Software Defined Networks

SIGCOMM'15 Topic Preview

Laurent Vanbever

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SIGCOMM'15

August, 17 2015

3 213

3 213

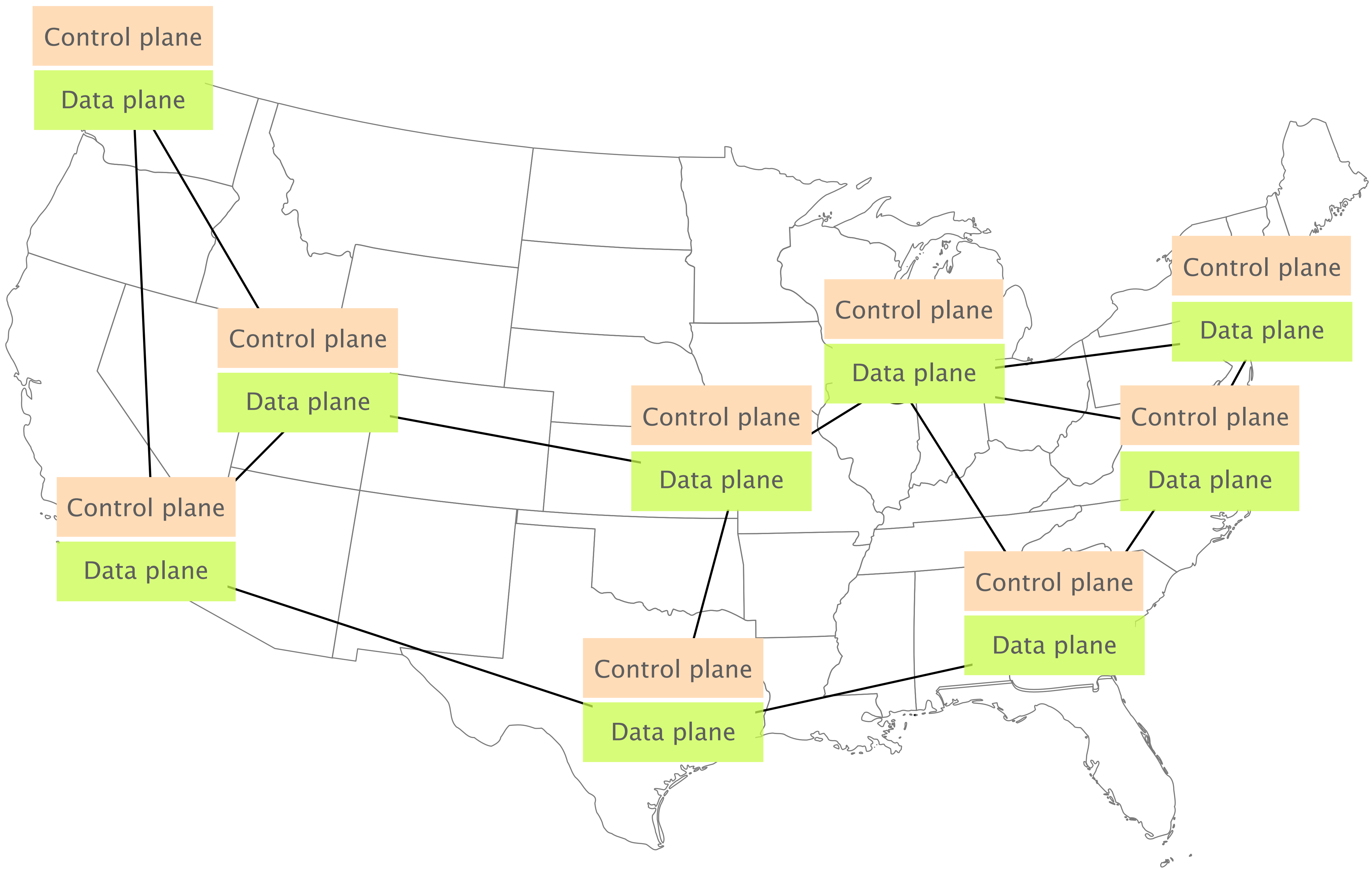
# of citations of the original OpenFlow paper in ~6 years

Software Defined Networks

Software Defined Networks

What is this thing?

A network is a distributed system whose behavior depends on each element configuration



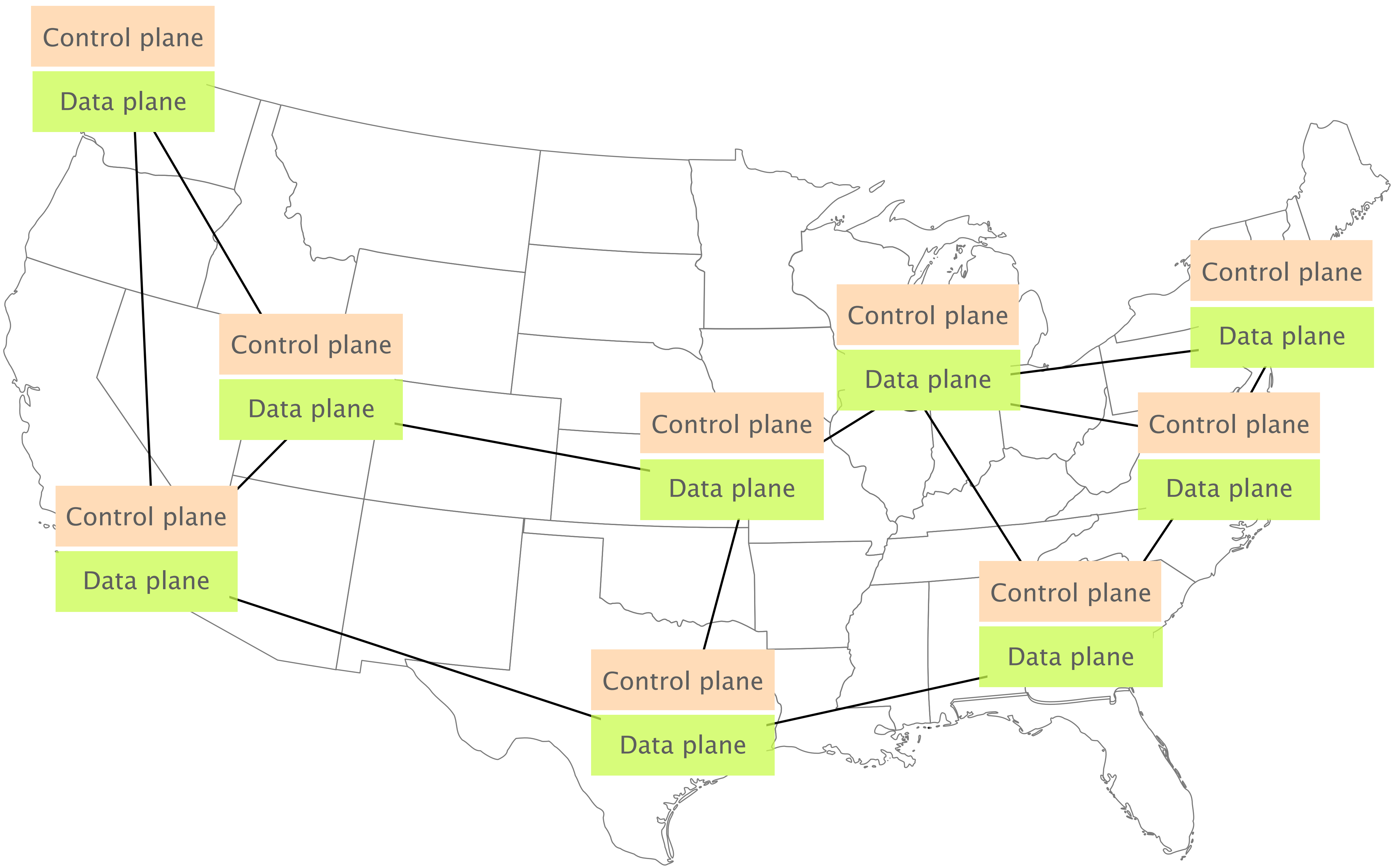
Configuring each element is often done manually, using arcane low-level, vendor-specific “languages”

"Human factors are responsible

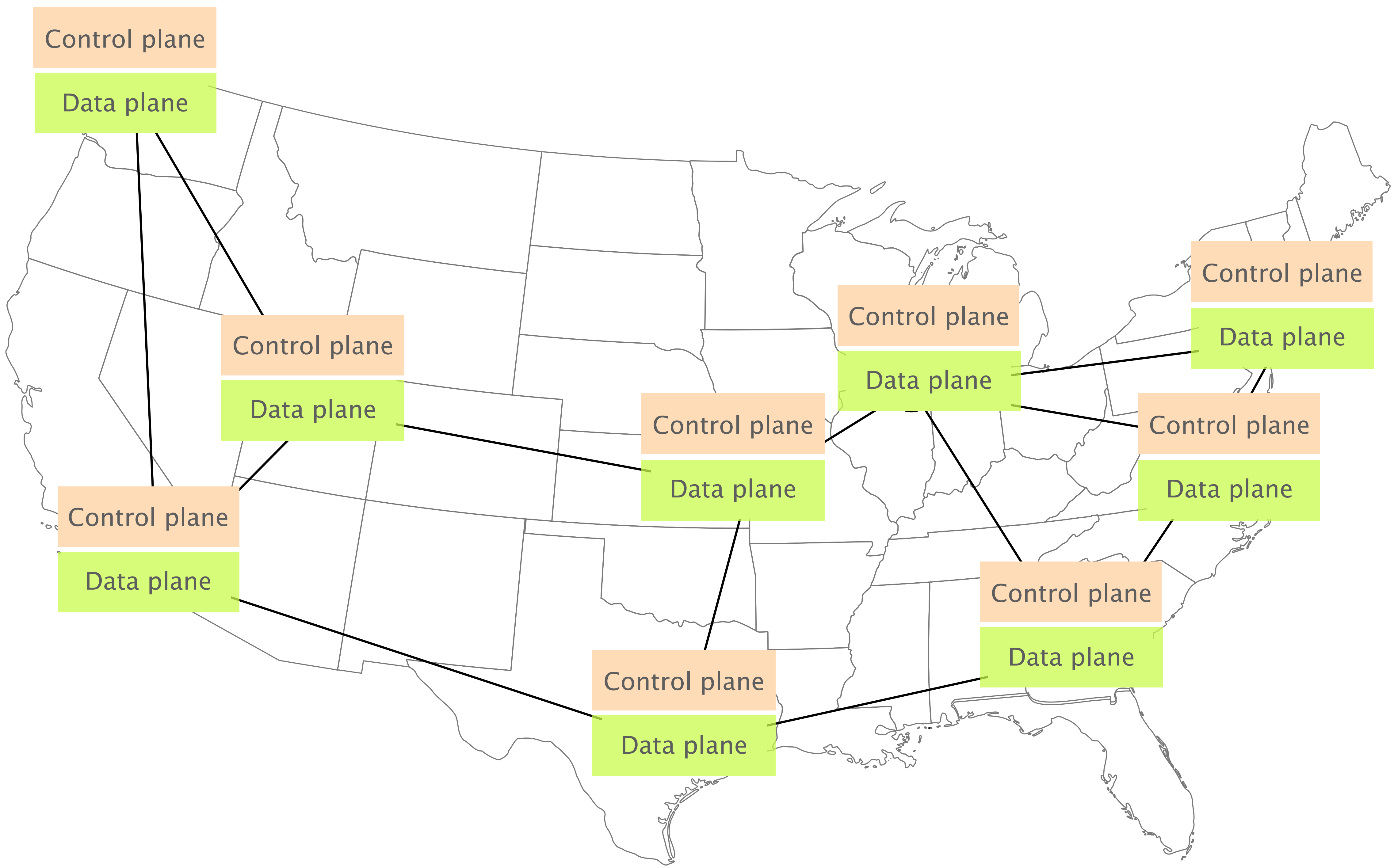
for 50% to 80% of network outages"

