Intent-based Network Programmability

Walter Cerroni
University of Bologna, Italy

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

The software (r)evolution in communication networks

- **Software** will play an unprecedented dominant role in upcoming communication environments
  - virtualization (computing & networks)
  - cloud/edge/fog computing
  - content delivery networks
  - 5G
  - IoT
- → **Network Softwarization**

- Softwarization means **Programmability**

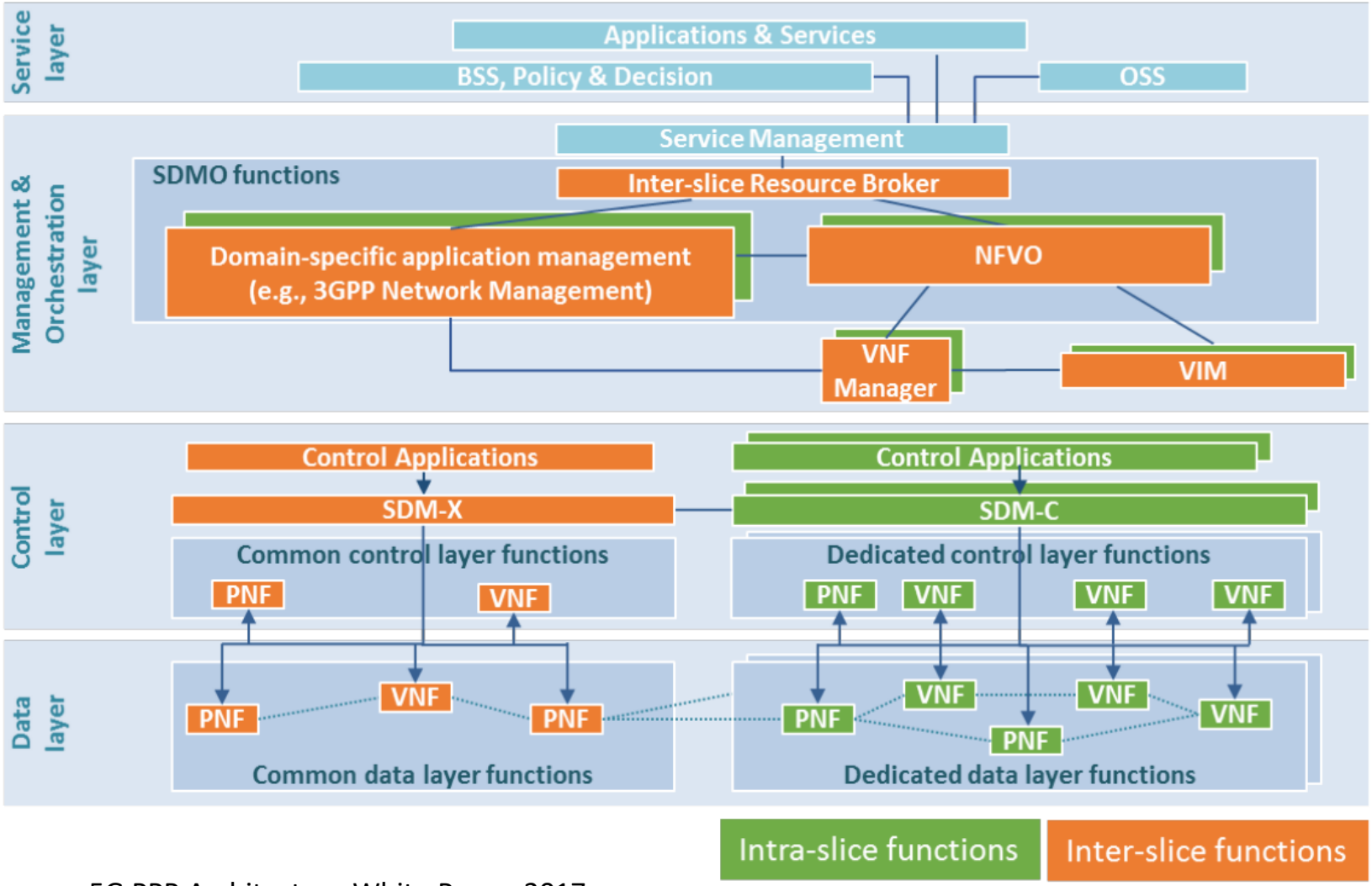
Network Programmability Timeline (i.e., the road to SDN)

1996	Programmable and Active Networks	First concept of network programmability, in the data plane Virtualized execution environments
2004 2006	IETF ForCES IETF PCE	Separation between control and data planes Standard, open interface between them Logically centralized, programmable control plane
2008	OpenFlow	Generalized forwarding device API Vision of a network operating system
2011	Open Networking Foundation (ONF)	Standardization of SDN
2014 2016	P4, OpenState, etc. DPDK, FD.io, XDP	Solutions for programmable and high-performance data plane

Network Virtualization

- Virtual Circuits (X.25, ATM)
- Virtual LANs (VLAN)
- Virtual Private Networks (VPN)
- Generic Routing Encapsulation (GRE)
- Virtual Route Forwarding (VRF)
- Link Aggregation Control Protocol (LACP)
- Virtual Extensible LANs (VXLAN)
- Virtual Switches (Linux Bridge, Open vSwitch, etc.)
- Network Namespaces
- Network Function Virtualization (NFV)
  - Virtual Machines
  - Containers
  - Microservices
  - Serverless Computing, Function-as-a-Service

5G architecture: functional layers



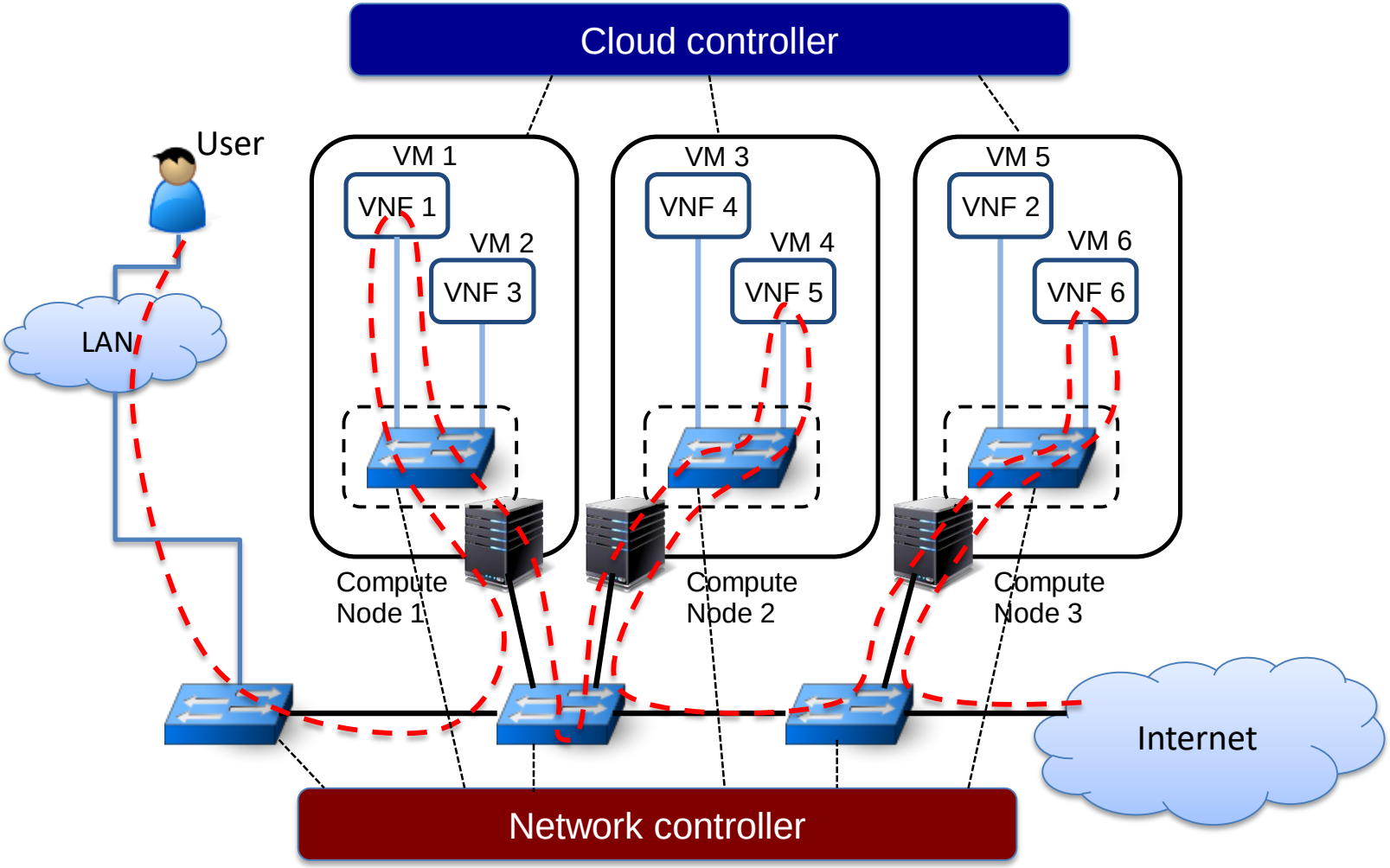
Source: 5G PPP Architecture White Paper, 2017

