SDN and NFV

Why SDN and NFV ?

Before explaining ***what*** SDN and NFV are
we need to explain ***why*** SDN and NFV are

Its all started with two related trends ...

1. The blurring of the distinction
between ***computation*** and ***communications***
revealing a fundamental disconnect
between ***software*** and ***networking***

2. The decrease in profitability
of ***traditional communications service providers***
along with the increase in profitability
of **Cloud and Over The Top service providers**

The 1st led directly to SDN
and the 2nd to NFV
but today both are intertwined

1. *Computation* and *communications*

Once there was little overlap
between *communications* (telephone, radio, TV)
and *computation* (computers)

Actually communications devices always ran complex algorithms
but these are hidden from the user

But this dichotomy has become blurred

Most home computers are not used for *computation* at all
rather for entertainment and communications (email, chat, VoIP)

Cellular telephones have become computers

The differentiation can still be seen in the terms *algorithm* and *protocol*
Protocol design is fundamentally harder
since there are two interacting entities (the *interoperability* problem)

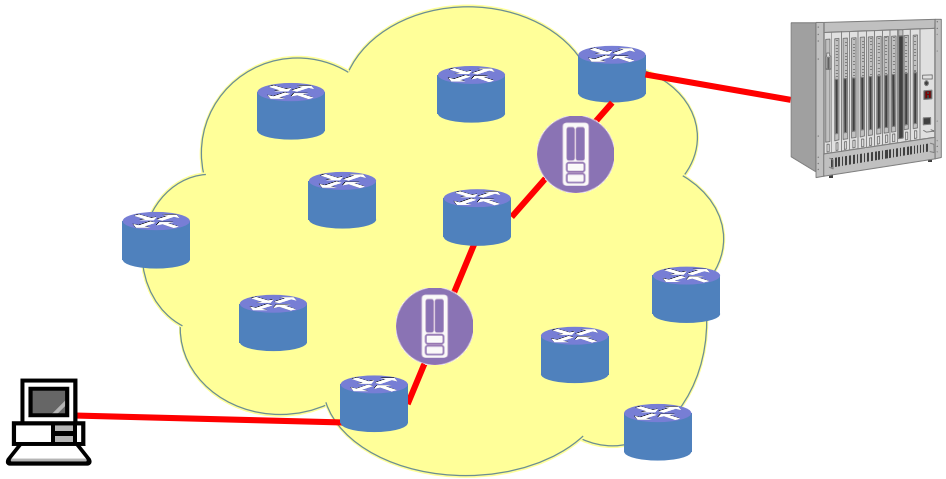
SDN academics claim that packet forwarding is a computation problem
and protocols as we know them should be avoided

1. Rich communications services

Traditional communications services are pure *connectivity* services
- transport data from A to B
  - with constraints (e.g., minimum bandwidth, maximal delay)
  - with maximal efficiency (minimum cost, maximized revenue)

Modern communications services are richer
- combining connectivity and network functionalities
  - e.g., firewall, NAT, load balancing, CDN, parental control, ...

Such services further blur the computation/communications distinction
- and make service deployment optimization more challenging



1. *Software* and *networking speed*

Today, developing a new *iOS/Android* app takes hours to days
but developing a new communications service takes months to years

Even adding new instances of well-known services
is a time consuming process for conventional networks

When a new service types requires new protocols, the timeline is

- protocol standardization (often in more than one SDO)
- hardware development
- interop testing
- vendor marketing campaigns and operator acquisition cycles
- staff training
- deployment

how long has it been since the first IPv6 RFC ?

This leads to a *fundamental disconnect*
between software and networking development timescales

An important goal of SDN and NFV is
to create new network functionalities at the *speed of software*

2. Today's communications world

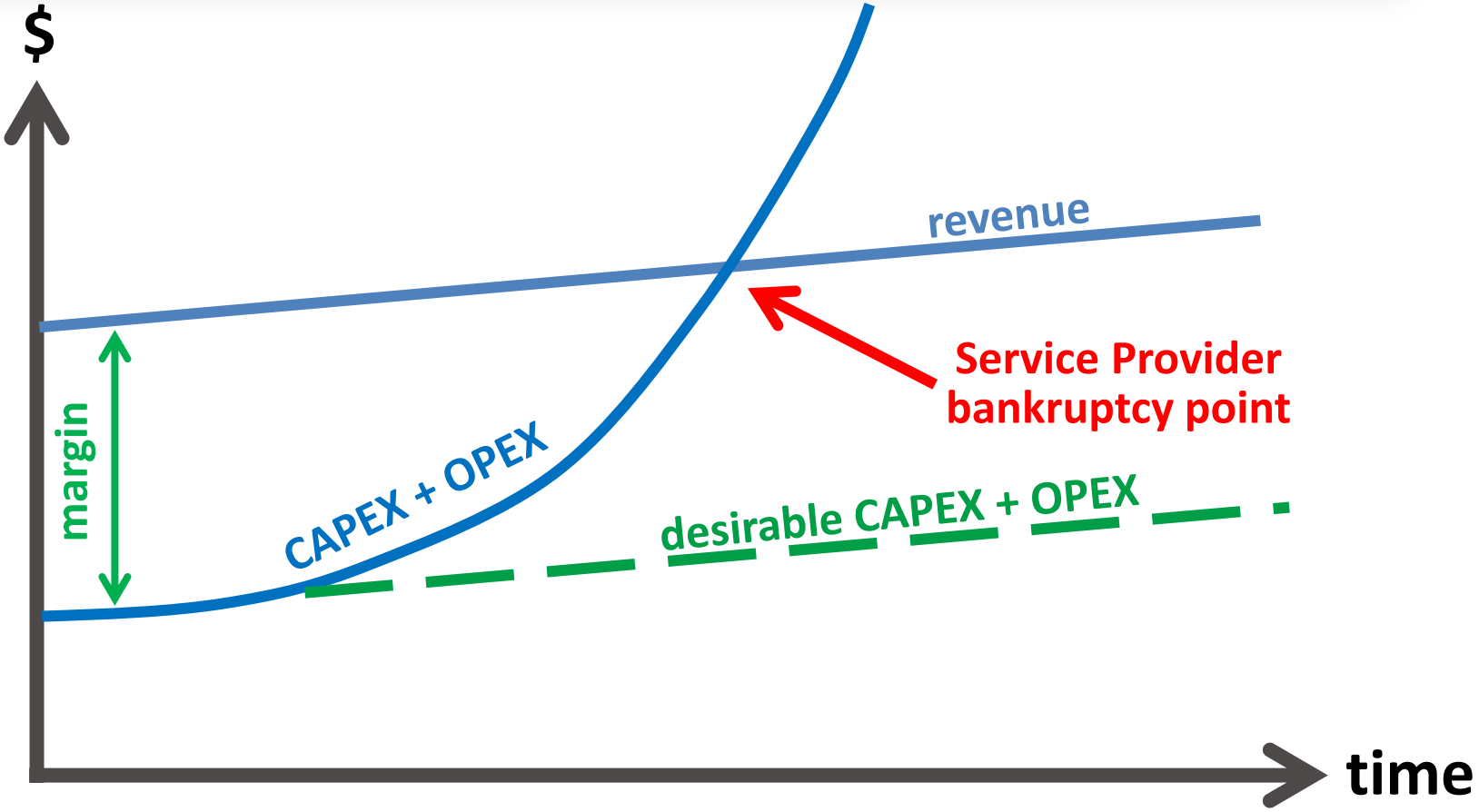
Today's infrastructures are composed of many different Network Elements (NEs)

- sensors, smartphones, notebooks, laptops, desk computers, servers,
- DSL modems, Fiber transceivers,
- SONET/SDH ADMs, OTN switches, ROADMs,
- Ethernet switches, IP routers, MPLS LSRs, BRAS, SGSN/GGSN,
- NATs, Firewalls, IDS, CDN, WAN aceleration, DPI,
- VoIP gateways, IP-PBXes, video streamers,
- performance monitoring probes , performance enhancement middleboxes,
- etc., etc., etc.

New and ever more complex NEs are being invented all the time,
and while equipment vendors like it that way
Service Providers find it hard to shelve and power them all !

In addition, while service innovation is accelerating
the increasing sophistication of new services
the requirement for backward compatibility
and the increasing number of different SDOs, consortia, and industry groups
which means that
it has become very hard to experiment with new networking ideas
NEs are taking longer to standardize, design, acquire, and learn how to operate
NEs are becoming more complex and expensive to maintain

2. The service provider crisis



This is a *qualitative* picture of the service provider's world
Revenue is at best increasing with number of users
Expenses are proportional to bandwidth – doubling every 9 months
This situation obviously can not continue forever !

Two complementary solutions

Software Defined Networks (SDN)

SDN advocates replacing standardized networking protocols
with centralized software applications
that configure all the NEs in the network

Advantages:

- easy to experiment with new ideas
- control software development is much faster than protocol standardization
- centralized control enables stronger optimization
- functionality may be speedily deployed, relocated, and upgraded

Network Functions Virtualization (NFV)

NFV advocates replacing hardware network elements
with software running on COTS computers
that may be housed in POPs and/or datacenters

Advantages:

- COTS server price and availability scales with end-user equipment
- functionality can be located where-ever most effective or inexpensive
- functionalities may be speedily combined, deployed, relocated, and upgraded

SDN

Abstractions

SDN was triggered by the development of networking technologies
not keeping up with the speed of software application development

Computer science theorists theorized
that this derived from not having the required **abstractions**

In CS an *abstraction* is a representation
that reveals semantics needed *at a given level*
while hiding implementation details
thus allowing a programmer to focus on necessary concepts
without getting bogged down in unnecessary details

Programming is fast because programmers exploit abstractions

Example:

It is very slow to code directly in assembly language (with few abstractions, e.g. opcode mnemonics)
It is a bit faster to coding in a low-level language like C (additional abstractions : variables, structures)
It is much faster coding in high-level imperative language like Python
It is much faster yet coding in a declarative language (coding has been abstracted away)
It is fastest coding in a domain-specific language (only contains the needed abstractions)

In contrast, in protocol design we return to *bit level* descriptions every time

Packet forwarding abstraction

The first abstraction relates to how network elements forward packets

At a high enough level of abstraction
all network elements perform the same task

Abstraction 1 *Packet forwarding as a computational problem*
The function of any network element (NE) is to

- receive a packet
- observe packet fields
- apply algorithms (classification, decision logic)
- optionally edit the packet
- forward or discard the packet

For example

- An Ethernet switch observes MAC DA and VLAN tags, performs exact match, forwards the packet
- A router observes IP DA, performs LPM, updates TTL, forwards packet
- A firewall observes multiple fields, performs regular expression match, optionally discards packet

We can replace all of these NEs with a configurable ***whitebox switch***

Network state and graph algorithms

How does a whitebox switch learn its required functionality ?

