Network Function Virtualization

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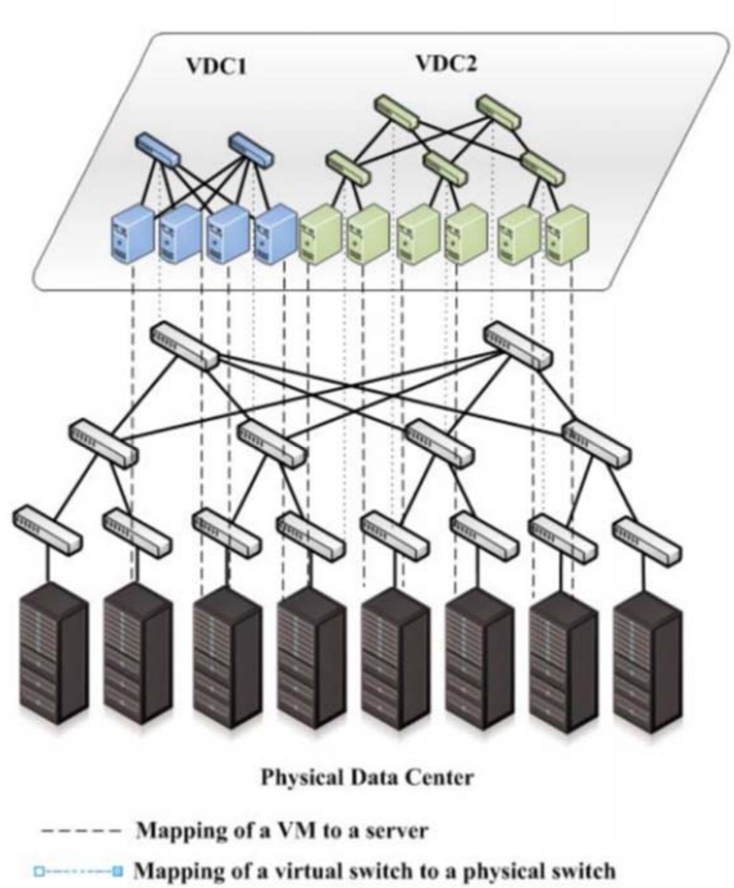
Learning Objectives and Outline

- Learning Objectives
  - Discuss main motivations behind network virtualization
  - Learn about key virtualization mechanisms
  - Gain awareness about network virtualization research
- Outline
  - Network Virtualization
  - Definition, business model, benefits and recent use cases
  - Network Virtualization mechanisms
  - Abstraction, partitioning and isolation
  - Node, link and network virtualization
  - Network Virtualization challenges and research directions

Virtualization

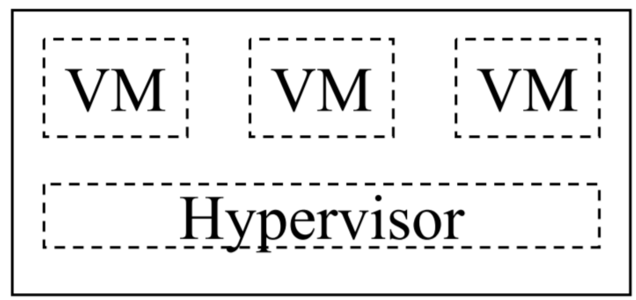
- Virtualization refers to dividing physical resources into isolated partitions (called slices or virtual resources)
- Examples
  - Servers => virtual machines or containers
  - Links => virtual links
  - Data centers => virtual data centers
  - Network function => virtual network function
- Tools and technologies:
  - Hypervisors: Xen, KVM
  - OpenStack Cloud Platform: OpenStack, CloudStack
  - SDN (e.g., FlowVisor)



Backgrounds: Virtual Machine (VM)

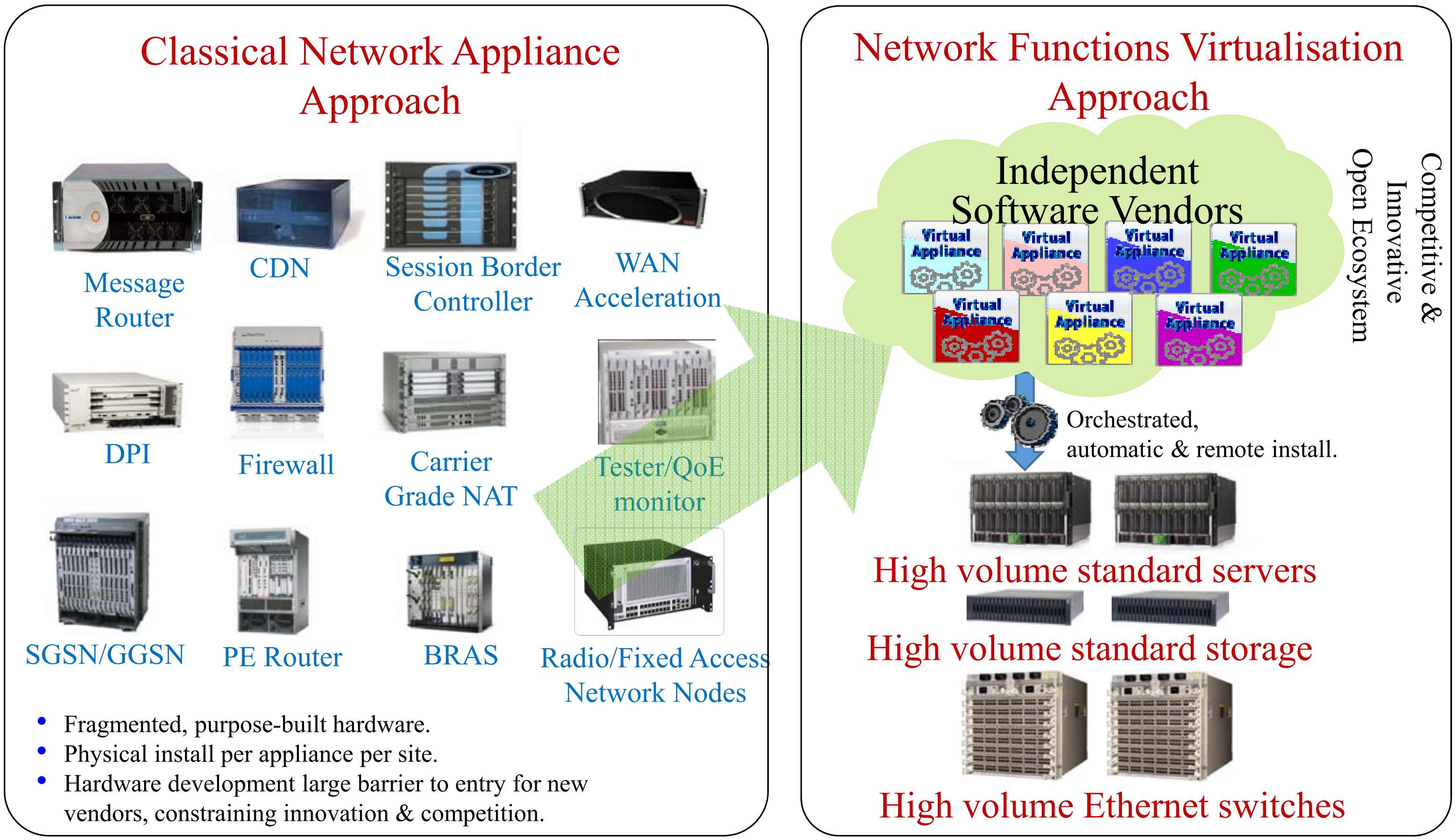
❖Virtual Machine implementation

- Virtual appliances
- All advantages of virtualization (quick provisioning, scalability, mobility, Reduced CapEx, Reduced OpEx, …)

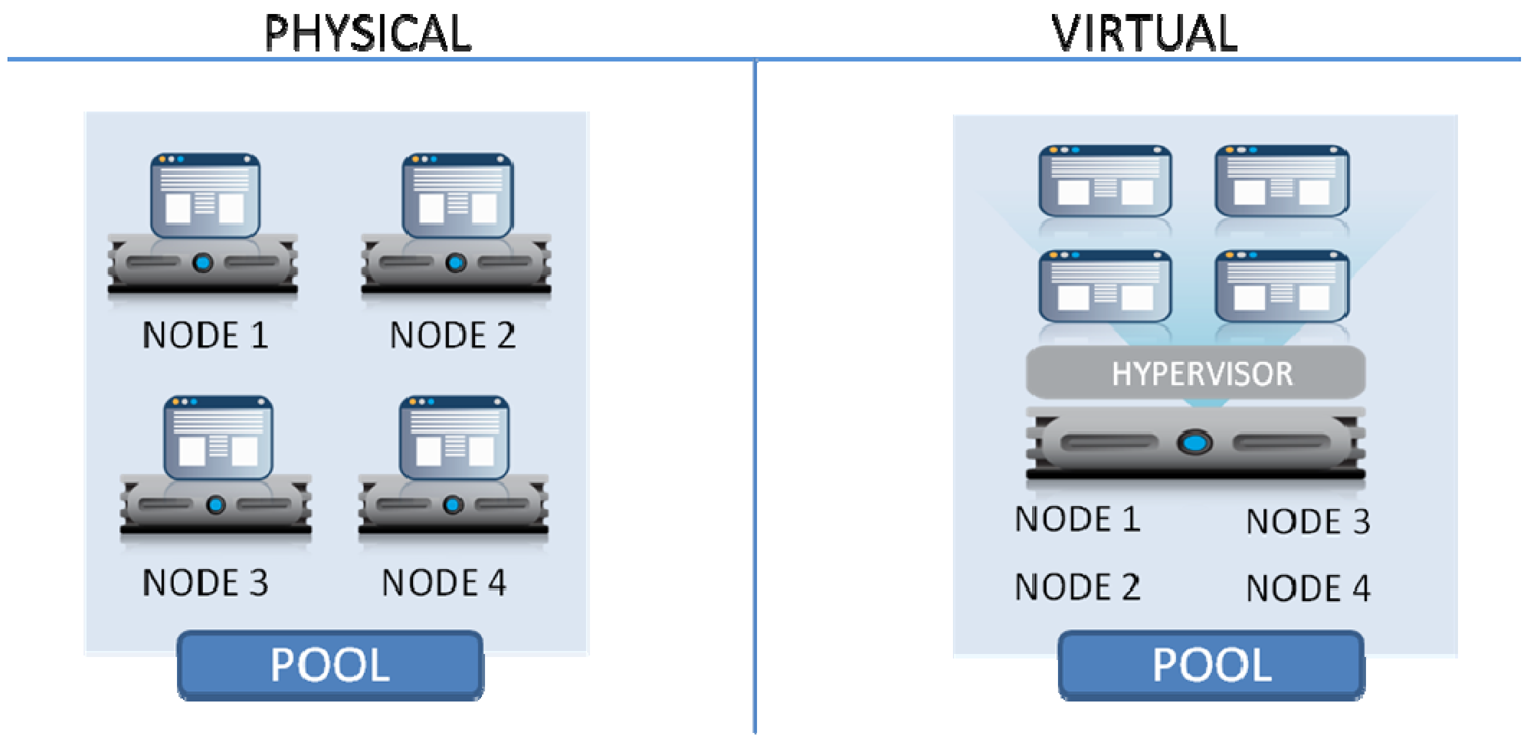


❖Standard APIs: New ISG (Industry Specification Group) in ETSI (European Telecom Standards Institute) set up in November 2012