Juniper Networks, *What's Behind Network Downtime?*, 2008

In contrast, SDN simplifies networks management…



…by removing the intelligence from the equipments



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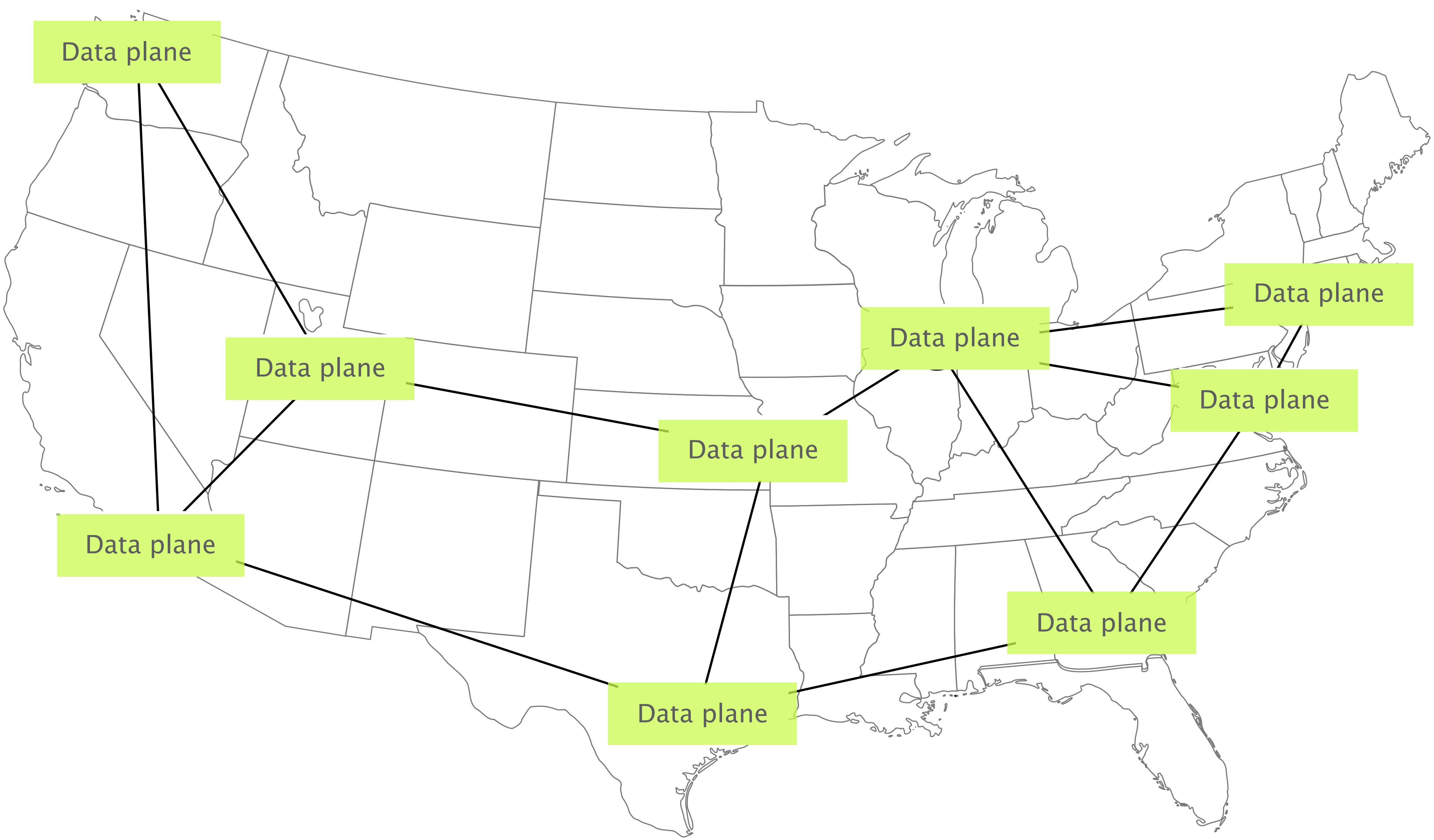
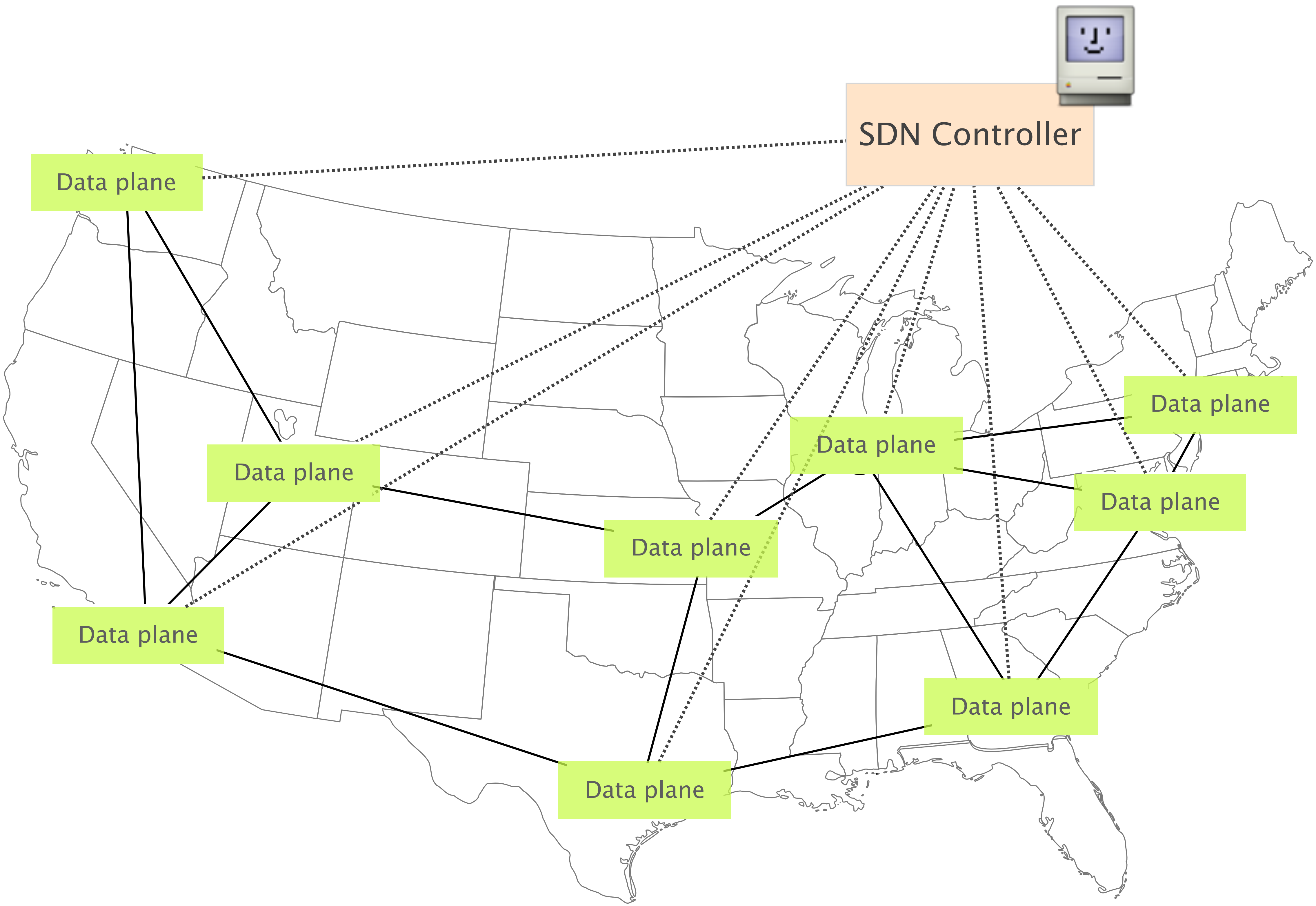
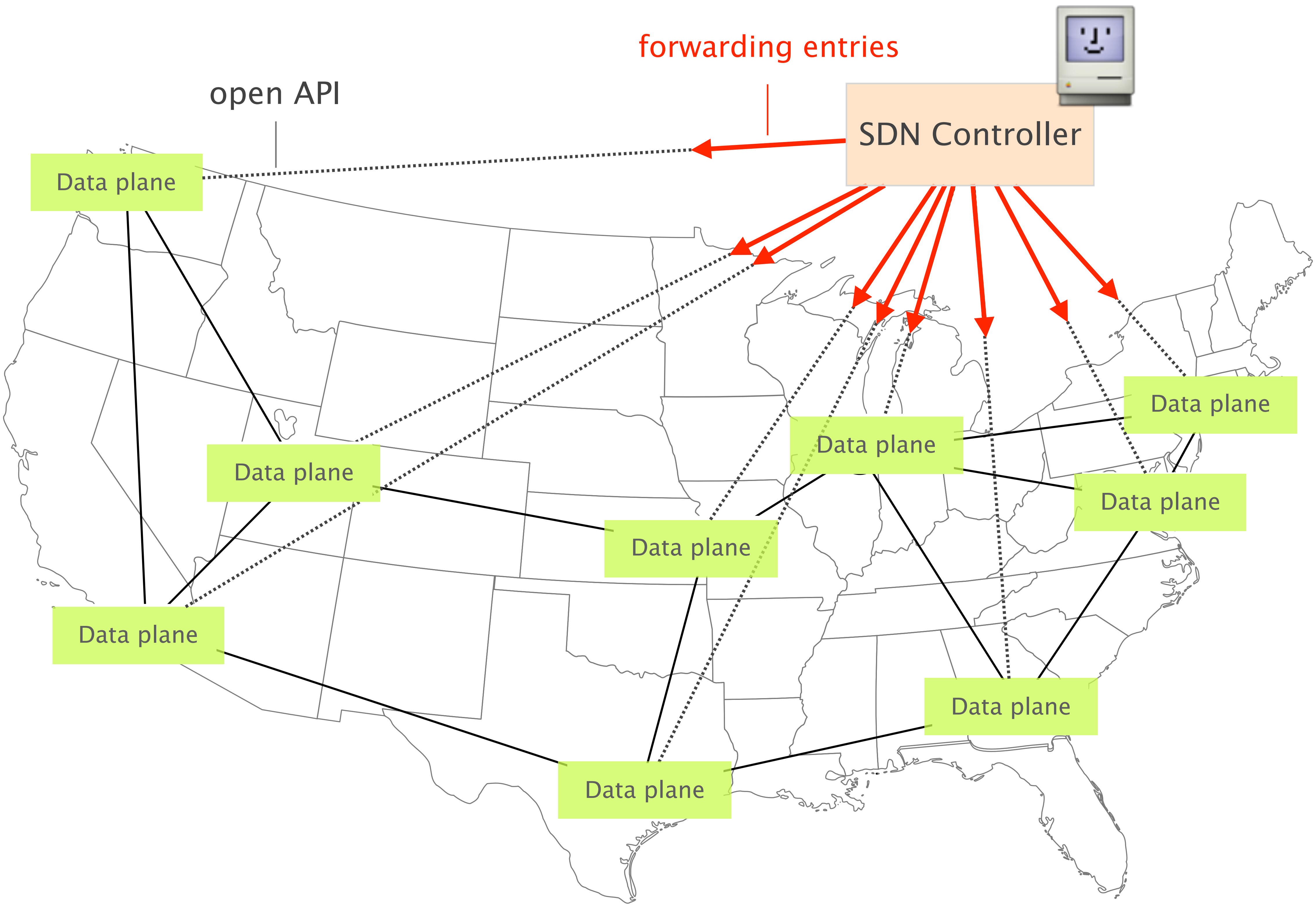


… and **centralizing it** in a SDN controller that can run arbitrary programs



The SDN controller programs forwarding state in the devices using an open API (e.g., OpenFlow)



Software Defined Networks

Why should you care?!