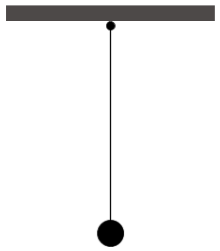
Forwarding decisions are optimal
when they are based on full global knowledge of the network

With full knowledge of topology and constraints
the path computation problem can be solved by a graph algorithm

While it may sometimes be possible to perform path computation (e.g., Dijkstra)
in a distributed manner
It makes more sense to perform them centrally

Abstraction 2 *Routing as a computational problem*
Replace distributed routing protocols with graph algorithms
performed at a central location

Note with SDN, the pendulum that swung
from the completely centralized PSTN
to the completely distributed Internet
swings back to completely centralized control



Configuring the whitebox switch

How does a whitebox switch acquire the information needed to forward
that has been computed by an omniscient entity at a central location ?

Abstraction 3 *Configuration*

Whitebox switches are directly *configured* by an *SDN controller*

Conventional network elements have two parts:

1. smart but slow CPUs that create a Forwarding Information Base
2. fast but dumb switch fabrics that use the FIB

Whitebox switches only need the dumb part, thus

- eliminating distributed protocols
- not requiring intelligence

The API from the SDN controller down to the whitebox switches
is conventionally called the *southbound API* (e.g., OpenFlow, ForCES)

Note that this SB API is in fact a *protocol*
but is a simple configuration protocol
not a distributed routing protocol

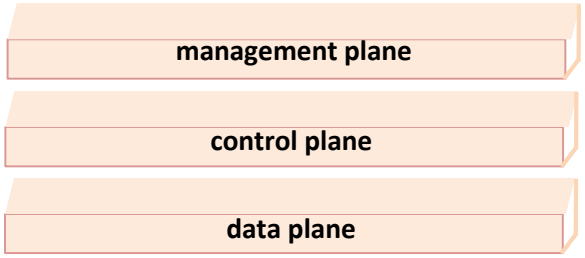
Separation of data and control

You will often hear stated that the *defining attribute* of *SDN* is the separation of the *data* and *control* planes

This separation was not invented recently by SDN academics
Since the 1980s all well-designed communications systems have enforced logical separation of 3 planes :

- data plane (forwarding)
- control plane (e.g., routing)
- management plane (e.g., policy, commissioning, billing)

What SDN really does is to
1) insist on ***physical*** separation of data and control
2) erase the difference between control and management planes



Control or management

What happened to the management plane ?

Traditionally the distinction between control and management was that :

- management had a human in the loop
- while the control plane was automatic

With the introduction of more sophisticated software
the human could often be removed from the loop

The difference that remains is that

- the management plane is *slow* and *centralized*
- the control plane is *fast* and *distributed*

So, another way of looking at SDN
is to say that it merges
the control plane
into a single centralized management plane

SDN PC vs. distributed routing

Distributed routing protocols are limited to

- finding simple connectivity
- minimizing number of hops (or other additive cost functions)

but find it hard to perform more sophisticated operations, such as

- guaranteeing isolation (privacy)
- optimizing paths under constraints
- setting up non-overlapping backup paths (the Suurballe problem)
- integrating networking functionalities (e.g., NAT, firewall) into paths

This is why MPLS created the **P**ath **C**omputation **E**lement architecture

An SDN controller is omniscient (the *God box*)
and holds the entire network description as a graph
on which arbitrary optimization calculations can be performed

But centralization comes at a price

- the controller is a single point of failure
  (more generally different CAP-theorem trade-offs are involved)
- the architecture is limited to a single network
- additional (overhead) bandwidth is required
- additional set-up delay may be incurred

Flows

It would be too slow for a whitebox switch
to query the centralized SDN controller
for every packet received

So we identify packets as belonging to **flows**

Abstraction 4 *Flows* (as in Open**Flow**)
Packets are handled solely based on the flow to which they belong

Flows are thus just like **F**orwarding **E**quivalence **C**lasses

Thus a flow may be determined by
- an IP prefix in an IP network
- a label in an MPLS network
- VLANs in VLAN cross-connect networks

The granularity of a flow depends on the application

Control plane abstraction

In the standard SDN architecture, the SDN controller is omniscient
but does not itself *program* the network
since that would limit development of new network functionalities

With software we create building blocks with defined APIs
which are then used, and perhaps inherited and extended, by programmers

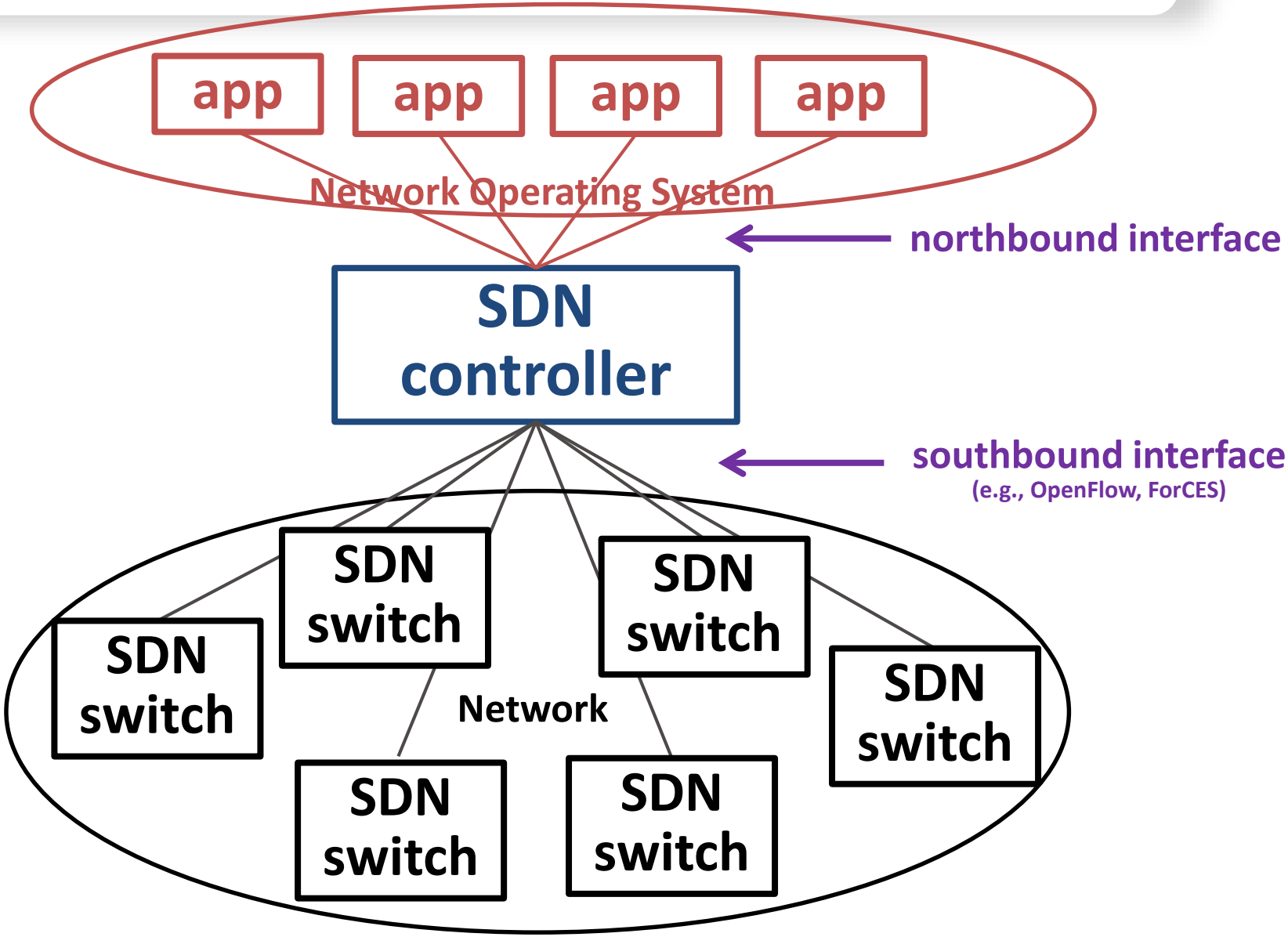
With networking, each network *application* has a tailored-made control plane
with its own element discovery, state distribution, failure recovery, etc.

Note the subtle change of terminology we have just introduced
instead of calling switching, routing, load balancing, etc. network *functions*
we call them network *applications* (similar to software *apps*)

Abstraction 5 Northbound *APIs instead of protocols*
Replace control plane protocols with well-defined APIs to network applications

This abstraction hide details of the network from the network application
revealing high-level concepts, such as requesting connectivity between A and B
but hiding details unimportant to the application
such as details of switches through which the path A → B passes

SDN overall architecture

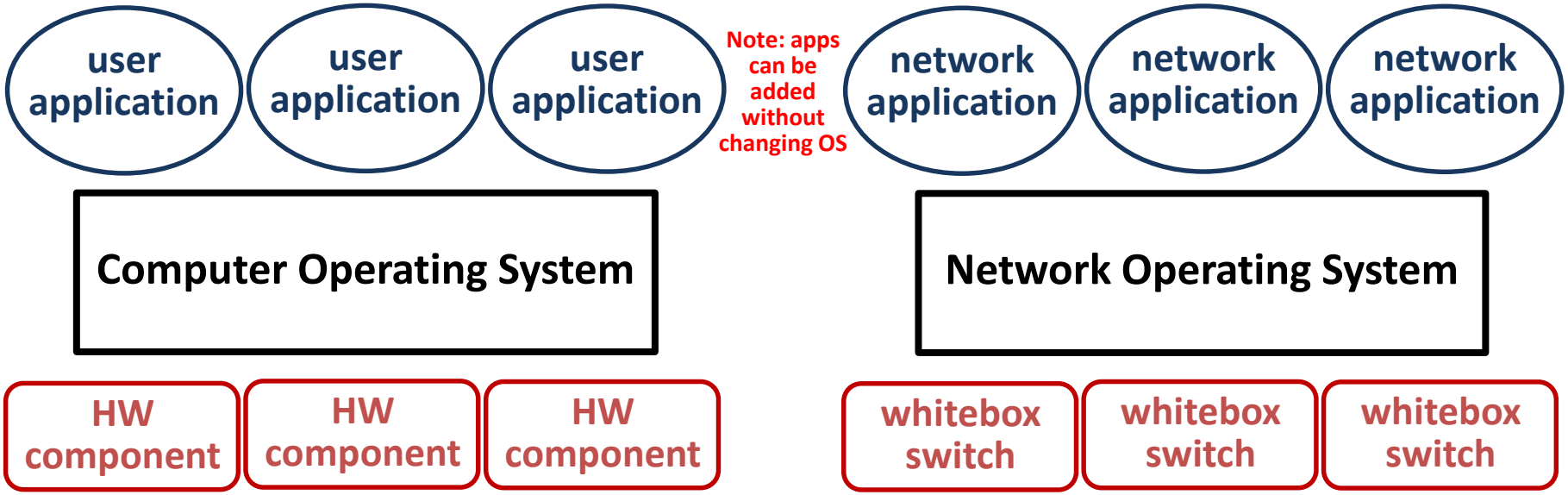


Network Operating System

For example, a computer operating system

- sits between user programs and the physical computer hardware
- reveals high level functions (e.g., allocating a block of memory or writing to disk)
- hides hardware-specific details (e.g., memory chips and disk drives)