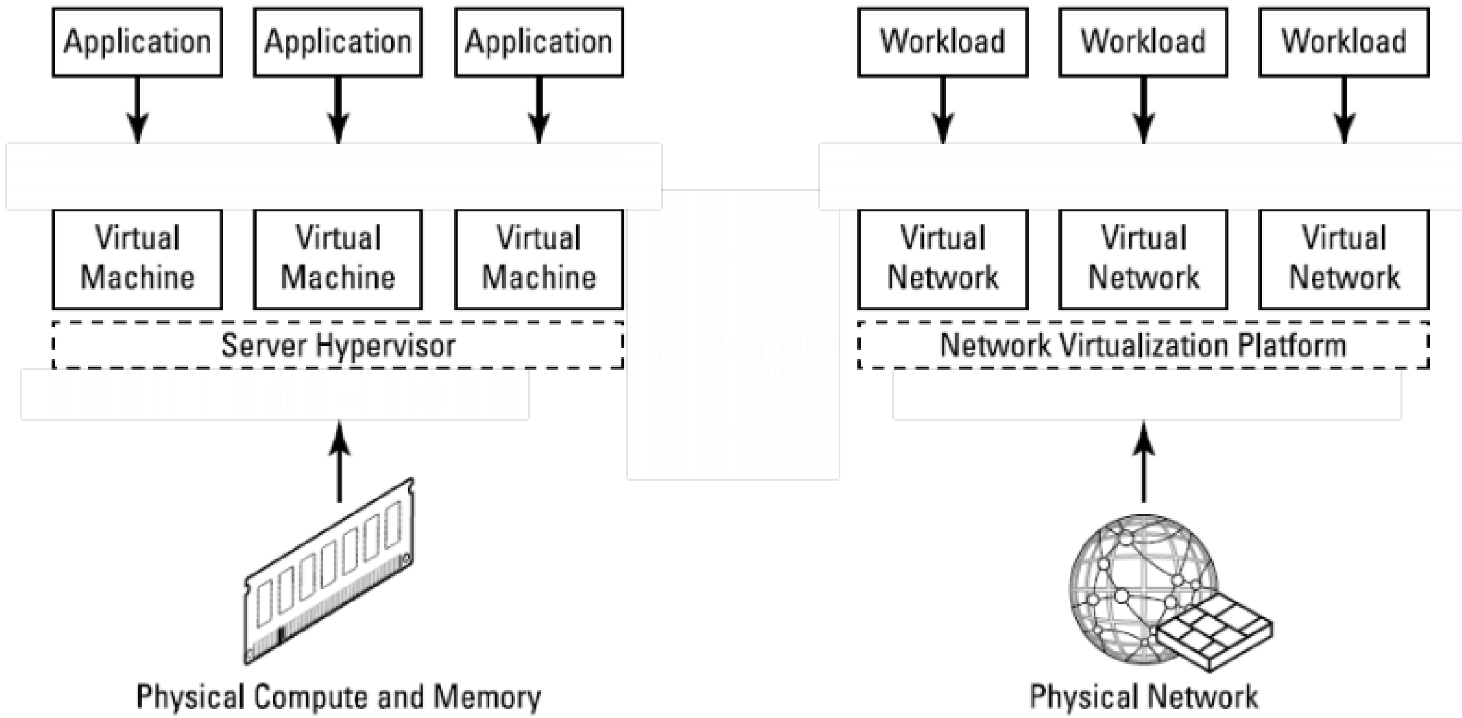
Back Ground


Classical Network Appliance Approach
Message Router
CDN
Session Border Controller
WAN Acceleration
DPI
Firewall
Carrier Grade NAT
Tester/QoE monitor
SGSN/GGSN
PE Router
BRAS
Radio/Fixed Access Network Nodes
• Fragmented, purpose-built hardware.
• Physical install per appliance per site.
• Hardware development large barrier to entry for new vendors, constraining innovation & competition.
Network Functions Virtualisation Approach
Independent Software Vendors
Virtual Appliance
Competitive & Innovative Open Ecosystem
Orchestrated, automatic & remote install.
High volume standard servers
High volume standard storage
High volume Ethernet switches

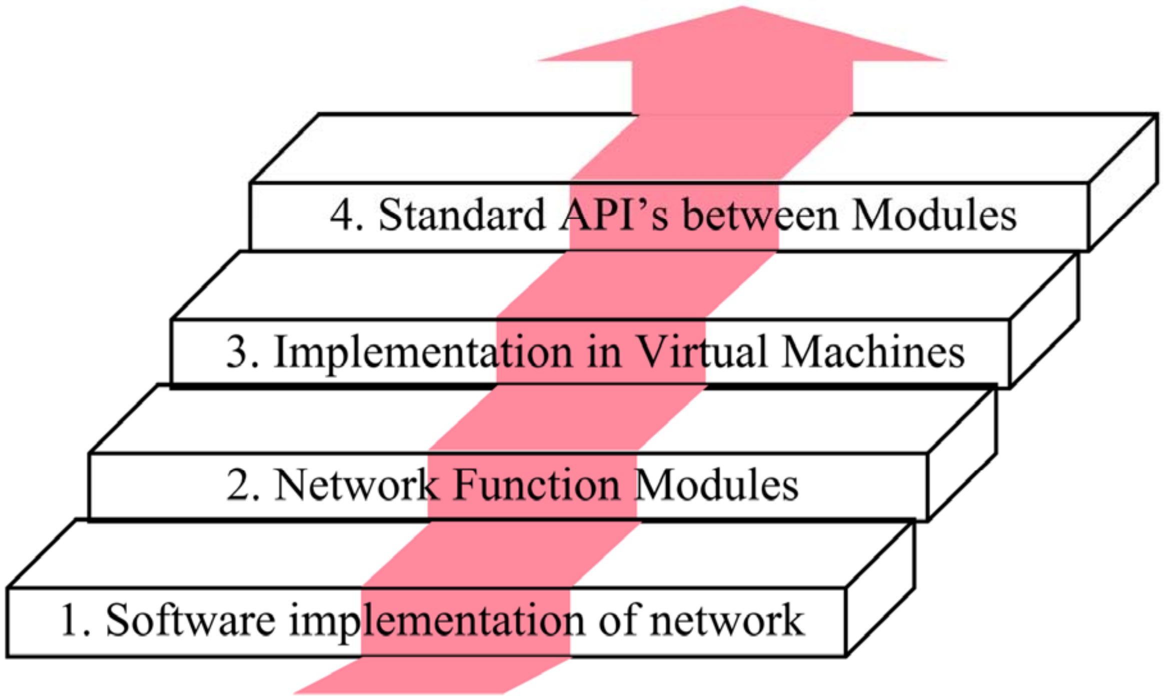
Physical versus Virtual Nodes



Server Virtualization Analogy



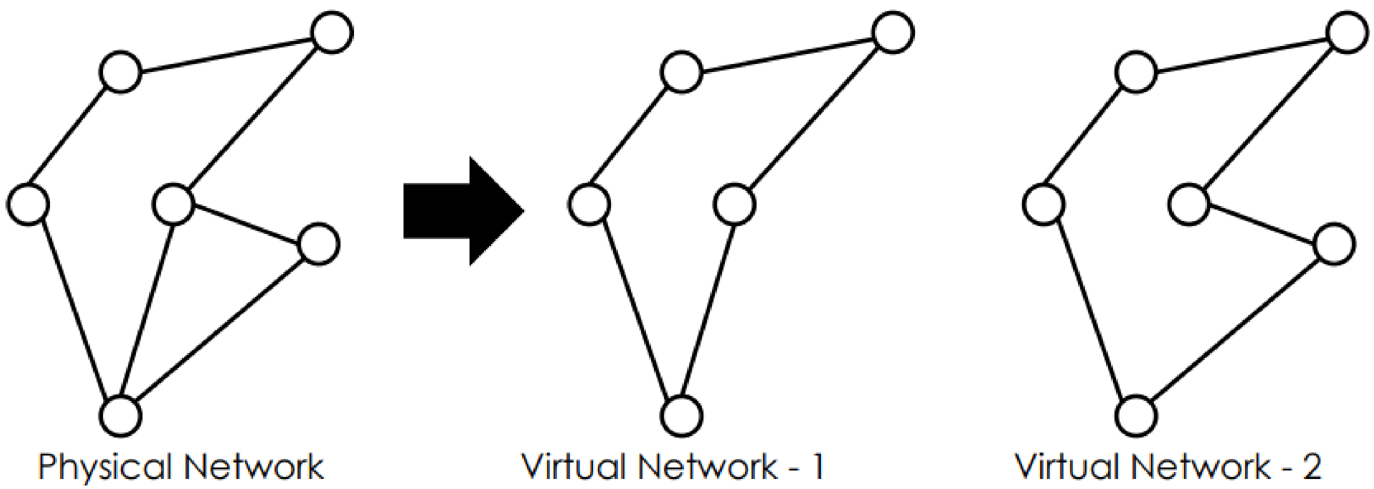
Four Implementation Steps of NFV



https://www.cse.wustl.edu/~jain/cse570-13/

Virtual Networks (VN)

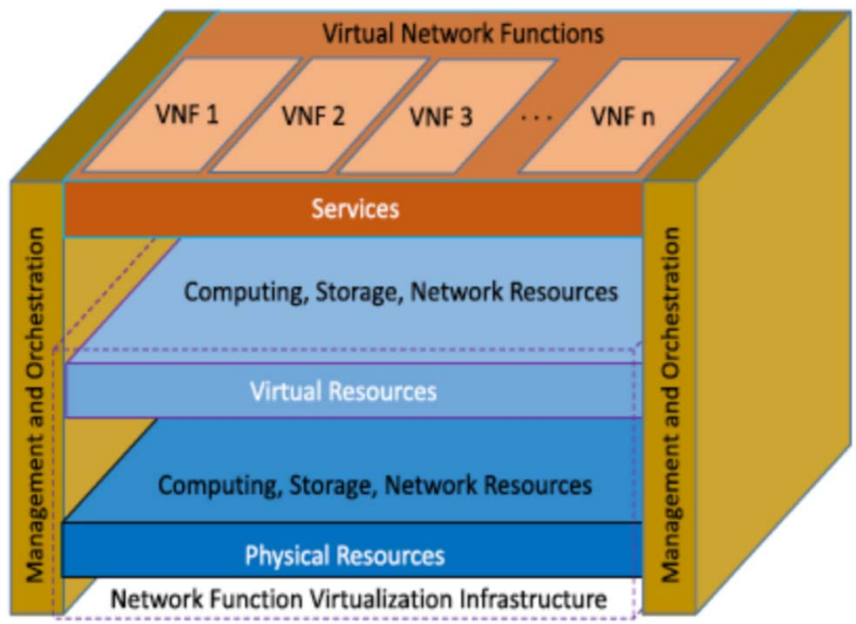
- Making a physical network appear as multiple logical ones



- A virtual network is a collection of virtual nodes and links

Network Virtualization (NV)

- A diversifying attribute for future inter-networking paradigm
  - A response to so-called Internet ossification (lots of band-aids and makeshift solutions to introduce changes, e.g., overlays)
- A new architecture is needed
  - Hard to come up with a one-size-fits-all architecture
- Almost impossible to predict what the future might unleash
  - Why not create an all-sizes-fit-into-one architecture instead
  - Open and expandable
  - Coexistence of heterogeneous architectures



Network function virtualization architecture.

Definition

- Network virtualization (NV) is a networking environment that allows
  - multiple service providers to dynamically compose multiple heterogeneous virtual networks that co-exist together
    - in isolation from each other,
    - to deploy customized end-to end services on-the-fly,
    - to manage them on those virtual networks for the end-users by effectively sharing and utilizing underlying network resources leased from multiple infrastructure providers.