Enablers for network programmability

- NFV
  - software-based network elements and/or functions
  - cloud-like (*aaS) approach to virtualized infrastructure
  - scalability, mobility, replicability, etc.
- SDN
  - (logically) centralized view of network infrastructure and resources
  - open, standardized interface to control network forwarding

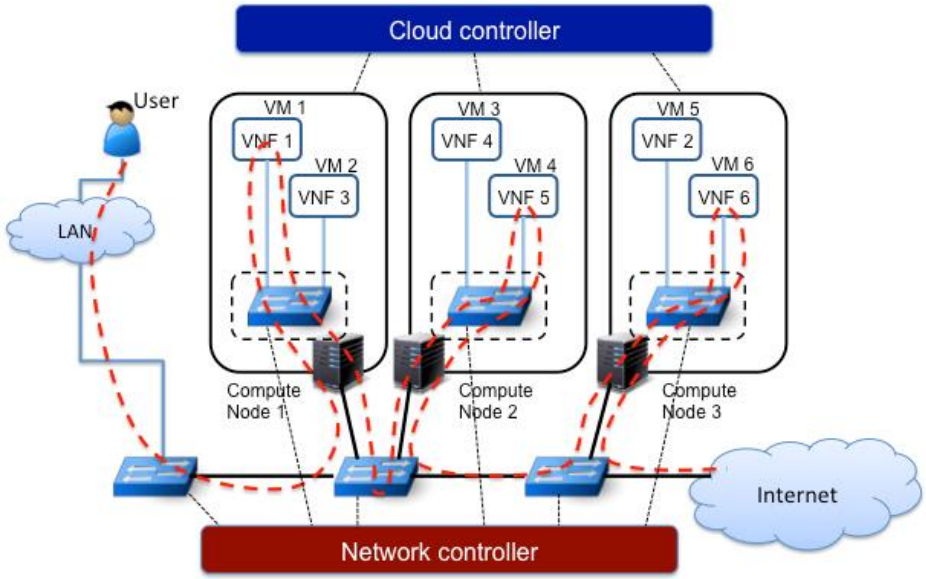
- Both contribute to enabling a programmatic approach to network management and service deployment
  - through controller's northbound interface
  - imperative vs. declarative

Example: VNF placement and traffic steering



Example: VNF placement and traffic steering

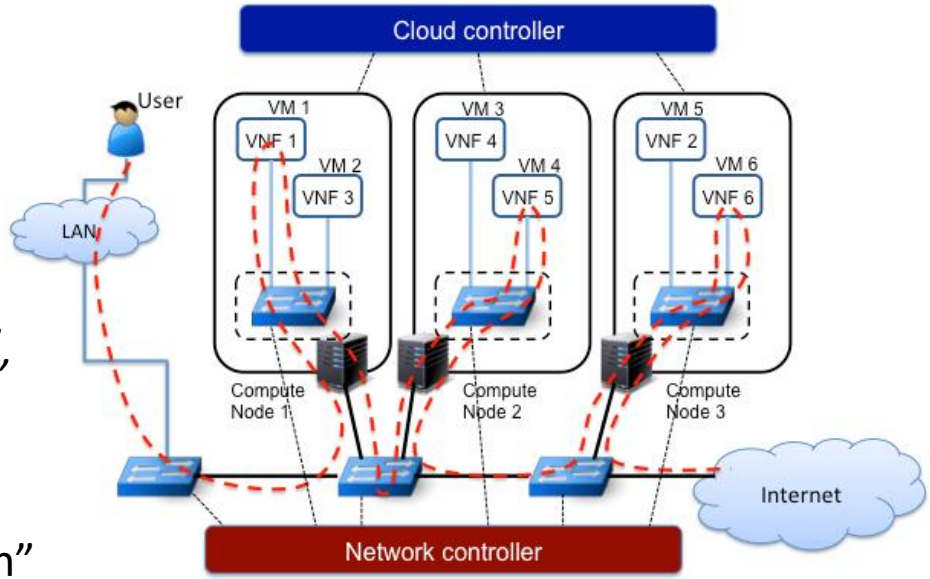
- Imperative network programming
  - specify step-by-step ***how*** the network must accomplish a given task
  - NFV
    - *"instantiate VM 1 on Compute Node 1 using VNF 1 image"*
    - *"instantiate VM 4 on Compute Node 2 using VNF 5 image"*
    - etc.
  - SDN
    - *"install flow F with matching rule R on physical switch PS 1 from port 3 to port 4"*
    - *"install flow F with matching rule R on virtual switch VS 2 from port 1 to port 2"*
    - etc.