We can think of SDN as a **Network Operating System**



SDN overlay model

We have been discussing the purist SDN model
where SDN builds an entire network using whiteboxes

For non-greenfield cases this model requires
upgrading (downgrading?) hardware to whitebox switches

An alternative model builds an **SDN overlay network**

The overlay tunnels traffic through the physical network
running SDN on top of switches that do not explicitly support SDN

Of course you may now need to administer two separate networks

NFV

Virtualization of computation

In the field of computation, there has been a major trend towards ***virtualization***

Virtualization here means the creation of a **virtual machine** (VM)
that acts like an independent physical computer

A **VM** is software that emulates hardware (e.g., an x86 CPU)
over which one can run software as if it is running on a physical computer

The VM runs on a *host* machine
and creates a *guest* machine (e.g., an x86 environment)

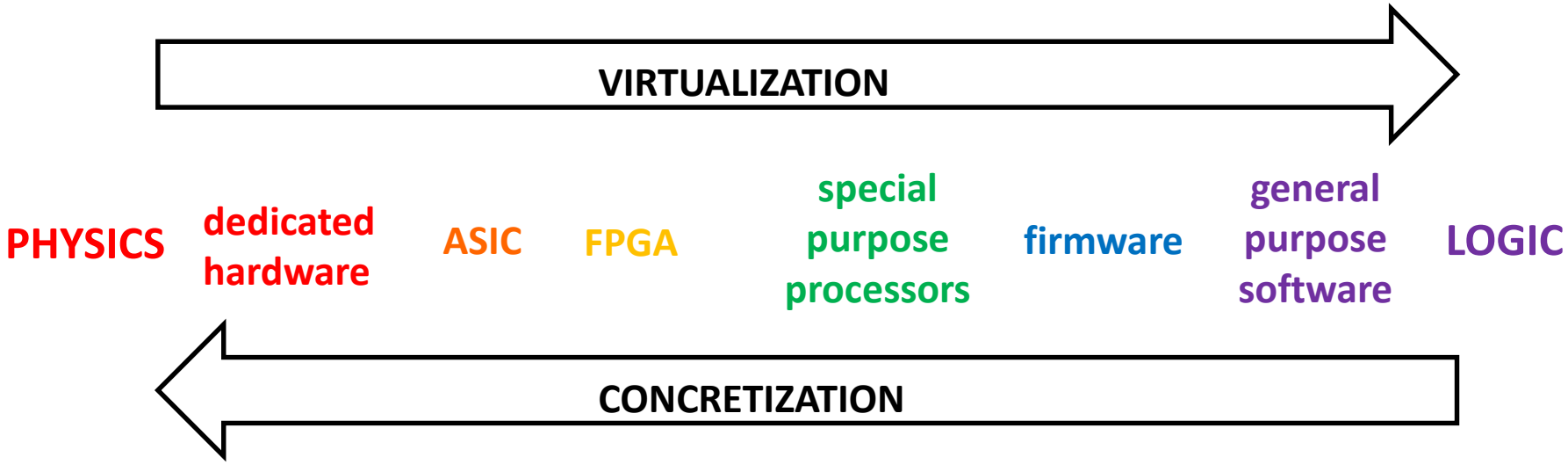
A single host computer may host many fully independent guest VMs
and each VM may run different Operating Systems and/or applications

For example

- a datacenter may have many racks of server cards
- each server card may have many (host) CPUs
- each CPU may run many (guest) VMs

A **hypervisor** is software that enables *creation* and *monitoring* of VMs

Concretization and Virtualization



Concretization means moving a task *to the left*

Justifications for concretization include :

- cost savings for mass produced products
- miniaturization/packaging constraints
- need for high processing rates
- energy savings / power limitation / low heat dissipation

Virtualization is the opposite - moving a task *to the right*

(although frequently reserved for the extreme case of HW → SW)

Network Functions Virtualization

CPUs are not the only hardware device that can be virtualized

Many (but not all) NEs can be replaced by software running on a CPU or VM

This would enable

- using standard COTS hardware (whitebox servers)
  - reducing CAPEX and OPEX
- fully implementing functionality in software
  - reducing development and deployment cycle times, opening up the R&D market
- consolidating equipment types
  - reducing power consumption
- optionally concentrating network functions in datacenters or POPs
  - obtaining further economies of scale. Enabling rapid scale-up and scale-down

For example, switches, routers, NATs, firewalls, IDS, etc.
are all good candidates for virtualization
as long as the data rates are not too high

Physical layer functions (e.g., Software Defined Radio) are not ideal candidates

High data-rate (core) NEs will probably remain in dedicated hardware

Potential VNFs

Potential **V**irtualized **N**etwork **F**unctions

- **forwarding elements**: Ethernet switch, router, Broadband Network Gateway, NAT
- **virtual CPE:** demarcation + network functions + VASes
- **mobile network nodes**: HLR/HSS, MME, SGSN, GGSN/PDN-GW, RNC, NodeB, eNodeB
- **residential nodes**: home router and set-top box functions
- **gateways:** IPSec/SSL VPN gateways, IPv4-IPv6 conversion, tunneling encapsulations
- **traffic analysis**: DPI, QoE measurement
- **QoS**: service assurance, SLA monitoring, test and diagnostics
- **NGN signalling**: SBCs, IMS
- **converged and network-wide functions**: AAA servers, policy control, charging platforms
- **application-level optimization**: CDN, cache server, load balancer, application accelerator
- **security functions**: firewall, virus scanner, IDS/IPS, spam protection

Function relocation

Once a network functionality has been virtualized
it is relatively easy to relocate it

By relocation we mean
placing a function somewhere other than its conventional location
e.g., at **P**oints **o**f **P**resence and **D**ata **C**enters

Many (mistakenly) believe that the main reason for NFV
is to move networking functions to data centers
where one can benefit from economies of scale

Some telecomm functionalities need to reside at their conventional location

- Loopback testing
- E2E performance monitoring

but many don't

- routing and path computation
- billing/charging
- traffic management
- DoS attack blocking

Note: even nonvirtualized functions *can* be relocated

Example of relocation with SDN

SDN is, in fact, a specific example of function relocation

In conventional IP networks routers perform 2 functions

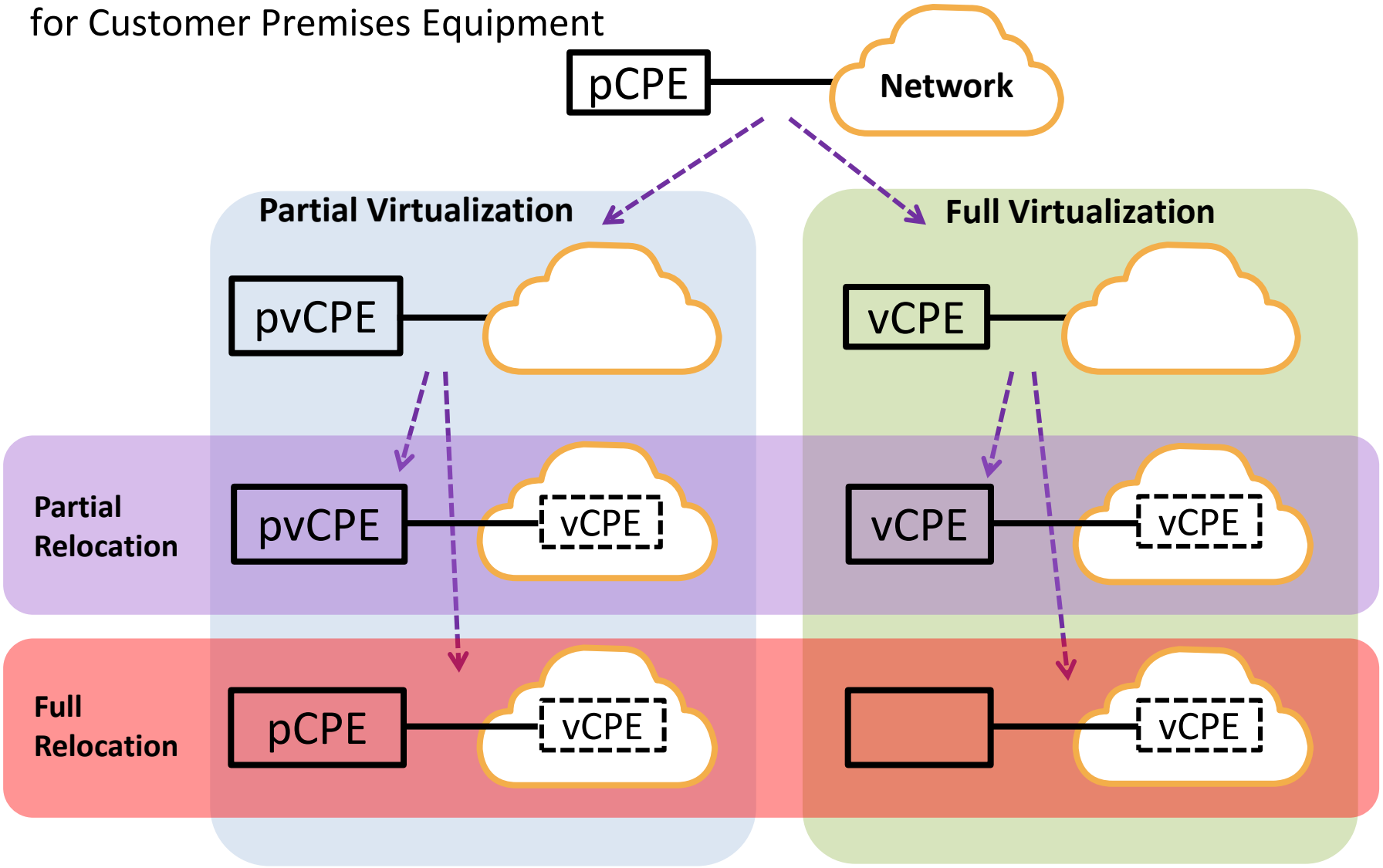
- forwarding
  - observing the packet header
  - consulting the **F**orwarding **I**nformation **B**ase
  - forwarding the packet
- routing
  - communicating with neighboring routers to discover topology (routing protocols)
  - runs routing algorithms (e.g., Dijkstra)
  - populating the FIB used in packet forwarding