SDN enables us, researchers,
to innovate, at a much faster pace

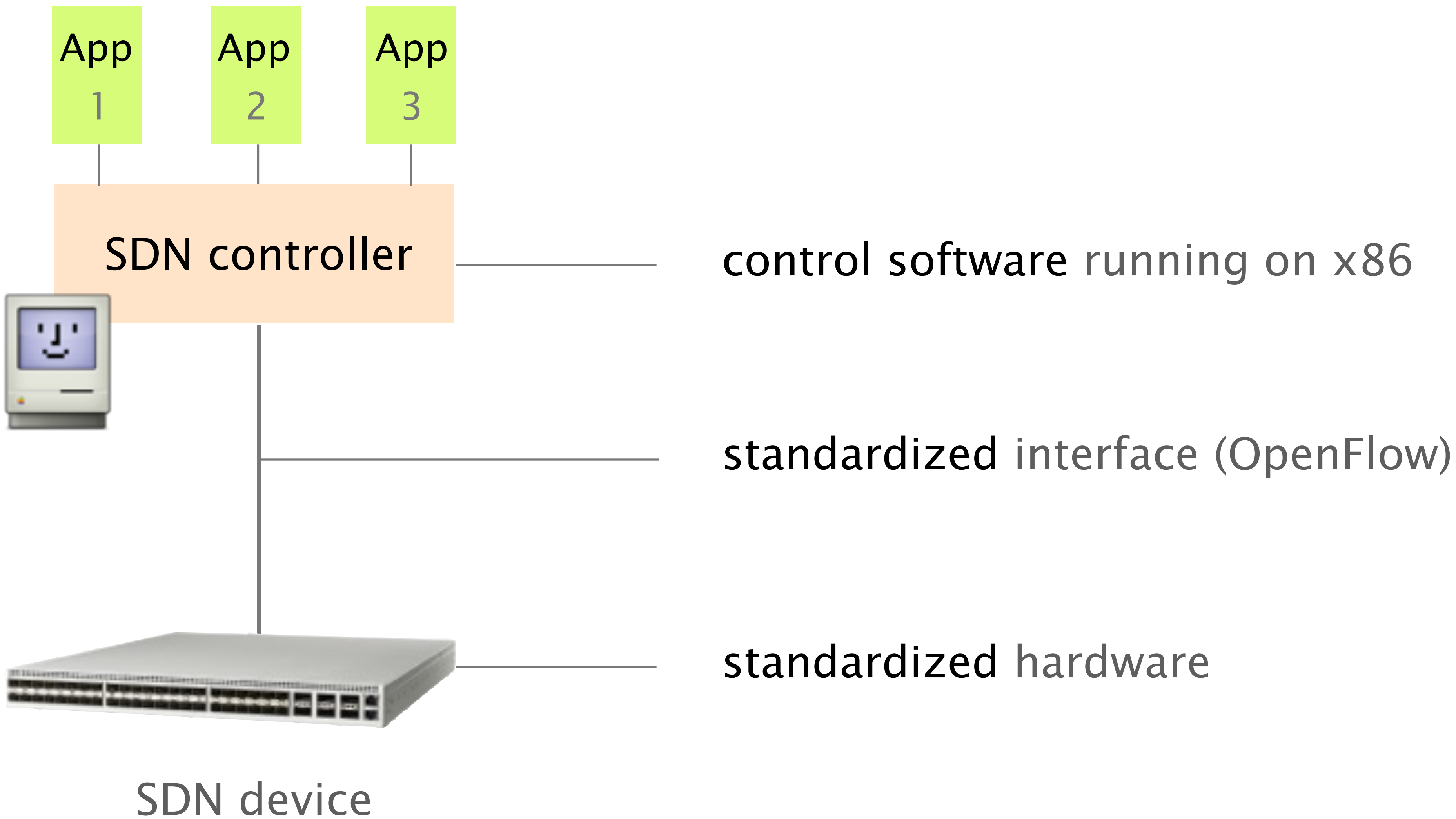
Before SDN

closed software

closed hardware

Cisco™ device

After SDN


App
1
App
2
App
3
SDN controller
control software running on x86
standardized interface (OpenFlow)
standardized hardware
SDN device

SDN track @SIGCOMM'15

BwE: Flexible, Hierarchical Bandwidth Allocation for WAN Distributed Computing

A Declarative and Expressive Approach to Control Forwarding Paths in Carrier-Grade Networks

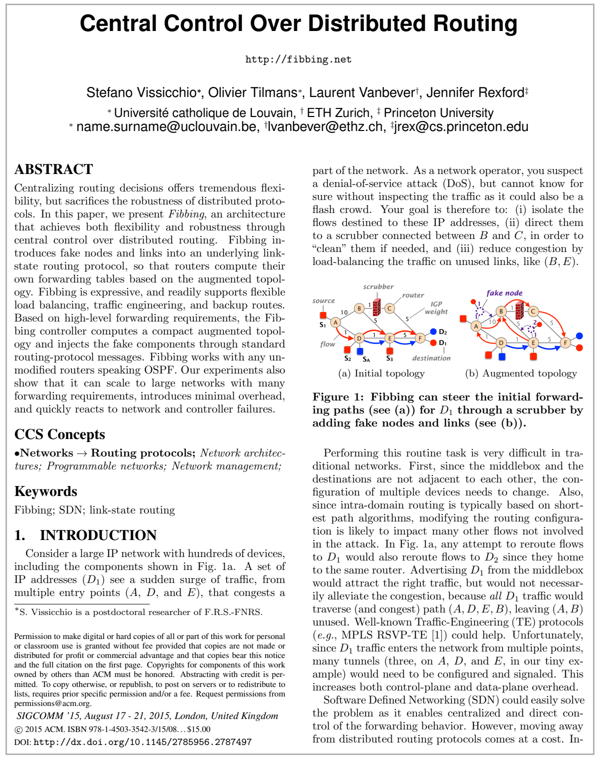
Renaud Hartert *, Stefano Vissicchio *, Pierre Schaus *, Olivier Bonaventure *, Clarence Filsfils †, Thomas Telkamp †, Pierre Francois ‡

* Université catholique de Louvain † Cisco Systems, Inc. ‡ IMDEA Networks Institute

PGA: Using Graphs to Express and Automatically Reconcile Network Policies

Chaithan Prakash, Jeongkeun Lee, Yoshio Turner, Joon-Myung Kang, Aditya Akella, Sujata Banerjee, Charles Clark, Yadi Ma, Puneet Sharma, Ying Zhang

University of Wisconsin-Madison, HP Labs, Banyan, HP Networking



Central Control Over Distributed Routing

http://fibbing.net

Stefano Vissicchio, Olivier Tilmans, Laurent Vanbever, Jennifer Rexford

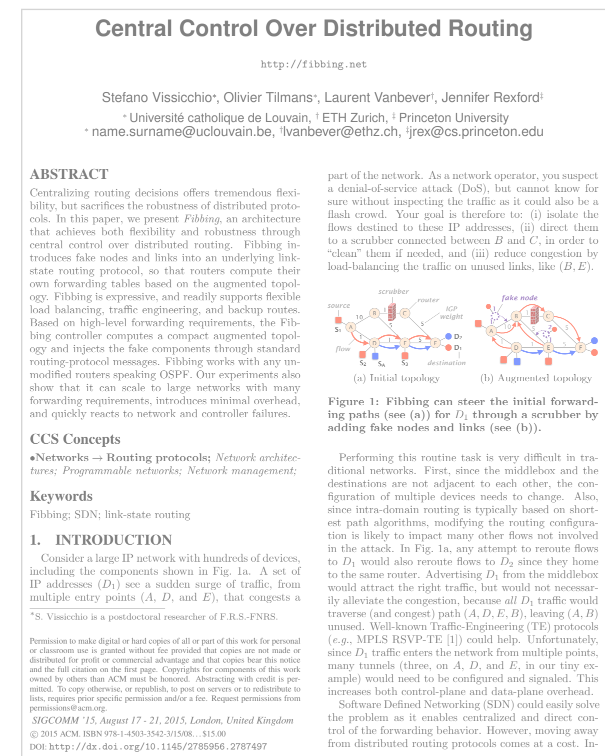
Université catholique de Louvain, ETH Zurich, Princeton University

bandwidth management

network policies

programmability

SDN track @SIGCOMM'15



bandwidth management

Network resources are expensive.

Making the best use of them is key

Network resources are expensive.
Making the best use of them is key, but hard

Configuring the network is complex

tons of protocols & mechanisms

Configuration must be adapted frequently

as demands or traffic shift

Lack of router coordination leads to poor utilization

average utilisation of 40-60% [SWAN, SIGCOMM'13]

BwE and DEFO improve network resources utilization

BwE: Flexible, Hierarchical Bandwidth Allocation for WAN Distributed Computing

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ABSTRACT

WAN bandwidth remains a constrained resource that is economically infeasible to substantially overprovision. Hence, it is important to allocate capacity according to service priority and based on the incremental value of additional allocation. For example, it may be the highest priority for one service to receive 10Gb/s of bandwidth but upon reaching such an allocation, incremental priority may drop sharply favoring allocation to other services. Motivated by the observation that individual flows with fixed priority may not be the ideal basis for bandwidth allocation, we present the design and implementation of Bandwidth Enforcer (BwE), a global, hierarchical bandwidth allocation infrastructure. BwE supports: i) service-level bandwidth allocation following prioritized bandwidth functions where a service can represent an arbitrary collection of flows, ii) independent allocation and delegation policies according to user-defined hierarchy, all accounting for a global view of bandwidth and failure conditions, iii) multi-path forwarding common in traffic-engineered networks, and iv) a central administrative point to override (perhaps faulty) policy during exceptional conditions. BwE has delivered more service-efficient bandwidth utilization and simpler management in production for multiple years.

CCS Concepts

•**Networks → Network resources allocation;** *Network management;*

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Keywords

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This paper re-examines bandwidth allocation for an important, emerging trend, distributed computing running across dedicated private WANs in support of cloud computing and service providers. Thousands of simultaneous such applications run across multiple global data centers, with thousands of processes in each data center, each potentially maintaining thousands of individual active connections to remote servers. WAN traffic engineering means that site-pair communication follows different network paths, each with different bottlenecks. Individual services have vastly different bandwidth, latency, and loss requirements.

