Alviu: An Intent-Based SD-WAN Orchestrator of Network Slices for Enterprise Networks

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***Abstract*—The introduction of the Software-Defined Networking paradigm for the operation, administration and management of WAN environments, known as SD-WAN, is becoming increasingly popular due to the clear advantages that this technology provides, such as the reduction of CAPEX and OPEX related to the networking infrastructure or the flexibility provided by the development and deployment of network applications regardless of the underlying infrastructure. However, there is still a lack of solutions for enterprise networks, without carrying a substantial increase in cost, adapted to their daily reality, in which the WAN can be split in several domains, each of them possibly managed by different operators and based on different technologies and protocols. As a result, today it is not possible to have a complete solution for SD-WAN that covers all domains, reducing its scope to a single set of domains which may interact with other external domains. To address this issue, this paper presents Alviu, a SD-WAN network orchestrator based on open-source technologies that assures end-to-end network slicing to managed enterprise and academic networks thanks to a dynamic intent-based configuration of the different elements of the managed network. In addition to positioning Alviu in the current state of the art and detailing its architecture, we also evaluate Alviu's operation in a testbed that emulates the interconnection between a set of SD-WAN domains with are also connected to other external domains based on legacy routing protocols, assessing the deployment time depending on the domains present in the complete network.**

Keywords— Intent-based networking, SD-WAN, SDN orchestration, Network slicing, Open source.

I. Introduction

The management and operation of traditional Wide Area Networks (WAN) are limited by two important factors: (i) cost and (ii) flexibility. Firstly, legacy WAN architectures are built using expensive and specialized vendor equipment. Secondly, as WAN equipment is forced to take control decisions based only on local information, it is difficult to perform global changes in the network configuration accurately, fast and dynamically, thus making legacy WAN architectures rigid and static. Furthermore, the flexibility is also limited in terms of adding new functionality to the WAN deployments, since they are limited to the capabilities provided by specialized network equipment.

One of the technologies that tries to overcome these limitations is Software-Defined Networking (SDN), so that the implementation of this paradigm in WAN architectures (*i.e.*, SD-WAN) is meant to be a potential enabler to facilitate the automation of network configurations and, eventually, fully program the network [1]. However, the networking industry has not yet seen widespread adoption of the SDN paradigm in the WAN [2], which does not mean that SD-WAN solutions are completely rejected in enterprise networks, but implies that they may have to coexist with legacy WAN networks, whose control plane is mostly based on routing protocols used in both intra-domain (*e.g.*, OSPF) or inter-domain (*e.g.*, BGP) routing.

In this way, a desirable SD-WAN solution for enterprises should be able to understand and learn from these legacy routing protocols used in domains that are external to the SD-WAN domain, in order to correctly forward the traffic between the SD-WAN domain (which acts as a transit network) and the legacy domains that are present on the SD-WAN network's edge. Furthermore, taking advantage of the benefits of SDN and network virtualization, a flexible management can also be applied to WAN traffic to meet particular quality of service (QoS) and service level agreement (SLA) requirements, introducing the concept of network slicing for this purpose. Nevertheless, this niche market is fully dominated by proprietary solutions, with hardly any competitive open-source solutions [3], causing considerable cost increases that are, in fact, contrary to the SDN philosophy.

To fill this empty space, this paper presents Alviu [4], a flexible, resilient and Cloud-native SD-WAN orchestration solution for enterprise and academic networks purely based on open-source tools[1], using ONOS as SDN controller [5]. Alviu's main novelty is that it brings together, with the support of open-source tools, a set of technologies and paradigms (*e.g.*, SD-WAN or intent-based networking) that enable the control and orchestration of pure SDN-based network domains, rather than software-driven networks (mostly used by current commercial solutions). Thus, Alviu is compatible with any Linux server or white-box switch that implement OpenFlow, avoiding the risk of vendor lock-in through the support of commodity networking equipment. This contributes to reducing the cost of network equipment and operational expenses while abstracting the complexity of the underlying physical and Cloud infrastructure.

