Intent-based Network Programmability

Walter Cerroni
University of Bologna, Italy

IRTF NMRG 56 – Interim Meeting – Oct. 3-4, 2019
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**
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Programmable and Active Networks</td>
<td>First concept of network programmability, in the data plane. Virtualized execution environments.</td>
</tr>
<tr>
<td>2004</td>
<td>IETF ForCES</td>
<td>Separation between control and data planes. Standard, open interface between them.</td>
</tr>
<tr>
<td>2006</td>
<td>IETF PCE</td>
<td>Logically centralized, programmable control plane.</td>
</tr>
<tr>
<td>2008</td>
<td>OpenFlow</td>
<td>Generalized forwarding device API. Vision of a network operating system.</td>
</tr>
<tr>
<td>2011</td>
<td>Open Networking Foundation (ONF)</td>
<td>Standardization of SDN.</td>
</tr>
<tr>
<td>2014</td>
<td>P4, OpenState, etc.</td>
<td>Solutions for programmable and high-performance data plane.</td>
</tr>
<tr>
<td>2016</td>
<td>DPDK, FD.io, XDP</td>
<td></td>
</tr>
</tbody>
</table>
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 $\rightarrow$ VNF 1
    - function B $\rightarrow$ VNF 5
    - function C $\rightarrow$ VNF 6
    - instantiate VMs
    - steer traffic flow F accordingly
Intent-Based Networking (for NFV/SDN)

User / Admin

Intent-based programmable northbound interface (NBI)

Automated Resource Management and Orchestration Platform

Controller-specific northbound interface

Cloud controller

Cloud infrastructure

Controller-specific northbound interface

Network controller

Network infrastructure

Technology-dependent southbound interface

Technology-dependent southbound interface
Definition of “intent”

**intent**

noun [U] • UK /ɪnˈtɛnt/  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.*

---

**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**
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
A first step toward standardization

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.

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

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

• 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
Intent NBI analogy: transport-for-hire service

“Get me from A to B”

- 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

- 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

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: 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: mappings

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

---

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.

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”

• 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.”

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

Other standardization efforts: IRTF

<table>
<thead>
<tr>
<th>Document</th>
<th>Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>draft-bernardos-nmrg-multidomain-00 Multi-domain Network Virtualization</td>
<td>2019-03-11</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-clemm-nmrg-dist-intent-02 Intent-Based Networking - Concepts and Overview</td>
<td>2019-07-08</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-kim-nmrg-rl-05 Intelligent Reinforcement-learning-based Network Management</td>
<td>2019-07-08</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-li-nmrg-intent-classification-01 Intent Classification</td>
<td>2019-07-08</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-pedro-nmrg-intelligent-reasoning-00</td>
<td>2019-07-08</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-sun-nmrg-intent-framework-00 An Intent-driven Management Framework</td>
<td>2019-07-08</td>
<td>I-D Exists</td>
</tr>
<tr>
<td>draft-du-anima-an-intent-05 ANIMA Intent Policy and Format</td>
<td>2017-02-14</td>
<td>Expired</td>
</tr>
<tr>
<td>draft-liu-anima-intent-distribution-00 Intent Distribution for Autonomic Networking</td>
<td>2015-06-11</td>
<td>Expired</td>
</tr>
<tr>
<td>draft-moulichan-nmrg-network-intent-concepts-00 Concepts of Network Intent</td>
<td>2017-10-29</td>
<td>Expired</td>
</tr>
</tbody>
</table>

Other standardization efforts: ETSI ENI

ETSI GR ENI 003 V1.1.1 (2018-05)

Experiential Networked Intelligence (ENI); Context-Aware Policy Management Gap Analysis

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

Other standardization efforts: ETSI ENI

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.
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.
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
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

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
   - high-level specification of network slicing requirements and automated configuration in an SDN infrastructure
   - definition of a service-oriented architecture for service composition based on microservices
   - scalable label-based abstraction of policy requirements for large cloud computing environments
   - unified SDN resource optimization with composition at the intent level
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
   - extensible intent definition language to install/remove P4 programs on-the-fly to/from the data plane
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
  

- multi-domain SDN intent decomposition into local graph abstractions and scalable intent compilation
  

- 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
  
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”

- **OpenDaylight**
  - Network Intent Composition (NIC)
    - connectivity intent, specifying endpoints and redirection
    - e.g., “connect endpoint A to endpoint B redirecting through C”

- **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](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