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Unfortunately, prior works on Software Defined Networking (SDN) do not cover carrier-grade networks, i.e., geographically-distributed networks with hundreds of nodes like Internet Service Provider (ISP) ones. Those networks have special needs: Beyond manageability and flexibility, ISP operators also have to guarantee high scalability (e.g., to support all the Internet prefixes at tens of Points of Presence) and preserve network performance upon failures (e.g., to comply with Service Level Agreements). Moreover, the large scale and geographical distribution of those networks exacerbates SDN challenges, like controller reactivity, controller-to-switch communication and equipment upgrade. Consequently, SDN solutions targeting campuses [2], enterprises [4] and data-centers (DCs) [5], cannot be easily ported to carrier-grade networks. Even approaches designed for wide area and inter-DC networks [6, 7, 8] do not fit. Indeed, they assume that (i) the scale of the network (e.g., number of devices and geographical distances) is small, (ii) scalability and robustness play a more limited role (e.g., because of the small number of destinations [6]), and (iii) the SDN controller may apply some control over traffic sources (e.g., [7]).

Nevertheless, carrier-grade networks would also benefit from an SDN-like approach. Currently, network management (i) relies on protocols with practical limitations, either in terms of expressiveness (as for link-state IGPs, constrained by the adopted shortest-path routing model) or of scalability and overhead (like for MPLS RSVP-TE, based on per-path tunnel signaling); and

BwE and DEFO improve network resources utilization.

They do so in two completely different contexts

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WAN

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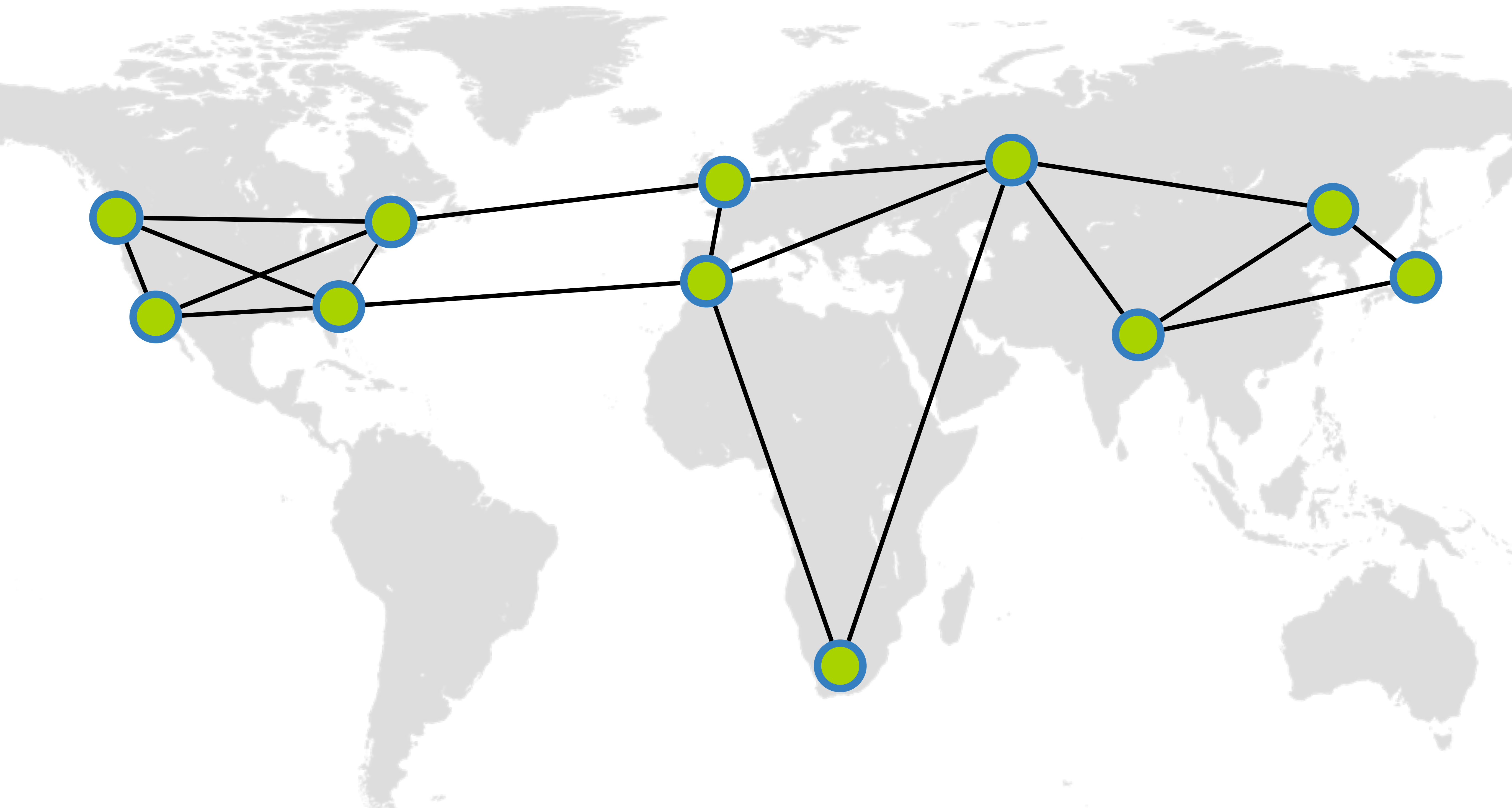

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A Declarative and Expressive Approach to Control Forwarding Paths in Carrier-Grade Networks

CGN

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ABSTRACT

SDN simplifies network management by relying on declarativity (high-level interface) and expressiveness (network flexibility). We propose a solution to support those features while preserving high robustness and scalability as needed in carrier-grade networks. Our solution is based on (i) a two-layer architecture separating connectivity and optimization tasks; and (ii) a centralized optimizer called DEFO, which translates high-level goals expressed almost in natural language into compliant network configurations. Our evaluation on real and synthetic topologies shows that DEFO improves the state of the art by (i) achieving better trade-offs for classic goals covered by previous works, (ii) supporting a larger set of goals (refined traffic engineering and service chaining), and (iii) optimizing large ISP networks in few seconds. We also quantify the gains of our implementation, running Segment Routing on top of IS-IS, over possible alternatives (RSVP-TE and OpenFlow).

CCS Concepts

•**Networks** → **Network architectures; Traffic engineering algorithms; Network management;** *Routing protocols;* •**Theory of computation** → *Constraint and logic programming;*

Keywords

SDN; traffic engineering; service chaining; segment routing; MPLS; ISP; optimization

*R. Hartert is a research fellow of F.R.S.-FNRS, and S. Vissicchio is a postdoctoral researcher of F.R.S.-FNRS.

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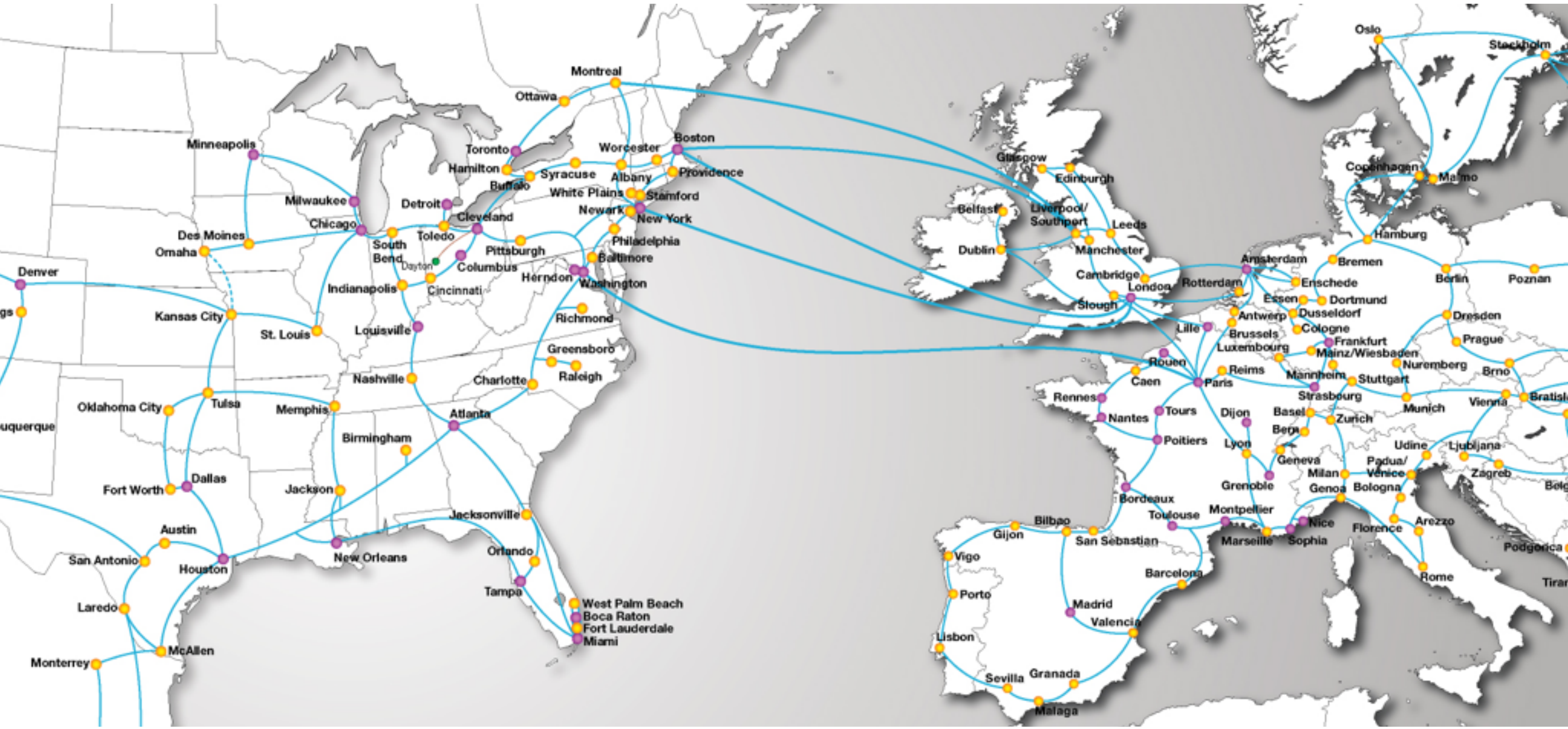
1. INTRODUCTION

By promising to overcome major problems of traditional per-device network management (e.g., see [1]), centralized architectures enabled by protocols like OpenFlow [2] and segment routing [3] are attracting huge interest from both researchers and operators. Two features are key to this success: declarativity and expressiveness. The former improves manageability, promoting abstractions and high-level interfaces to configuration. The latter enables flexibility of network behavior, e.g., in terms of packet forwarding and modification.

Unfortunately, prior works on Software Defined Networking (SDN) do not cover carrier-grade networks, i.e., geographically-distributed networks with hundreds of nodes like Internet Service Provider (ISP) ones. Those networks have special needs: Beyond manageability and flexibility, ISP operators also have to guarantee high scalability (e.g., to support all the Internet prefixes at tens of Points of Presence) and preserve network performance upon failures (e.g., to comply with Service Level Agreements). Moreover, the large scale and geographical distribution of those networks exacerbates SDN challenges, like controller reactivity, controller-to-switch communication and equipment upgrade. Consequently, SDN solutions targeting campuses [2], enterprises [4] and data-centers (DCs) [5], cannot be easily ported to carrier-grade networks. Even approaches designed for wide area and inter-DC networks [6, 7, 8] do not fit. Indeed, they assume that (i) the scale of the network (e.g., number of devices and geographical distances) is small, (ii) scalability and robustness play a more limited role (e.g., because of the small number of destinations [6]), and (iii) the SDN controller may apply some control over traffic sources (e.g., [7]).