The rest of the paper is organized as follows:

- Section II presents the state of the art of the key concepts that are present in Alviu's core, including orchestration solutions for SD-WAN scenarios, the intent-based networking paradigm and the interaction with legacy WAN networks.
- Section III details Alviu's modular architecture, designed to offer a secure, easy-to-manage and centralized control over the managed SD-WAN domains.
- Section IV shows a performance evaluation to evaluate the intent deployment time, depending on the number of SDN domains to be managed, verifying that the system is able to handle a higher number of SDN domains without saturating.
- Finally, Section V concludes and presents our future work.

II. Background and related work

According to [6], practically all the global IT leaders have already deployed SD-WAN or expect to deploy it within 24 months to automate the network infrastructure. Given its increasing popularity, several publications from the academia and various business solutions have been introducing a set of novel techniques within SD-WAN scope to strengthen its capabilities. This section intends to review the following state-of-the-art topics: SD-WAN orchestration, intent-based networking and integration with legacy networks.

[1]Alviu's code and related information, such as programming languages or execution environments, are not free, as it is a Telcaria's commercial product.

Table I. Comparison of commercial SD-WAN products, also positioning Alviu in the current state of the art. Information extracted from [3] and [7].

SD-WAN product	**Gartner status**	**Orientation**	**WAN architecture**	**Form factor**	**Firewall**	**WAN optimization**	**Application path selection**
VeloCloud	Leaders	Software	100+ Global PoP gateways	Physical, virtual, Cloud	Basic (advanced via partners)	No	Yes
Silver Peak	Leaders	Software	Edge based	Physical, virtual, Cloud	Basic (advanced via partners)	Yes	No
Fortinet	Challengers	Hardware	Edge based	Physical	Advanced	Yes (in some models)	No
Cisco Meraki	Challengers	Hardware	Edge based	Physical, Cloud	Advanced	Limited	No
Cisco Viptela	Challengers	Hardware	Edge based	Physical, virtual, Cloud	Basic (Viptela hw.), advanced (Cisco hw.)	Yes (Cisco hw.)	Yes (Cisco hw.)
Citrix	Challengers	Hardware	Edge based	Physical, virtual, Cloud	Advanced	Yes (in some models)	Yes
CloudGenix	Visionaries	Hardware	Edge based	Physical, virtual, Cloud	Basic (advanced via partners)	No	Yes
Aryaka	Visionaries	Software	25 Global PoP backbone	Physical	Basic (advanced via partners)	Yes	Yes
Alviu	**Not ranked**	**Software**	**Edge based**	**Physical, virtual, Cloud**	**Basic**	**No**	**Yes**

A. Orchestration of SD-WAN networks

To summarize the heterogeneity of SD-WAN solutions available in today's market, Table I presents some of the most important SD-WAN platforms, according to the last magic quadrant for WAN edge infrastructure made by Gartner [3], with their main characteristics [7], reflecting the idea that each solution tries to focus on particular aspects of the network to be eventually controlled and orchestrated, and not finding a solution that covers all the features of the network. In this comparison, Alviu is also positioned in the state of the art, checking that it is aligned with the current trends in the market.

In general terms, according to manufacturers' vision, two tendencies can be identified in the design and development of SD-WAN solutions: (i) *software-orientation*, led by software-related companies (*e.g.*, VMware), which proposes a software-based architecture that is compatible with different hardware technologies, and (ii) *hardware-orientation*, where specialized hardware manufacturers (*e.g.*, Cisco) build the environment based on their own proprietary hardware.

In any case, it is expected that, through 2021, more than the 80% of the SD-WAN solutions will still be delivered on dedicated hardware, maintaining this trend [3]. Unlike most enterprise network solutions, Alviu differs from them as it does not lock to a certain vendor and range of telecommunications equipment, this being one of the key aspects from Alviu's value proposal. Furthermore, in terms of simplicity, Alviu offers a flexible and movable platform with an easy-to-use interface to define the SD-WAN scenario to be managed, which eventually triggers the installation of the dynamic intent-based routes that provide connectivity to the network and, also, activates specific value-added capabilities, such as policy-based control, monitoring and error detection services, network virtualization, zero-touch deployment, distributed firewall rules, data encryption, dedicated QoS policies, load balancing in redundant topologies, or the integration of legacy routing protocols (*e.g.*, OSPF or BGP) [4].