Benefits of VN

- Transparent abstraction of networking platform and resources
  - Multiple logical interpretations of the physical characteristics
- Resource partitioning and isolation
  - Dynamic provisioning and configuration
- Rapid innovation
  - Easier to deploy new network services
- Scalability
  - Can be rapidly scaled to respond to shifting demands
- Cost savings
  - Maximize resource utilization and amortize CAPEX and OPEX

Benefits of VN(cont)

- Flexibility
  - selection of arbitrary network topology
  - customizable control and data planes (e.g., routing and forwarding)
- Manageability
  - defined accountability of infrastructure and service providers
- Programmability
  - network elements, e.g. switches, routers
- Isolation
  - faults, bugs, misconfigurations, and security
- Heterogeneity of networking technologies
  - Optical, copper cable, wireless, etc.
- Experimental and Deployment Facility
  - E.g., GENI

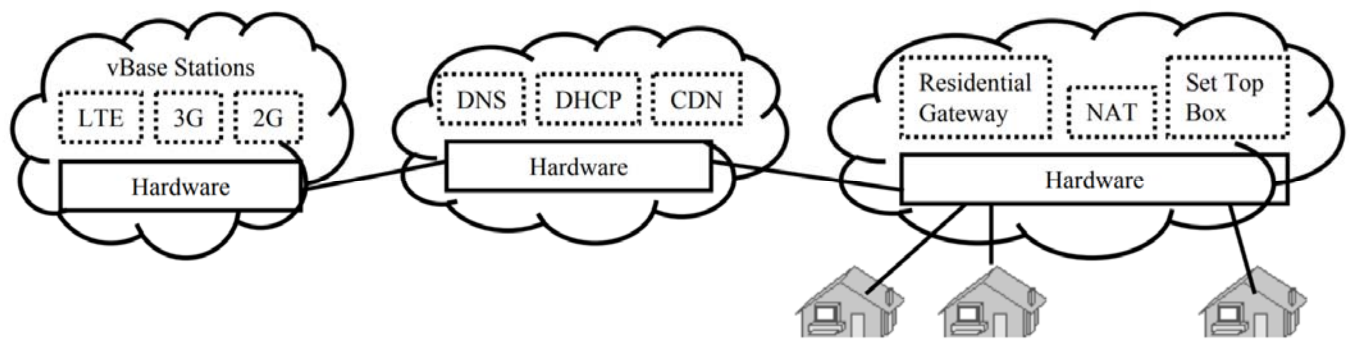
Network Function Virtualization (NFV)

1) Fast standard hardware => Software based

- Devices Routers, Firewalls, Broadband Remote Access Server (BRAS)

2) Function Modules (Both data plane and control plane)

- DHCP (Dynamic Host control Protocol), NAT (Network Address Translation), Rate Limiting, Ref: ETSI, "NFV – Update White Paper," Oct 2013, http://www.tid.es/es/Documents/NFV_White_PaperV2.pdf (Must read) Set Top NAT Box Residential

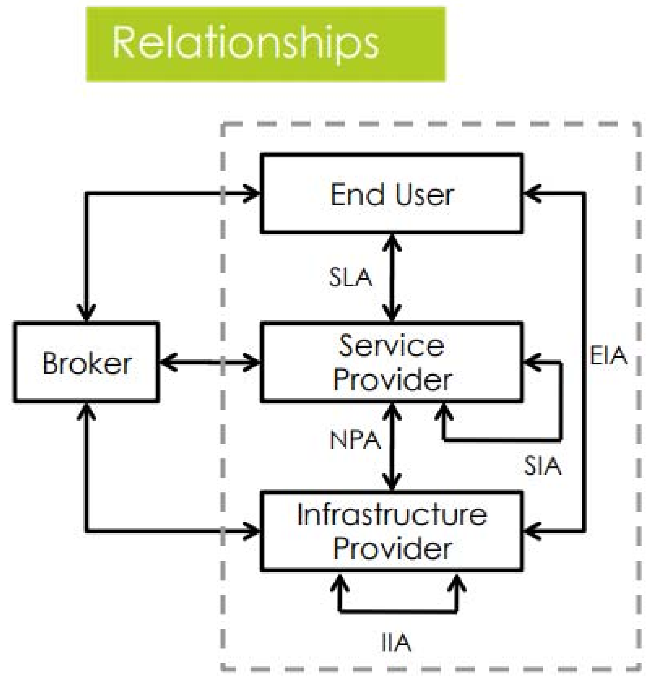


Ref: ETSI, "NFV – Update White Paper," Oct 2013, http://www.tid.es/es/Documents/NFV_White_PaperV2.pdf (Must read)

VN Business Model

Players

- Infrastructure Providers (InP)
  - Manage underlying physical networks
- Service Providers (SP)
  - Create and manage virtual networks
  - Deploy customized end-to-end services
- End Users
  - Buy and use services from different service providers
- Brokers
  - Mediators/Arbiters



Example: NV in Mobile Networks

Example: VN in Mobile Networks

Players

Infrastructure Providers (InP)

owns the infrastructure

Mobile virtual network provider (MVNP)

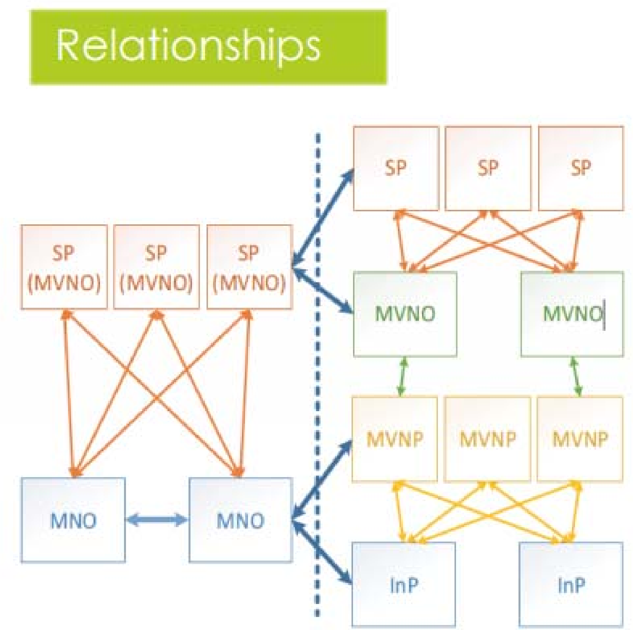
Leases network resources and creates virtual resources

Mobile virtual network operator (MVNO)

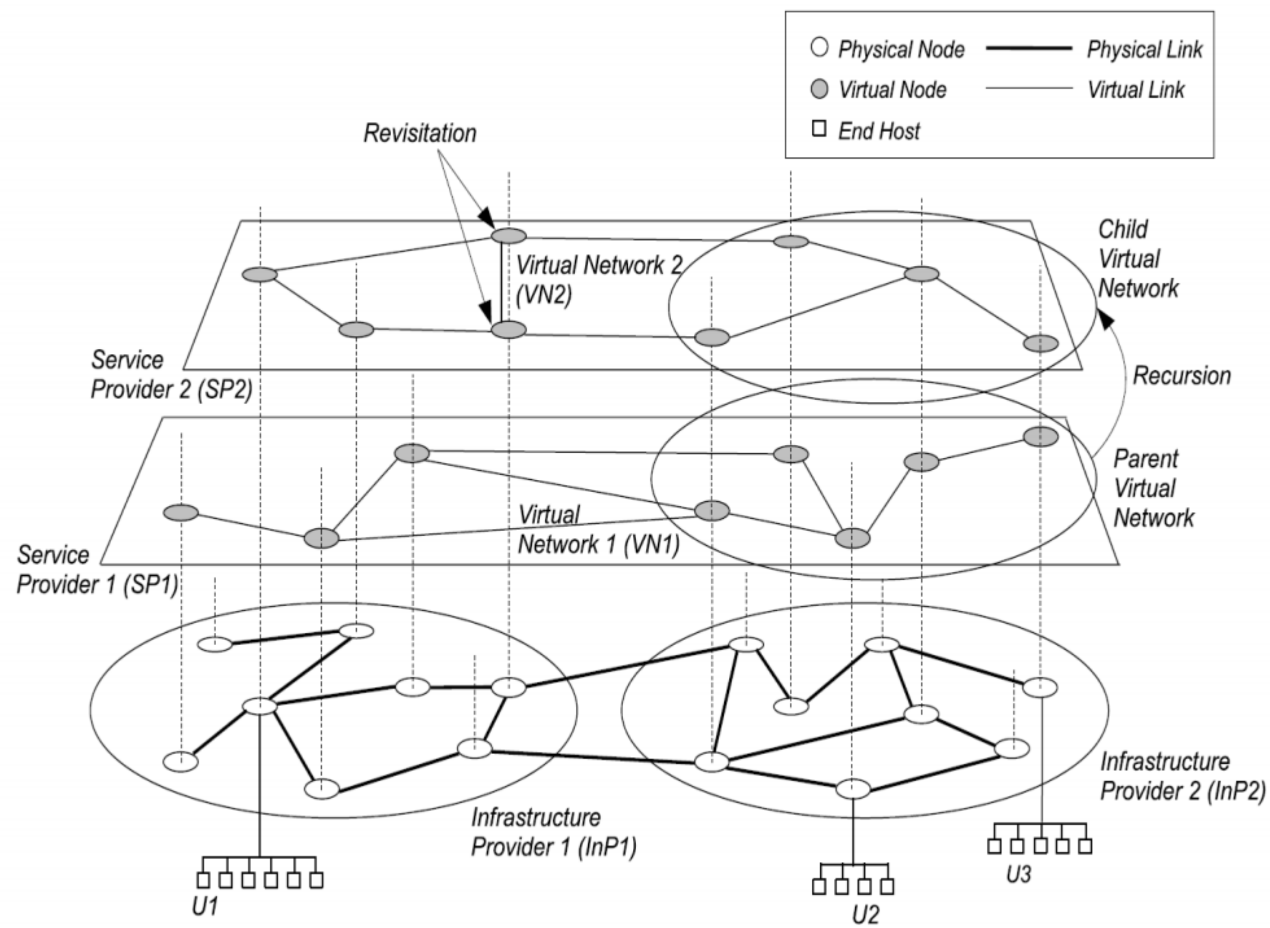
operates and assigns virtual resources to SPs

Service Providers (SP)

provides services to subscribers using virtual resources from MVNOs

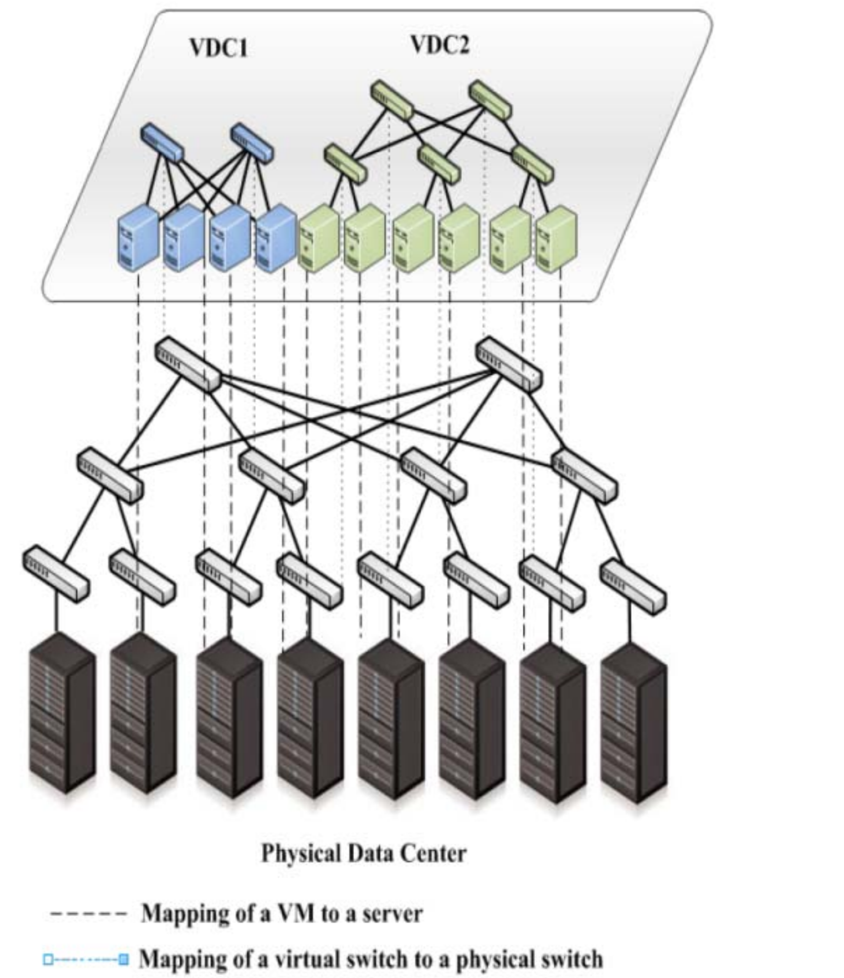


Virtual Network Instantiation



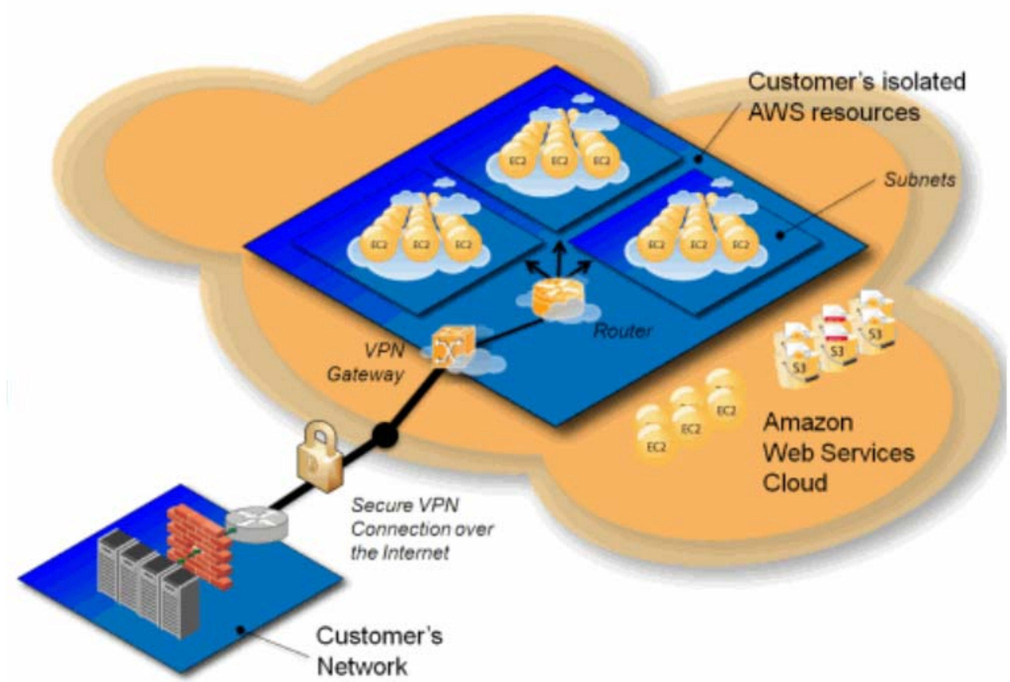
Recent Use Cases : VDC

- Virtual Data Centers
  - Performance issues for many Cloud apps
    - Network is the bottleneck
  - Cloud provides computing resources but no guaranteed bandwidth
  - Virtual Data Centers (VDCs)
    - Virtual machines, routers, switches and links

