find the Pareto frontier for large networks and/or large number of controllers.

The network topology is described by a weighted graph where each node represents a switch; each edge represents the physical connection between the corresponding switches and is associated with a latency value. Each controller is connected directly to a switch. We assume that the master controller of a switch is the one with the minimum Sw-Ctr delay. We also assume that all the communications are routed along the shortest path.

Coherently with previous work [14], we have considered specifically the topology available in the Internet topology zoo website [15]. This repository collects around 250 network topologies of ISPs, at POP level. For each ISP, the repository provides the network graph, with each node (i.e. switch) labeled with its geographical coordinates. From these, we computed the propagation delay between the nodes and associated it as latency of the corresponding edge. For any given controller placement, we evaluate both the Sw-Ctr delay (as the average delay between the switches and their master controllers) and the Ctr-Ctr delay (as the average delay among controllers).

B. Tradeoff between Sw-Ctr and Ctr-Ctr delay

We report only the analysis of three different ISP: (1) HighWinds, a world-wide network with 18 nodes, (2) Abilene, a USA-wide network with 11 nodes, (3) York, a UK-wide network with 23 nodes. Very similar results have been obtained for other topologies.

\footnote{When considering two performance metrics \( x \) and \( y \) to minimize, a solution \((x_p, y_p)\) is Pareto optimal if does not exist any other configuration \((x', y')\) dominating it, i.e. better in terms of both metrics; thus, it cannot be that \( x' \leq x_p \) and \( y' \leq y_p \). The set of all Pareto-optimal solutions denotes the Pareto-optimal frontier.}
Fig. 9: Delay tradeoffs in HighWinds network

Fig. 10: Delay tradeoffs in Abilene network

Fig. 11: Delay tradeoffs in York network

Fig. 12: Delay tradeoffs in HighWinds network with 4 controllers

Fig. 13: Delay tradeoffs in HighWinds network with 5 controllers

Figs. 9-11 show the scatter plot with the Sw-Ctr and Ctr-Ctr delays achievable by all possible placements of 3 controllers, for the three ISPs, respectively. In total, all the possible \((18 \choose 3) = 816\), \((11 \choose 3) = 165\) and \((23 \choose 3) = 1771\) different placements are shown; the corresponding Pareto-optimal placements are also highlighted. As observed when discussing the toy example of Figs. 1-2, high (or small) Sw-Ctr delays imply small (or high) Ctr-Ctr delays, respectively. The graphs show the large variety of Pareto-optimal placements. We denote by \(P_1\) the Pareto point with the minimum Sw-Ctr delay (i.e. the most right-low point), and by \(P_2\) the one with the minimum Ctr-Ctr delay (i.e. the most left-high point). Table III shows the delay reduction when we compare \(P_1\) with \(P_2\) and can be read as follows: if we allow the Sw-Ctr delay to increase by the factor shown in the second column, then the Ctr-Ctr delay decreases by the factor shown in the third column. Notably, in HighWinds if we allow the Sw-Ctr delay to increase by 6.0 times, then the Ctr-Ctr delay decreases by 34.8 times, which is very high gain. Also in York the gain is relevant, since an increase in the Sw-Ctr delay by 2.9 times corresponds to a Ctr-Ctr delay reduction.
TABLE III: Delay reductions for the extreme Pareto-optimal placements

| ISP       | Sw-Ctr delay in P1 | Ctr-Ctr delay in P1 | Sw-Ctr delay in P2 | Ctr-Ctr delay in P2 |
|-----------|---------------------|---------------------|---------------------|---------------------|
| HighWinds | 2.4                 | 15.0                | 2.4                 | 15.0                |
| Abilene   | 2.9                 | 4.9                 | 2.9                 | 4.9                 |
| York      | 5.5                 | 15.0                | 5.5                 | 15.0                |

![Graph](image)

Fig. 14: Ctr-Ctr reduction factor when doubling the Sw-Ctr delay of 15.0 times.