B. Intent-based networking

Intent-based networking (IBN) systems are expected to be used by more than 1000 large enterprises in production by 2020, up from less than 15 in 2018's second quarter [8]. This paradigm just requires to input the desired business requirements to be achieved by the network in an abstract way (*i.e.*, with intents). Then, it automatically translates the intents into real-time operations to be performed in every networking phase (*i.e.*, provisioning, deployment, management, troubleshooting and remediation) to satisfy the requirements exposed and to provide more intelligence and autonomy [6] [9].

Since its first official specification by the Open Networking Foundation (ONF) [10], this technology has been of interest to different research entities (*i.e.*, standardization organizations, open source communities, industry and academia), which are actively studying the mechanisms of IBN [9]. In what concerns Alviu, it leverages the lessons learned from open source's and academia's efforts related to the integration of IBN in the ONOS SDN controller [5].

Being more precise, Alviu builds an orchestration solution on top of the ONOS controller that uses the states and the transition between states proposed by the ONOS Intent Framework to create its own vision of the network intent. In this way, all the entities involved in a given intent share a common set of states to define their status during the intent operation. In this scope, the notion of intent is related to the operation performed by Alviu to manage the lifecycle of network equipment's configuration.

The input received by Alviu contains the configuration to be applied in the SD-WAN scenario, triggering the execution of different operations to fulfil the configuration proposed. One of the purposes of this approach is to make the network management and orchestration (MANO) operations easier for system and network administrators, as the current IBN commercial solutions in the industry market are mainly focused on solutions based on the traditional telco operator's MANO mechanisms, whose workflows are too complex for these types of networks, advocating simplicity and agility instead.

C. Integration with legacy networks

With the help of the increasing adoption of hybrid Cloud and enterprises' expanding bandwidth requirements, business WAN traffic flow patterns are becoming more software-based and hybrid by nature [6], coexisting legacy routing protocols (*e.g.*, OSPF or BGP) and mechanisms (*e.g.*, MPLS) with novel SDN technologies. This makes sense in operator-controlled networks with a significant networking infrastructure, where it is not an option to demolish everything and rebuild from scratch a full SDN-based architecture, as changes cannot be made overnight. In this context, SD-WAN should be introduced in progressive deployments such as the renovation of a part of the network or the construction of a new localized infrastructure [11].

The current solutions from the state of the art that take this topic into account are mostly based on multi-domain SDN scenarios, where there are different domains controlled by SDN that may need to be connected. For instance, [12] introduces a West-East Bridge (WE-Bridge) mechanism to enable different SDN administrative domains to peer and cooperate, or [13] performs a strict analysis of multi-

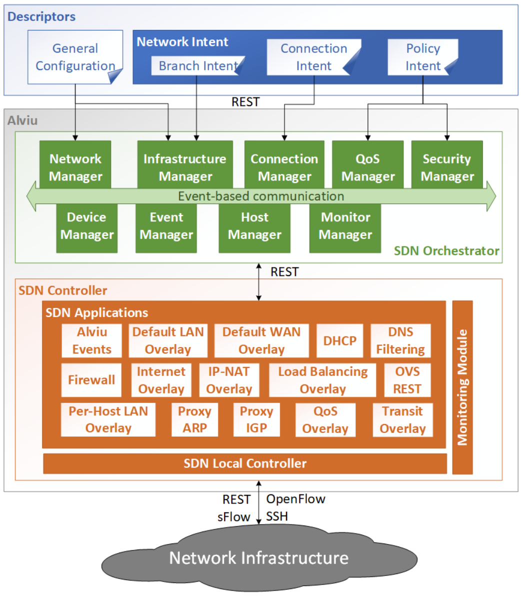

Fig. 1. Alviu architecture, including the building blocks that compose the SDN Orchestrator and the SDN Controller.

domain SDN interconnections focusing on the programmability properties and their effect on the performance of connectivity services.

However, there are also other approaches that consider the connection between SDN and non-SDN domains, achieving a full integration between SDN and legacy networks, as already done in [14], which proposes a topology-based hybrid model, separating the nodes controlled by each paradigm (*i.e.*, IP and SDN networks) in different regions that may be interconnected. This is, in fact, the approach selected by Alviu, allowing to maintain the network granularity with domains based on different technologies that can be interconnected, also introducing the concept of transit network describing a SDN domain that interconnects with multiple legacy domains.