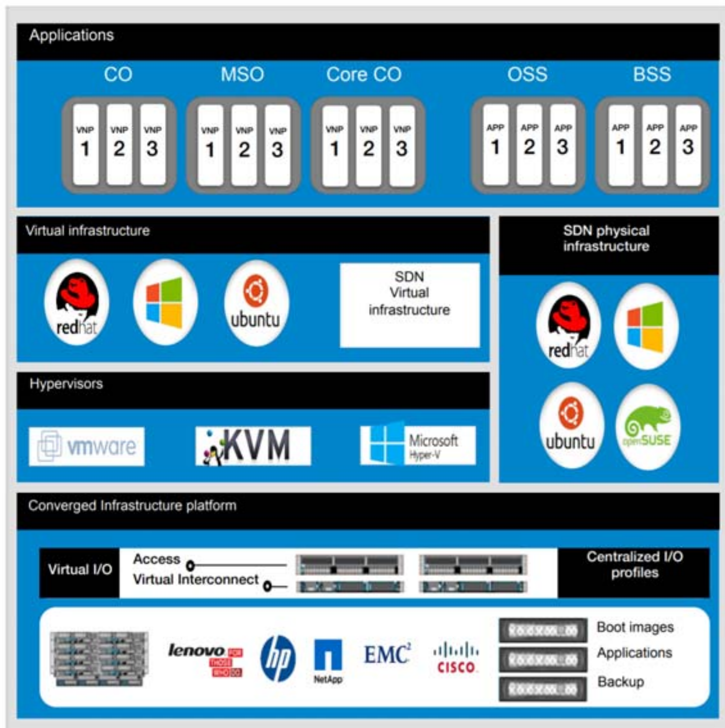


Amazon Virtual Private Cloud

- Collection of interconnected VMs
  - Customers can define own network and address space
- Extends enterprise data center
  - VPN between Amazon VPC and enterprise data center



Software Defined Data Centers



Standard unified platform to scale up/down

Support for multi-tenancy

E2E provisioning and orchestration

Highly available, reliable and resilient

Application agnostic geo-redundancy

Stateless compute nodes – any node can assume any function within a resource pool

Decouples the function/application from the server.

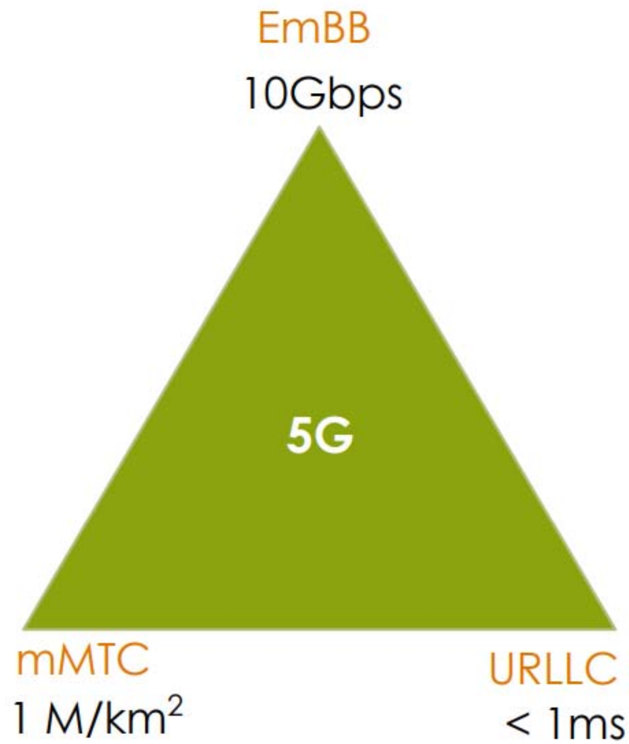
Recent Use Cases: 5G Slicing

3 major service classes :

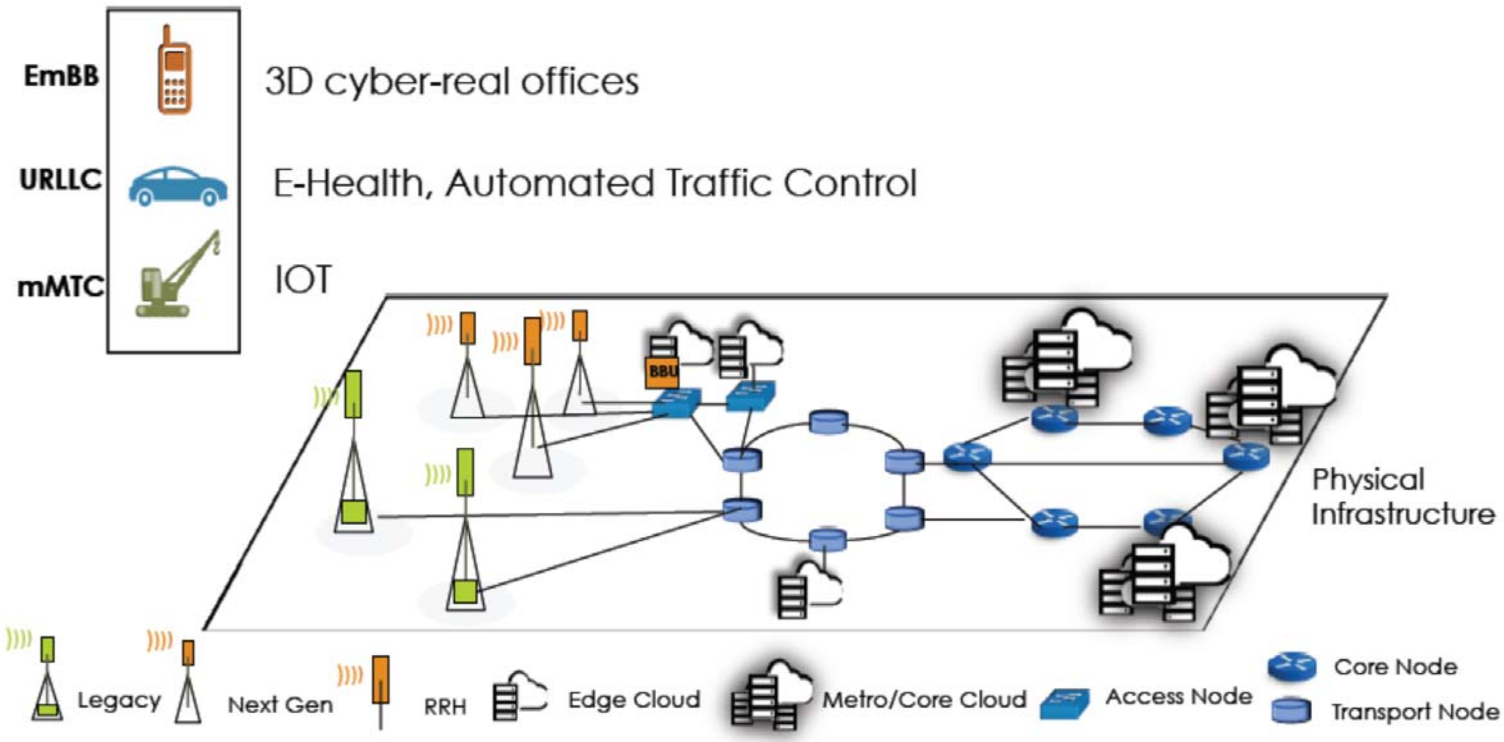
- Enhanced mobile BroadBand
  delivers Gbytes of bandwidth on demand
- massive Machine-Type Communication
  connects billions of IoT devices
- ultra Reliable Low Latency Communication
  for ultra fast high reliable services