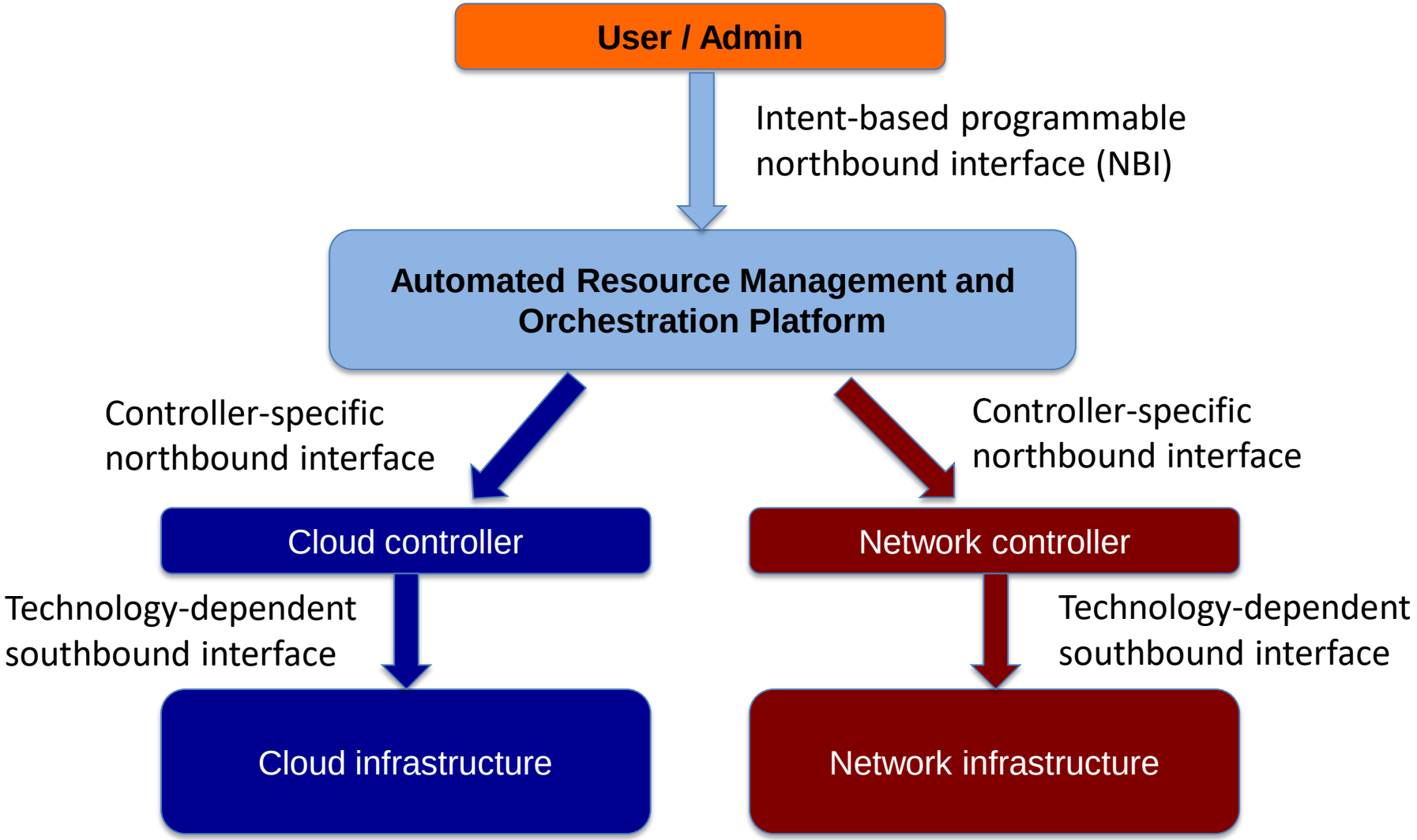
How about abstractions?

Example: VNF placement and traffic steering

- Declarative network programming
  - specify ***what*** the network must accomplish (the ***intent***)
  - leave the details of how to do it to specific implementation
  - *"my service requires functions A, B, and C before entering the Internet"*
  - something else will take care of translating the intent into an infrastructure-specific "prescription" taking advantage of NFV and SDN technologies
    - function A → VNF 1
    - function B → VNF 5
    - function C → VNF 6
    - instantiate VMs
    - steer traffic flow F accordingly



Intent-Based Networking (for NFV/SDN)



Definition of “intent”

Cambridge Dictionary

intent

noun [U] · UK /ɪnˈtent/ US /ɪnˈtent/ FORMAL OR SPECIALIZED

C2 **the fact that you want and plan to do something:**

I spent half the morning on the phone, which wasn't really my intent.

[+ to infinitive] *It was not his intent **to** hurt anyone.*

*She was charged with possessing weapons **with** intent **to** endanger life.*

Merriam-Webster

intent

noun | in·tent | \in-ˈtent\

Popularity: Top 20% of words

Tip: Synonym Guide | Examples: INTENT in a Sentence

Definition of INTENT

1 a : the act or fact of intending : PURPOSE; *especially* : the design or purpose to commit a wrongful or criminal act • admitted wounding him with *intent*

b : the state of mind with which an act is done : VOLITION

2 : a usually clearly formulated or planned intention : AIM • the director's *intent*