SDN enables moving the routing algorithms to a centralized location

- replace the router with a simpler but configurable whitebox switch
- install a centralized SDN controller
  - runs the routing algorithms (internally – w/o on-the-wire protocols)
  - configures the NEs by populating the FIB

Virtualization and Relocation of CPE

Recent attention has been on NFV
for Customer Premises Equipment



Distributed NFV

The idea of optimally placing virtualized network functions in the network
from edge (CPE) through aggregation through PoPs and HQs to datacenters
is called **Distributed-NFV** (DNFV)

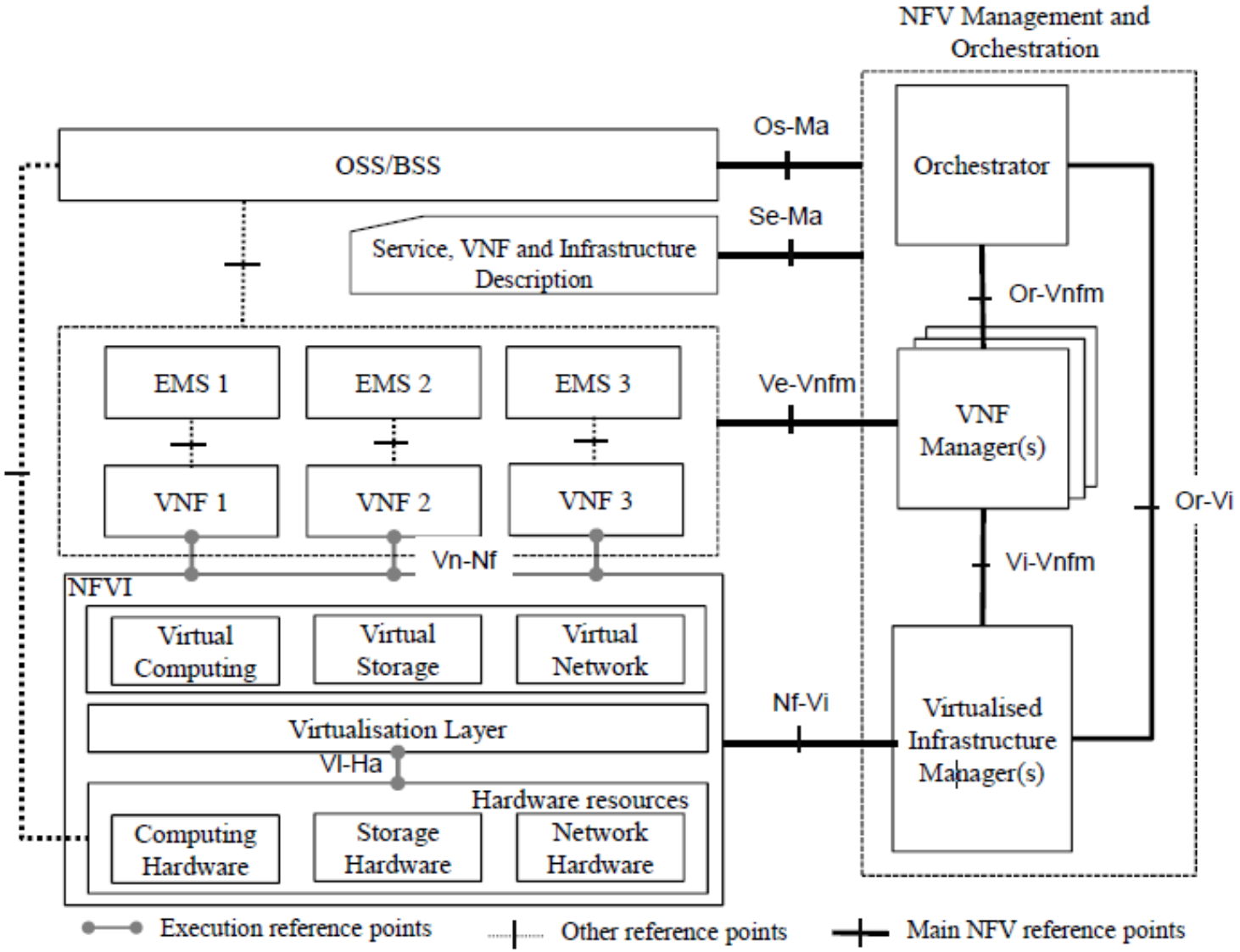
Optimal location of a functionality needs to take into consideration:

- resource availability (computational power, storage, bandwidth)
- *real-estate* availability and costs
- energy and cooling
- management and maintenance
- other economies of scale
- security and privacy
- regulatory issues

For example, consider moving a DPI engine from where it is needed
this requires sending the packets to be inspected to a remote DPI engine

If bandwidth is unavailable or expensive or excessive delay is added
then DPI must not be relocated
even if computational resources are less expensive elsewhere!

ETSI NFV-ISG architecture



MANO ? VIM ? VNFM? NFVO?

Traditional NEs have NMS (EMS) and perhaps are supported by an OSS

NFV has *in addition* the MANO (Management and Orchestration) containing :

- an orchestrator
- VNFM(s) (VNF Manager)
- VIM(s) (Virtual Infrastructure Manager)
- lots of reference points (*interfaces*) !

The VIM (usually OpenStack) manages NFVI resources in one NFVI domain

- life-cycle of virtual resources (e.g., set-up, maintenance, tear-down of VMs)
- inventory of VMs
- FM and PM of hardware and software resources
- exposes APIs to other managers

The VNFM manages VNFs in one VNF domain

- life-cycle of VNFs (e.g., set-up, maintenance, tear-down of VNF instances)
- inventory of VNFs
- FM and PM of VNFs

The NFVO is responsible for resource and service orchestration

- controls NFVI resources everywhere via VIMs
- creates end-to-end services via VNFMs

Joint SDN & NFV Optimization

work with TAU team – Boaz Patt-Shamir and Guy Even

Recap: rich communications services

Traditional communications services are pure *connectivity* services
transport data from A to B
with constraints (e.g., minimum bandwidth, maximal delay)
with maximal efficiency (minimum cost, maximized revenue)

Modern communications services are richer
combining connectivity and network functionalities
e.g., firewall, NAT, load balancing, CDN, parental control, ...

We deal with a service provider that

- maintains a network of communications and computational resources
- maintains an inventory of VNFs
- dynamically sets up and tears down services
- charges based on
  - service requirements
  - time between set-up and tear-down

The service provider employs an orchestrator to maximize profits
(profit is the difference between revenue and expenses)

DNFV Optimization Problems (1)

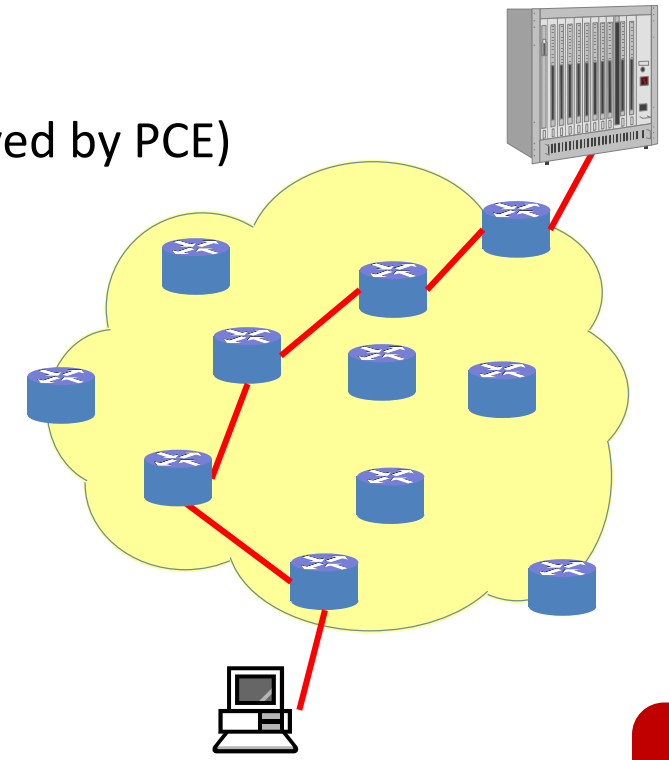
We should distinguish between
- pure connectivity (transport) services
- services containing nontrivial functionalities

The first problem is the well-known *path computation problem* for a pure connectivity service

Pure path computation problem (the problem solved by PCE)

Given:
- traffic source and sink points
- full topology information
- link and node resource information
- service bandwidth and delay requirements

Find the optimal path for a pure connectivity service

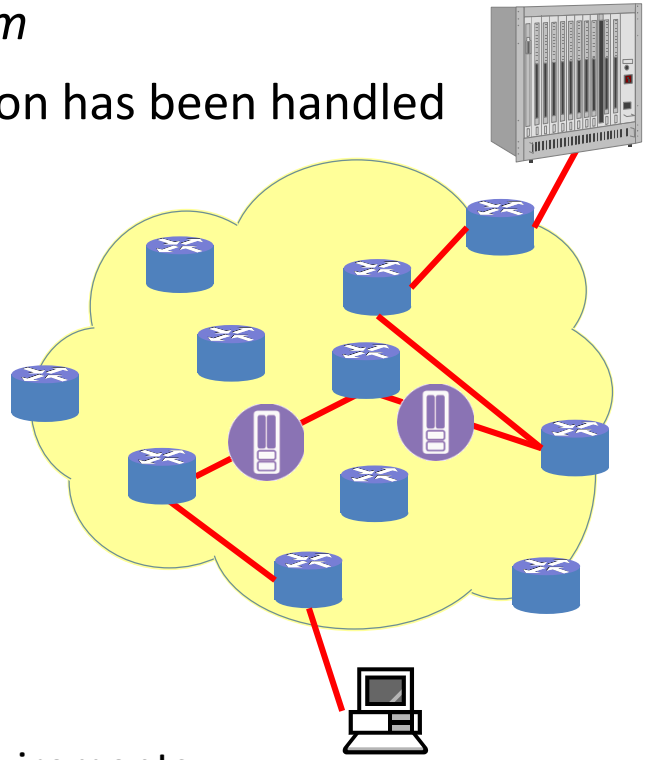


DNFV Optimization Problems (2)