For this purpose, the Quagga routing suite [15] is used in the edge SDN switches (*i.e.*, the switches from a SDN domain that are connected to legacy domains) to handle legacy protocols messages exchanged with edge routers from other domains, whose relevant information is eventually used by the SD-WAN orchestrator to enable or disable the traffic between domains.

III. Alviu Architecture

Alviu orchestrator's architecture is detailed in Figure 1, which includes the full definition of each level in which the orchestrator can be decomposed. These levels will be analyzed from top to bottom in the following paragraphs.

A. Intent-based networking characterization

Network characterization is mainly declared by using descriptors. This input information, provided by the users of the platform (mainly network administrators), serves to fully define the managed network and the desired configuration. They are codified in JSON, a well-known text format to wrap information exchanged through RESTful applications, following a data model to specify the fields that must be declared in each type and the possible values to be included.

There are two main descriptors types. The first one is grouped in the Network Intent Descriptors, used for configuring the entities related to the intents. In particular, these descriptors can be divided in three main classes, depending on the elements of the network to be defined:

1) Branch Intent Descriptor: it declares the SDN locations or branches, in terms of SDN switches and networks managed for each branch.
2) Connection Intent Descriptor: it states the logical connections between SDN zones and/or switches.
3) Policy Intent Descriptor: it serves to establish corporate policies to be applied in specific parts of the networks, such as the specification of distributed firewalls or QoS rules.

The second type of descriptors is the General Configuration Descriptor, related to the declaration of the regions (with their corresponding controllers) and the virtual networks that are present in all the scenario managed by Alviu.

B. Alviu specification

Alviu has been designed as a modular system, decomposing the SDN network orchestration and control platform into smaller building blocks with a specific function in the system. These blocks can be grouped into two main categories: orchestration modules and control modules.

The orchestration part, role played by the SDN Orchestrator, is in a higher level of abstraction, without interacting directly with the network equipment to be managed. Based on that model, the intents and configuration of the SDN domains received through the descriptors are translated into specific operations that can be internal or directed towards the control part, which has direct connection to the infrastructure, so that it is able to apply the configuration needed on the network infrastructure in order to meet the requirements declared in the intents.

All the modules running on it have a similar design from an implementation point of view, being oriented to a microservice architecture. For this purpose, each module defines REST endpoints to be accessed by external components (*e.g.*, for the provision of the descriptors), and, at the other end, it has REST clients to connect to the applications of the SDN Controller. Between both REST connectors, the orchestrator implements the main functionalities carried out by the module, handling the lifecycle of the module: receive data from the REST endpoints, perform operations (including the event-based communication with other modules) and send instructions to the SDN Controller.

In the case of the SDN Controller, it is based on ONOS[2] [5] and it has been built by following the classical SDN approach [16], separating the control plane from the data plane with the definition of a well-defined programming interface between the Network Infrastructure and the SDN Local Controller (*i.e.*, the southbound API), where the controller platform is able to configure and control the network equipment by using different protocols (mainly OpenFlow).

In addition to this, all the standard functionalities provided by the SDN Local Controller (control of the topology, link status, etc.) are complemented by specific-purpose SDN Applications, which interact with the SDN Local Controller through another well-defined API (*i.e.*, the northbound API) to enhance the control of the network. In this particular case, the SDN Applications, together with the SDN Orchestrator (which is also in charge of orchestrating the operation of each SDN Application), form the management plane of the platform. Each SDN Application takes care of a particular aspect of the network, being also related to a set of modules of the SDN Orchestrator to coordinate their joint action.

Finally, a Monitoring Module completes the SDN Controller, being able to manage the information related to network traffic flows (bandwidth consumed, networking data such as IP addresses, ports, etc.) to be used in specific use cases, such as the load balancing between switches connected through multiple links based on the bandwidth consumed by each link.

[2]Even though Alviu uses ONOS as main SDN Controller, the technology used can be interchangeable if required, maintaining the same interfaces.

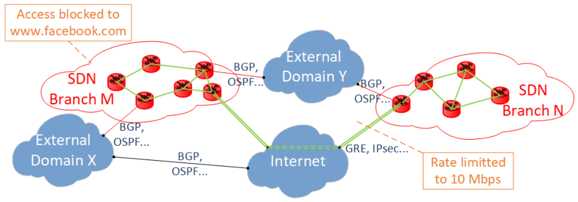

Fig. 2. Mapping between the type of descriptors that can be defined and the configuration applied by Alviu in the managed network infrastructure.