3 a : MEANING, SIGNIFICANCE

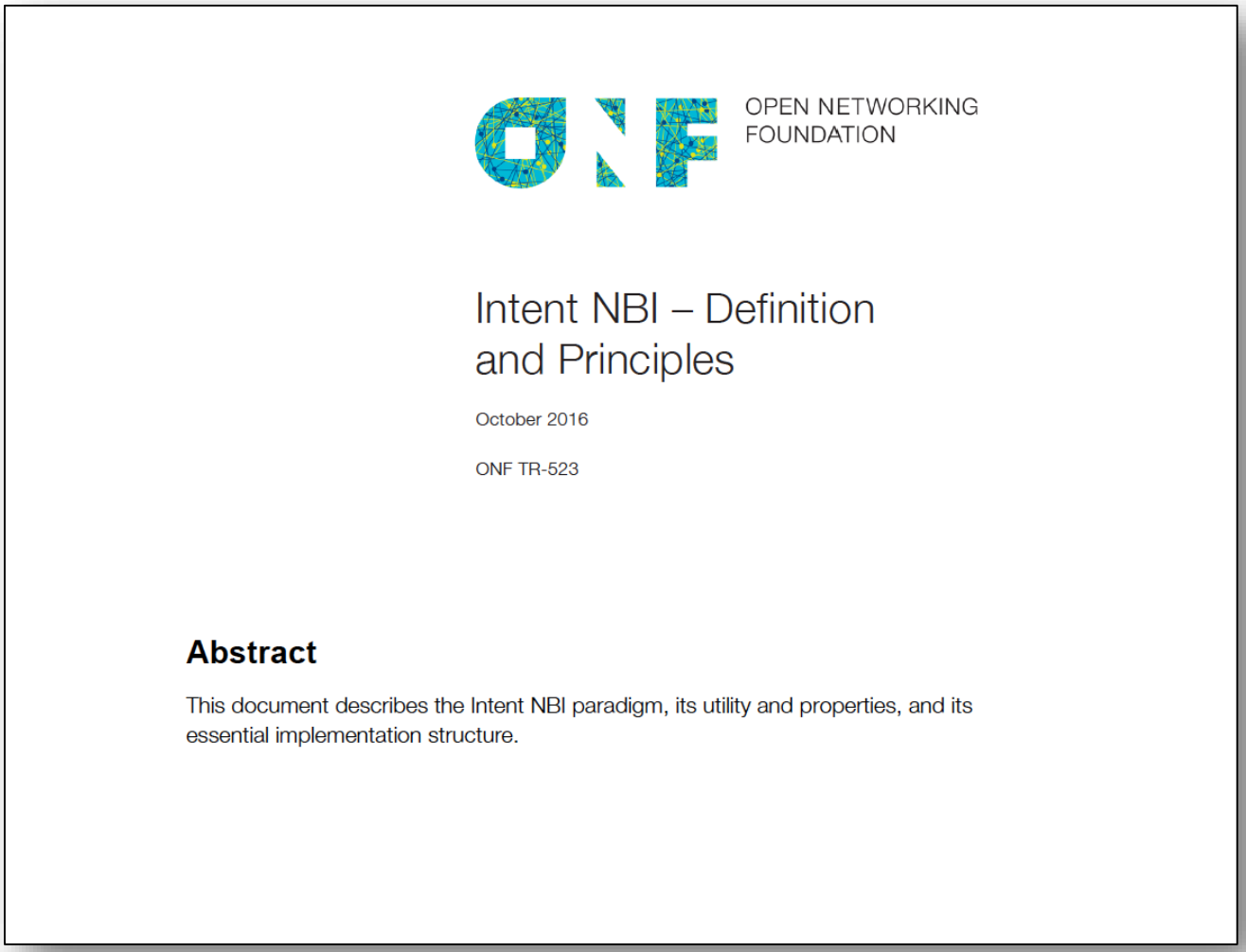
b : CONNOTATION 3

Intent-Based Networking: early definition

- An intent-based ***interface*** (typically a NBI)
  - is ***invariant***
    - infrastructure- and technology-agnostic by design
  - is ***portable***
    - not bound to specific protocols, vendors, infrastructure provider solutions
  - is ***compose-able***
    - extensible and designed to allow disparate services, developed independently, to express their resource requirements in a common language
    - accessible services share a common resource allocation and management engine
  - ***scales out***, not up
    - same intent for single large domain or multiple small domains, enabling scaling out
  - provides ***context***
    - allows to determine actual or apparent conflicts of the multiple-client services

David Lenrow, *Intent: Don't Tell Me What to Do! (Tell Me What You Want)*, SDxCentral, Feb. 12, 2015

A first step toward standardization



OPEN NETWORKING FOUNDATION

Intent NBI – Definition and Principles

October 2016

ONF TR-523

Abstract

This document describes the Intent NBI paradigm, its utility and properties, and its essential implementation structure.

Intent NBI: ONF approach

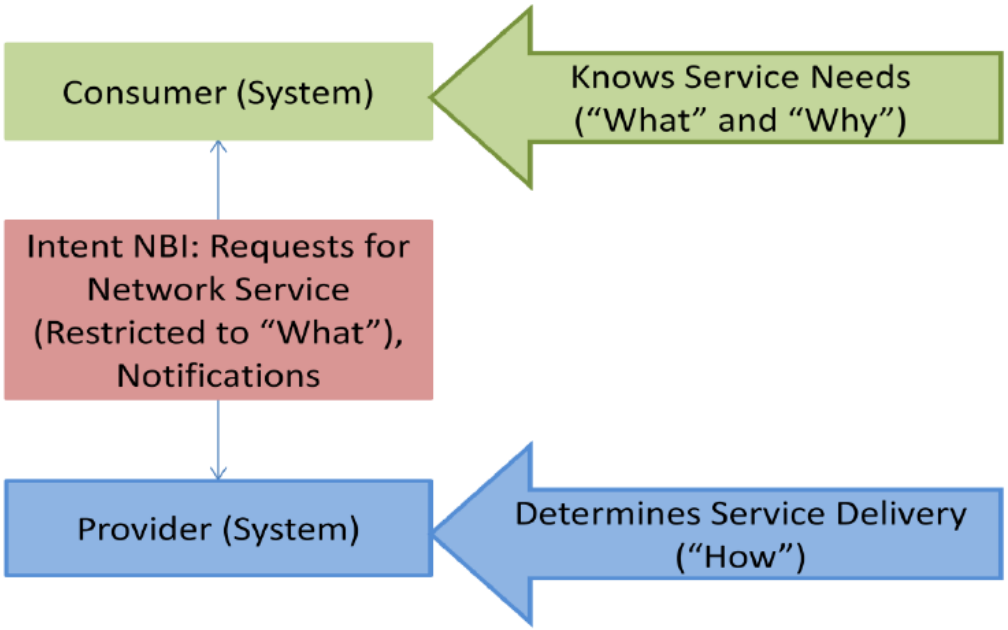


Figure 3 Consumer-provider interactions using Intent NBI.

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

Intent NBI analogy: transport-for-hire service

"Get me from A to B"

Consumer

Provider

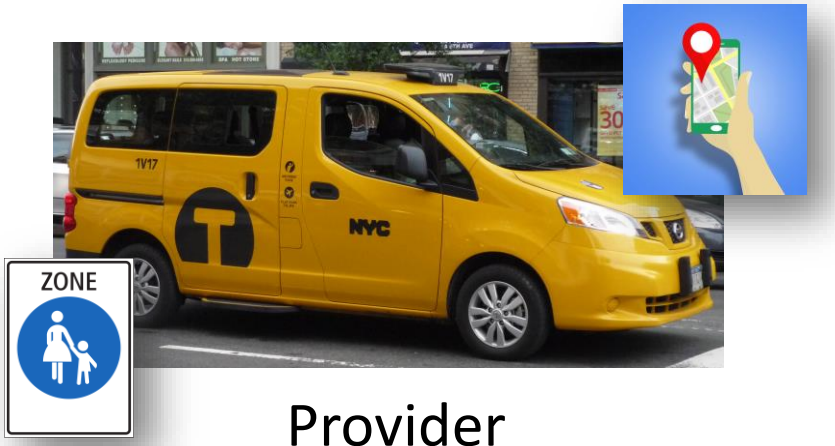
- Request involves only ***information relevant*** and ***intrinsically known*** to the consumer
- It does not contain any references to the transport provider's infrastructure, operational methodologies, or constraints (***provider's policies***)
- Why the customer should want to get from A to B (***consumer's policies***) is neither known by nor relevant to the transport provider

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

Intent NBI analogy: transport-for-hire service

Consumer

"Get me from A to B"



Provider

- Request involves only information relevant and intrinsically known to the consumer
- Such information is either naturally comprehensible to the transport provider, or becomes so through the equivalent of a ***mapping lookup***
  - e.g., by consulting maps, business or residential address databases, etc.
- ***Notifications from provider to consumer*** are also part of the Intent NBI
  - unavoidable service-impacting events → can no longer maintain the service as requested

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

Intent NBI analogy: transport-for-hire service

Consumer

"Get me from A to B"

Provider

- Request may be offered to any transport provider, and is therefore ***independent of transport providers***
- Requests may include "***modifiers***" that constrain or add detail to the request
  - "Get me from A to B before time C"
  - "Get me from A to B for a price not exceeding D"

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

ONF Intent NBI: definition

- Intent NBI is a ***declarative*** paradigm/methodology for interaction between service ***consumers*** and service ***providers***
  - generic consumers/providers (not necessarily human vs. dashboard)
  - focus on network controllers → Intent NBI = A-CPI
  - from a recursive/hierarchical perspective → Intent NBI = D-CPI