Next, we consider the *pure DNFV placement problem*

In this problem we assume that the path computation has been handled by

- manual static routing or
- via routing protocols or
- via path computation



Pure D-NFV placement optimization problem

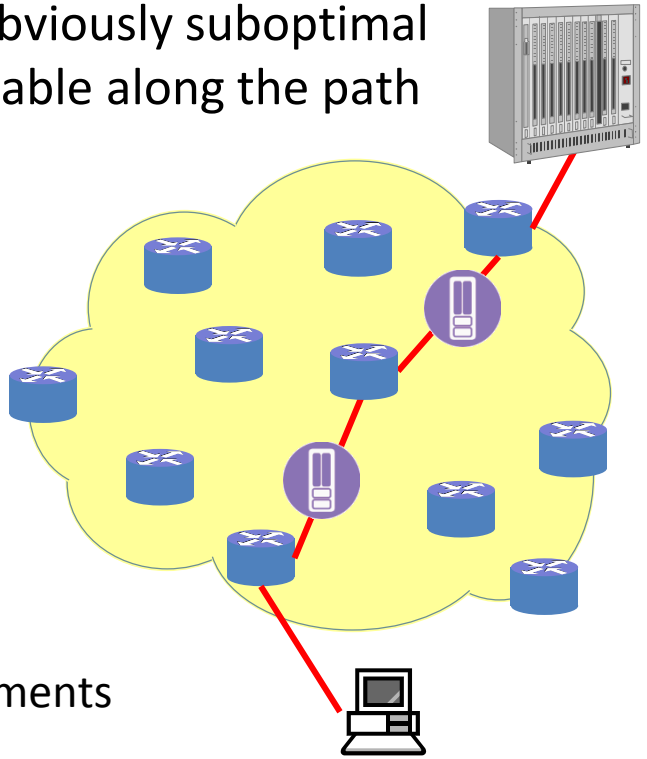
Given:

- the path taken by the traffic
  (and the availability of extra bandwidth if needed)
- the VNF(s) to be installed, including computational requirements
- for multiple VNFs – the (partial) ordering of VNFs
- places where computational resources are available, and present loadings
- D-NFV criteria and constraints

Find the optimal D-NFV placement(s)

DNFV Optimization Problems (3)

Separate path computation and VNF placement is obviously suboptimal unless plentiful computational resources are available along the path



Joint PC/D-NFV optimization

Given:

- traffic source and sink points
- full topology information
- link and node resource information
- service bandwidth and delay requirements
- VNF(s) to be installed, including computational requirements
- for multiple VNFs – the (partial) ordering of VNFs
- places where computational resources are available, and present loadings
- D-NFV criteria and constraints

Find the optimal path and VNF placement(s)

On-line optimization

A batch (off-line) algorithm receives the list of all services to be set up and simultaneously finds all the allocations for a *clean* network

We require an on-line algorithm
that services requests of unknown duration as they come in

We do not allow pre-emption or re-optimization of service already set-up

The on-line case is harder since we don't know ahead of time
whether it is worthwhile to use up resources for a given request
and risk having to deny some later request that may be more profitable

Simple example

- first request requires 100% of a resource and pays **x**
- later requests require some of that resource and together pay **y>>x**

How do we know whether to accept or deny the first request ?

- if we accept, we lose **y-x** if later requests *do* arrive
- if we deny and later requests never arrive, we lose **x**

Formal definition of the joint problem

Known

- full network topology graph
  - link and node current resource loading information
- places where computational resources are available
  - resource availability
- other SDN or NFV criteria and constraints

Service request definition

- traffic ingress and egress points
- service data-rate and delay requirements
- sequence of VNF(s) to be installed

  Note: we do not yet support partial ordering of VNFs
  other than by exhaustively testing every possible order
  - computational (including memory, storage, etc.) requirements
- service set-up or tear-down ?

Find

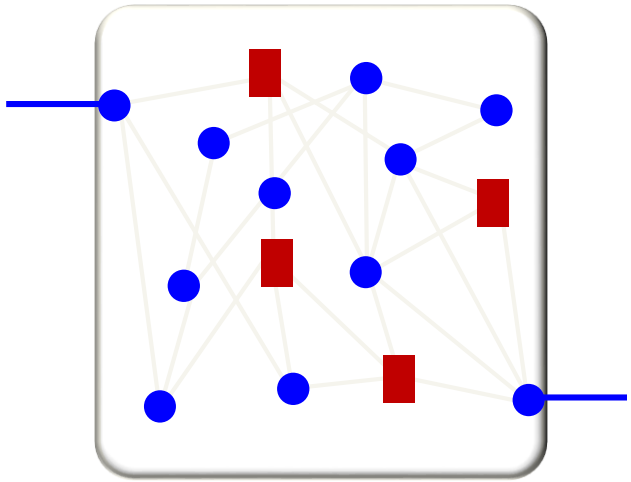
- the optimal path and VNF placement(s)

The solution

The new solution combines two ideas:

1. use of Cartesian Graph Product
2. use of an ACCEPT/STANDBY mechanism

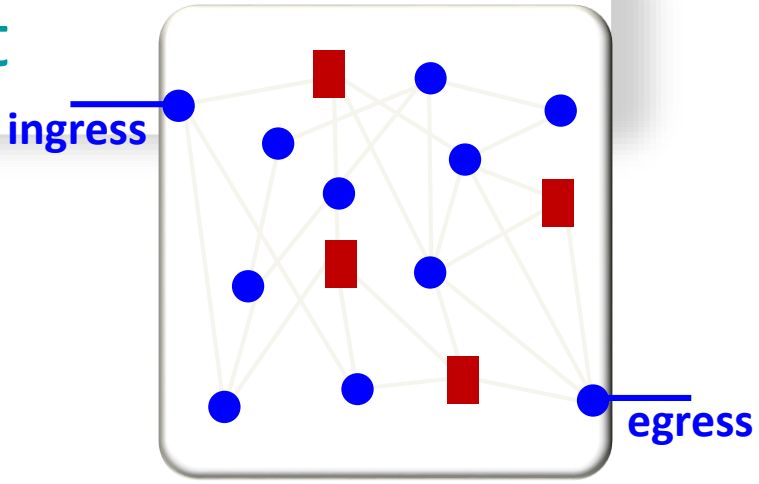
The first idea is a method of transforming the joint problem
into a conventional path computation problem on a single network graph



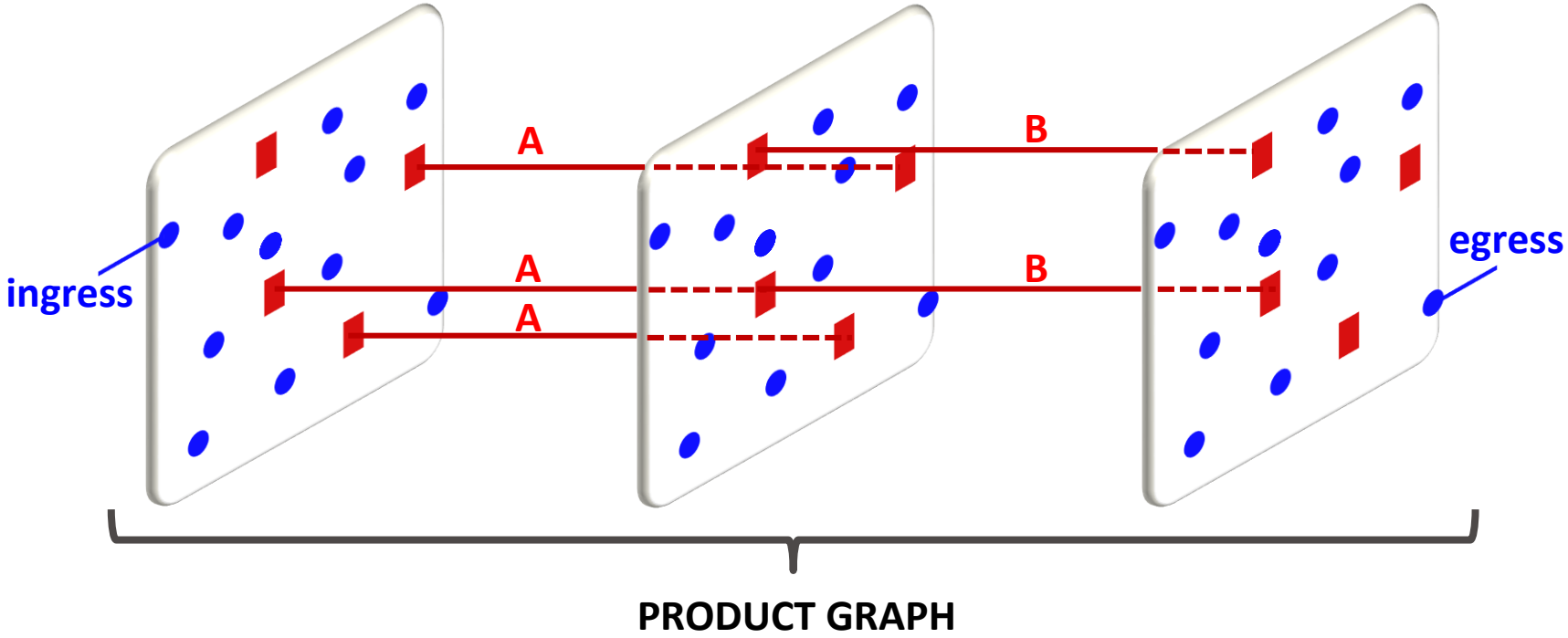
switch (network resource)

server (compute resource)

Step 1 : Cartesian Product



Assume 2 VNFs : **A** and **B**



The product graph is much larger than the original graph, but still manageable

Performance of competitive algorithms

The standard on-line mechanism receives service requests, and returns

- ACCEPT + service routing and placement
- DENY

Given an on-line optimization problem
we can quantify the (*worst case*) performance of an algorithm ALG as follows

For each input I define

- $\mathrm{OPT}(I)$: profit of best possible solution
  one that knows the future, can pre-empt/reroute/load-balance, etc.
- $\mathrm{ALG}(I)$: profit obtained by the algorithm

The algorithm's competitive ratio is defined to be $\mathbf{C} = \max_{\text{all inputs } I} \left\{ \frac{\mathrm{OPT}(I)}{\mathrm{ALG}(I)} \right\}$

This means that the algorithm's profit is at least 1/C times the optimal profit
Good competitive algorithms have small C ! (Beware of alternative definitions!)

The *AAP algorithm* has competitive factor $O(\log n)$ n= number of network nodes
assuming

- small demands – no service request consumes the majority of any resource
- requests are of known finite durations

Step 2: ACCEPT/STANDBY response

In our problem, services may potentially indefinite duration
leading to potentially dismal worst case performance

Simple example

- reject service request that would have indefinitely paid x per unit time
- no further service requests are ever received

To avoid this problem, we never reject a request, instead we return

- ACCEPT + service routing and placement
- STANDBY – service request placed on hold until can be serviced

note that the service request may be rescinded before it is ever serviced!