C. Application of intents over the network infrastructure

Alviu is able to control a set of SDN switches, distributed in domains or branches. Each domain can be controlled by a set of SDN Controllers (depending on the clustering configuration), using OpenFlow for the switch-controller communication. Currently, Alviu has already been integrated in network domains with an order of tens of switches, interconnected with legacy domains using OSPF and BGP protocols.

The relationship between the three classes of descriptors/intents and the configuration applied over the network infrastructure is depicted in Figure 2. Different colours are used to differentiate each case: (i) red colour represents the definition of the SDN branches and their switches, (ii) green colour shows the connections between switches by using tunneling protocols (excepting the connections to external domains, which is managed by the previous class) and (iii) orange colour presents possible corporate policies that may appear in this kind of scenarios (*e.g.*, the usage of DNS filtering to block traffic to a particular web page in a branch, or the data rate limitation in a specific link).

In this particular example, apart from having SDN domains interacting with each other, there are also configurations where a SDN branch is connected to one or more external domains (*e.g.*, *SDN Branch M* connects *External Domains X* and *Y* acting as a transit network, or *SDN Branch N* is connected to *External Domain Y*), in which case the SDN switch directly connected to the external domain must handle the legacy protocols used by the external domain (*e.g.*, BGP or OSPF) to extract the reachable networks (and even routes to reach the Internet[3]) from that domain, providing it upwards to Alviu through REST in order to properly install the flow rules in the SDN switches to correctly route the traffic to/from external domains.

This flexible configuration allows the definition of scenarios in which the SDN branches are more than isolated domains, but they can even act as transit networks that connect several external domains (*e.g.*, *SDN Branch M*, which interconnects *External Domains X* and *Y*).

IV. Platform Evaluation

Apart from building a complete and functional service to orchestrate and control SDN domains, the solution must also fulfil some specific performance requirements, ensuring the convergence of the intent deployment in a reasonably predictable time, avoiding deployment times with an exponential evolution as the number of SDN branches increases.

In this Section, a full deployment of a network controlled by Alviu will be evaluated in terms of the deployment time, which is the time elapsed from the launch of the intent until the infrastructure is properly deployed (*i.e.*, all the branches are in active state) and there is connectivity between all the switches on the network in a given topology.

[3]For example, in the case of the interconnection between *SDN Branch M* and *External Domain X*, the external domain is connected to the Internet and can propagate a default network to reach the Internet to the edge SDN switch from the SDN branch.

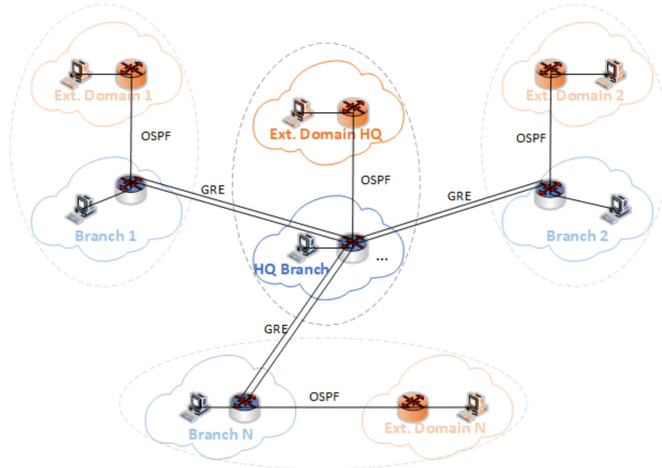

Fig. 3. Star topology evaluated in the performance evaluation analysis.

A. Testbed setup

The testbed used for the evaluation of this deployment consists of an Ubuntu Server 16.04 LTS virtual machine, with 12 vCPU and 12 GB of RAM, deployed in a server virtualized with Proxmox, which is equipped with 40 Intel(R) Xeon(R) CPU E5-2630 v4 at 2.20GHz and 128 GB RAM. In the virtual machine, all the components involved (*i.e.*, Alviu and the network infrastructure) have been deployed with Docker containers.