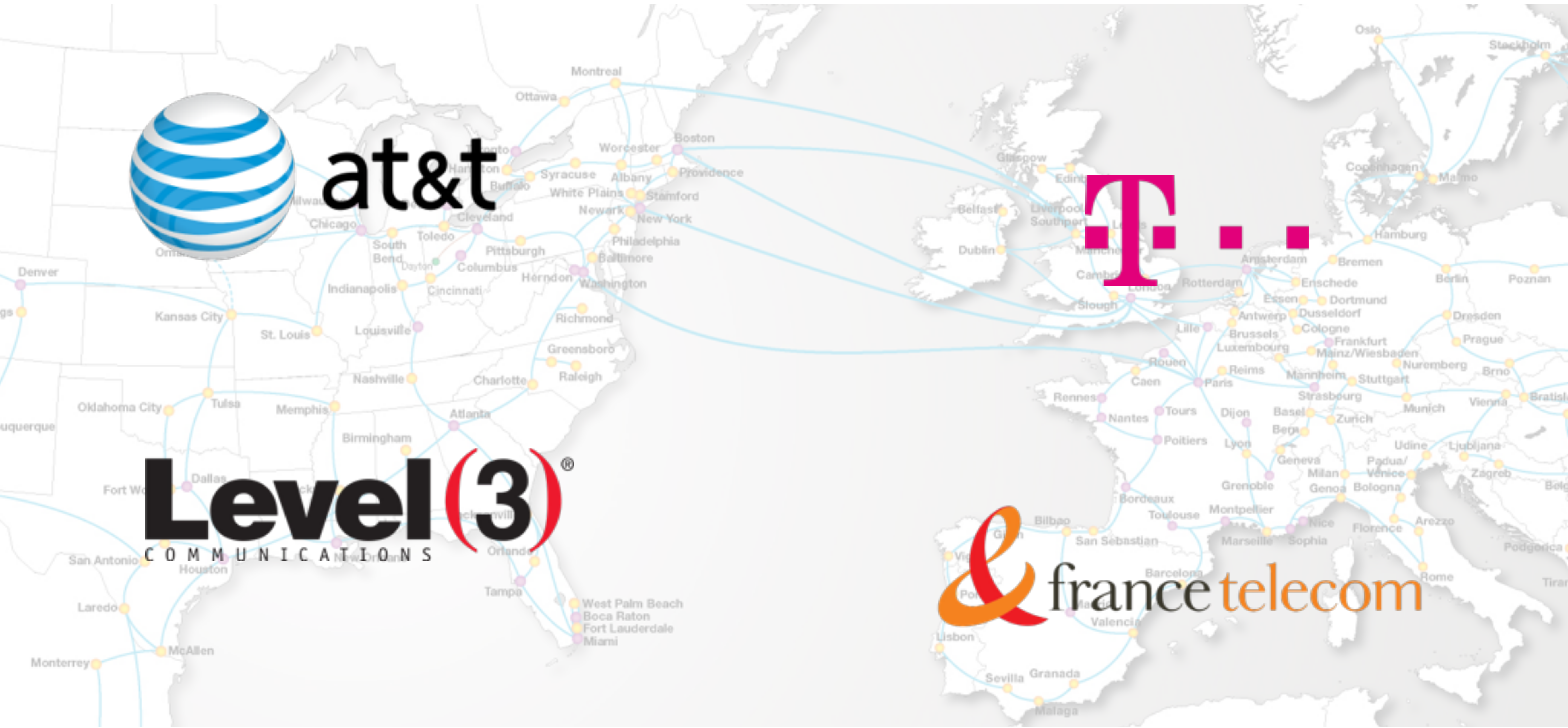
Nevertheless, carrier-grade networks would also benefit from an SDN-like approach. Currently, network management (i) relies on protocols with practical limitations, either in terms of expressiveness (as for link-state IGPs, constrained by the adopted shortest-path routing model) or of scalability and overhead (like for MPLS RSVP-TE, based on per-path tunnel signaling); and

Carrier-Grade Networks provide Internet services (often) worldwide



Cogent Network Map

Carrier-Grade Networks provide Internet services (often) worldwide



WAN and CGN differ in terms of scale

	WAN	CGN
# of nodes	O(10)	$O(10^2 – 10^3)$
destinations (forwarding table)	$O(10^3)$	$O(10^6)$

WAN and CGN differ in terms of scale and control

	WAN	CGN
# of nodes	O(10)	$O(10^2–10^3)$
destinations (forwarding table)	$O(10^3)$	$O(10^6)$
control	end-to-end	network only

Because of these differences,
the two papers differ widely

BwE allocates bandwidth to applications and enforces it hierarchically *starting from the hosts*

BwE: Flexible, Hierarchical Bandwidth Allocation for WAN Distributed Computing

Alok Kumar, Sushant Jain, Uday Naik, Anand Raghuraman, Nikhil Kasinadhuni, Enrique Cauich Zermeno, C. Stephen Gunn, Jing Ai, Björn Carlin, Mihai Amarandei-Stavila, Mathieu Robin, Aspi Siganporia, Stephen Stuart, Amin Vahdat

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ABSTRACT

WAN bandwidth remains a constrained resource that is economically infeasible to substantially overprovision. Hence, it is important to allocate capacity according to service priority and based on the incremental value of additional allocation. For example, it may be the highest priority for one service to receive 10Gb/s of bandwidth but upon reaching such an allocation, incremental priority may drop sharply favoring allocation to other services. Motivated by the observation that individual flows with fixed priority may not be the ideal basis for bandwidth allocation, we present the design and implementation of Bandwidth Enforcer (BwE), a global, hierarchical bandwidth allocation infrastructure. BwE supports: i) service-level bandwidth allocation following prioritized bandwidth functions where a service can represent an arbitrary collection of flows, ii) independent allocation and delegation policies according to user-defined hierarchy, all accounting for a global view of bandwidth and failure conditions, iii) multi-path forwarding common in traffic-engineered networks, and iv) a central administrative point to override (perhaps faulty) policy during exceptional conditions. BwE has delivered more service-efficient bandwidth utilization and simpler management in production for multiple years.

CCS Concepts

•**Networks → Network resources allocation;** *Network management;*

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Keywords

Bandwidth Allocation; Wide-Area Networks; Software-Defined Network; Max-Min Fair

1. INTRODUCTION

TCP-based bandwidth allocation to individual flows contending for bandwidth on bottleneck links has served the Internet well for decades. However, this model of bandwidth allocation assumes all flows are of equal priority and that all flows benefit equally from any incremental share of available bandwidth. It implicitly assumes a client-server communication model where a TCP flow captures the communication needs of an application communicating across the Internet.

This paper re-examines bandwidth allocation for an important, emerging trend, distributed computing running across dedicated private WANs in support of cloud computing and service providers. Thousands of simultaneous such applications run across multiple global data centers, with thousands of processes in each data center, each potentially maintaining thousands of individual active connections to remote servers. WAN traffic engineering means that site-pair communication follows different network paths, each with different bottlenecks. Individual services have vastly different bandwidth, latency, and loss requirements.

We present a new WAN bandwidth allocation mechanism supporting distributed computing and data transfer. BwE provides work-conserving bandwidth allocation, hierarchical fairness with flexible policy among competing services, and Service Level Objective (SLO) targets that independently account for bandwidth, latency, and loss.

BwE's key insight is that routers are the wrong place to map policy designs about bandwidth allocation onto per-packet behavior. Routers cannot support the scale and complexity of the necessary mappings, often because the semantics of these mappings cannot be captured in individual packets. Instead, following the End-to-End Argument[28], we push all such mapping to the source host machines. Hosts rate limit their outgoing traffic and mark packets using the DSCP field. Routers use the DSCP marking to determine which

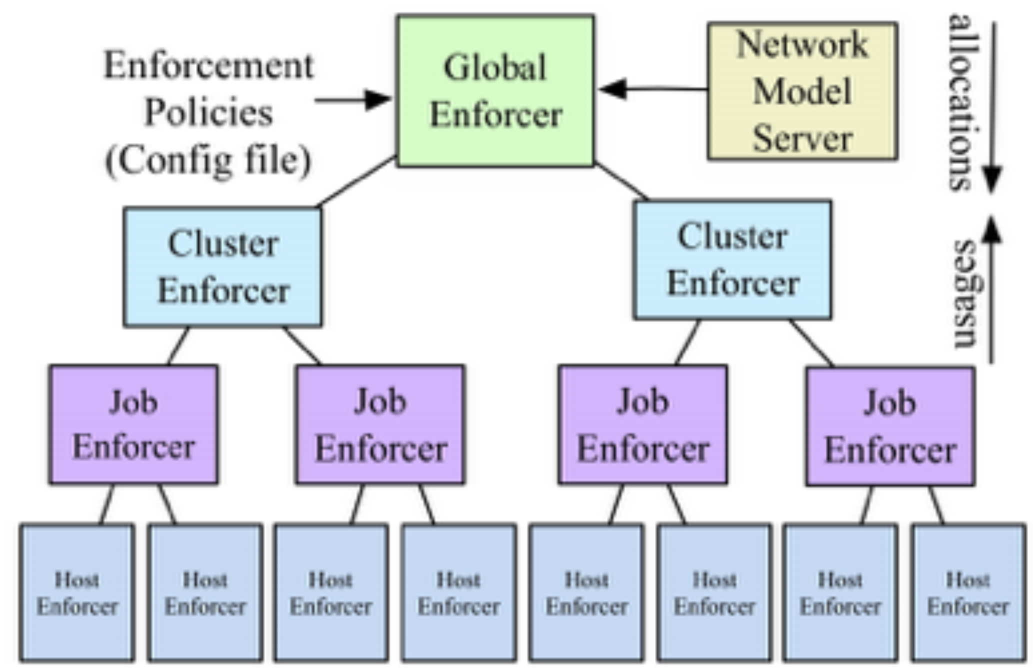
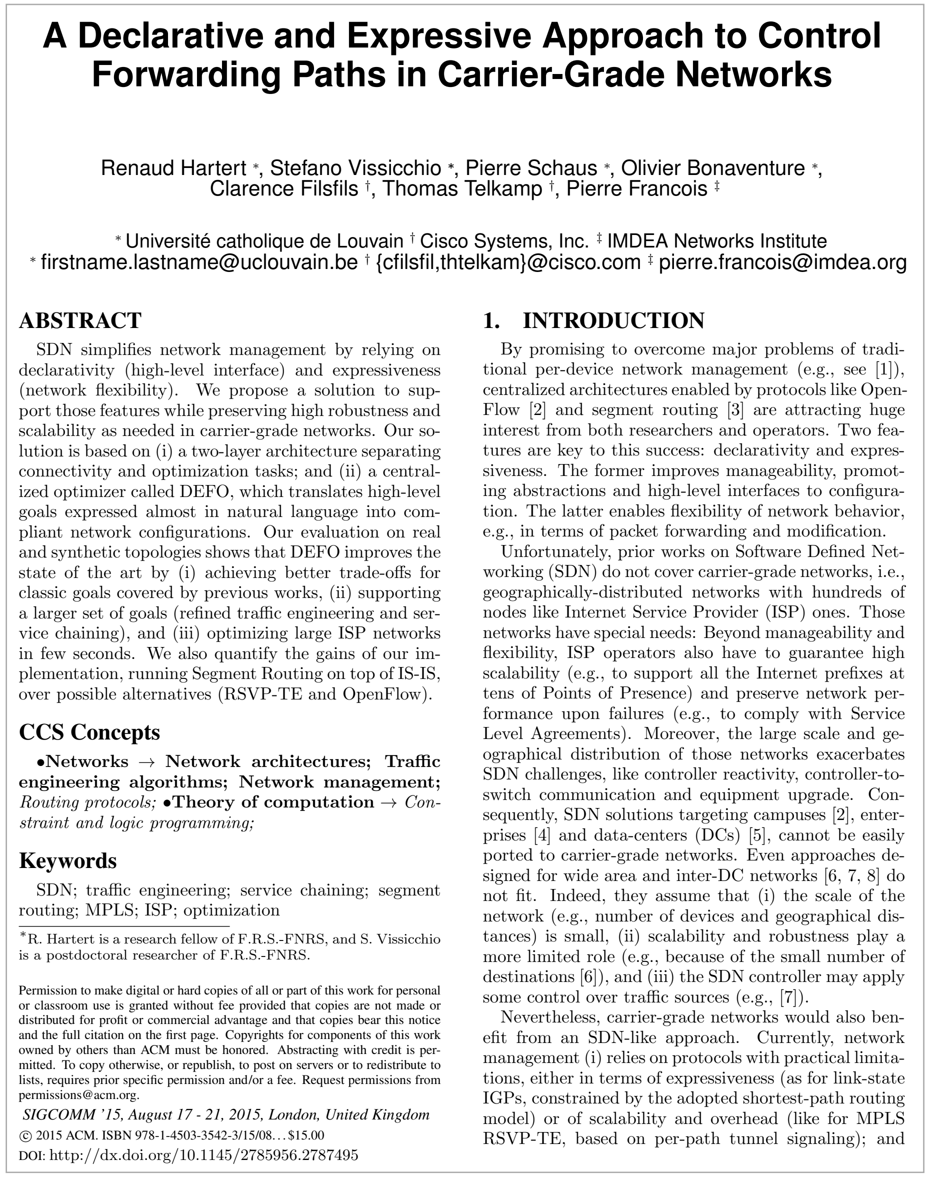


