Lessons learnt from the NetIDE project: Taking SDN programming to the next level
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Abstract—Software-Defined Networking promises to overcome vendor lock-in by enabling a multi-vendor hardware and software ecosystem in operator networks. However, we observe that this is currently not happening. A framework allowing to compose SDN applications combining different frameworks can help revert the trend. In this paper, we analyze the challenges in the current SDN landscape and present the multi-controller SDN framework developed by the NetIDE project. Our architecture supports different SDN southbound protocols and we have implemented a proof of concept using the OpenFlow protocol, which has given us a greater insight on its shortcomings.

Index Terms—Software-Defined Networking, Portability, Conflict resolution, OpenFlow

I. INTRODUCTION

As a flourishing –but young– paradigm, Software-Defined Networking (SDN) still needs to tackle several challenges. When network operators face adoption of SDN in their infrastructures, they are confronted with the need to maximize reusability of use cases and applications. However, currently available network applications are not easily portable from a specific SDN deployment to a different one, especially when it implies changing the SDN platform they are built upon. The main reason for this is that SDN Northbound Interfaces (NBIs) are still not standardized. This causes network applications to depend on the NBI implemented by the SDN platform they are written for. Which, in turn, causes similar vendor lock-in for SDN users as they had with network apparel vendors before moving to SDN.

SDN applications interact with the network in two ways: (i) by generating SDN commands for the network infrastructure they control pro-actively and (ii) by reactively generating SDN commands as a response to network events. In this paper, we present a novel SDN framework developed within the NetIDE project [1], which implements SDN application composition for heterogeneous SDN controller frameworks. We concentrate on the problem space of reactive SDN applications both in our architectural work and in our implementation. The Network Engine is complemented by an Integrated Development Environment (IDE) that helps SDN programmers mix and match the SDN platforms that best fit their needs, and benefit from current best practices in programming (e.g. reusing existing and proven code) when developing network applications.

The whole NetIDE framework is available as open source code [2].

II. CHALLENGES IN CURRENT SDN LANDSCAPE

Developing applications for different SDN platforms requires different mindsets. First of all, the SDN programmer has to face the different programming languages or NBIs that have been used for creating the different SDN controller frameworks: e.g. Ryu [3] is Python-based while Floodlight [4], OpenDaylight [5] and ONOS [6] are Java-based. And then, there is the additional burden of the different programming models used by the different frameworks. For example, the OpenDaylight (ODL) application model builds on an interaction with local data stores that reflect the network nodes controlled by the SDN controller. These are modeled using YANG. To write an ODL application, the first step is to define its YANG model. Then, ODL internal tools generate the skeletons of the different modules that make up the implementation. In addition, ODL supports Maven archetypes as a means to automate the process.

Staying on the realm of Java-based SDN controller frameworks, we have ONOS. It supports archetypes too. However, the underlying libraries used to interact with the network elements are quite different: for example, ONOS introduces an intermediate layer called network intents which, in essence, is a programmatic abstraction library, to interact with the network devices without the need for YANG models. The closest ODL gets to these network intents is MAPLE [7]. Other projects labeled as intent in ODL diverge significantly in nature and approach, empowering the user instead of the programmer.

In addition to all this, the East-West Interface (EWI) would be able to grant the synchronization of network applications on different SDN platforms. However the implications of the EWI need to be further researched and standardized. In this line, mechanisms to resolve conflicts between applications are also needed. Currently, the most popular SDN frameworks (ODL, ONOS, etc.) implement simple composition mechanisms applying priorities for the execution of events, but do not handle conflicts.

Finally, the Open Networking Foundation (ONF) also includes the management functions in their definition of the SDN architecture [8]. However, many SDN platforms ignore them in practice. Including management tools in their networks is thus tedious for operators, who end up implementing their own tailored management solutions; hence increasing the operational cost.

Thus, we can say that despite softwarizing the network, we are not taking advantage of the goodies of software
CoVisor \cite{11} brings together the following features: (i) assembly of multiple controllers, (ii) definition of abstract topologies and (iii) protection against misbehaving controllers. In particular, it allows the administrator to combine different client controllers in parallel, in sequence, or in an override/default relationship. However it has several limitations, e.g. it makes the adaptation of an SDN operational set-up difficult by forcing the replacement of a running SDN controller with a network hypervisor; it can not recognize when an SDN application has finished processing a network event, thus potentially leading to network deadlocks. FlowBricks \cite{12} is designed to compose client controllers, but only runs on an emulated environment with heavy hacks on the OpenFlow switches and cannot be used over off-the-shelf network hardware.