We still assume that no request consumes a sizeable amount of any resource

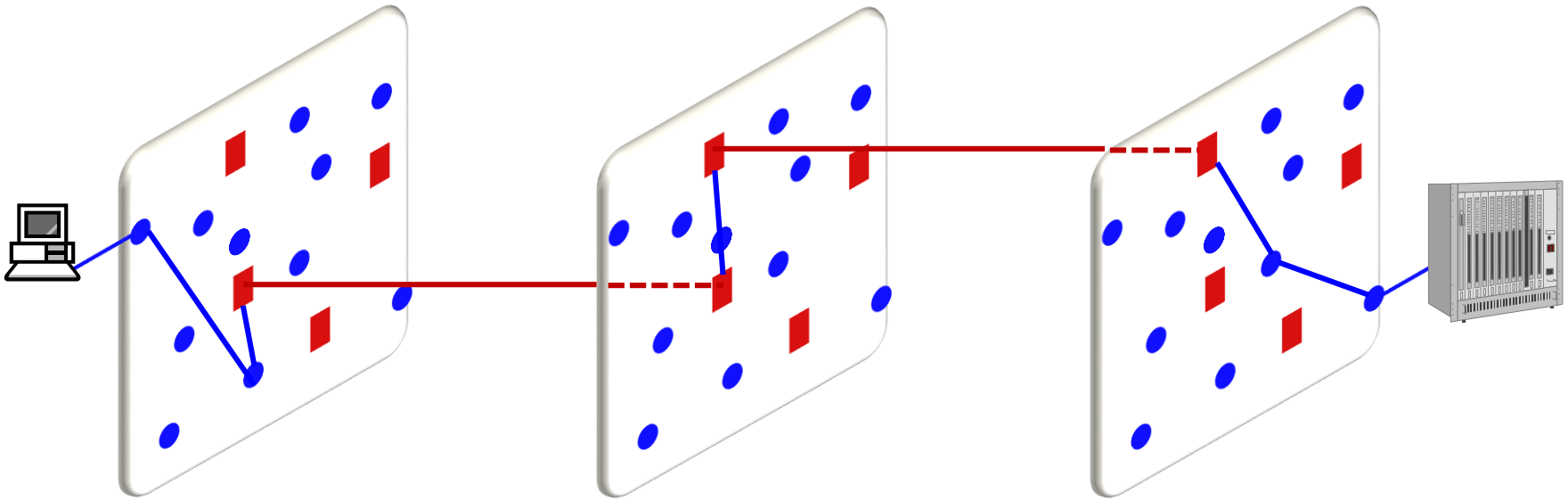
The mechanism has a competitive ratio of $O(k \log n)$
where k is the maximum number of VNFs in a service request
New ideas may improve this to $O(\log(nk))$

Summary

By combining the two ideas

1. use of Cartesian Graph Product
2. use of an ACCEPT/STANDBY mechanism

we obtain a tractable on-line joint SDN/NFV optimization algorithm



Hype and Doubts

Doubts

On the other hand
there are some very good reasons that may lead us to doubt
that SDN and NFV will ever completely replace all networking technologies

The four most important (in my opinion) are :

1. Moore's law vs. Butter's law (NFV)
2. Consequences of SDN layer violations
3. CAP theorem tradeoffs (SDN)
4. Scalability of SDN
5. Robustness (SDN)

Moore's law vs. Butter's law

Moore's law is being interpreted to state
computation power is doubling per unit price about every two years

However, this reasoning neglects **Butter's Law** that states
optical transmission speeds are doubling every nine months

So, if we can't economically perform the function in NFV now
we may be able to perform it at today's data-rates next year
But we certainly won't be able to perform it *at the required data-rates !*

The driving bandwidth *will* increase faster than Moore's law, due to

- increased penetration of terminals (cellphones, laptops)
- increased number of data-hungry apps on each terminal

SDN layer violations

SDN's main tenet is that packet forwarding is a computational problem

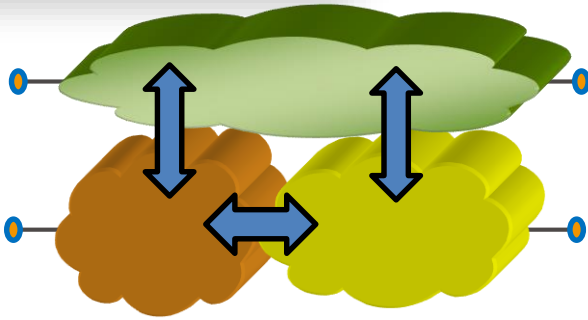
- receive packet
- observe fields
- apply algorithm(classification, decision logic)
- optionally edit packet
- forward or discard packet

In principle an SDN switch could do any computation on any fields
for example forwarding could depend on an arbitrary function of packet fields (MAC addresses, IP addresses, TCP ports, L7 fields, …)

While conventional network elements are limited to their own scope
Ethernet switches look at MAC addresses + VLAN, but not IP and above
routers look at IP addresses, but not at MAC or L4 and above
MPLS LSRs look at top of MPLS stack

A *layer violation* occurs when a NE observes / modifies a field outside its scope
(e.g., DPI, NATs, ECMP peaking under MPLS stack, 1588 TCs, …)

Consequences of layer violations



Client/server (G.80x) layering enables Service Providers
- to serve a higher-layer SP
- to be served by a lower-layer SP

Layer violations may lead to security breaches, such as :
- billing avoidance
- misrouting or loss of information
- information theft
- session highjacking
- information tampering

Layer *respect* is often automatically enforced by network element functionality

A fully programmable SDN forwarding element creates layer violations
these may have unwanted consequences, due to :
- programming bugs
- malicious use

The CAP Theorem

There are three desirable characteristics
of any distributed computational system

1. Consistency
   (get *the same* answer no matter which computational element responds)
2. Availability
   (get *an* answer without unnecessary delay)
3. Partition tolerance
   (get *an* answer even if there a breaks in the system)

The CAP (Brewer's) theorem states that you can have any 2 of these
but not all 3 !

SDN teaches us that **routing/forwarding packets is a computational problem**
so a **network is a distributed computational system**

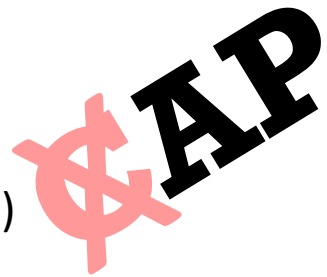
So networks can have at most 2 of these characteristics

Which characteristics do we need, and which can we forgo ?

CAP: the SP Network Choice

SPs pay dearly for service failures
not only in lost revenues, but in SLA violation penalties

Once set up, the network control plane guarantees:
- high **A**vailability (e.g., five nines) and
- high **P**artition tolerance (e.g., 50 millisecond restoration times)



So, **C**onsistency must suffer
- black-holed packets (compensated by TTL fields, CV testing, etc.)
- *eventual* consistency (but steady state may never be reached)

When a new service is being set up (by the management plane)
- **C**onsistency is emphasized
- **A**vailability suffers (thus, set-up is a lengthy process!)
- Partitions are not allowed (faults during commissioning trigger manual operations)

These are *conscious decisions* on the part of the SP
The precise *trade-off* is maintained by a judicious combination
of centralized management and distributed control planes

CAP: the SDN Choice

SDN has emphasized consistency (perhaps natural for software proponents)

So such SDNs must forgo either *availability* or *partition tolerance* (or both)
Either alternative may rule out use of SDN in SP networks

Relying solely on a single[1] centralized controller
(which in communications parlance is a pure management system)
may lead to more efficient bandwidth utilization
but means giving up partition tolerance

However, there are no specific mechanisms to attain availability either !

Automatic protection switching needs to be performed quickly
which can not be handled by a remote controller alone[2]

[1] Using multiple collocated controllers does not protect against connectivity failures.
Using multiple non-collocated controllers requires synchronization, which can lead to low availability.

[2] There are solutions, such as triggering preconfigured back-up paths,
but present SDN protocols do not support conditional forwarding very well.

Scalability

In **centralized protocols** (e.g., NMS, PCE, SS7, OpenFlow)
all network elements talk with a centralized *management system* (AKA Godbox)
that collects information, makes decisions, and configures elements
In **distributed protocols** (e.g., STP, routing protocols)
each network element talks to its *neighbors*
and makes *local* decisions based currently available information

Distributed protocols are great at discovering connectivity
but are not best for more general optimization
Distributed protocols scale without limit
but may take a long time to completely converge (only eventual consistency)

Centralized protocols can readily solve complex network optimization problems
but as the number of network elements increases
the centralized element becomes overloaded
Dividing up the centralized element based on clustering network elements
is the first step towards a distributed system (BGP works this way)

Robustness

SDN academicians complain about
the *brittleness / fragility* of communications protocols
As opposed to the *robustness* their approach can bring

To investigate this claim, we need to understand what *robustness* means

We say that a system is **robust to X**
when it can continue functioning even when X happens

For example,

- A communications network is **robust to failures**
  if it continues functioning even when links or network elements fail
- A communications network is **robust to capacity increase**
  if it continues functioning
  when the capacity it is required to handle increases

So it is meaningless to say that a system is *robust* without saying to *what* !

Robustness (cont.)

Unfortunately, *robustness to X* may contradict *robustness to Y*

For example,

- In order to achieve robustness to failures
  the network is designed with redundancy (e.g., 1+1)
- In order to achieve robustness to capacity increase
  the network is designed for efficiency, i.e., with no redundancy

Thus networks can not be designed to be robust to everything
Instead, networks are designed to profitably provide services

The X that seems to be most on the minds of SDN proponents is
creation of new types of services

In the past, new service type creation was infrequent
so networks were not required to be robust to it

This is an area where SDN can make a big difference !

OpenFlow

What is OpenFlow ?