We can generalize these findings: Ctr-Ctr delays corresponding to Pareto points vary much more than Sw-Ctr delays in a generic network. Indeed, Ctr-Ctr delays are by construction between a minimum of 1-2 hops (when all the controllers are at the closest distance) and the maximum equal to the diameter of the network. The gains for the Sw-Ctr delays are lower, since the availability of multiple controllers decreases the maximum distance to reach the master controller from a switch. We can conclude that larger Sw-Ctr delays with respect to the minimum ones are well compensated by much smaller Ctr-Ctr delays. This highlights the relevant role of the proper design of the Ctr-Ctr plane in SDN networks.

Figs. 12 and 13 show the delay tradeoff achievable for 4 and 5 controllers. Qualitatively the performance confirm our findings above for 3 controllers, even if now the absolute values of the delays for Pareto-optimal points are smaller, due to the larger number of controllers.

C. Comparison among topologies

We now analyze the results obtained for different topologies. To highlight the difference with respect to a standard placement problem that minimizes the Sw-Ctr delay, we define a new metric that evaluates the reduction in Ctr-Ctr delay whenever we accept to double the Sw-Ctr delay. Let $P' = (d_{sc}', d_{cc}')$ be the Pareto placement that minimizes the average delay, where $d_{sc}'$ and $d_{cc}'$ are the corresponding Sw-Ctr and Ctr-Ctr delays. Consider now the specific Pareto placement $P'' = (d_{sc}^*, d_{cc}^*)$ with the minimum Ctr-Ctr delay such that the Sw-Ctr delay increases at most by a factor 2, i.e. $d_{sc}^* \leq 2d_{sc}$. We define the Ctr-Ctr reduction factor as the ratio $d_{cc}' / d_{cc}^*$, which evaluates the relative reduction of Ctr-Ctr delay whenever we accept to double the Sw-Ctr delay.

Figs. 14 reports the Ctr-Ctr reduction factor for different network topologies obtained for 3 and 4 controllers. The reduction is larger for 3 controllers, since the average distance between controllers is larger by construction. The gain for 3 controllers depends heavily on the particular topology. For the first 2 topologies, the growth in the Sw-Ctr delay is not compensated by the same reduction in Ctr-Ctr delay. Instead, for the remaining 8 topologies, the reduction in the Ctr-Ctr delay is much higher, achieving also a factor 6; in this case, increasing a little the Sw-Ctr delay has a very strong beneficial effect on the Ctr-Ctr delay.

It is interesting to note that in some cases the reduction decreases from 3 to 4 controllers (as in Highwinds and HiberniaCanada). It can be shown that this is actually due to the peculiar clustered topology of the two ISPs, that are similar to a single star connected to one or two nodes very far (e.g. in Highwinds, we have one star-like cluster in North America and very few nodes in South America and in Europe).

D. Reaction time for SDO and MDO models

We investigate the reaction times achievable for different data-ownership models, based on Properties 1 and 2. Given a controller placement, we study the effect of selecting the data owner among the controllers on the perceived controller reactivity.

In Figs. 15-17 we report the scatter plots of the average reaction times for the SDO and the MDO models when considering all possible controllers’ placements and all possible selections for the data owner, in the case of 3 controllers. Each controller placement appears with 3 points aligned horizontally, one for each data owner, since the data owner selection does not affect the MDO reaction time. In the plots we have highlighted the placements with the minimum reaction time according to the SDO and MDO models. By construction, the minimum reaction time for the MDO is always smaller.
than the one for SDO model. From these results, the optimal placements are shown to be very different for the two data-ownership models and this fact motivates the need for a careful choice of the controllers placement and the owner, based on the adopted data-ownership model.

To highlight the role of the proper selection of the data owner for the SDO model, in Figs. 18-20 we investigate the benefit achievable when considering the best data owner among the 3 available controllers, for the three ISPs under consideration. Assume that a given controller placement corresponds to three values of reaction times: \(d_1, d_2\) and \(d_3\), sorted in increasing order. The minimum reduction factor is defined as \(d_2/d_1\) and the maximum reduction factor as \(d_3/d_1\). We plot the delay reduction factor due to the optimal choice of the data owner, for any possible placement. For the sake of readability, the placements have been sorted in decreasing order of minimum reduction factor. Figs. 18-20 show that a
careful choice of the data owner in the SDO model decreases the reaction time by a factor around 2 and 4.