Approaches based on module orchestration are: Corybantic \cite{13}, which resolves conflicts over specific OpenFlow rules, Statesman \cite{14}, which defines three views of the network and only lets application modules propose changes into one of them –later merged by the orchestrator–, and Athens \cite{15}, which is a compromise between Corybantic and Statesman, allowing more participation in the state that will be sent to the network. However, they all require SDN applications to interface with it through a specific Application Programming Interface (API), forcing the administrator to modify the applications s/he wants to reuse from different SDN environments. Some other composition options still based on the NBI are based on alternative NBI. PGA \cite{16} aims to merge SDN applications representing them as graphs and even considering automatic composition. Redactor \cite{17} is based on the declarative programming language Prolog and resolves conflicts via a heuristic approach. Other authors leverage CoVisor to provide anomaly-free policy composition \cite{18}.

Finally, FlowConverterror \cite{19} works at Southbound Interface (SBI) level, translating policy updates from any origin pipeline to any target pipeline, where one example of pipeline is the OpenFlow switch. However, it does not consider merging different pipelines into a single one.

In the case of the offline approaches, some authors introduce the Semantics Rule (SR) concept \cite{20}, similarly to the Intermediate Representation (IR) for PC compilers, so that SDN application modules are first compiled into SRs (front end), optimized afterwards and finally translated into network low-level rules. Some others propose a Model-Driven Networking (MDN) framework \cite{21} where modules are translated –or directly written– into a Domain-Specific Modeling Language (DSML), allowing easy merging and verification, and finally generating the corresponding code for a targeted SDN platform.

## III. RELATED WORK

Several solutions have been proposed to allow network applications implemented for different SDN control platforms to control a common infrastructure. They could be divided into two different groups: online approaches, which try to combine the application modules during run time, and offline approaches, which perform the merging before the execution.

Regarding the online approaches, hypervisors like FlowVisor \cite{9} and OpenVirteX \cite{10} split the traffic into “slices”, which permit the execution of multiple network applications but impede them to cooperate in processing the same traffic as a single network application.

### TABLE II: Summary of the challenges in the current SDN landscape

| Challenge                          | Mean to solve it          | Why not sufficient                                                                 |
|------------------------------------|---------------------------|-----------------------------------------------------------------------------------|
| Combining heterogeneous SDN applications | Common NBI                | NBI still not standardized. Each SDN platform fight for its own final NBI that will solve application development |
| Combining heterogeneous SDN applications | Common EWI               | EWI still not standardized. Composition and conflict resolution mechanisms still to be discussed in the research community |
| Network control and management     | Definition of management interfaces | Current solutions based on specific architectures. Most SDN platforms do not even implement it |

## IV. NETIDE NETWORK ENGINE ARCHITECTURE

As mentioned in the introduction, the NetIDE project has developed an SDN platform with a companion IDE \cite{22} that provides a true cross-platform development and deployment experience. The SDN platform, called Network Engine, is based on a three-tier approach, with a layer of client controllers executing applications and a layer of server controllers driving the network elements. The Network Engine’s controllers are
orchestrated by a core layer that includes composition and conflict resolution mechanisms. In this Section we provide a high-level overview of the NetIDE Network Engine architecture. A detailed description is available on [23].

The proposed Network Engine (Fig. 1) combines unmodified SDN applications running on multiple client controllers (called Modules in the figure), organizing them to cooperate with modules running on top of the network-facing controller (represented by the Server Controller in the figure). In this regard, a Network Application is understood as a set of SDN software modules, possibly written for different SDN controller platforms, which are orchestrated to cooperate on controlling the same network. These network applications behave as single entities that compute SDN combining the rules produced by the modules it is comprised of with custom-defined semantics.