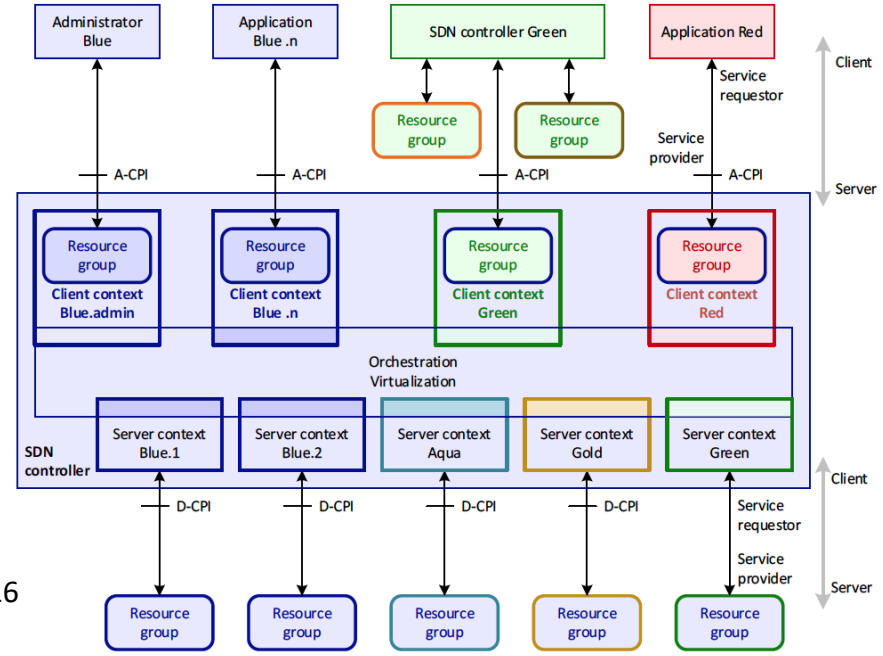


Figure 2 – Core of the SDN architecture

ONF, *SDN Architecture – Issue 1.1*, ONF TR-521 , 2016

ONF Intent NBI: properties

- ***Non-prescriptive***
  - separate consumer systems from detailed operations of producer systems
  - specify “what” (services are requested) and not “how” (those services are to be delivered)
  - decisions on use of resources are left to the provider
  - implementation choices regarding technology, vendor, media, node, port, link, path, server, virtual machine, etc. are left to the provider (***mappings***)
- ***Provider-independent***
  - the same request may be presented to any accepting provider
  - terms appearing in service requests from consumers are translated into terms directly relevant to providers (using ***mapping lookups***)
- ***Declarative***
  - the consumer system “declares” what it wants
  - no request of details (e.g., network topology)

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

ONF Intent NBI: mappings

- ***Mappings***: mechanism to translate Intent NBI requests into forms that lower-level entities can understand
  - make consumer and provider systems communicate in terms that are "natural" to each
  - fully separate consumer and provider system implementations
  - render human and/or machine consumer-originated requests to provider systems as simple as possible
- Intent NBI systems make use of ***continuous-loop*** comparison among:
  - existing and new Intent requests
  - mappings
  - controlled-resource sets and (evolving) states

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

ONF Intent NBI: mappings

- ***Key-value stores***, used by providers to translate from the ("simple and intuitive") consumer intent to the detailed, specific provider terms

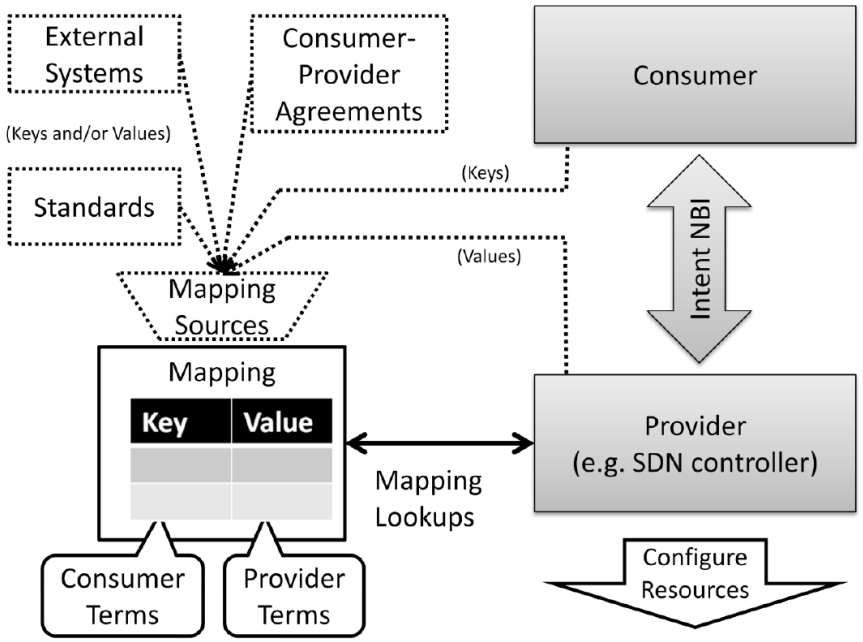


Figure 4 Architectural representation of Intent NBI, mapping and potential sources of mapping contents and/or their dynamic updates. The illustration of mappings as standing outside of provider systems is not prescriptive.

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

ONF Intent NBI: notifications

- ***Notifications***: mechanism by which providers signal actual or incipient service failures to consumers
  - providers are entirely responsible for the active management of resources to fulfill and maintain requested service states
  - consumers are not equipped to interpret detailed resource or other state information, in order to anticipate a service failure
  - notifications are transmitted on the Intent NBI and should signal to consumers what aspect(s) of the requested service definition cannot or will not be delivered or maintained
  - consumer systems have the responsibility to react to the indicated failure(s), e.g., by suspending traffic to the service, by requesting service modification or suspension, etc.

ONF, *Intent NBI – Definition and Principles*, ONF TR-523 , Oct. 2016

Intent-Based Networking System

- Lifecycle management software for networking infrastructure
  - "a piece of networking software that ***helps to plan***, ***design*** and ***implement/operate*** networks that can improve availability and agility"

Andrew Lerner, *Intent-based Networking*, Gartner Blog Network, Feb. 7, 2017

- The idea of a network administrator defining a desired state of the network, and having ***automated network orchestration software*** implement those policies
  - "currently, translation is manual, and algorithmic validation is absent… Intent-based networking systems ***monitor***, ***identify*** and ***react*** in real time to changing network conditions"
  - "***machine learning algorithms*** have advanced to a point where intent-based networking systems could become a reality soon"

Brandon Butler, *What is intent-based networking?*, Network World, June 29, 2017

Intent-Based Networking System

- Four key characteristics:
  1. ***Translation and Validation***
     "The system takes a higher-level business policy (*what*) as input from end users and converts it to the necessary network configuration (*how*). The system then generates and validates the resulting design and configuration for correctness."
  2. ***Automated Implementation***
     "The system can configure the appropriate network changes (*how*) across existing network infrastructure. This is typically done via network automation and/or network orchestration."
  3. ***Awareness of Network State***
     "The system ingests real-time network status for systems under its administrative control, and is protocol- and transport-agnostic."
  4. ***Assurance and Dynamic Optimization/Remediation***
     "The system continuously validates (in real time) that the original business intent of the system is being met, and can take corrective actions (such as blocking traffic, modifying network capacity or notifying) when desired intent is not met."