The topology type chosen for the performance evaluation process is the star topology, as it is the most common option followed by enterprise and academic networks to connect their domains, having a central SDN branch acting as headquarters and the rest of branches connected to the central one.

In particular, to simplify the scenario evaluated, each SDN branch deployed is composed by a single SDN switch with OVS and Quagga installed, with a host connected to it, and with another connection to a router, based on Quagga, from an external domain, using OSPF to exchange routes with it. This router will also have a host connected to it, in order to check the connectivity between hosts from different domains. Finally, one branch will act as headquarters, and the rest of branches will be connected to it through a tunnel connection established between SDN switches.

This particular deployment is depicted in Figure 3, presenting the HQ Branch as the root branch of the star topology, and several branches, from 1 to N, attached to it through a GRE tunnel between SDN switches, which are also secured with IPsec.

B. Deployment time evaluation

The evaluation of the deployment time has been done by measuring the time spent by Alviu to meet the requirements defined in the intents, which are mainly two: (i) deploy an active branch with one SDN switch connected to a host and to an external domain (*i.e.*, Branch Intent), and (ii) connect the SDN switch to the endpoint located in the HQ Branch through a tunnel (*i.e.*, Connection Intent). However, the convergence time to learn the prefixes from external domains has been excluded from the analysis, as it is difficult to predict beforehand, directly impacting in the accuracy measurements during the evaluation.

The evolution of this performance metric, changing the number of branches deployed in the topology from one (only the HQ branch) to ten, can be seen in Figure 4. Several conclusions can be extracted from this graph, which shows the linear trend of the deployment time, confirming that the time spent to deploy a given topology is quite predictable and scalable, which is a desired behavior against

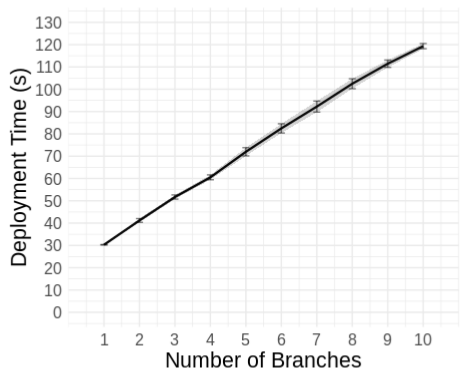

Fig. 4. Evolution of the deployment time, in seconds, varying the number of branches deployed in the star topology.

exponential trends that can saturate the system. This has been possible due to the concurrent management of multiple intents provided by Alviu, which is able to process intent requests in parallel to improve system's scalability.

V. Conclusions and Future Research

To conclude, the main contribution that has been provided in this paper is the definition of a full SD-WAN orchestration solution which is capable of managing different SDN-based scenarios presenting different configurations that are usual in enterprise and academic networks. To get to this point, the network intents have been introduced; whose definition, in terms of the so-called Network Intent Descriptors, has been another relevant contribution to the IBN state of the art, followed by Alviu's modular architecture, which has been designed to properly manage the intent-based networking capabilities applied over SD-WAN scenarios. This platform has been finally evaluated to confirm the system scalability in terms of the deployment time spent by Alviu to achieve intent's fulfillment, as the measured deployment time depends linearly (and not exponentially) on the number of SDN branches.

In terms of future research, Alviu is in constant evolution, as network programmability allows the platform to achieve the implementation of new capabilities in a relatively simple way. An example of this is the introduction of Alviu in other network architectures; such as mobile networks, where 5G is currently enabling the introduction of a wide ecosystem of software and cloud-native technologies. This way, examples like [17], where SDN is used in a 5G dense multi-infrastructure provider, are now possible with the technologies available.

Apart from introducing new features to widen the use cases covered by Alviu, other future research lines are related to the introduction of new technologies to enhance the user experience and the performance of the platform. In the first case, the sights are set on the evolution of intent definition towards a *human-based language*, where the intent could be defined in terms of sentences that are eventually translated into operations and configurations to be managed by the orchestrator. The objetive of this is to leverage SDN and IBN to the next level, with the so-called Human-Defined Networking, where information and interactions are provided by the network managers instead of being strictly software or hardware-dependent [18].