difficult to support on same network infrastructure

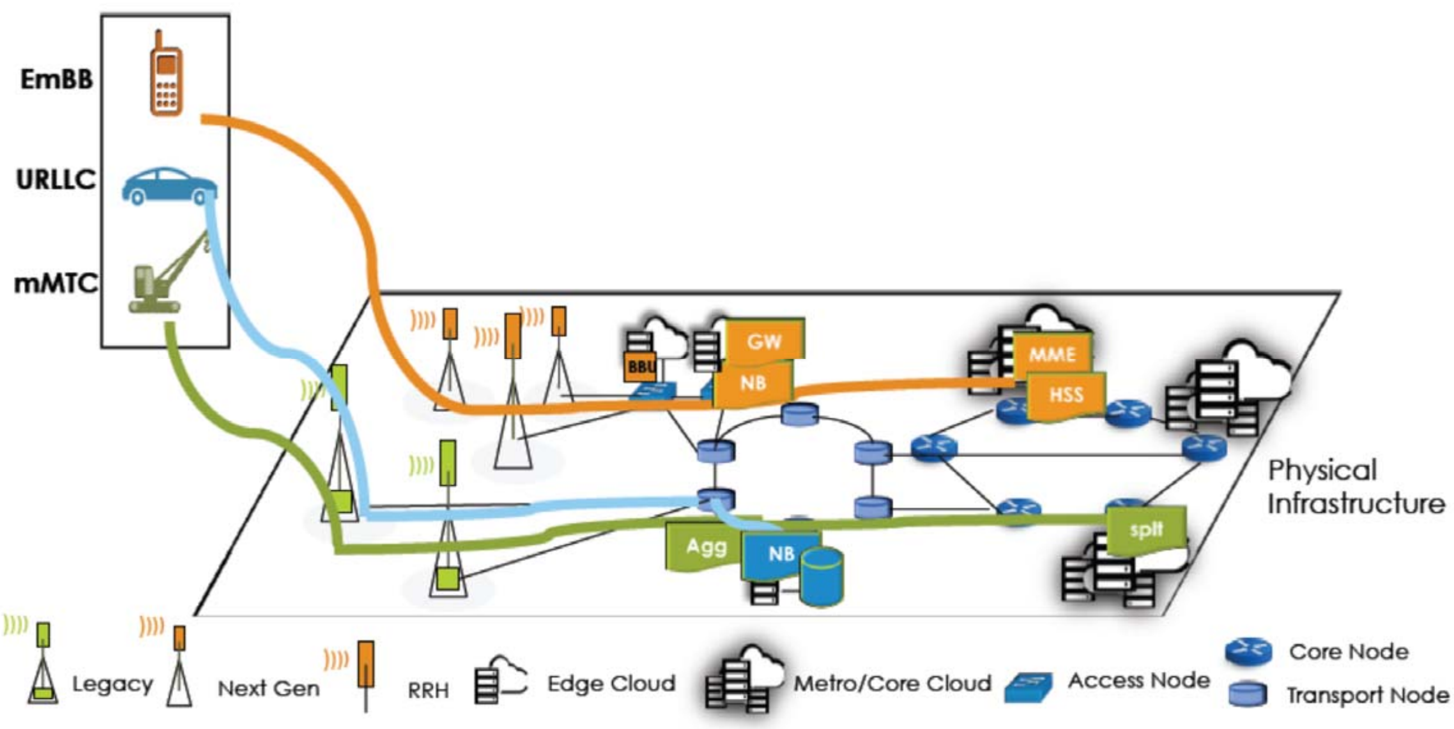
Solution: Network slicing via NV



5G Architecture



5G Slicing

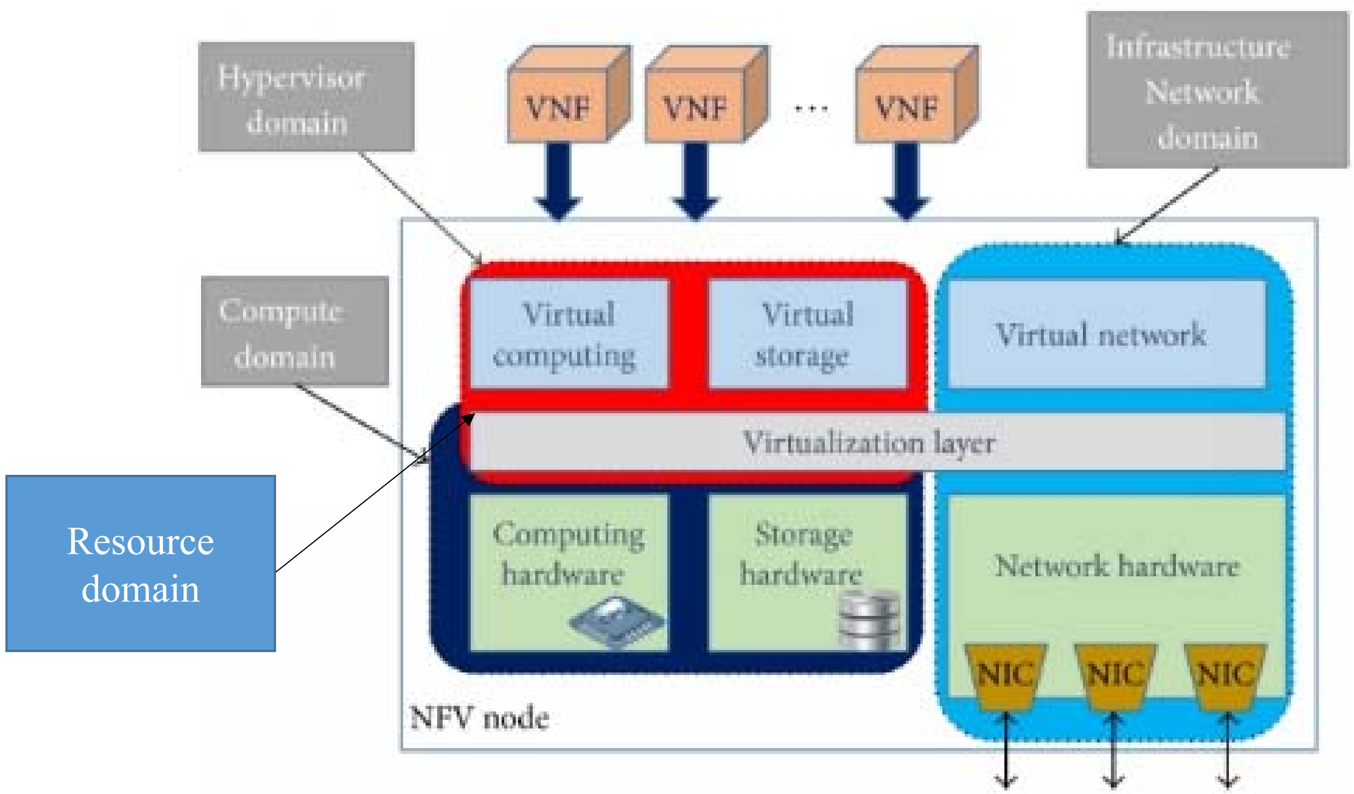


EmBB
URLLC
mMTC
BBU
GW
NB
MME
HSS
Physical Infrastructure
Agg
NB
split
Legacy
Next Gen
RRH
Edge Cloud
Metro/Core Cloud
Access Node
Core Node
Transport Node

Network Virtualization Mechanisms

- Learning objectives
  - Understand how different network elements are virtualized
  - Existing Technologies for node, link and network virtualization
- Outline
  - Resource abstraction, partitioning and isolation
  - Node virtualization
  - Link virtualization
  - Network virtualization

Network Node Virtualization



Resource Abstraction

- Hides technology specific details of physical resources
- Represents resources as a uniform set attributes, characteristics, and functionalities
- Gives users the illusion of sole ownership of a resource
- Node and link abstractions
  - Virtual switch/router
  - Virtual Network Interface Card
  - Virtual link
- Network abstraction
  - Collection of virtual nodes connected through virtual links

Resource Partitioning & Isolation

- Partitions physical resources into multiple independent slices (virtual resources)
- Hard partitioning
  - E.g., dedicated switch ports, dedicated wavelengths
- Soft partitioning
  - E.g., rate limiting, CPU execution capping
- Isolation between slices is critical
  - Hard vs. Soft partitioning

Illustration of Resource Virtualization

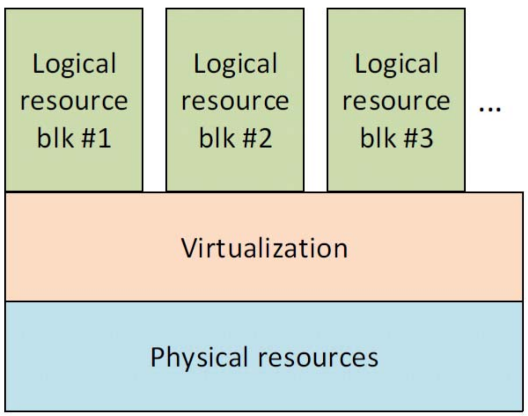
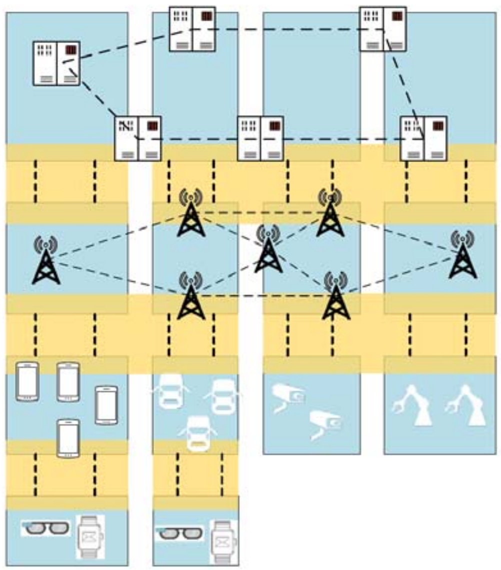


Illustration of resource virtualization

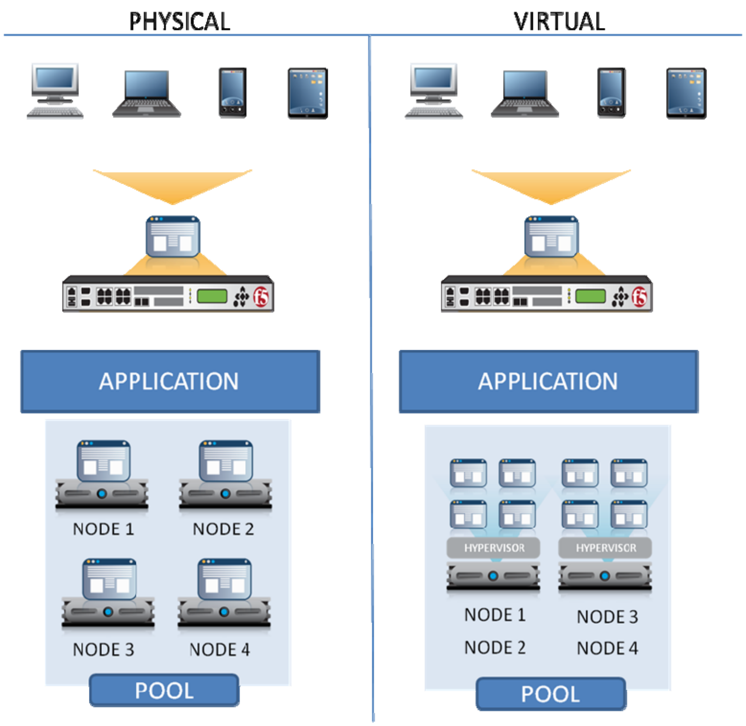


Conceptual design of vertical and horizontal network slicing

Q. Li, and etal, "End-to-end Network Slicing in 5G Wireless. Communication Systems" ETSI workshop, 2016, Farance

Node virtualization

- Node resource partitioning
  - CPU, Memory
  - Interfaces/ports
  - Optical switching resources, e.g., cross-connects, transponders, ROADMs, etc.
  - Wireless infrastructure, e.g., antennas, radio resource controllers, access points, etc.
- Data plane partitioning
  - Forwarding table
  - Address space
- Control plane partitioning
  - Routing tables
  - Protocolsd

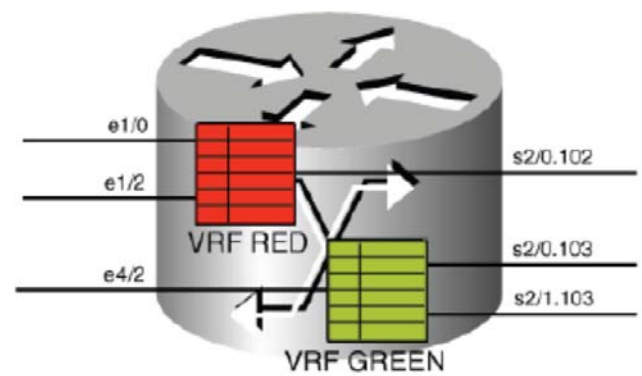


Hard partitioned routers

- Hardware partitioning to create multiple routing entities on a single device
- Run across different processors on different cards
- Allocated hardware and software resources are dedicated to a routing entity
  - Network processors, interfaces, RIB and FIB
- Requires abundant hardware
- Examples
  - "Logical routers" by Cisco
  - "Protected system domains" by Juniper

Router partitioning with VRF

- Virtual Routing and Forwarding
- Allows multiple instances of routing and forwarding tables to co-exist within the same router
- Routing Information Base (RIB) is virtualized into multiple routing tables
- Forwarding Information Base (FIB) is virtualized into multiple forwarding tables
- VRFs are interconnected to form a VN
  - using dedicated physical links (costly)
  - using virtual links (discussed later)

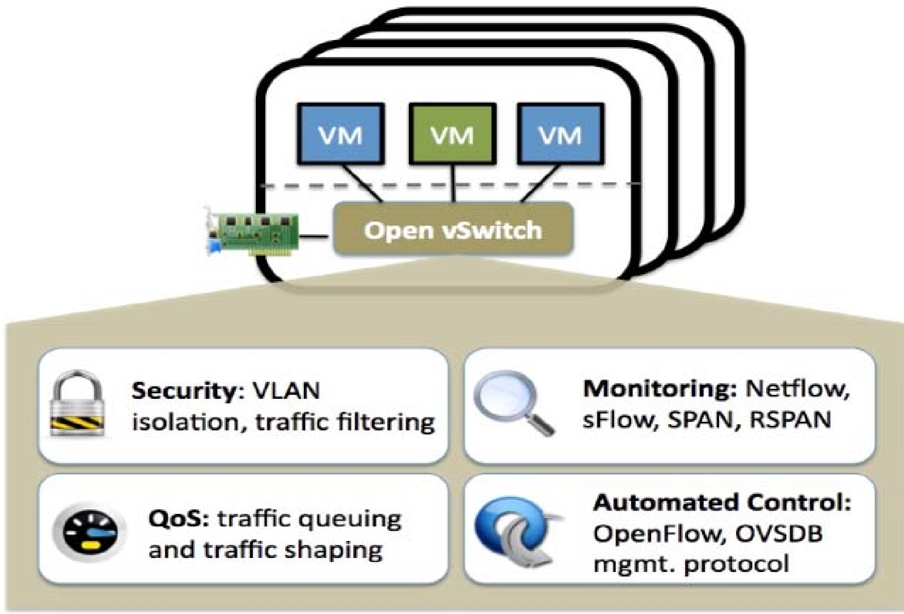


Virtual Router (vRouter)

- Separates router software from hardware
- Can be run on standard Commercial Off-the-Shelf (COTS) hardware or on virtual machines
- Shares physical machine resources with other virtual routers
- Examples
  - RouterOS, Untangle, Click Router, Vyatta