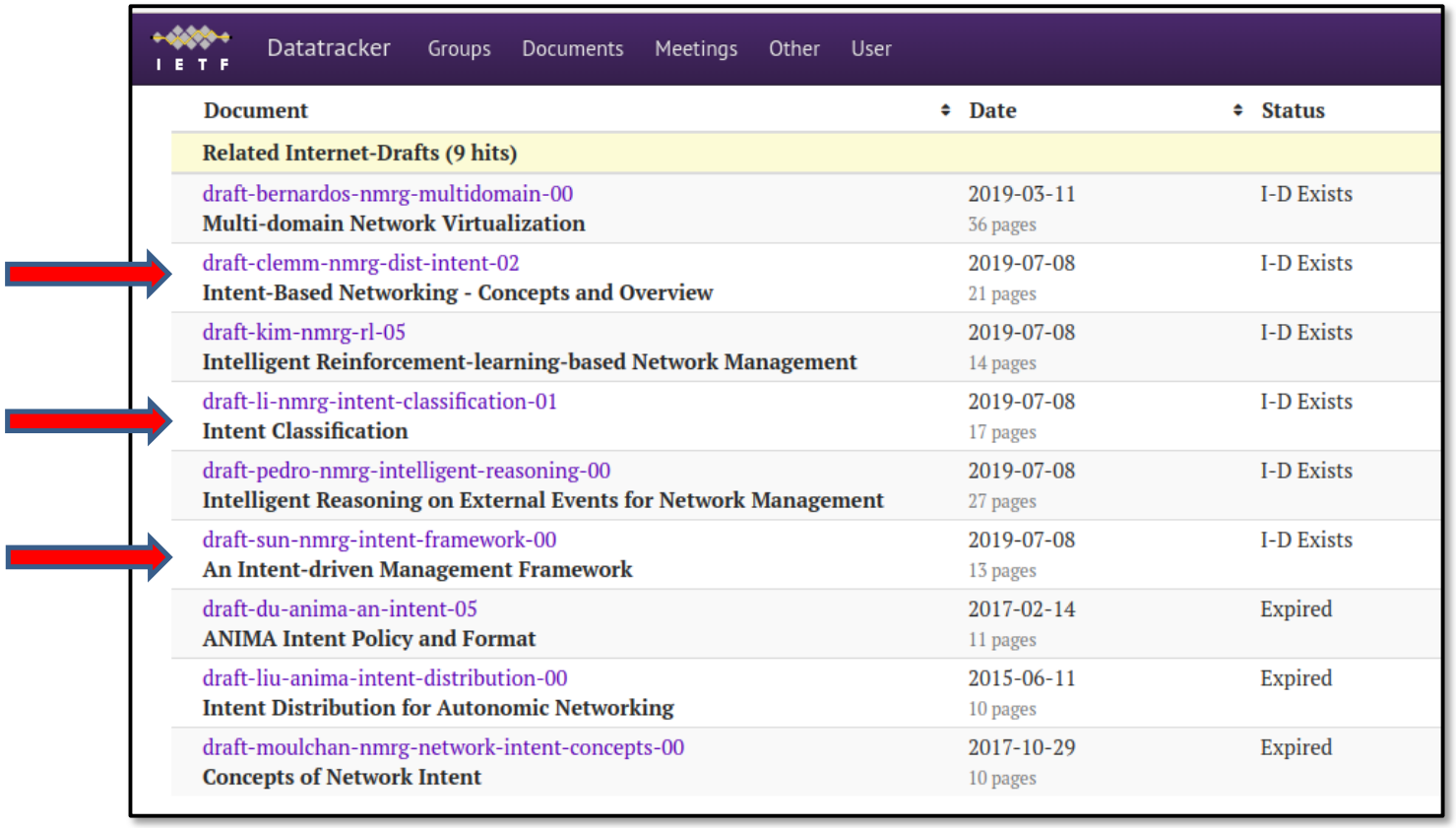
Andrew Lerner, *Intent-based Networking*, Gartner Blog Network, Feb. 7, 2017

More on Intent-Based Networking

- ***Is Intent just rebranded SDN?***
  - "No. Intent-based networking software helps to plan, design and implement/operate networks. SDN is an architecture for networks. Intent-based network software can "drive" a network that is either SDN-based or non-SDN based."
- ***Isn't Intent just a fancy term for advanced automation?***
  - "No, although the early usage and value will seem similar. Advanced automation solutions typically do not a) translate what to how, b) mathematically validate that desired intent is being met and c) continuously ingest a broad set of real-time network state indicators. A good intent-based networking system will embed advanced automation, but you can (and many do) advanced automation without Intent."
- ***A contrarian view is that intent-based networking will never reach a meaningful level of mainstream adoption***
  - "may prove to be technologically infeasible in the mainstream"
  - "a 15-plus year history of predominantly incremental changes within enterprise networks doesn't bode well for major paradigm shifts"
  - "network automation alone may provide *just enough* network agility/availability advancements"
  - certified engineers with vendor-specific CLI skills still represent a significant asset

Andrew Lerner, *Intent-based Networking FAQ*, Gartner Blog Network, July 11, 2017