Figure 5: BwE Architecture.

DEFO computes paths compliant with given constraints and programs them *in the network*

function	DSL syntax	semantics
max load	d.load	maximum load of any link in $F(d)$
max delay	d.delay	maximum delay of source-destination paths in $F(d)$
deviations	d.deviations	number of deviations from connectivity paths in $F(d)$
traversal	d passThrough S	true if $F(d)$ crosses any node in S, false otherwise
sequencing	d passThrough S_1 then S_2 ... then S_k	true if $F(d)$ sequentially crosses nodes in $S_1 \dots S_k$
avoid	d avoid S	true if no node in S is also in $F(d)$, false otherwise

```
var MaxLoad = max(for(l<-topology.links){yield l.load})
val goal = new Goal(topology){ minimize(MaxLoad) }
```



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PGA: Using Graphs to Express and Automatically Reconcile Network Policies

Chaithan Prakash^* Jeongkeun Lee† Yoshio Turner°* Joon-Myung Kang† Aditya Akella^ Sujata Banerjee† Charles Clark‡ Yadi Ma† Puneet Sharma† Ying Zhang†
^University of Wisconsin-Madison, †HP Labs, °Banyan, ‡HP Networking

Central Control Over Distributed Routing

http://fibbing.net

Stefano Vissicchio*, Olivier Tilmans*, Laurent Vanbever†, Jennifer Rexford‡
* Université catholique de Louvain, † ETH Zurich, ‡ Princeton University
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network policies

Networks often rely on forwarding policies,
especially enterprise and campus networks

Policies are often defined by different people

Customer relationship administrator

Company network administrator

Forwarding policy

Customer relationship administrator

Company network administrator

Forwarding policy

Customer relationship administrator	Only marketing employee can use a CRM application, using port 7000. Traffic must go via a Load-Balancer first.
Company network administrator	

	Forwarding policy
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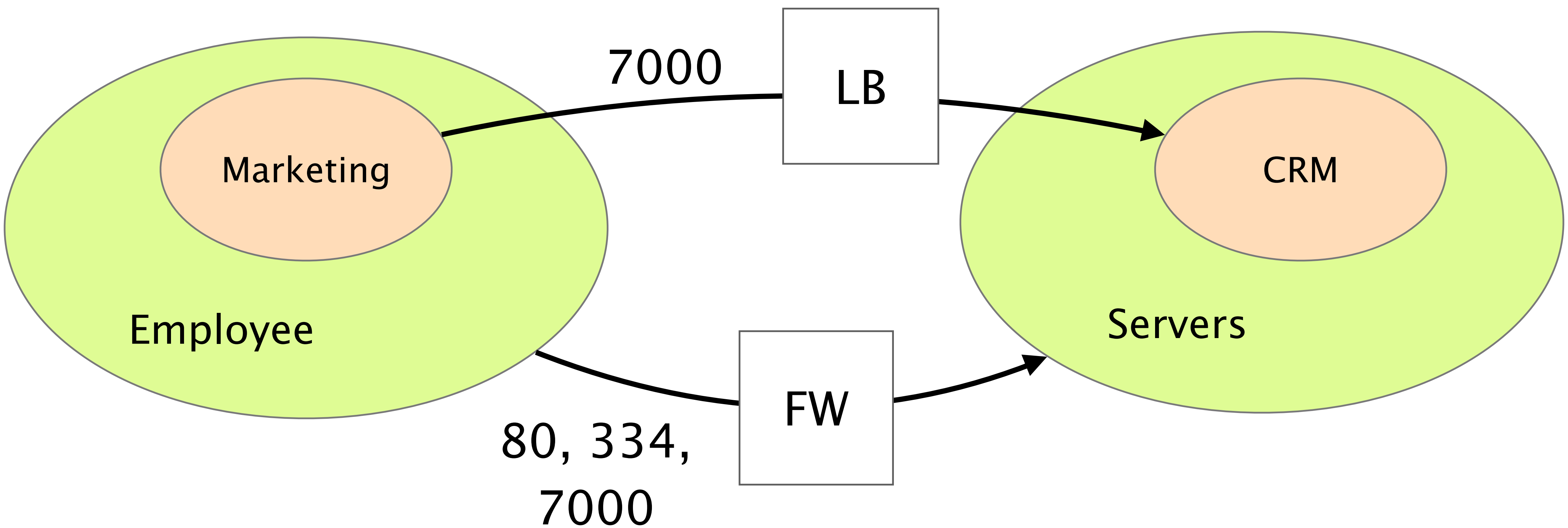
Company network administrator	Any employee can only access servers using port 80, 334 and 7000. All traffic must go via a Firewall first.


7000
LB
Marketing
CRM
Employee
Servers
FW
80, 334,
7000

Customer relationship administrator	Only marketing employee can use a CRM application, using port 7000. Traffic must go via a Load-Balancer first.
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What about marketing employees' traffic to the CRM?

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It must go through a LB

Customer relationship administrator

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It must go through a LB *and* a Firewall

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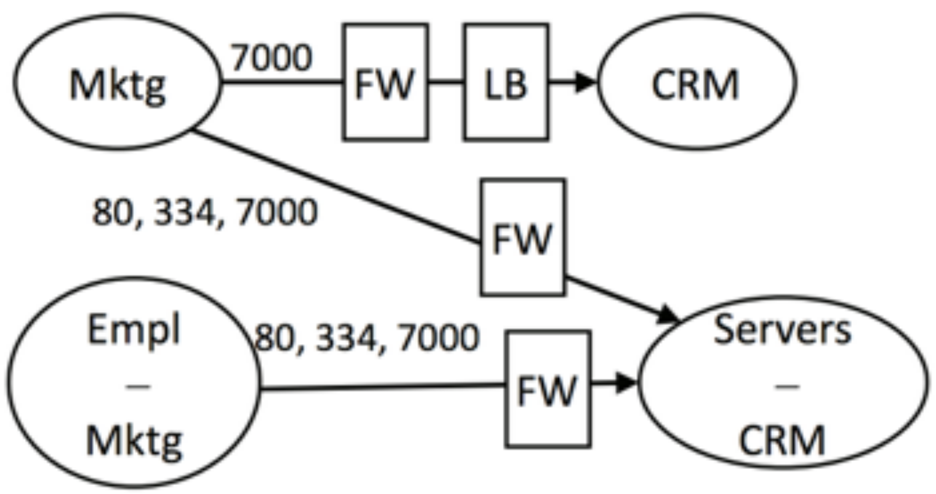
Composing different policies is tricky
as we must reason on the joint intent

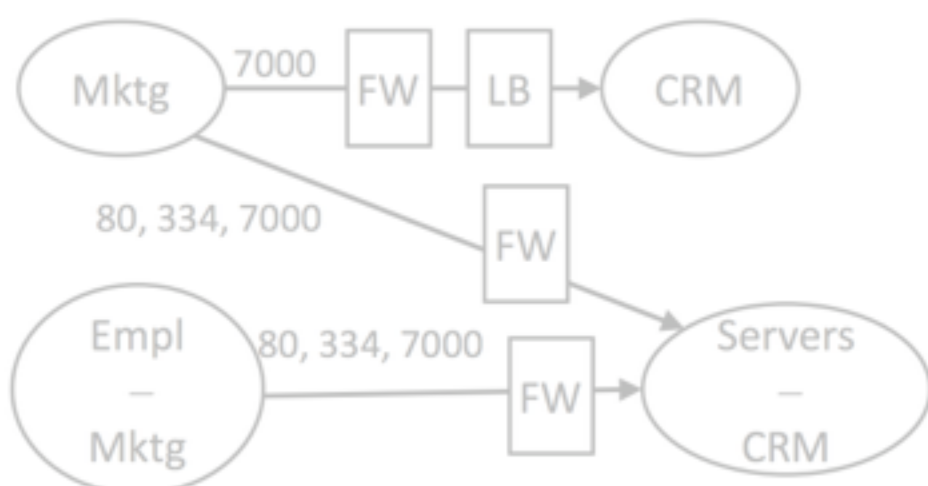
PGA uses a graph abstraction to specify policies

PGA high-level policy



PGA uses a graph abstraction to specify policies and automatically composes and compiles them

PGA high-level policy



PGA framework

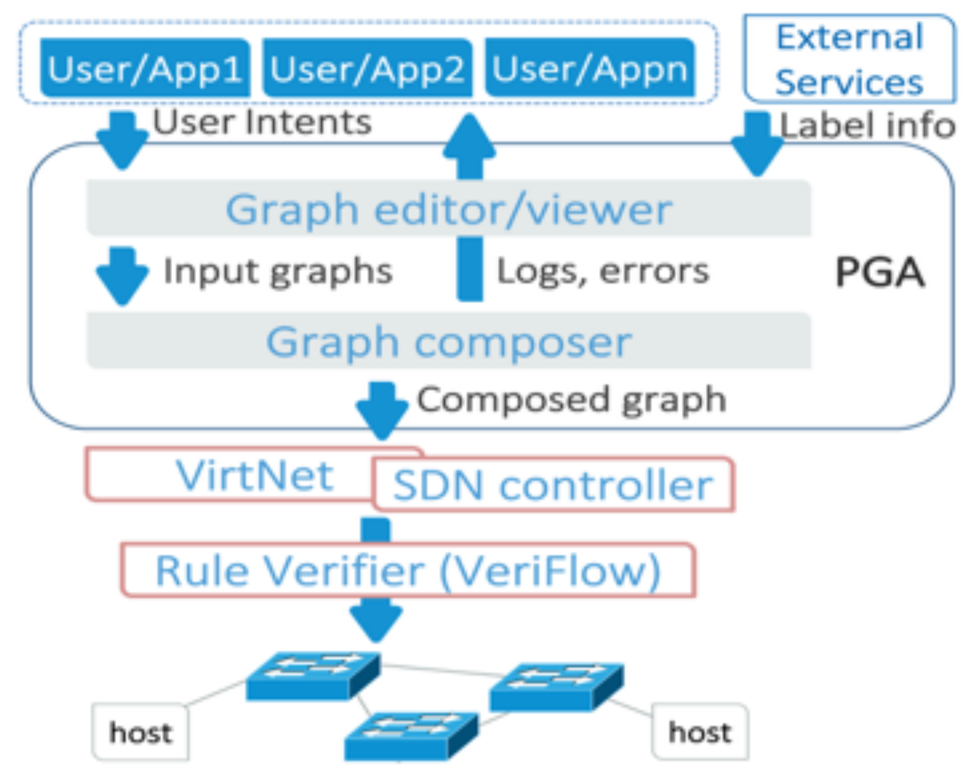


Figure 2: PGA system architecture.