**Fig. 1: Network Engine architecture.**

The most challenging aspect of the Network Engine is integrating client and server controllers. A first idea is to connect the SBI for the client controllers to the NBI of the server controllers. But as these interfaces do not normally match, adaptation is necessary. To maximize reuse, we use separate adaptors for the SBI, called Backend, and for the NBI, called Shim. An intermediate layer, or Core, communicates with the Shims and Backends. It implements the SDN controller framework agnostic functions, thereby making the implementation of both Shims and Backends for new SDN frameworks light-weight.

### A. The Core

The Core is a platform-independent component that orchestrates the execution of individual modules, that are potentially spread across multiple controllers. It controls all messages exchanged between application modules and the network. In this sense, the operations of the Core can be divided into three categories: (i) handling the asynchronous events from the network, such as new flows, port status, flows removed, (ii) composing the configuration messages generated by the application modules and checking them for conflicts, and (iii) pairing read-state request messages issued by the application modules and the corresponding replies from the network.

The Core intercepts network events from the server controller and distributes them to the client controllers based on a

**Composition Specification** file that defines which modules are used in the composition and the flow of execution between them. The Core supports two execution semantics: Sequential and Parallel (akin to the Sequential and Parallel operators in [24, 25]).

- Sequential execution invokes modules in the sequence defined by the composition specification. The first module is fed the original input event; each subsequent module uses the original input modified with the actions returned by previous modules in the chain.
- Parallel execution invokes modules in parallel using the same input for all.

The Core implements policies to merge the actions returned by the modules into a consistent set of actions that can be installed in the network to handle the traffic. Policies are used to determine how conflicting outputs are handled; options include checking for conflicts in a specific field of an action. Standard policies are discard conflicts by dropping conflicting results; ignore conflicts by installing all results without further processing; and prioritize and resolve conflicts by picking the result with the highest priority out of the set of conflicting results.

### B. Shim and Backend

The Shim and Backend are platform-specific components that integrate existing controller frameworks into the NetIDE architecture.

The Shim translates the NBI of the server controller to the NetIDE API, exposing it to the Network Engine. As shown in Fig. 2 it overrides the server controller’s processing logic in the SBI and routes all messages from the network to itself.

The Backend is an additional SBI for the client controller that interacts with the underlying layers of the Network Engine. At boot-time, the Backend registers the application modules running on the client controller to the Core, which, in turn, assigns a specific identifier to each of them.

At runtime, Backends use the module identifier to identify the module sending the message. On the other direction, the Core uses the identifier based on pre-defined policies to indicate which module handles an event. The Backend steers the event distribution inside the client controller, ensuring events are sent to the correct modules.

**Fig. 2** shows a detailed view of our architecture. We include in it the mechanism we use to integrate modules written for the server controller framework into our applications. Specifically, we place a Backend in the server controller to steer the message flow for the modules composing Network Application that run on the server controller, exactly like for any other module running on a client controller. In this case, the modules can only interact with the Backend, since the other SBIs are hidden to them by the Shim, as explained above in this section.

### C. NetIDE Intermediate Protocol

The NetIDE Intermediate protocol implements the following functions: (i) to carry management messages between the
Fig. 2: Detailed architecture of the Network Engine.

Network Engine’s layers (Core, Shim and Backend); e.g., to exchange information on the supported SBI protocols, to provide unique identifiers for application modules, implement the fence mechanism, (ii) to carry event and action messages between Shim, Core, and Backend, properly demultiplexing such messages to the right module based on identifiers, and (iii) to encapsulate messages from different SBIs to a common format handled by the Core.

It includes fields to identify network elements for SBI messages, application modules running on the client controllers and transactions (i.e. groups of related network events and commands as described above).

D. Fencing

The way different SDN frameworks, and particularly OpenFlow (OF), work is that SDN modules receive network events and optionally produce network commands in response. This implies that modules may quit silently, without producing any tangible response. A prerequisite to implement application composition is to know when all modules of an application have finished processing a network event. Otherwise, there is a risk that the Core performs composition operations too early, i.e. when some modules are still processing the event, or that it freezes waiting for a response which will never arrive. We introduced fences, i.e. end-of-execution markers, to tackle this problem and require that Backends monitor the execution flow within the client controllers to this avail. The Core supports interleaved communication with the application modules to improve the performance of the Engine. In order to preserve the semantic of the network policies installed by the modules, the Core ensures that the composed output goes back to the network consistently with the time ordering of events.