OpenFlow is an SDN southbound interface –
i.e., a protocol from an SDN controller to an SDN switch (*whitebox*)
that enables configuring forwarding behavior

What makes OpenFlow different from similar protocols is its *switch model*
it assumes that the SDN switch is based on TCAM matcher(s)
so flows are identified by exact match with wildcards on header field
supported header fields include:

- Ethernet - DA, SA, EtherType, VLAN
- MPLS – top label and BoS bit
- IP (v4 or v6) – DA, SA, protocol, DSCP, ECN
- TCP/UDP ports

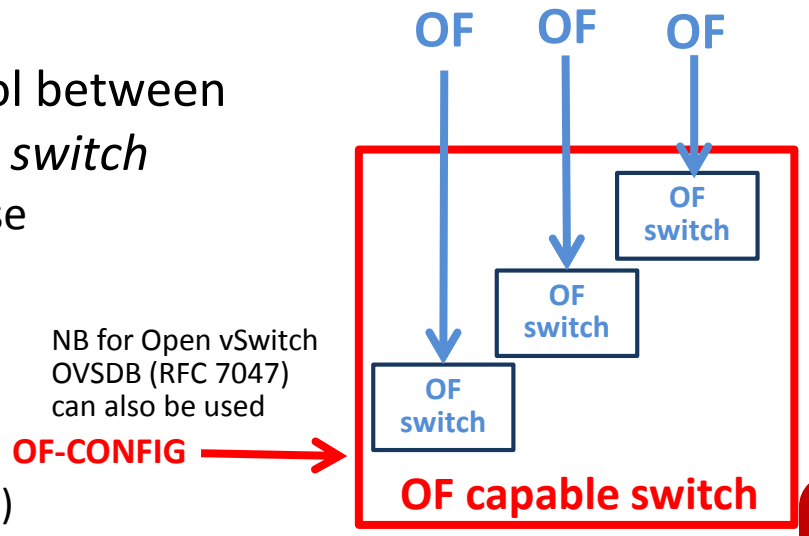
OpenFlow grew out of *Ethane* and is now developed by the ONF
it has gone through several major versions
the latest is 1.5.0

OpenFlow

The OpenFlow specifications describe
- the southbound protocol between OF controller and OF switches
- the operation of the OF switch

The OpenFlow specifications do not define
- the northbound interface from OF controller to applications
- how to boot the network
- how an E2E path is set up by touching multiple OF switches
- how to configure or maintain an OF switch (which can be done by of-config)

The **OF-CONFIG** specification defines
a configuration and management protocol between
OF configuration point and *OF capable switch*
- configures which OpenFlow controller(s) to use
- configures queues and ports
- remotely changes port status (e.g., up/down)
- configures certificates
- switch capability discovery
- configuration of tunnel types (IP-in-GRE, VxLAN)



OF matching

The basic entity in OpenFlow is the ***flow***

A flow is a sequence of packets
that are forwarded through the network in the same way

Packets are classified as belonging to flows
based on **match fields** (switch ingress port, packet headers, metadata)
detailed in a **flow table** (list of match criteria)

Only a finite set of match fields is presently defined
and an even smaller set that must be supported

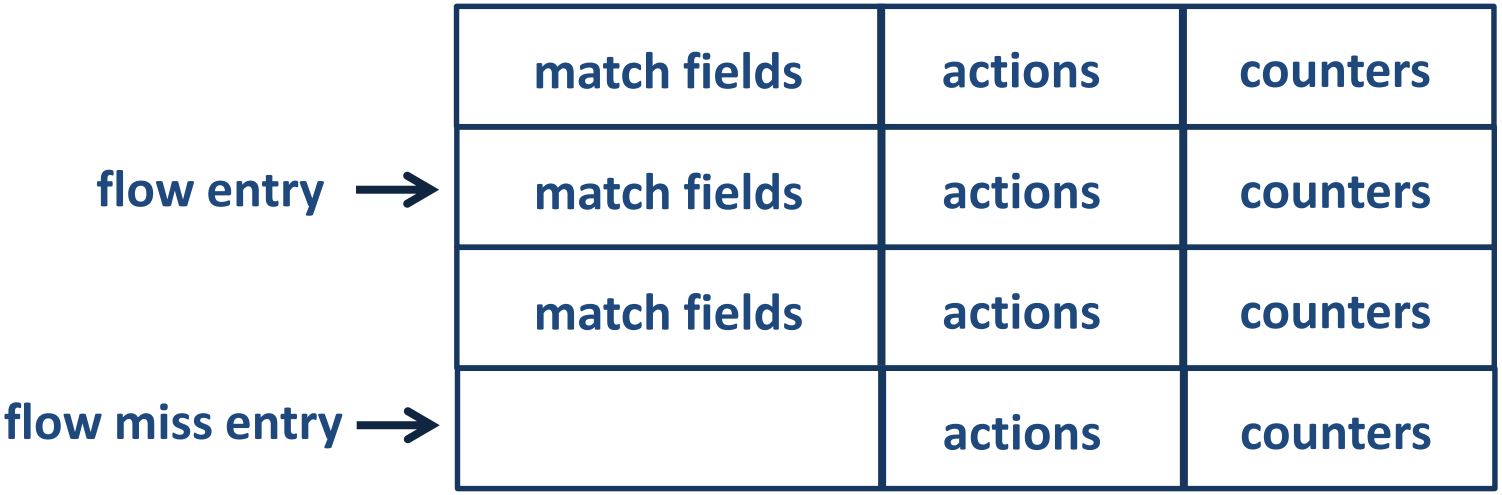
The matching operation is *exact match*
with certain fields allowing *bit-masking*

Since OF 1.1 the matching proceeds in a **pipeline**

Note: this limited type of matching is too primitive
to support a complete NFV solution
(it is even too primitive to support IP forwarding, let alone NAT, firewall ,or IDS!)

However, the assumption is that DPI is performed by the network application
and all the relevant packets will be easy to match

OF flow table



The flow table is populated by the controller

The incoming packet is matched by comparing to match fields

For simplicity, matching is exact match to a static set of fields

If matched, actions are performed and counters are updated

Entries have priorities and the highest priority match succeeds

Actions include editing, metering, and forwarding

OpenFlow 1.3 basic match fields

- **Switch input port**
- Physical input port
- Metadata

- **Ethernet DA**
- **Ethernet SA**
- **EtherType**
- VLAN id
- VLAN priority

- IP DSCP
- IP ECN
- **IP protocol**
- **IPv4 SA**
- **IPv4 DA**
- IPv6 SA
- IPv6 DA

- **TCP source port**
- **TCP destination port**
- **UDP source port**
- **UDP destination port**
- SCTP source port
- SCTP destination port

- ICMP type
- ICMP code
- ARP opcode
- ARP source IPv4 address
- ARP target IPv4 address
- ARP source HW address
- ARP target HW address

- IPv6 Flow Label
- ICMPv6 type
- ICMPv6 code
- Target address for IPv6 ND
- Source link-layer for ND
- Target link-layer for ND
- IPv6 Extension Header pseudo-field

- MPLS label
- MPLS BoS bit

- PBB I-SID

- Logical Port Metadata (GRE, MPLS, VxLAN)

bold match fields MUST be supported

OpenFlow Switch Operation

There are two different kinds of OpenFlow compliant switches

- OF-only all forwarding is based on OpenFlow
- OF-hybrid supports conventional and OpenFlow forwarding

Hybrid switches will use some mechanism (e.g., VLAN ID) to differentiate between packets to be forwarded by conventional processing and those that are handled by OF

The switch first has to classify an incoming packet as

- conventional forwarding
- OF protocol packet from controller
- packet to be sent to flow table(s)

OF forwarding is accomplished by a flow table or since 1.1 by flow table**s**

An OpenFlow compliant switch must contain at least one flow table

OF also collects PM statistics (counters) and has basic rate-limiting (metering) capabilities

An OF switch can not usually react by itself to network events but there is a *group* mechanism that can be used for limited reactions

Matching fields

An OF flow table can match multiple fields

So a single table may require

ingress port = P *and*
source MAC address = SM *and* destination MAC address = DM *and*
VLAN ID = VID *and* EtherType = ET *and*
source IP address = SI *and* destination IP address = DI *and*
IP protocol number = P *and*
source TCP port = ST *and* destination TCP port = DT

This kind of exact match of many fields is expensive in software
but can readily implemented via TCAMs

OF 1.0 had only a single flow table
which led to overly limited hardware implementations
since practical TCAMs are limited to several thousand entries

OF 1.1 introduced **multiple tables** for scalability

OF 1.1+ flow tables

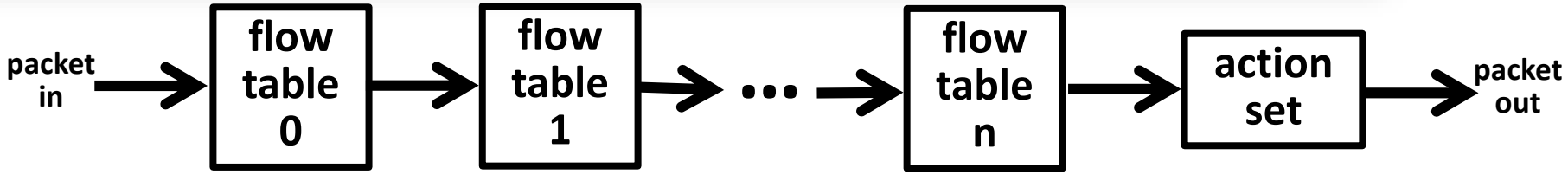


Table matching

- each flow table is ordered by priority
- highest priority match is used (match can be made "negative" using drop action)
- matching is exact match with certain fields allowing bit masking
- table may specify ANY to wildcard the field
- fields matched may have been modified in a previous step

Although the pipeline was introduced mainly for scalability
it gives the matching syntax more expressibility to (although no additional semantics)
In addition to the verbose

```
if (field1=value1) AND (field2=value2) then …
if (field1=value3) AND (field2=value4) then …
```

it is now possible to accommodate

```
if (field1=value1) then if (field2=value2)  then …
                        else  if (field2=value4)  then …
```

Unmatched packets

What happens when no match is found in the flow table ?