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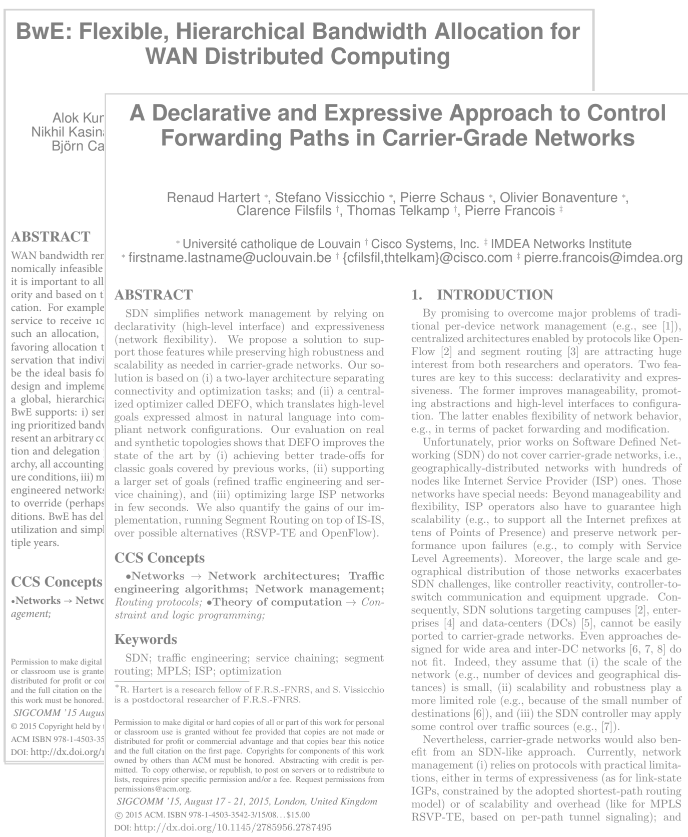

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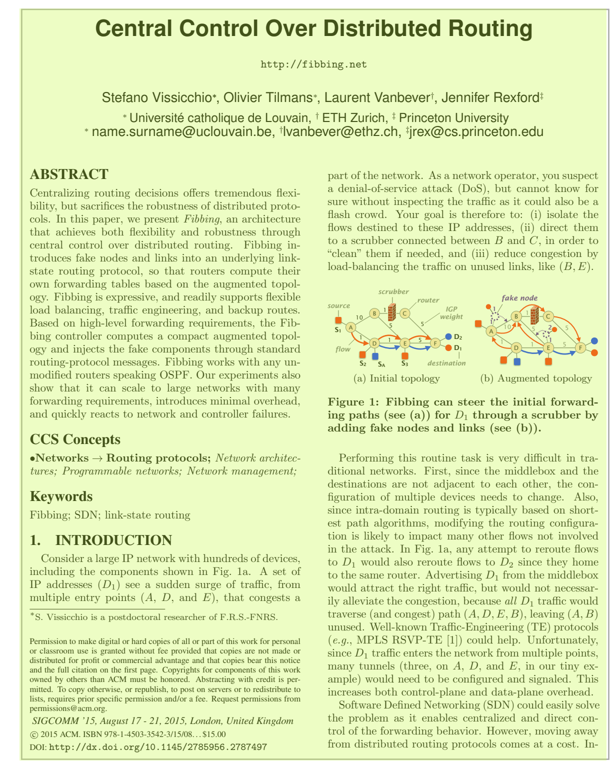

Central Control Over Distributed Routing

http://fibbing.net

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Université catholique de Louvain, ETH Zurich, Princeton University

programmability

SDN is great, but we need compatible devices

(which aren’t deployed in most networks)

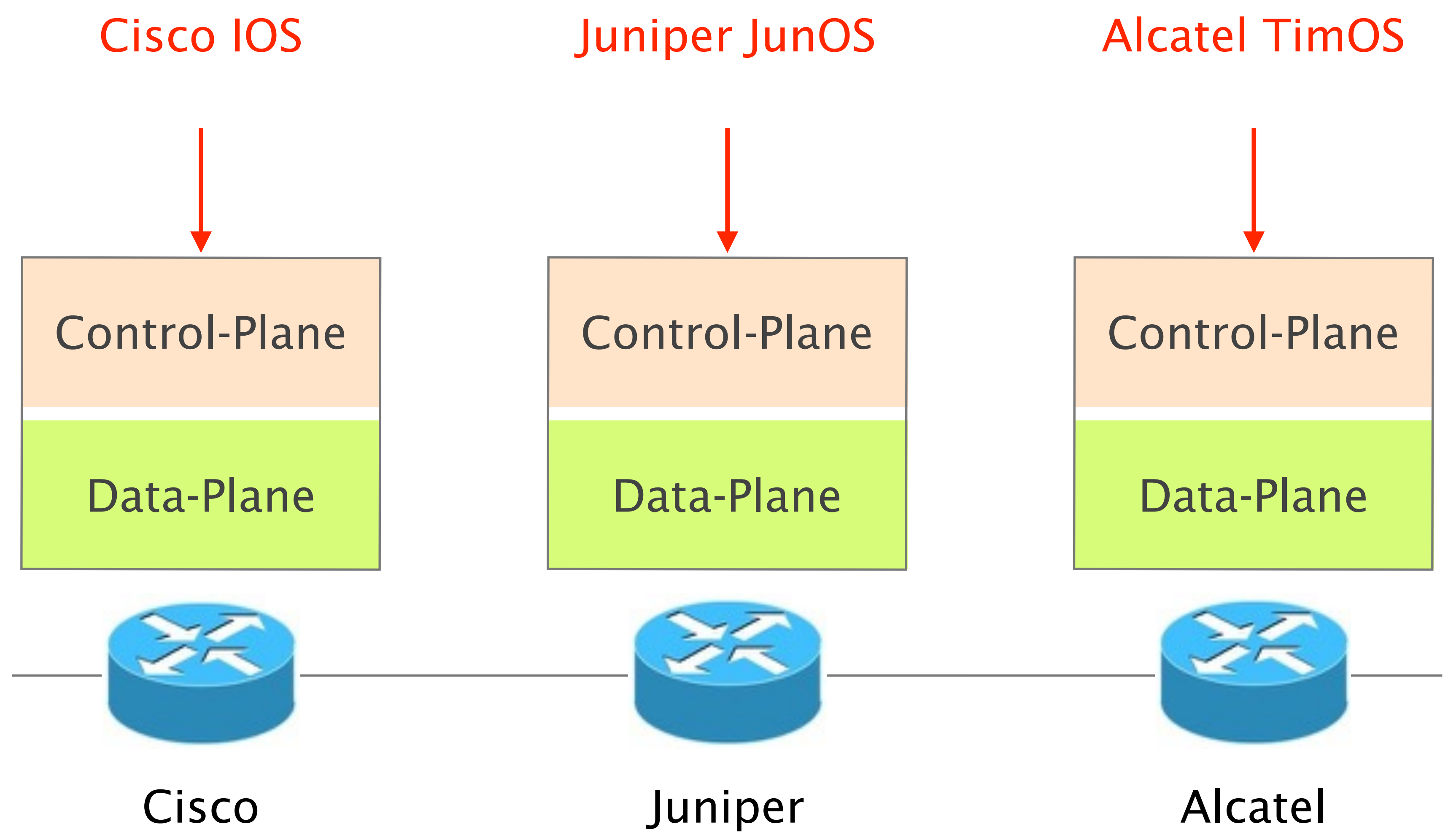
Wouldn’t it be great to program

an existing network “à la SDN”?

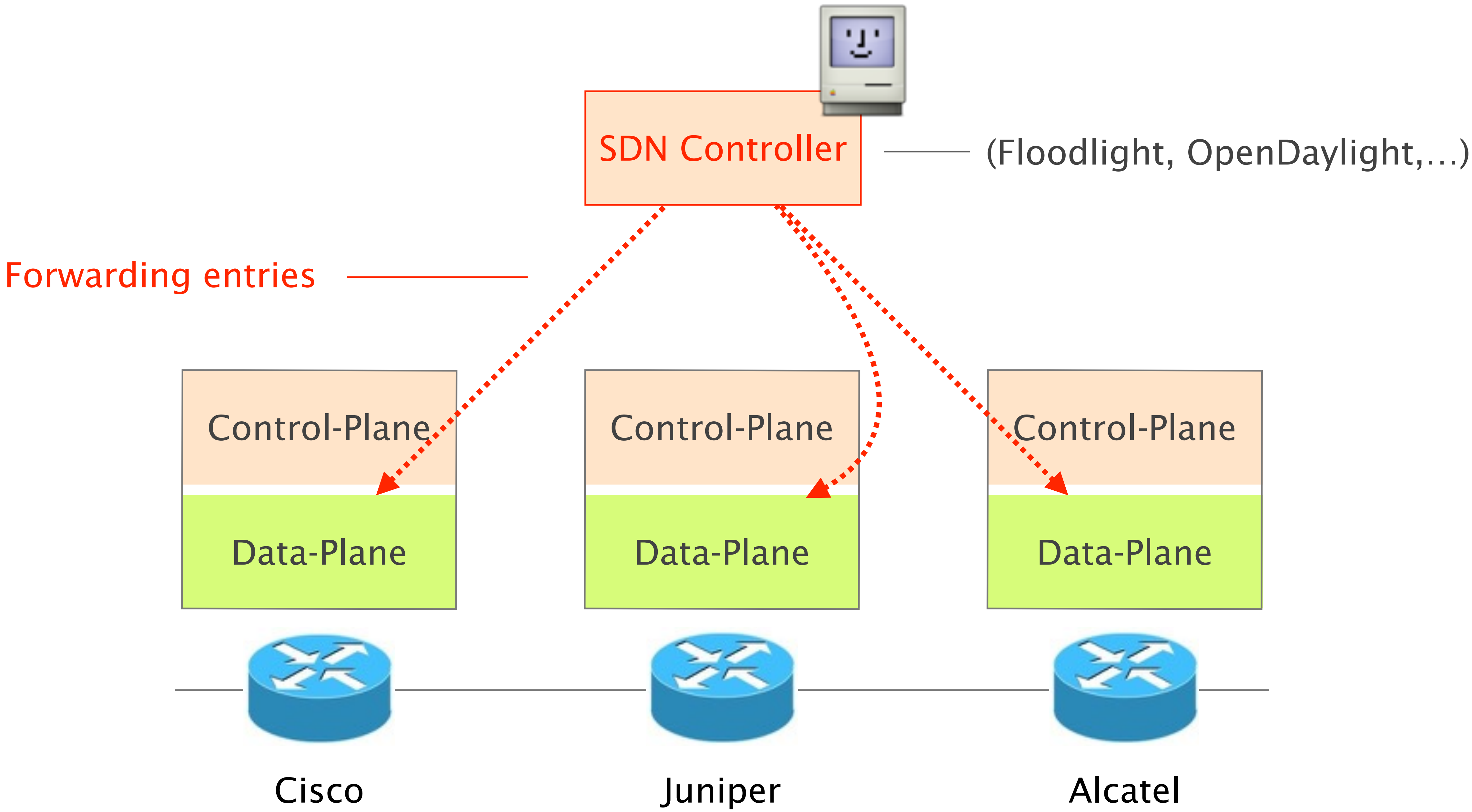
Wouldn't it be great to program
an existing network "à la SDN"?

what does it mean?