Other standardization efforts: IRTF

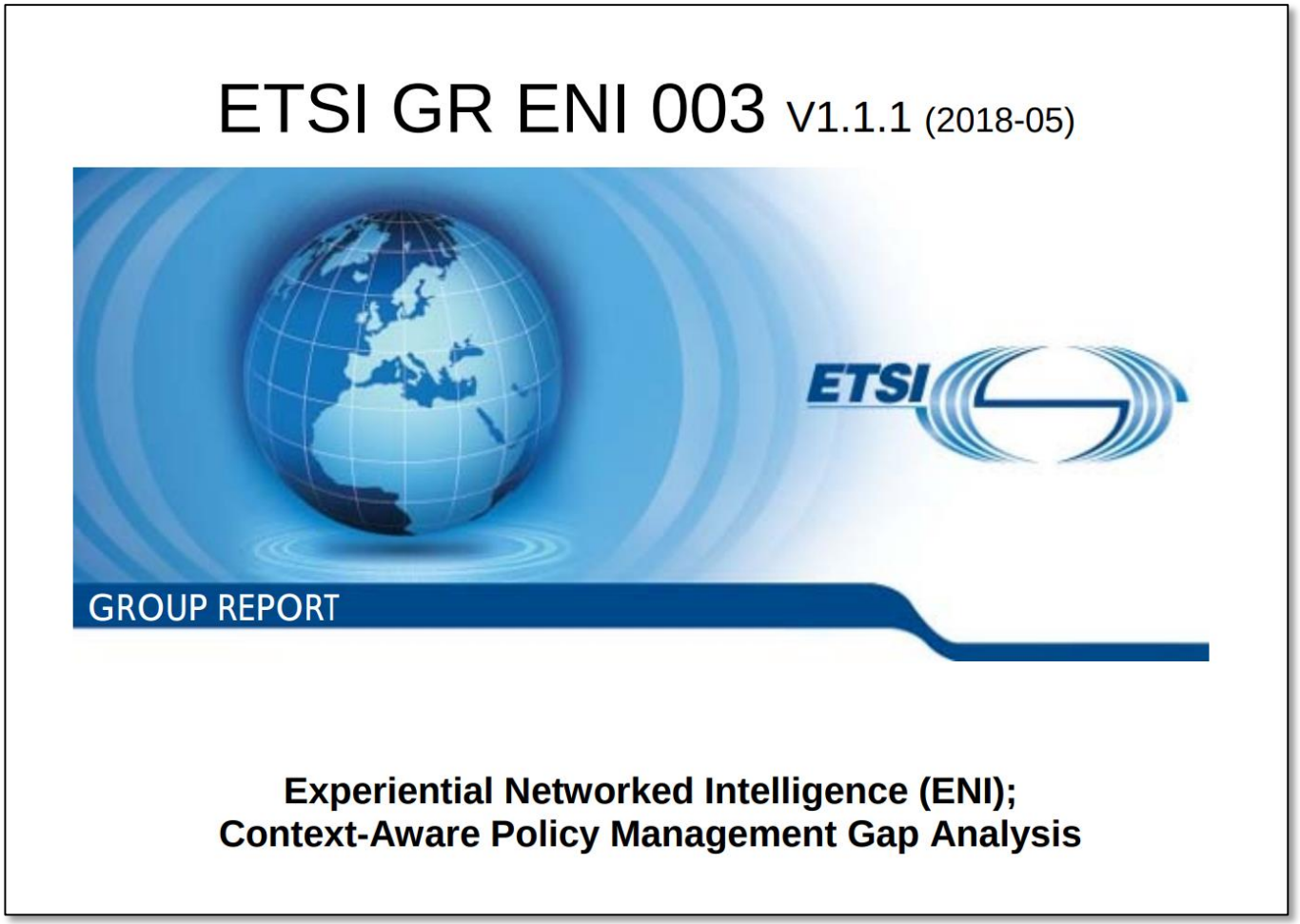


Datatracker Groups Documents Meetings Other User

Document	Date	Status
Related Internet-Drafts (9 hits)		
draft-bernardos-nmrg-multidomain-00 **Multi-domain Network Virtualization**	2019-03-11 36 pages	I-D Exists
draft-clemm-nmrg-dist-intent-02 **Intent-Based Networking - Concepts and Overview**	2019-07-08 21 pages	I-D Exists
draft-kim-nmrg-rl-05 **Intelligent Reinforcement-learning-based Network Management**	2019-07-08 14 pages	I-D Exists
draft-li-nmrg-intent-classification-01 **Intent Classification**	2019-07-08 17 pages	I-D Exists
draft-pedro-nmrg-intelligent-reasoning-00 **Intelligent Reasoning on External Events for Network Management**	2019-07-08 27 pages	I-D Exists
draft-sun-nmrg-intent-framework-00 **An Intent-driven Management Framework**	2019-07-08 13 pages	I-D Exists
draft-du-anima-an-intent-05 **ANIMA Intent Policy and Format**	2017-02-14 11 pages	Expired
draft-liu-anima-intent-distribution-00 **Intent Distribution for Autonomic Networking**	2015-06-11 10 pages	Expired
draft-moulchan-nmrg-network-intent-concepts-00 **Concepts of Network Intent**	2017-10-29 10 pages	Expired

IRTF Network Management Research Group: https://datatracker.ietf.org/rg/nmrg/documents/

Other standardization efforts: ETSI ENI



https://www.etsi.org/technologies/experiential-networked-intelligence

Other standardization efforts: ETSI ENI

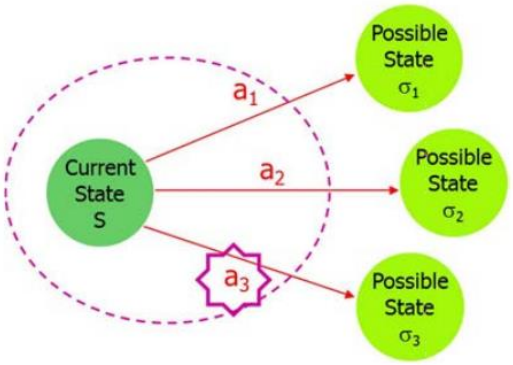


Figure 4.4-1: The Imperative Policy Paradigm

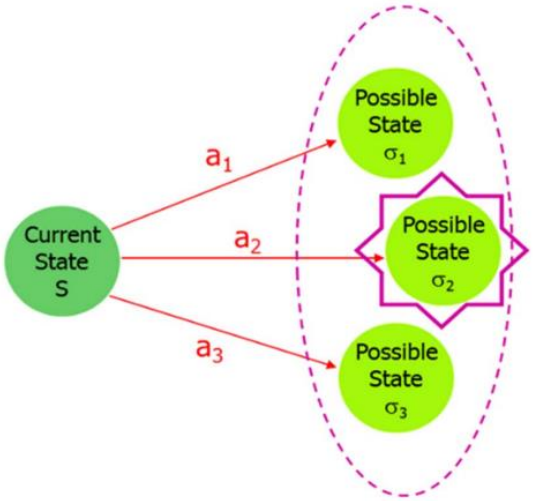


Figure 4.4-2: The Declarative Policy Paradigm

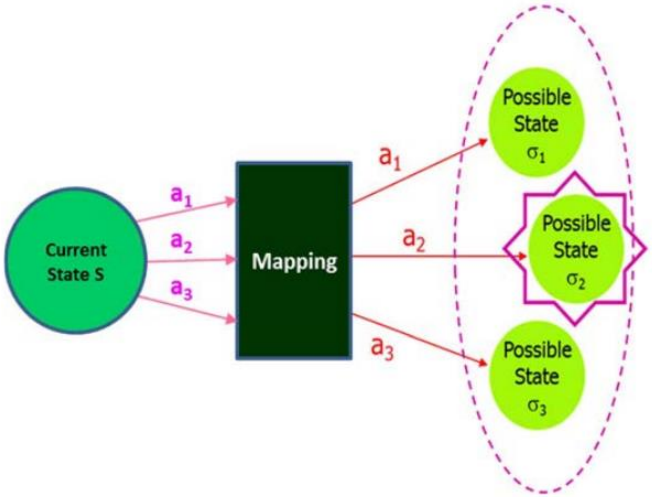


Figure 4.4-3: The Intent Policy Paradigm

ETSI GR ENI 003: Context-Aware Policy Management Gap Analysis (2018)

Other standardization efforts: ETSI ENI

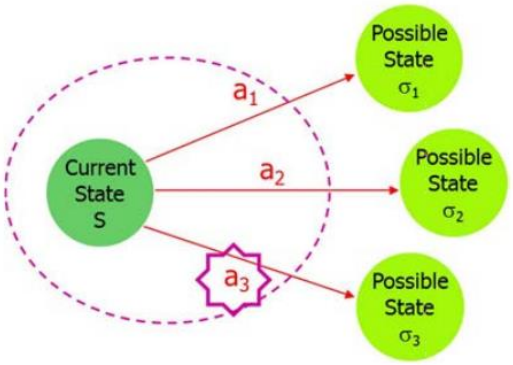


Figure 4.4-1: The Imperative Policy Paradigm

Imperative policies follow the imperative programming paradigm, which focuses on describing how a program operates.
[…] policies are structured such that they explicitly control the transitioning of one state to another state.
In this approach, only one target state is allowed to be chosen. This is done by defining the order in which operations occur […]
A commonly accepted and generic form of imperative policies is the ECA (Event-Condition-Action) Policy.

ETSI GR ENI 003: Context-Aware Policy Management Gap Analysis (2018)

Other standardization efforts: ETSI ENI

The purpose of declarative programming is to describe the set of computations that need to be done without describing how to execute those computations.
[…] declarative policies are written in a formal logic language, such as First Order Logic. This is contrasted with intent policies (see clause 4.4.4), which are written in a (controlled) natural language and then translated to a different form.

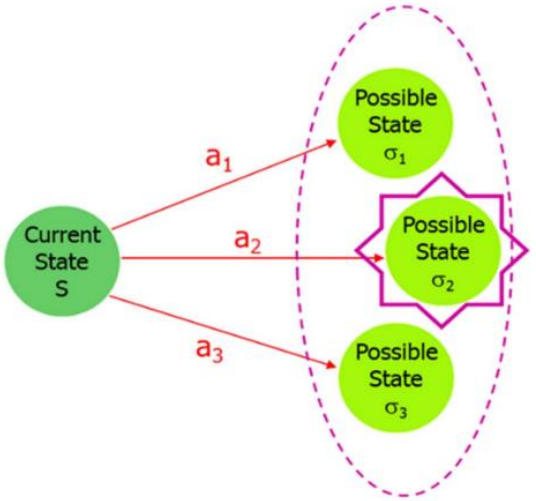


Figure 4.4-2: The Declarative Policy Paradigm

ETSI GR ENI 003: Context-Aware Policy Management Gap Analysis (2018)

Other standardization efforts: ETSI ENI

[…] an intent policy is a type of declarative policy that uses statements to express the goals of the policy, but not how to accomplish those goals.
[…] Intent Policy will refer to policies that do not execute as theories of a formal logic. They typically are expressed in a restricted natural language, and require a mapping to a form understandable by other managed functional entities.
[…] The advantage of Intent is its flexibility, in that it enables its users to express policies using concepts and terminology that are familiar to the user. This is, of course, its disadvantage, since natural languages are typically ambiguous.