On the other hand, the objective of improving the system performance is quite related to the introduction of techniques such as Machine Learning or Artificial Intelligence, as happens in examples like [19], where Machine Learning modules are introduced to ensure the automation and self-assurance of an Intent-Based Orchestration platform. Therefore, these techniques would provide intelligence to Alviu's programmable network, based on the current status of the network infrastructure and the forecasts made by these technologies.

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References

[1] F. Bannour, S. Souihi, and A. Mellouk, "Distributed SDN Control: Survey, Taxonomy, and Challenges," *IEEE Communications Surveys Tutorials*, vol. 20, no. 1, pp. 333–354, 2018.

[2] R. Ahmed and R. Boutaba, "Design considerations for managing wide area software defined networks," *IEEE Communications Magazine*, vol. 52, no. 7, pp. 116–123, 2014.

[3] Gartner, "Gartner Magic Quadrant for WAN Edge Infrastructure," Nov. 2019. [Online]. Available: https://www.gartner.com/en/documents/3975600/magic-quadrant-for-wan-edge-infrastructure

[4] Telcaria Ideas S.L., "Alviu Brochure," Feb. 2018. [Online]. Available: https://www.telcaria.com/docs/sd-wan/Alviu_Brochure.pdf

[5] P. Berde *et al.*, "ONOS: Towards an Open, Distributed SDN OS," in *Proceedings of the Third Workshop on Hot Topics in Software Defined Networking*, ser. HotSDN '14, 2014, p. 1–6.

[6] Cisco, "Cisco Annual Internet Report (2018–2023) White Paper," Mar. 2020. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[7] J. Casey, "Who are the 20 top/best SD-WAN providers & vendors?" Sep. 2020. [Online]. Available: https://www.netify.co.uk/learning/top-best-sd-wan-providers-vendors

[8] N. Rickard and A. Lerner, "Gartner's 2018 Strategic Roadmap for Networking," May 2018. [Online]. Available: https://www.gartner.com/en/documents/3873650/2018-strategic-roadmap-for-networking

[9] L. Pang, C. Yang, D. Chen, Y. Song, and M. Guizani, "A Survey on Intent-Driven Networks," *IEEE Access*, vol. 8, pp. 22 862–22 873, 2020.

[10] ONF, "Intent NBI – Definition and Principles," ONF TR-523, Oct. 2016. [Online]. Available: https://www.opennetworking.org/wp-content/uploads/2014/10/TR-523_Intent_Definition_Principles.pdf

[11] G. Pujolle, "Fabric, SD-WAN, vCPE, vRAN, vEPC," in *Software Networks: Virtualization, SDN, 5G, and Security*, 2nd ed. Wiley, 2020, pp. 33–50.

[12] P. Lin *et al.*, "A west-east bridge based sdn inter-domain testbed," *IEEE Communications Magazine*, vol. 53, no. 2, pp. 190–197, 2015.

[13] F. X. A. Wibowo and M. A. Gregory, "Software Defined Networking properties in multi-domain networks," in *2016 26th International Telecommunication Networks and Applications Conference (ITNAC)*, 2016, pp. 95–100.

[14] L. He, X. Zhang, Z. Cheng, and Y. Jiang, "Design and implementation of SDN/IP hybrid space information network prototype," in *2016 IEEE/CIC International Conference on Communications in China (ICCC Workshops)*, 2016, pp. 1–6.

[15] P. Jakma and D. Lamparter, "Introduction to the quagga routing suite," *IEEE Network*, vol. 28, no. 2, pp. 42–48, 2014.

[16] D. Kreutz, F. M. V. Ramos, P. E. Veríssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-Defined Networking: A Comprehensive Survey," *Proceedings of the IEEE*, vol. 103, no. 1, pp. 14–76, 2015.

[17] J. Lun and D. Grace, "Software defined network for multi-tenancy resource sharing in backhaul networks," in *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015, pp. 1–5.

[18] E. Rojas, "From Software-Defined to Human-Defined Networking: Challenges and Opportunities," *IEEE Network*, vol. 32, no. 1, pp. 179–185, 2018.

[19] T. A. Khan, A. Mehmood, J. J. Diaz Ravera, A. Muhammad, K. Abbas, and W. Song, "Intent-Based Orchestration of Network Slices and Resource Assurance using Machine Learning," in *NOMS 2020 - IEEE/IFIP Network Operations and Management Symposium*, 2020, pp. 1–2.