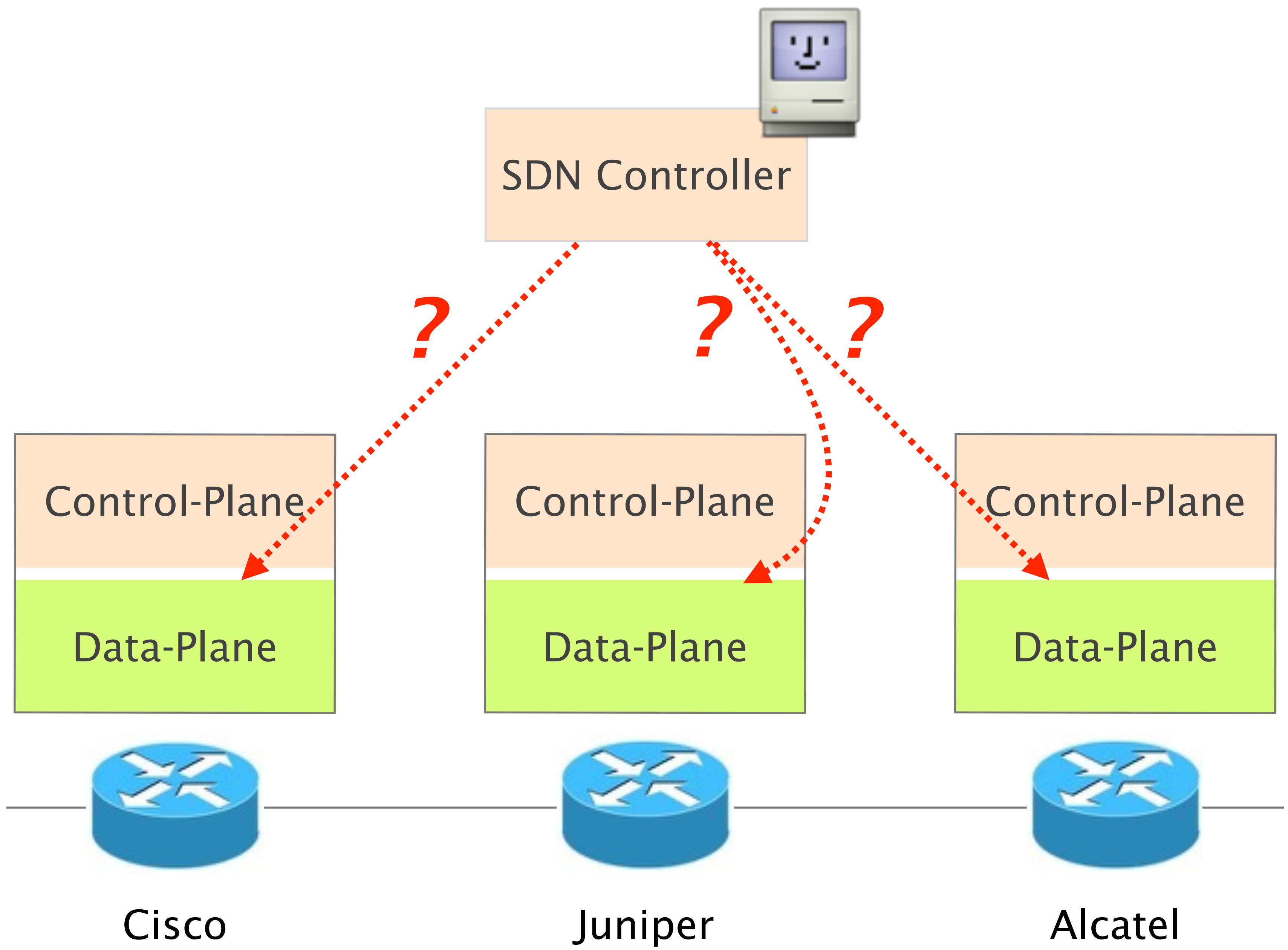
Instead of configuring a network using configuration "languages"...



...program it from a central SDN controller



For that, we need an API
that *any* router can understand



Routing protocols are perfect candidates to act as such API

- messages are standardized

  all routers speak the same language

- behaviors are well-defined

  e.g., shortest-path routing

- implementations are widely available

  nearly all routers support OSPF

Fibbing

Fibbing

= lying

Fibbing

to **control** router's forwarding table

Given a set of forwarding entries
to install network-wide

Given a set of forwarding entries
to install network-wide,

Fibbing generates fake routing messages
which trick routers into computing the
appropriate forwarding entries.

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Fibbing generates fake routing messages
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In a way that is scalable and robust

SDN track @SIGCOMM'15


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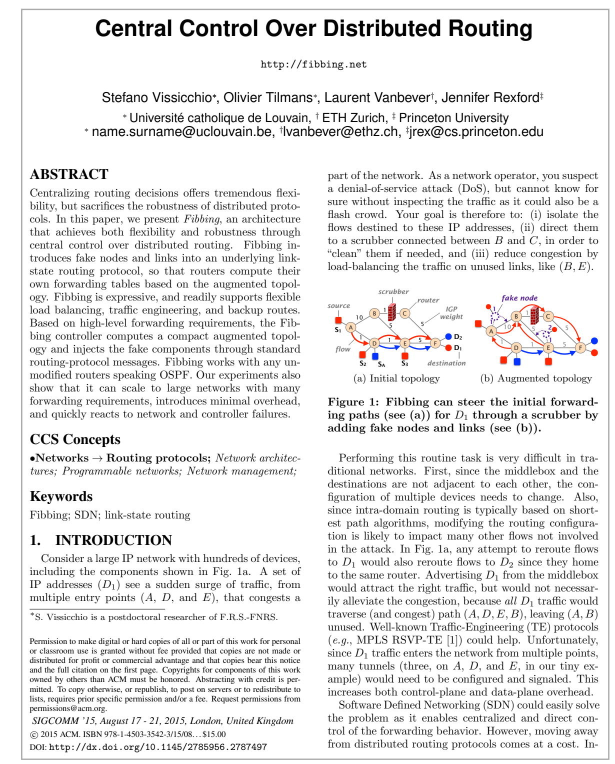
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bandwidth management

network policies

programmability

One more thing…

P4: Programming Protocol-Independent Packet Processors

Pat Bosshart[†], Dan Daly[*], Glen Gibb[†], Martin Izzard[†], Nick McKeown[‡], Jennifer Rexford[**], Cole Schlesinger[**], Dan Talayco[†], Amin Vahdat[¶], George Varghese[§], David Walker[**]
[†]Barefoot Networks [*]Intel [‡]Stanford University [**]Princeton University [¶]Google [§]Microsoft Research

ABSTRACT

P4 is a high-level language for programming protocol-independent packet processors. P4 works in conjunction with SDN control protocols like OpenFlow. In its current form, OpenFlow explicitly specifies protocol headers on which it operates. This set has grown from 12 to 41 fields in a few years, increasing the complexity of the specification while still not providing the flexibility to add new headers. In this paper we propose P4 as a strawman proposal for how OpenFlow should evolve in the future. We have three goals: (1) Reconfigurability in the field: Programmers should be able to change the way switches process packets once they are deployed. (2) Protocol independence: Switches should not be tied to any specific network protocols. (3) Target independence: Programmers should be able to describe packet-processing functionality independently of the specifics of the underlying hardware. As an example, we describe how to use P4 to configure a switch to add a new hierarchical label.

1. INTRODUCTION

Software-Defined Networking (SDN) gives operators programmatic control over their networks. In SDN, the control plane is physically separate from the forwarding plane, and one control plane controls multiple forwarding devices. While forwarding devices could be programmed in many ways, having a common, open, vendor-agnostic interface (like OpenFlow) enables a control plane to control forwarding devices from different hardware and software vendors.

Version	Date	Header Fields
OF 1.0	Dec 2009	12 fields (Ethernet, TCP/IPv4)
OF 1.1	Feb 2011	15 fields (MPLS, inter-table metadata)
OF 1.2	Dec 2011	36 fields (ARP, ICMP, IPv6, etc.)
OF 1.3	Jun 2012	40 fields
OF 1.4	Oct 2013	41 fields

Table 1: Fields recognized by the OpenFlow standard

The OpenFlow interface started simple, with the abstraction of a single table of rules that could match packets on a dozen header fields (e.g., MAC addresses, IP addresses, protocol, TCP/UDP port numbers, etc.). Over the past five years, the specification has grown increasingly more complicated (see Table 1), with many more header fields and multiple stages of rule tables, to allow switches to expose more of their capabilities to the controller.

The proliferation of new header fields shows no signs of stopping. For example, data-center network operators increasingly want to apply new forms of packet encapsulation (e.g., NVGRE, VXLAN, and STT), for which they resort to deploying software switches that are easier to extend with new functionality. Rather than repeatedly extending the OpenFlow specification, we argue that future switches should support flexible mechanisms for parsing packets and matching header fields, allowing controller applications to leverage these capabilities through a common, open interface (i.e., a new "OpenFlow 2.0" API). Such a general, extensible approach would be simpler, more elegant, and more future-proof than today's OpenFlow 1.x standard.

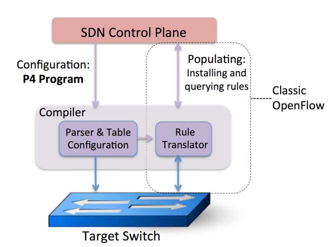

Figure 1: P4 is a language to configure switches.

Recent chip designs demonstrate that such flexibility can be achieved in custom ASICs at terabit speeds [1, 2, 3]. Programming this new generation of switch chips is far from easy. Each chip has its own low-level interface, akin to microcode programming. In this paper, we sketch the design of a higher-level language for Programming Protocol-independent Packet Processors (P4). Figure 1 shows the relationship between P4—used to configure a switch, telling it how packets are to be processed—and existing APIs (such as OpenFlow) that are designed to populate the forwarding tables in fixed function switches. P4 raises the level of abstraction for programming the network, and can serve as a

Learn how to:

- adapt the forwarding logic of a SDN device
- define your very own OpenFlow protocol!

Best of CCR session, Thu 20

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