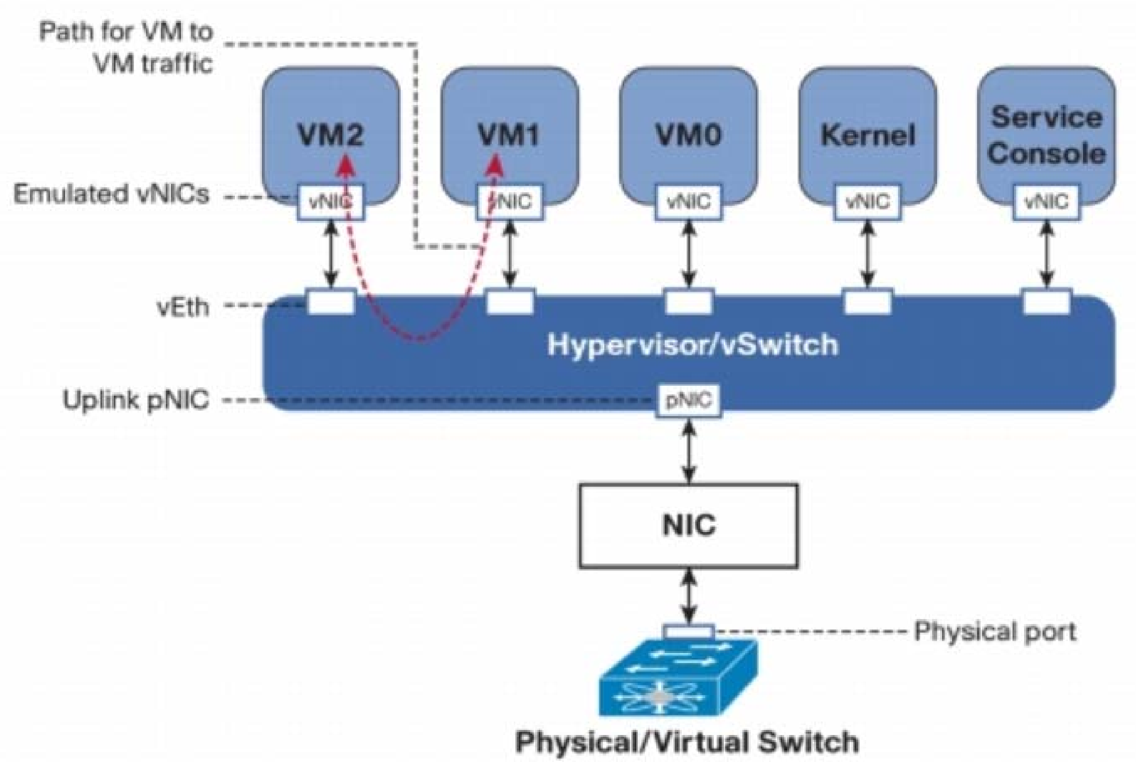
Virtual Switch (vSwitch)

- Works much like a physical Ethernet switch
- Traffic switching, Multiplexing, Scheduling
- Bridges vNIC(s) with physical NIC(s)
- Detects which VMs are logically connected to its virtual ports
- Forwards traffic to the correct VMs
- Example
  - Open vSwitch
  - Cisco Nexus 1000v
  - VMware virtual switch



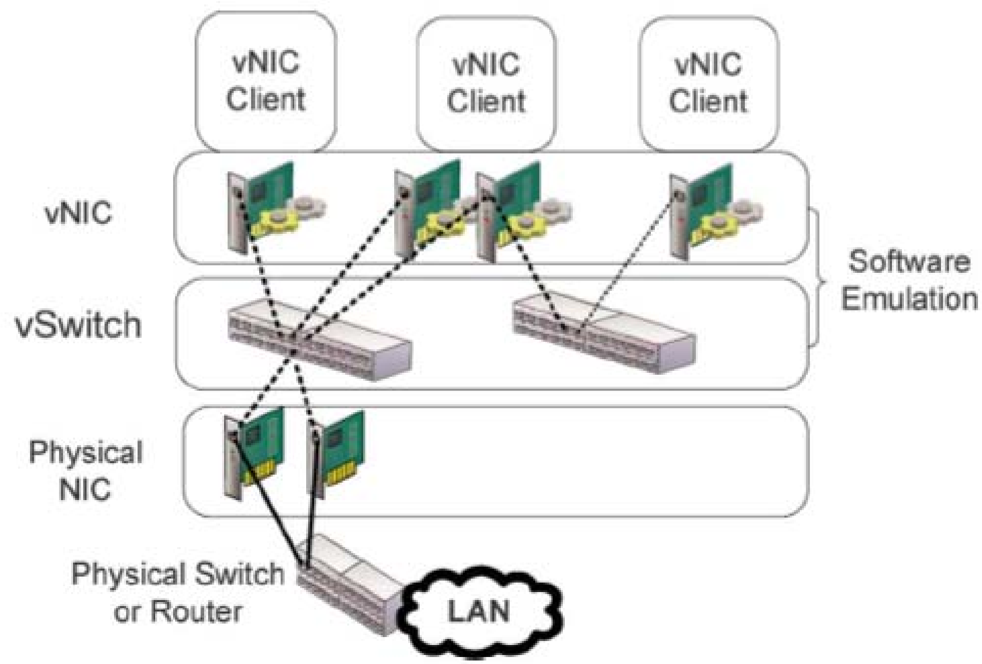
Virtual NIC (vNIC)

- A software emulation of a physical NIC
- Can be assigned own dedicated IP and MAC addresses
- A regular NIC only provides one Peripheral Component Interconnect express (PCIe) channel
  - I/O bottleneck
- Single root I/O virtualization (SR-IOV)
  - Creates multiple instances of PCI functions called Virtual Functions (VFs)
  - A Virtual Machine can be directly mapped to a VF for direct access to NIC
  - Provides better throughput, scalability, and lower CPU utilization



Connecting vNICs to vSwitch

- Links between vNIC and vSwitch are software emulated links
- Bandwidth of these links limited by host processing capabilities
  - link bandwidth allocation by setting upper limit on emulated link speed
  - do not support guaranteed bandwidth

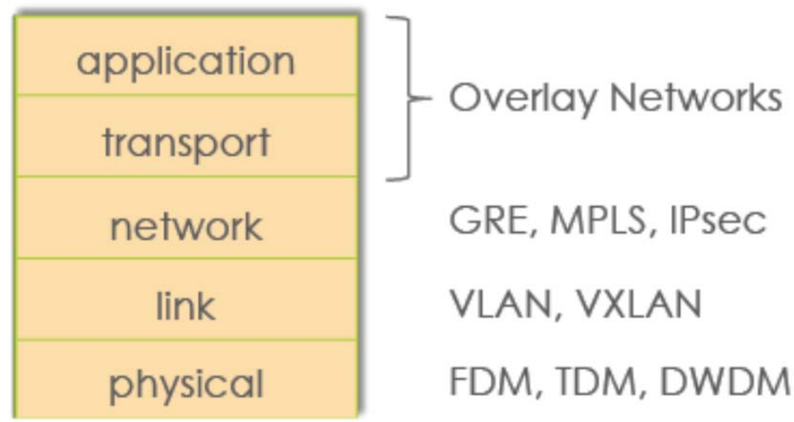


Link virtualization

- Physical medium partitioning
  - Optical fiber, Copper wire, Radio spectrum, etc.
  - Frequency/Wavelength/time multiplexing
  - Must consider physical layer constraints and physical impairments
- Datapath virtualization
  - Frame labeling and tagging (Enabled by nodes)
  - Tunneling
    - Ensures isolation of traffic from multiple virtual networks transported over a shared network
    - Provides direct connection between non adjacent network devices
    - Uses encapsulation and occasionally encryption
    - E.g., IEEE 802.1Q, L2TP, GRE, IPsec, MPLS

Link virtualization

- Virtual link can span a single physical link or a multi-hop physical path
- Link virtualization can be performed at different layers of the protocol stack

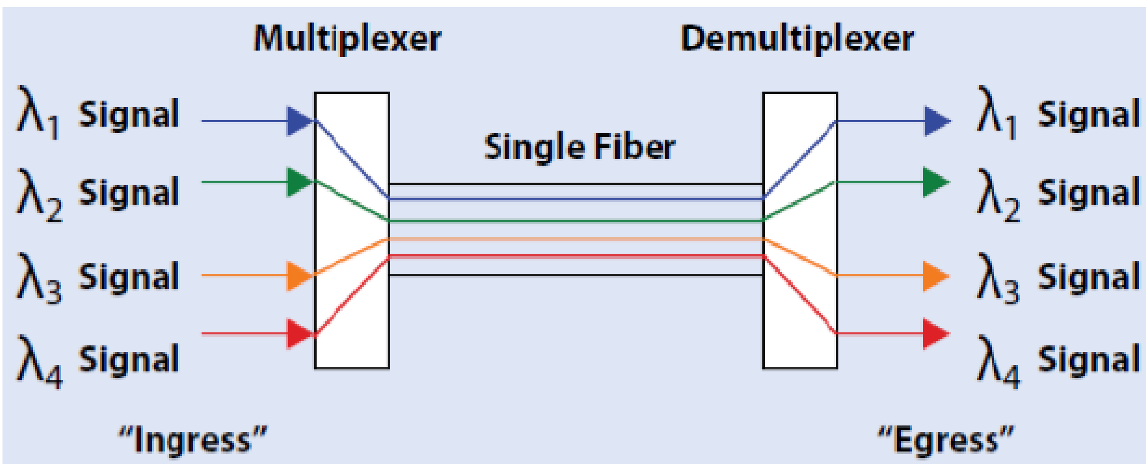


Layer 1 Virtualization

- Enables multiple transport (optical) or access (wireless) networks over a common physical infrastructure
- Media-specific resource partitioning
  - Optical fiber
  - Radio spectrum
  - Other media
- Common techniques
  - Frequency/Wavelength/time division multiplexing
  - Must consider physical layer constraints and physical impairments

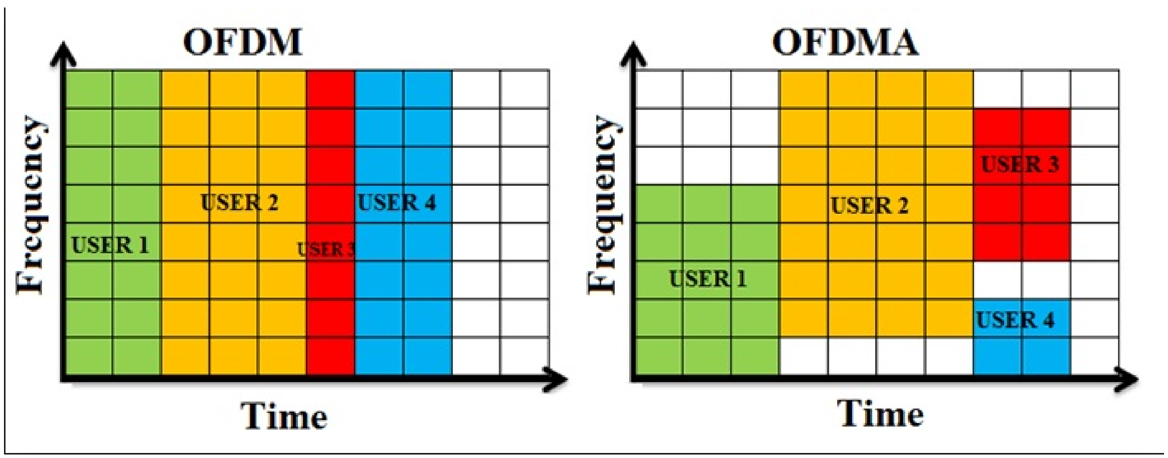
WDM

- Multiplexes a number of optical carrier signals (i.e., wavelengths) onto a single optical fiber
- Similar to frequency-division multiplexing
- A multiplexer at the transmitter merges several signals together
- A demultiplexer at the receiver splits signals apart
- Dense WDM employs denser wavelength spacing to increase number of channels



OFDMA

- A multi-user version of the popular orthogonal frequency division multiplexing (OFDM) digital modulation scheme
- Suitable for broadband wireless networks
- Assigns subsets of frequency subcarriers to individual users
- Different numbers of sub-carriers can be assigned to different users
- Support differentiated QoS (data rate, error probability, etc.)
- Allows simultaneous low-data-rate transmissions from several users