V. PRACTICAL SCENARIO

One of the scenarios that has driven the research and implementation work of the project is the SDN-driven data center, where we explore the possibility of implementing the networking components of a virtual data center (vDC) service as SDN applications. We consider a typical vDC offering including components like an unprotected zone connected to the Internet, a Demilitarised Zone (DMZ) and an interior zone. The logical topology of the vDC (shown in Fig. 3a) is implemented using SDN applications written for a specific SDN controller platform (Fig. 3b) to provide firewall and Layer 3 network services, and stitching between the different virtual machines that implement the individual components of this vDC offering such as Web and DNS services.

We observe that there is a logical grouping into zones (exterior zone, DMZ and interior zone) that can be used as predefined blocks in vDC implementations; for example, a provider can offer micro-vDCs that consist of a DMZ only, vDCs with more than one isolated DMZ for different organizations within a company, etc. In turn, each of these building blocks uses atomic building blocks like the firewall, router, etc. This structure calls for the use of patterns, component reuse and other software development techniques.

The operator may require to activate new network services on the operational vDC to improve, for instance, the performance and the security of the network. Thus, she/he may want to spread the users requests over different servers via a Load Balancer, or to hide part of the internal network behind a single IP address using a Network Address Translation (NAT) service.

With NetIDE, the operator enhances the existing vDC module shown in Fig. 3a with the router and firewall modules, which executed are as-is on different SDN controller frameworks (as shown in Fig. 3b), instead of porting them to—or writing them from scratch for—the platform he/she initially chose.

VI. LESSONS LEARNT AND SHORTCOMINGS OF OPENFLOW

The architecture we present in this paper implements the composition of SDN applications. We have concentrated on OpenFlow for our implementation because many, diverse controller frameworks for OpenFlow are available as Free Open-Source Software (FOSS). Although the experience we have gathered shows the shortcomings of the approach taken by the OpenFlow community, many of them can be generalized to other state-of-the-art SDN environments.
On the one hand, most frameworks have no way of telling from the outside when a controller has completely consumed a network event. This resulted in run-to-completion problems in our composition core, until we introduced the fencing mechanism. Partially coupled with this, we also had to struggle with the fact that OpenFlow also lacks clearly defined No-Operation semantics, i.e., how to interpret the situation when a controller consumes a network event and produces no output.

The separation of control and data plane into different entities, which communicate through a standardized interface is the most valuable contribution of OpenFlow to the development of SDN. However, timing matters in SDN applications; when writing composed applications, we have experienced situations where independently running modules may introduce transient network state that then influences the way the network responds to network events in an uncontrolled manner. In the OpenFlow model, applications are not aware of the actual network state. When they need to be, they have to reproduce it internally in the application and it is then where spurious interactions can have a significant (and negative) impact on the network behavior.

NetIDE represents a consistent approach to parallel composition of SDN applications. Sequential composition, that is using the response of a module as the input for another one, is an issue which deserves further study [26]. The output of a module is a combination of network commands and generated packets and transforming that into valid network events for the subsequent modules in a sequential composition chain is not evident: first of all, there is no one-to-one transformation from input to output events of SDN modules because their very natures are not reconcilable and, secondly, there is the need of a snapshot of the network state to try any approximate transformation.

VII. Conclusion

In order to introduce software development paradigms in Software-Defined Networking, we have developed the NetIDE architecture. It provides an IDE to lower the entry barrier to SDN and a Network Engine that allows composing SDN application using pre-existing ones as building blocks.

Our Network Engine concept is SBI-independent and we have implemented it for OpenFlow as a proof-of-concept. In this process, we had to face all the shortcomings for the OpenFlow paradigm, including insufficiently defined semantics in some operations, incompatible semantics of events, coexistence of SDN application models that can not be composed, etc. We have overcome some of these limitations with our architecture and have contributed both architectural concepts and a fully functional development and runtime architecture to the SDN community.

From our experience, we strongly feel that facing all these shortcomings and developing an evolved architectural model for SDN would result in a more robust yet flexible architecture for future software-defined networks, which truly overcomes vendor or platform lock-in risks.

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