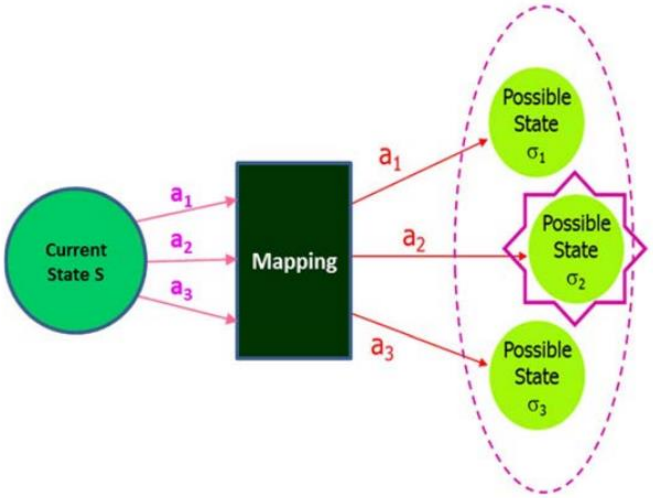


Figure 4.4-3: The Intent Policy Paradigm

ETSI GR ENI 003: Context-Aware Policy Management Gap Analysis (2018)

Intents vs. Policies

- Intent-based networking is often considered similar to **high-level policy-based network management**
  - especially with reference to **policy refinement** techniques, aimed at deriving (or refining) lower-level policies from higher-level, goal-oriented specifications [1]
- Both terms “intent” and “policy” refer to **high-level abstractions for managing networks without delving into device-specific details** [2], however:
  - a **policy** typically involves a set of rules used to define what to do under what circumstances (events, conditions, and actions), but it does not necessarily specify a desired outcome
  - an **intent** is used to define network-wide outcomes and high-level operational goals, without the need to enumerate specific events, conditions, and actions
- Policy refinement can be considered equivalent to the ONF mappings needed to translate intents into lower-level policies

[1] J. Rubio-Loyola et al., *Using linear temporal model checking for goal-oriented policy refinement frameworks*, IEEE POLICY 2005

[2] A. Clemm et al., *Intent-Based Networking - Concepts and Overview*, IRTF Internet-Draft, draft-clemm-nmrg-dist-intent-02, July 2019

Industry perspective: a few examples

- **Cisco** Digital Network Architecture (DNA)
  - open, extensible, software-driven architecture
  - powered by deep intelligence and integrated security to deliver automation
  - built on SDN control, rich contextual analytics, network virtualization
- **Huawei** Intent-Driven Network for CloudFabric
  - intent-driven network automation for data centers
  - network behavior model based on big data analytics and machine learning
  - predictive analysis and anomaly detection
- **Apstra** Operating System (AOS)
  - vendor-agnostic, closed-loop intent-based network operating system
  - automated design and deployment of network configurations
  - real-time telemetry and analytics that provide continuous validation
- **Veriflow**
  - business-oriented intent, technology- and vendor-agnostic
  - network designed and operated as an end-to-end system
  - continuous verification of intent

Research perspective: an incomplete survey

1. **Single-domain** solutions
   - abstraction for virtualized network management in a multi-tenant data center environment
     [1] R. Cohen et al., *An intent-based approach for network virtualization*, IEEE IM 2013
   - high-level specification of network slicing requirements and automated configuration in an SDN infrastructure
     [2] Y. Han et al., *An intent-based network virtualization platform for SDN*, CNSM 2016
   - definition of a service-oriented architecture for service composition based on microservices
     [3] M. Pham et al., *SDN applications - The intent-based northbound interface realisation for extended applications*, IEEE NetSoft 2016
   - scalable label-based abstraction of policy requirements for large cloud computing environments
     [4] J. Kang et al., *LMS: label management service for intent-driven cloud management,* IEEE IM 2017
   - unified SDN resource optimization with composition at the intent level
     [5] V. Heorhiadi et al., *Intent-Driven Composition of Resource-Management SDN Applications*, ACM CoNEXT 2018

Research perspective: an incomplete survey

1. **Single-domain** solutions (cont'd)
   - intent-refinement process with machine learning and feedback from the operator to translate intents into network configurations through intermediate intent representation close to natural language
     [6] A. S. Jacobs et al., *Refining Network Intents for Self-Driving Networks*, ACM SIGCOMM SelfDN 2018
   - extensible intent definition language to install/remove P4 programs on-the-fly to/from the data plane
     [7] M. Riftadi et al., *P4I/O: Intent-Based Networking with P4*, IEEE NetSoft 2019 Workshops

Research perspective: an incomplete survey

2. **Multi-domain** solutions
   - intent-based mobile backhauling interface for 5G networks, with integrated management of radio access and backhaul segments, including Wi-Fi access points and OpenFlow switches
     [8] T. Subramanya et al., *Intent-based mobile backhauling for 5G networks*, CNSM 2016
   - multi-domain SDN intent decomposition into local graph abstractions and scalable intent compilation
     [9] S. Arezoumand et al., *MD-IDN: multi-domain intent-driven networking in software-defined infrastructures*, CNSM 2017
   - northbound interface for intent declaration using natural language
     [10] F. Esposito et al., *A behavior-driven approach to intent specification for software-defined infrastructure management*, IEEE NFV-SDN 2018
   - intent-based NBI for end-to-end service management across multiple technological domains, including OpenFlow, IoT and NSH
     [11] G. Davoli et al., *Intent-based service management for heterogeneous software-defined infrastructure domains*, Int. J. Network Mgmt., Vol. 29, No. 1, 2019

Intent-Based SDN: some open source projects

- OpenDaylight / OpenStack Neutron
  - Group Based Policy (GBP)
    - communication policies (contracts) between groups of endpoints (VMs, containers, ports)
    - e.g., “allow web traffic to web server endpoint group”
    - http://docs.opendaylight.org/en/stable-nitrogen/user-guide/group-based-policy-user-guide.html
- OpenDaylight
  - Network Intent Composition (NIC)
    - connectivity intent, specifying endpoints and redirection
    - e.g., “connect endpoint A to endpoint B redirecting through C”
    - http://docs.opendaylight.org/en/stable-nitrogen/user-guide/network-intent-composition-(nic)-user-guide.html
- ONOS
  - Intent Framework
    - connectivity intent, specifying endpoints or connect-points, even multiple
    - e.g., “connect endpoint A to endpoints B and C”
    - https://wiki.onosproject.org/display/ONOS/Intent+Framework

Intent-Based Networking – Summary

- Network admins express “what” instead of “how“
- An automated network management platform creates the desired state and enforces the required policies
- Closed-loop approach: continuous validation and verification

- Open issues:
  - express the intent → language, formalism
  - communicate the intent → northbound interface, APIs, vendor-independence
  - validate the intent → manage conflicts, data consistency, available resources
  - translate the intent → mapping intents to specific configurations
  - make the intent resilient and secure → continuous validation and verification, context awareness

Thank you

walter.cerroni@unibo.it