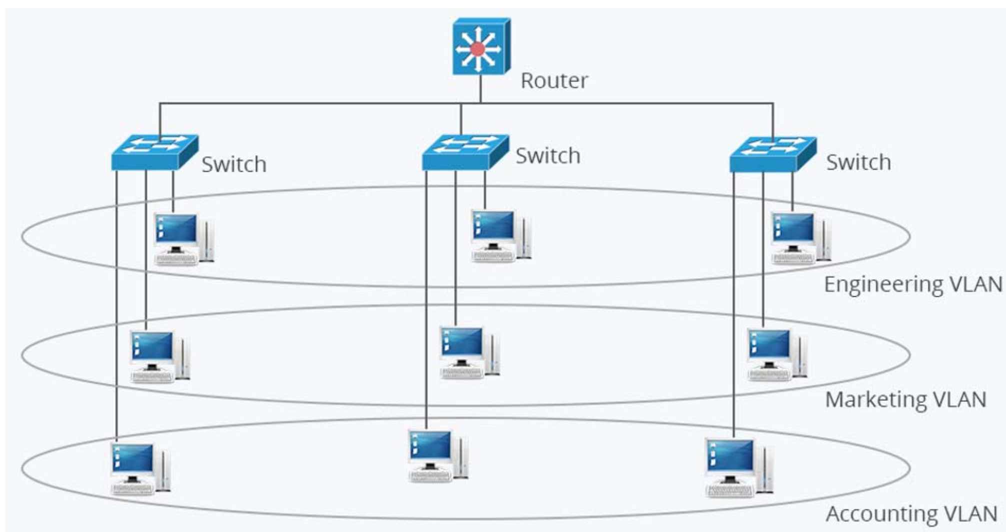


Layer 2 Virtualization

- Main usages
  - Local Area Networks
  - Data Center Networks
- Common techniques
  - VLAN
  - 802.1Q
  - VXLAN

Virtual Local Area Networks (VLANs)

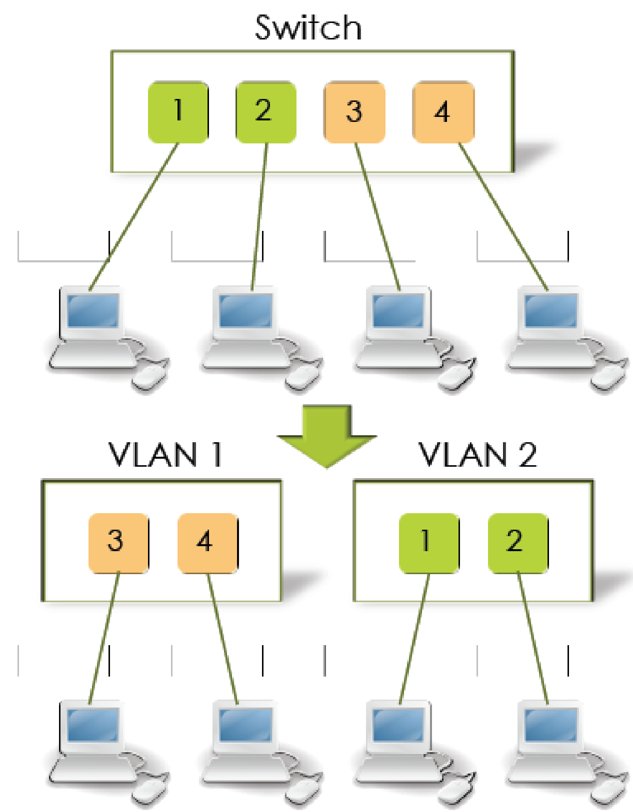
- A layer-2 broadcast domain that is partitioned and isolated
  - VLAN separates traffic between regular users and network administrators
  - VLAN separates different types of traffic, e.g., users or low priority traffic cannot directly affect the rest of the network's functioning



Port-based VLANs

A VLAN is a logical grouping of ports on a switch

- Grouping done by switch management software
  - ports can be dynamically assigned to VLANs
- Hosts in a VLAN can only communicate with other hosts in the same VLAN
  - frames to/from ports 1-2 can only reach ports 1-2
- Single physical switch operates as multiple virtual switches

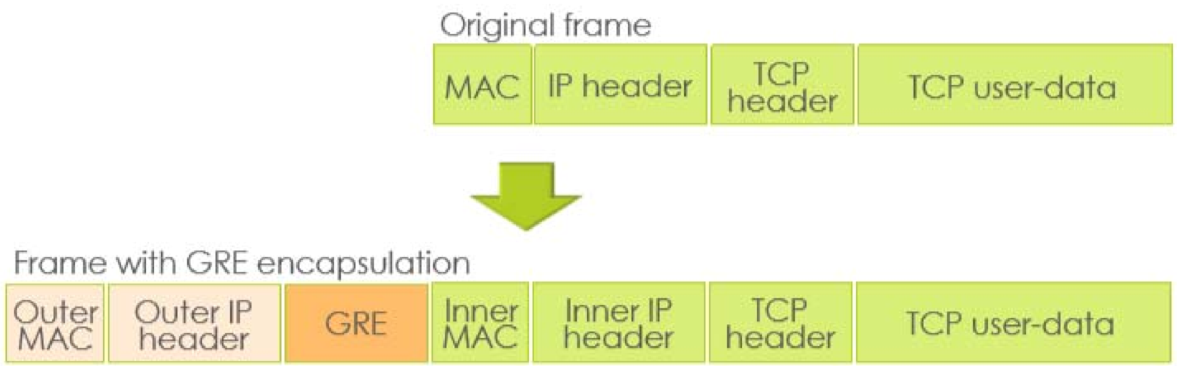


Layer 3 Virtualization

- Main usages
  - Virtual Private Networks
  - Virtual IP Networks
- Common techniques
  - Generic Routing Encapsulation (GRE)
  - Multiprotocol Label Switching (MPLS)
  - Layer 3 VPN
  - IPsec

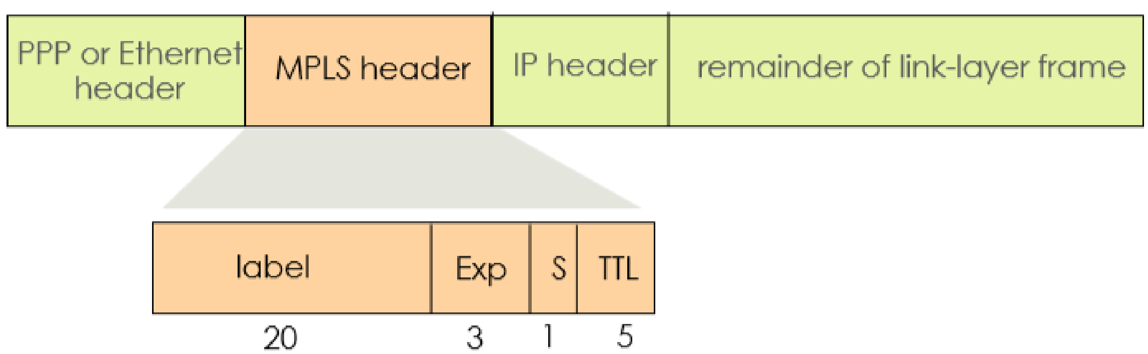
Generic Routing Encapsulation (GRE)

- Provides encapsulation of a wide variety of network layer protocols inside virtual point-to-point links over an Internet Protocol internetwork
- Encapsulates arbitrary packets of one protocol type in packets of another protocol



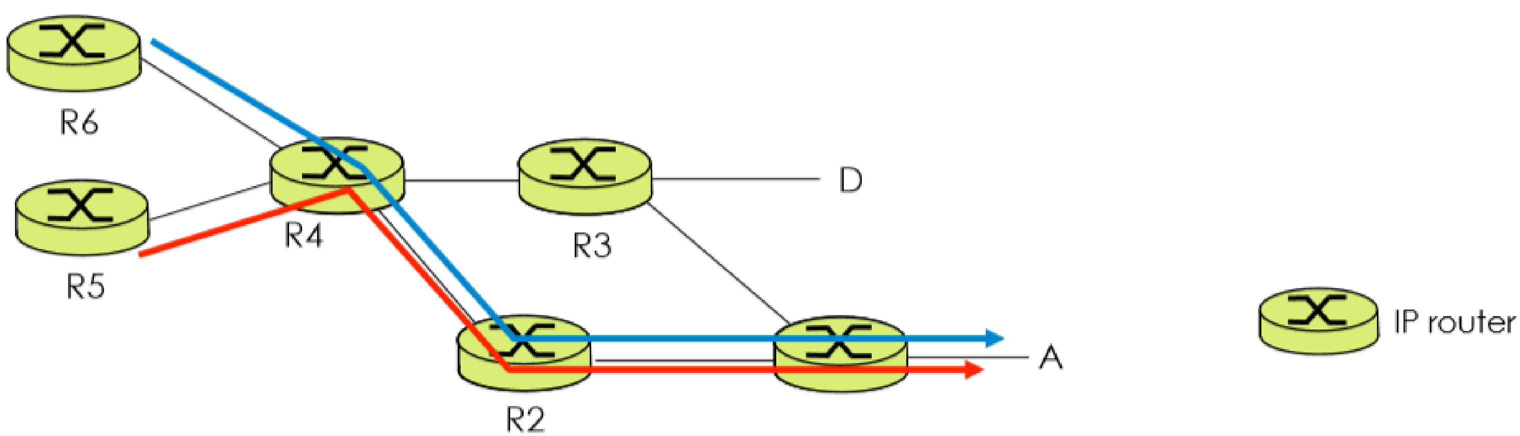
Multiprotocol Label Switching (MPLS)

- High-speed IP forwarding using fixed length label (instead of IP address)
  - labels identify virtual links (paths) between distant nodes
  - fast lookup using fixed length identifier (rather than longest prefix matching)



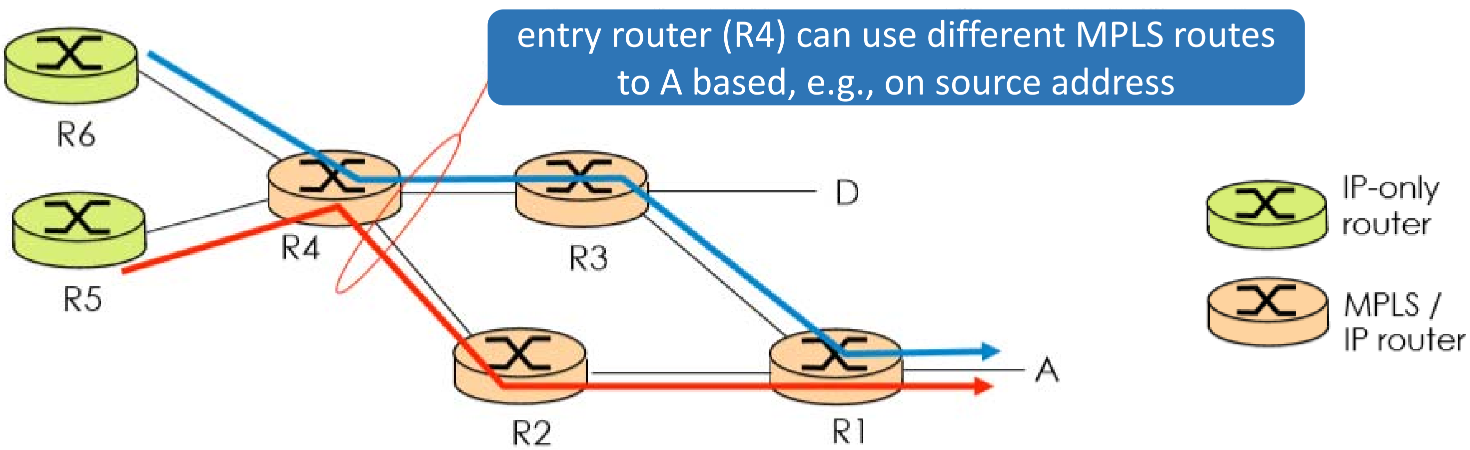
Label-switched Routing

- IP routing: path to destination determined by destination address alone



Label-switched Routing

- IP routing: path to destination determined by destination address alone
- MPLS routing: path to destination can be based on source and destination address
- MPLS directs data from one network node to the next based on short path labels rather than long network addresses, avoiding complex lookups in a routing table