These results show that the selection of the data owner in the SDO model has the largest impact on the perceived performance of the controller, and can be easily optimally solved by considering all the possible $C$ cases, after having fixed the controller placement.

VI. A EVOLUTIONARY ALGORITHM TO FIND PARETO-OPTIMAL PLACEMENT FOR LARGE NETWORKS

In this section, we present an evolutionary algorithm, denoted as EVO-PLACE, to compute the Pareto optimal controller placements without performing an exhaustive search, as pursued in Sec. V-A since not feasible for large networks. Our algorithm continuously optimizes both average Ctr-Ctr delay and Sw-Ctr delay through controller positions perturbation in each iteration. We run our algorithm on different network topologies with varying number of controllers, and compare the results with both the optimal Pareto frontier and the one obtained by a pure random placement algorithm. Thus, we show that our algorithm can locate the Pareto optimal controller placements with high accuracy and with a small complexity.

A. The algorithm for controller placement

The basic idea of our algorithm is to discover new non-dominated solutions by perturbing the actual set of Pareto solutions for the controller placement. Specifically, starting from a given controller placement in the network, we may get a new controller placement with better Ctr-Ctr delay by putting the controllers closer, and a new controller placement with better Sw-Ctr delay by distributing the controllers more evenly in the network. By continuously perform such perturbation, we achieve a good approximation of the Pareto frontier for the placement problem.

We start by defining the pseudocode of a basic randomized algorithm, denoted as RND-PLACE and reported in Algorithm 1 able to find a set of Pareto solutions just using a random sampling. The input parameters are the number of controllers $C$, the number of nodes $N$ and the number of iterations $i_{\text{max}}$. We assume that function RANDOM-PERMUTATION($N, C$) provides the first $C$ elements of a random permutation of size $N$, with $C \in [1, N]$; its complexity is $O(C)$ thanks to the classical Knuth shuffle algorithm. Let $P$ be the current set of all Pareto (i.e. non-dominated) solutions. At each iteration, a new placement is generated (step 4). Now function ADD-PRUNE eventually adds $\pi$ to $P$. More precisely, if $\pi$ is dominated by any Pareto solution in $P$, then it not added to $P$ since it is not Pareto (step 10). Instead, if any current solution $p \in P$ is dominated by $\pi$, then it is removed (step 12) and then $\pi$ is added as new Pareto solution (step 13). ADD-PRUNE returns true if $\pi$ was added successfully, otherwise it returns false.

The set $P$ returned by RND-PLACE at the end of $i_{\text{max}}$ iterations collects all the Pareto placements found by the procedure, and corresponds to an approximation of the optimal Pareto frontier for the controller placement problem. The randomized approach is simple but quite inefficient in terms of complexity, since it takes $O(|\Omega| \log |\Omega|)$ iterations (thanks to the well known results about the coupon collector problem) to approach the exhaustive search and find the optimal Pareto placements.

We have modified RND-PLACE to exploit an evolutionary approach to boost the efficiency of the algorithm. Algorithm 2 reports the pseudocode of our proposed EVO-PLACE. At each iteration, the algorithm selects a random placement $\pi$ (step 4) and try to add to $P$, as in RND-PLACE. If the addition is successful (i.e. $\pi$ is Pareto), then $\pi$ is perturbed (step 7) and the new placement $\pi'$ is eventually added to $P$ (step 8). The loop for the perturbation ends when the newly perturbed solution cannot be added to $P$, since dominated by other solutions (steps 9, 10). The perturbation phase is described by DECREASE-CTR-DELAY, whose pseudocode is reported in Algorithm 3. DECREASE-CTR-CTR-DELAY perturb the given placement solution $\pi$ by decreasing the Ctr-Ctr delay. The intuition is to move the farthest controller closer to the others. Indeed, in steps 2, 3 the average distance is computed for each controller to all the others (actually, we omit the division by $C-1$ since useless for the following steps). We define $d_{ij}$ as the minimum delay from node $i$ to $j$, based on the propagation delays in the network topology. Now we choose $c'$ as the controller with the maximum average delay towards the others (step 8) and find $c''$ as the closest controller to $c'$ (step 9). Now we move $c'$ one hop towards $c''$ (steps 6, 7) along the shortest path from $c'$ to $c''$; note that the check that $c''$ is at least 2 hops far from $c'$ guarantees that the movement is possible. As result, our approach tends to decrease the average Ctr-Ctr distance most of the times, but does not guarantee this happening always.