A flow table *may* contain a flow miss entry
to catch unmatched packets
The flow miss entry must be inserted by the controller just like any other entry
and is defined as wildcard on all fields, and lowest priority

The flow miss entry may be configured to :

- discard packet
- forward to a subsequent table
- forward (OF-encapsulated) packet to controller
- use “normal” (conventional) forwarding (for OF-hybrid switches)

If there is no flow miss entry
the packet is by default discarded
but this behavior may be changed via of-config

OF switch ports

The ports of an OpenFlow switch can be physical or logical

The following ports are defined :

- physical ports (connected to switch hardware interface)
- logical ports connected to tunnels (tunnel ID and physical port are reported to controller)
- ALL output port (packet sent to all ports except input and blocked ports)
- CONTROLLER packet from or to controller
- TABLE represents start of pipeline
- IN_PORT output port which represents the packet's input port
- ANY wildcard port
- LOCAL optional – switch local stack for connection over network
- NORMAL optional port sends packet for conventional processing (hybrid switches only)
- FLOOD output port sends packet for conventional flooding

Instructions

Each flow entry contains an **instruction set** to be executed upon match

Instructions include:

- Metering : rate limit the flow (may result in packet being dropped)
- Apply-Actions : causes actions in *action list* to be executed immediately
  (may result in packet modification)
- Write-Actions / Clear-Actions : changes *action set* associated with packet
  which are performed when pipeline processing is over
- Write-Metadata : writes metadata into metadata field associated with packet
- Goto-Table : indicates the next flow table in the pipeline
  if the match was found in flow table k
  then goto-table m must obey m > k

Actions

OF enables performing actions on packets

- **output** packet to a specified port
- **drop** packet (if no actions are specified)
- apply **group** bucket actions (to be explained later)
- overwrite packet header fields
- copy or decrement TTL value
- push or pop push MPLS label or VLAN tag
- set QoS queue (into which the packet will be placed before forwarding)

mandatory to support

optional to support

Action lists are performed immediately upon match

- actions are accumulatively performed in the order specified in the list
- particular action types may be performed multiple times
- further pipeline processing is on the modified packet

Action sets are performed at the end of pipeline processing

- actions are performed in the order specified in OF specification
- actions can only be performed once

Meters

OF is not very strong in QoS features
but does have a metering mechanism

A flow entry can specify a **meter**, and the meter measures and limits the aggregate rate of all flows to which it is attached

The meter can be used directly for simple rate-limiting (by discarding) or can be combined with DSCSP remarking for DiffServ mapping

Each meter can have several **meter bands**
if the meter rate surpasses a meter band, the configured action takes place
where possible actions are

- drop
- increase DSCP drop precedence

OpenFlow statistics

OF switches maintain **counters** for every

- flow table
- flow entry
- port
- queue
- group
- group bucket
- meter
- meter band

Counters are unsigned integers and wrap around without overflow indication

Counters may count received/transmitted packets, bytes, or durations

See table 5 of the OF specification for the list of mandatory and optional counters

Flow removal and expiry

Flows may be explicitly deleted by the controller at any time

However, flows may be preconfigured with finite lifetimes
and are automatically removed upon expiry

Each flow entry has two timeouts

- hard_timeout : if non-zero, the flow times out after X seconds
- idle_timeout : if non-zero, the flow times out after not receiving a packet for X seconds

When a flow is removed for any reason,
there is flag which requires the switch to inform the controller

- that the flow has been removed
- the reason for its removal (expiry/delete)
- the lifetime of the flow
- statistics of the flow

Groups

Groups enable performing some set of actions on multiple flows
thus common actions can be modified once, instead of per flow

Groups also enable additional functionalities, such as

- replicating packets for multicast
- load balancing
- protection switch

Group operations are defined in group table

Group tables provide functionality not available in flow table

While flow tables enable dropping or forwarding to one port
group tables enable (via group *type*) forwarding to :

- a random port from a group of ports (load-balancing)
- the first live port in a group of ports (for failover)
- all ports in a group of ports (packet replicated for multicasting)

Action buckets are triggered by type:

- **All** execute all buckets in group
- **Indirect** execute one defined bucket
- **Select** (optional) execute a bucket (via round-robin, or hash algorithm)
- **Fast failover** (optional) execute the first live bucket

Slicings

Network slicing

A network can be divided into isolated *slices*
each with different behavior
each controlled by different controller

Thus the same switches can treat different packets in completely different ways
(for example, L2 switch some packets, L3 route others)

Bandwidth slicing

OpenFlow supports multiple queues per output port
in order to provide some minimum data bandwidth per flow

This is also called *slicing* since it provides a *slice* of the bandwidth to each queue

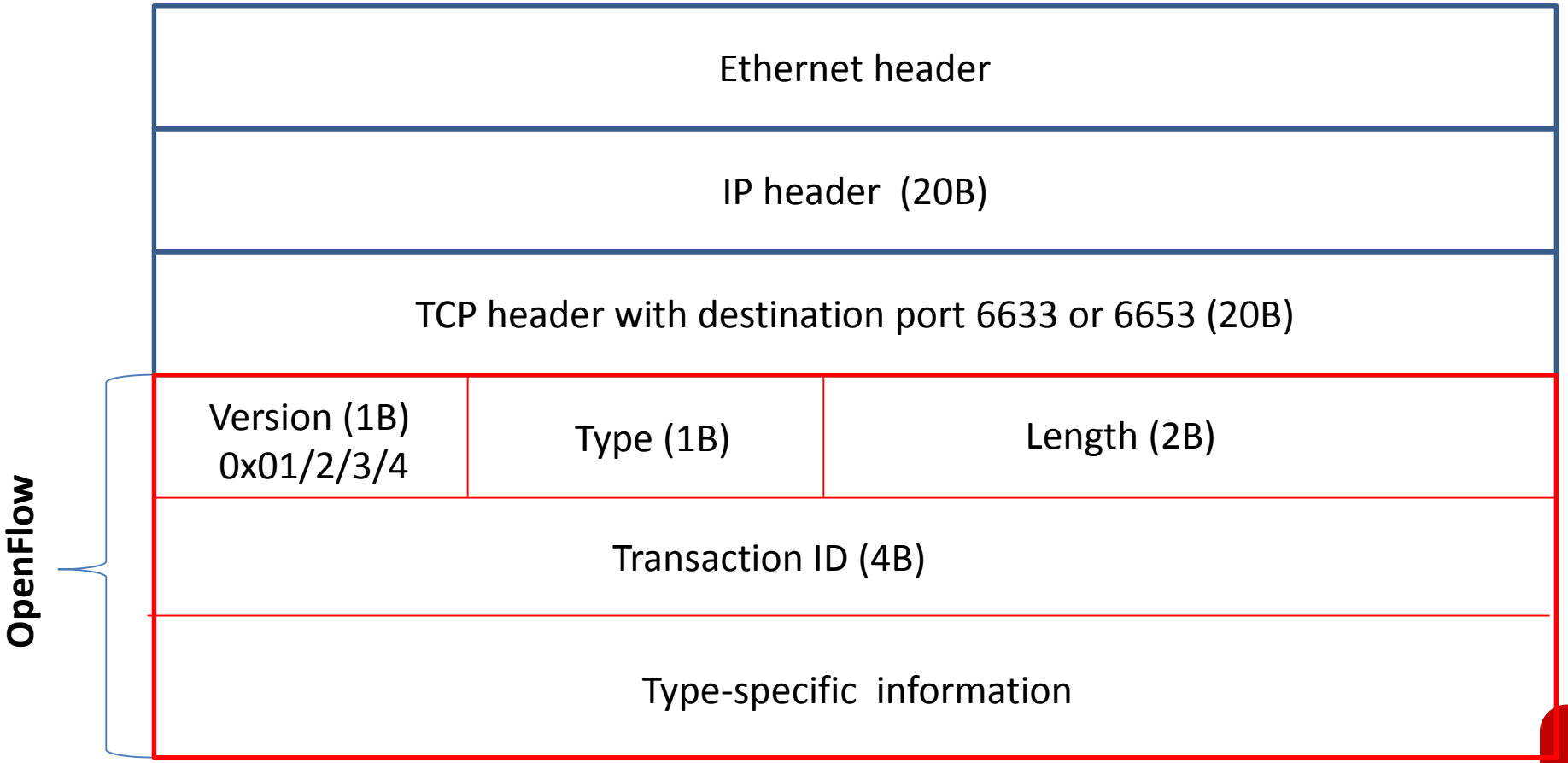
Queues may be configured to have ：

- given length
- minimal/maximal bandwidth
- other properties

OpenFlow protocol packet format

OF runs over TCP (optionally SSL for secure operation) using port 6633 and is specified by C **struct**s

OF is a very low-level specification (assembly-language-like)



OpenFlow messages

The OF protocol was built to be *minimal* and *powerful*

There are 3 types of OpenFlow messages :

OF controller to switch

- populates flow tables which SDN switch uses to forward
- request statistics

OF switch to controller (asynchronous messages)

- packet/byte counters for defined flows
- sends packets not matching a defined flow

Symmetric messages

- hellos (startup)
- echoes (heartbeats, measure control path latency)
- experimental messages for extensions

OpenFlow message types

Symmetric messages
- **0** HELLO
- **1** ERROR
- **2** ECHO_REQUEST
- **3** ECHO_REPLY
- **4** EXPERIMENTER

Switch configuration
- **5** FEATURES_REQUEST
- **6** FEATURES_REPLY
- **7** GET_CONFIG_REQUEST
- **8** GET_CONFIG_REPLY
- **9** SET_CONFIG

Asynchronous messages
- **10** PACKET_IN = 10
- **11** FLOW_REMOVED = 11
- **12** PORT_STATUS = 12

Controller command messages
- **13** PACKET_OUT
- **14** FLOW_MOD
- **15** GROUP_MOD
- **16** PORT_MOD
- **17** TABLE_MOD

Multipart messages
- **18** MULTIPART_REQUEST
- **19** MULTIPART_REPLY

Barrier messages
- **20** BARRIER_REQUEST
- **21** BARRIER_REPLY

Queue Configuration messages
- **22** QUEUE_GET_CONFIG_REQUEST
- **23** QUEUE_GET_CONFIG_REPLY

Controller role change request messages
- **24** ROLE_REQUEST
- **25** ROLE_REPLY

Asynchronous message configuration
- **26** GET_ASYNC_REQUEST
- **27** GET_ASYNC_REPLY
- **28** SET_ASYNC

Meters and rate limiters configuration
- **29** METER_MOD

Interestingly, OF uses a protocol version and TLVs for extensibility
These are 2 generic control plane mechanisms,
of the type that SDN claims don't exist …

Session setup and maintenance

An OF switch may contain default flow entries to use
before connecting with a controller

The switch will boot into a special failure mode

An OF switch is usually pre-configured with the IP address of a controller

An OF switch may establish communication with multiple controllers in order to improve reliability or scalability; the hand-over is managed by the controllers.

OF is best run over a secure connection (TLS/SSL),
but *can* be run over unprotected TCP

Hello messages are exchanged between switch and controller upon startup
hellos contain version number and optionally other data

Echo_Request and **Echo_reply** are used to verify connection liveliness
and optionally to measure its latency or bandwidth

Experimenter messages are for experimentation with new OF features

If a session is interrupted by connection failure
the OF switch continues operation with the current configuration

Upon re-establishing connection the controller may delete all flow entries

Bootstrapping

How does the OF controller communicate with OF switches before OF has set up the network ?

The OF specification explicitly avoids this question

- one may assume conventional IP forwarding to pre-exist
- one can use spanning tree algorithm with controller as root, once switch discovers controller it sends topology information

How are flows initially configured ?

The specification allows two methods

- proactive (push) flows are set up without first receiving packets
- reactively (pull) flows are only set up after a packet has been received

A network may mix the two methods

Service Providers may prefer proactive configuration while enterprises may prefer reactive

Barrier message

An OF switch does not explicitly acknowledge message receipt or execution

OF switches may arbitrarily reorder message execution
in order to maximize performance

When the order in which the switch executes messages is important
or an explicit acknowledgement is required
the controller can send a **Barrier_Request** message

Upon receiving a barrier request
the switch must finish processing all previously received messages
before executing any new messages

Once all old messages have been executed
the switch sends a **Barrier_Reply** message back to the controller