Algorithm 1 Random algorithm for finding Pareto controller placements

```
1: procedure RND-PLACE($C, N, i_{\text{max}}$)
2:     $P = \emptyset$ \Comment{Init the set of Pareto solutions}
3:     for $i = 1 \rightarrow i_{\text{max}}$ do \Comment{For $i_{\text{max}}$ iterations}
4:         $\pi = \text{RANDOM-PERMUTATION}(N, C)$
5:         ADD-PRUNE($P, \pi$)
6:     return $P$
7: procedure ADD-PRUNE($P, \pi$)
8:     for all $p \in P$ do
9:         if $\pi$ is dominated by $p$ then
10:             return false \Comment{Unsuccessful addition of $\pi$}
11:         if $p$ is dominated by $\pi$ then
12:             $P = P \setminus \{p\}$ \Comment{Remove $p$}
13:     $P = P \cup \{\pi\}$ \Comment{Add $\pi$ since not dominated}
14: return true \Comment{Successful addition of $\pi$}
```

B. Results

We have compared the performance of EXA-PLACE, RND-PLACE and EVO-PLACE on many different networks with varying number of controllers. In Fig. 21 we show the results for the Garr network, a nation-wide Italian ISP, taken from [13], with 35 nodes, for the case of 3 controllers. Thus, $N = 35, C = 3$ and thus $(\frac{N}{C}) = 6,545$ are all the possible placements, drawn in the graph and evaluated by the exhaustive search EXA-PLACE. The corresponding Pareto points represent the optimal Pareto frontier, used as a reference for the frontiers
In order to evaluate in a quantitative way the “distance” between the optimal Pareto frontier computed by EXA-PLACE and the approximated ones obtained by RND-PLACE and EVO-PLACE, we define two error indexes, as depicted in Fig. 22, derived from classical volume based performance indexes for Pareto sets [10]: (i) the average Sw-Ctr error, computed as the average vertical distance between the optimal Pareto frontier and the approximated Pareto frontier, (ii) the average Ctr-Ctr error, computed as the average horizontal distance between the two frontiers. Fig. 23 shows the behavior of the two errors in function of the number of iterations, in the same scenario considered in Fig. 21. Each experiment, for a given number of iterations, was repeated multiple times to get an accurate estimation of the error. After 10 iterations, corresponding to a sampling ratio 10/6, 545 = 0.15%, RND-PLACE shows an average error of 1.6 ms for the Ctr-Ctr delay whereas 0.8 ms for the Sw-Ctr delay. Given the same number of iterations, EVO-PLACE obtains a reduction in both delays by a factor 4. After 50 iterations (i.e. almost 1% sampling ratio), EVO-PLACE reaches a stable error, around 0.1 and 0.2 ms for the two delays, thus approximating quite well the optimal Pareto region. When the number of iterations is large, the errors in the Pareto frontier obtained by RND-PLACE is more than twice than EVO-PLACE. This fact shows that the boost in performance due to the DECREASE-CTR-CTR-DELAY procedure is very effective.

We extended our investigation to other larger topologies, for which the approximated approach is much faster than the exhaustive search. Figs. 24 and 25 show the errors in...
the Pareto frontiers obtained for China-Telecom and ITC-Deltacom networks, respectively, taken from [13]. In China-Telecom, (38 nodes) RND-PLACE with 10 iterations achieve errors of 1.2 and 0.6 ms, respectively, and both Sw-Ctr and Ctr-Ctr delays are reduced by a factor 2 thanks to EVO-PLACE. This reduction factor remains quite constant also for larger number of iterations. Similarly to Garr network, around 1% of sampling ratio EVO-PLACE tends to reach the minimum error.

Fig. 25 shows the errors for ITC-Deltacom network, which is a large USA ISP with 100 nodes. In this case, after only 50 iterations (corresponding to a very small sampling ratio) EVO-PLACE reaches the minimum error, which is still 2× better than RND-PLACE.

We have also evaluated the scenario with Colt-Telecom from [15], an Europe-wide ISP covering 149 nodes, in the case of 10 controllers. In this scenario EXA-PLACE cannot run since the total number of possible placements is larger than 10^{15} and thus we cannot evaluate the average errors with respect to the optimal Pareto points. We instead observe that EVO-PLACE is always outperforming RND-PLACE by reducing the average Sw-Crt and Ctr-Ctr delays of 0.25 – 1 ms.

In conclusion, for all the scenarios we investigated, we were able to observe a better Pareto frontier obtained by EVO-PLACE with respect to RND-PLACE, given the same number of iterations and thus the same computation complexity. Thus, the evolutionary approach adopted in EVO-PLACE appears efficient in finding the Pareto placements for a given network topology, especially when the network is large and an exhaustive approach is not feasible anymore.

VII. RELATED WORK

The work in [17] emphasizes the importance of the network state consistency, and indicates that inconsistent network states degrade the performance of network applications. Thus, [17] motivates our work, since we devise the controller placement problem to target small Ctr-Ctr delays in the MDO model, thus improving the resilience of the network to possible state inconsistencies between controllers.

Many works address the control placement problem in SDN, but with slightly different objectives. The works [18, 19] target fault tolerance, whereas [20] aims at balancing the load on the controllers. Both [14, 21] focus on the optimal controller placement by considering only the minimization of Sw-Ctr delays (average or maximum). Differently from us, they neglect completely the interaction among controllers and thus the Ctr-Ctr delays. In the case of SDO model, [14, 21] neglects the relevant role of the data owner. In the case of MDO, we have shown in Sec. V-D that by relaxing the minimum switch-to-controller delay target, it is possible to significantly reduce the Ctr-Ctr delays and improve the convergence to a consistent network state.

Similarly to our approach, [22, 23] consider the possible Pareto optimal controllers’ placements under a variety of performance and resilience factors, as controller failure tolerance, network disruption, load balancing and Ctr-Ctr delays. Their main contribution is the algorithm to find the Pareto placements, not the analysis of the structure of all the Pareto optimal solutions, as also considered in our work. Finally, [24] provides a general mathematical framework to compute the optimal controllers’ placement, under generic cost functions, but it neglects the role of Ctr-Ctr delays.

VIII. CONCLUSIONS

We considered a distributed architecture of SDN controllers, with an in-band control plane. We investigated the performance issues related to the placement of the controllers across the network nodes. Differently from previous work, we highlighted the importance of the interaction among the controllers in the placement problem. We identified two possible models for the shared data structures: the single and the multiple data-ownership models, which are both implemented in state-of-art controllers. We evaluated analytically the controllers reactivity as perceived by the switches for the two models, and showed the accuracy of our models in a SDWAN. We studied the optimal controllers placement problem taking into account all the communications in the control plane (from the switches to the controllers, and among the controllers). We computed the optimal Pareto frontier for some realistic ISP
topologies. We also proposed a new evolutionary algorithm to compute such frontier for large networks. Based on our numerical results, the choice of the placement of the specific controller with the role of data owner appears of paramount importance for the single data-ownership (SDO) model, since the reactivity of the controller depends heavily on the delay between the controllers and the leader controller. For the multiple data-ownership (MDO) model, we studied the possible tradeoffs between controller reactivity and convergence time to reach a consistent view of the network state among the controllers.

We believe that our investigation provides a solid methodology to design the network supporting the control plane in large networks, as in the scenario of SDWANs.

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