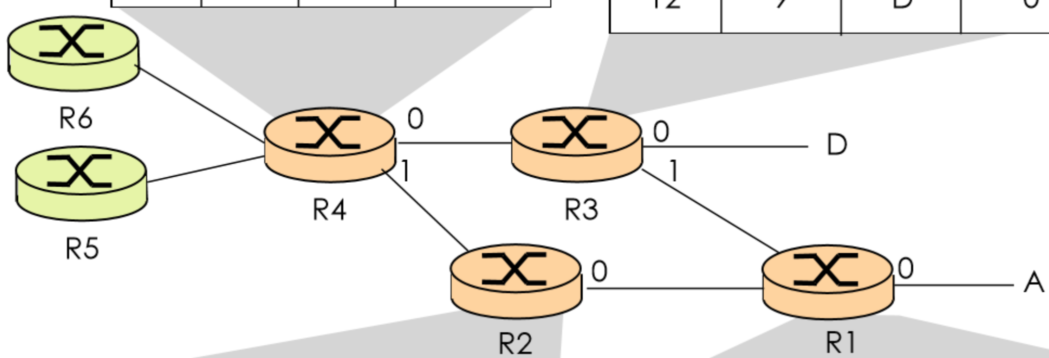
MPLS forwarding tables

R4:

in label	out label	dest	out interface
	10	A	0
	12	D	0
	8	A	1

R3:

in label	out label	dest	out interface
10	6	A	1
12	9	D	0



R2:

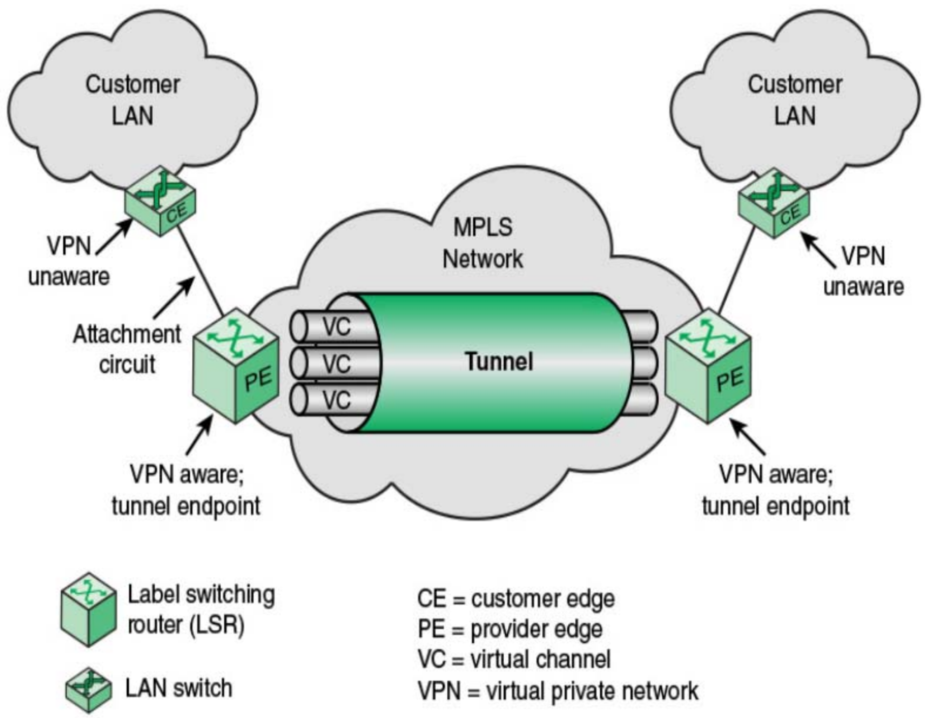
in label	out label	dest	out interface
8	6	A	0

R1:

in label	out label	dest	out interface
6	-	A	0

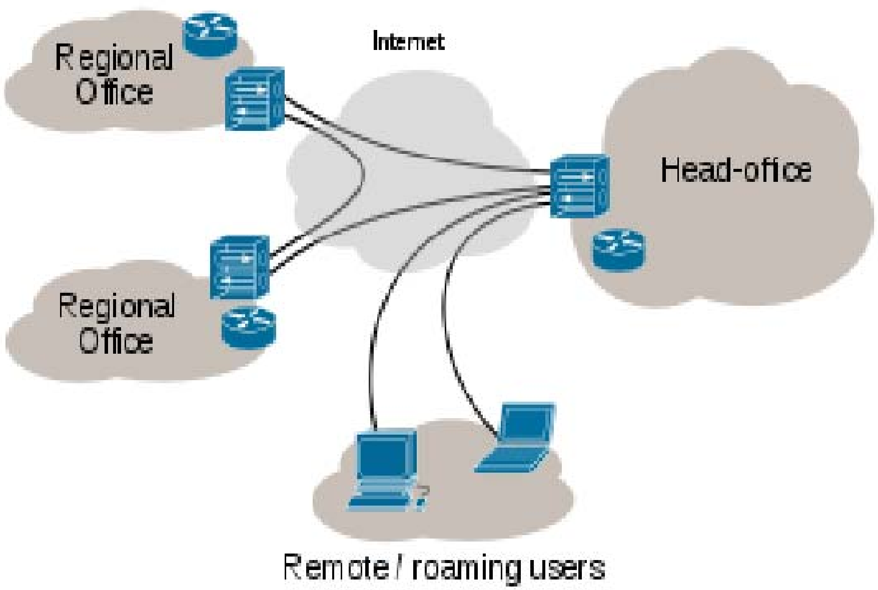
LSR and Edge LSR

- Label Switching Router (LSR)
  - switches based on labels
  - swaps labels
  - uses incoming label to find the outgoing interface (and label)
- Edge LSR
  - sits on the edge of an MPLS network
  - adds/removes labels from packets
  - often referred to as provider edge (PE) routers
- Label Distribution Protocol (LDP) stores labels in a Label Information Base (LIB)
- Label values are added to the existing forwarding information in a Label Forwarding Information Base (LFIB)



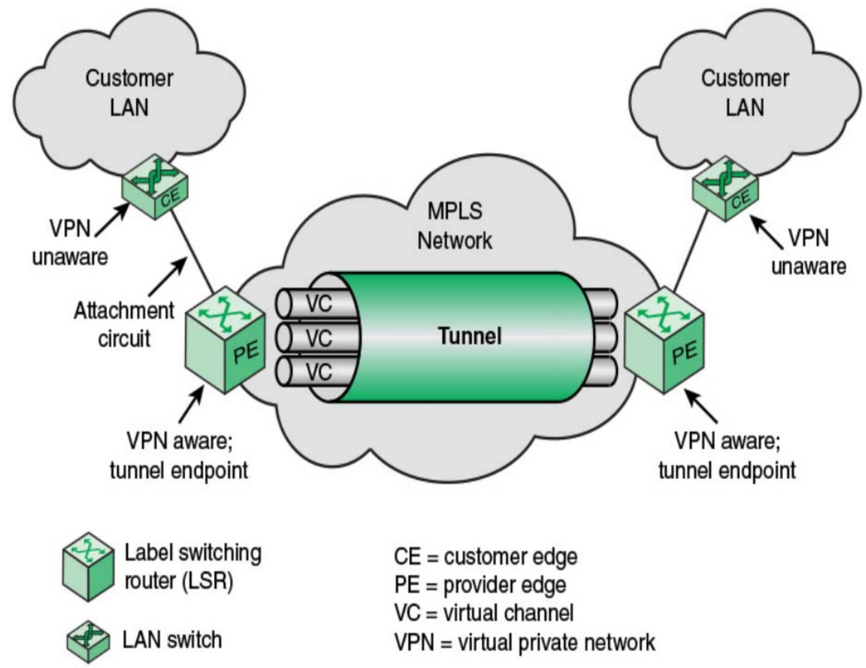
Layer 3 VPNs

- Layer 3 Virtual Private Network connecting distributed sites
- Isolated from public network (e.g., the Internet) aı other customers' VPNs
  - Provides network-layer confidentiality over public network
- Institutions want private networks for security
  - o costly: separate routers, links, DNS infrastructure
- VPN: institution's inter-office traffic is sent over public Internet instead
  - o encrypted before entering public Internet
  - o logically separate from other traffic



Provider Provisioned VPN

- Customer Edge attached to provider edge router
- Serves different customers using the same address space
- How to disambiguate overlapping addresses ?
  - BGP extensions with 8-byte route distinguisher
  - Using VRF
    - No modification to protocols needed
    - PE maintains one VRF per VPN eliminating ambiguities



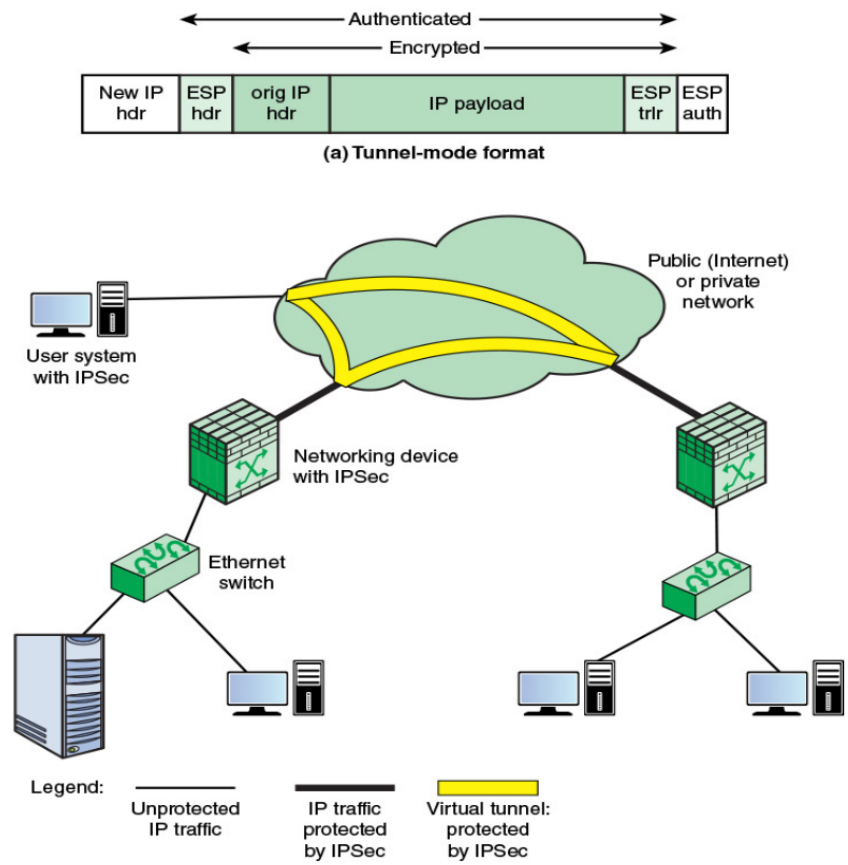
Internet Protocol security (IPsec)

- Allows private network data to be securely transported across shared, possibly public network
  - Used to construct secured layer 3 VPNs
- Prevents unauthorized access and eavesdropping
  - Encrypt/authenticate traffic at the IP layer
- 2 Modes
  - IPsec transport mode
    - Only payload is encrypted
  - IPsec tunnel mode
    - Full packet encrypted and encapsulated in another IP packet

IPsec (cont)

Participating nodes negotiate security association that include

- Security algorithms
- Cryptographic Keys
- IPSec protocol service
    - Encapsulating Security Payload (ESP) protocol: provides origin authenticity, integrity and confidentiality
    - Authentication Header (AH) protocol: provides integrity and data origin authentication

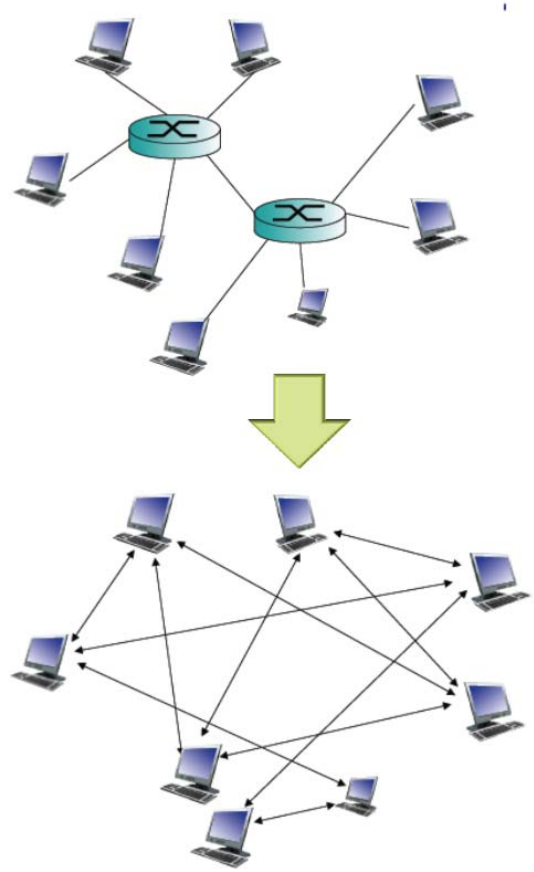


(a) Tunnel-mode format

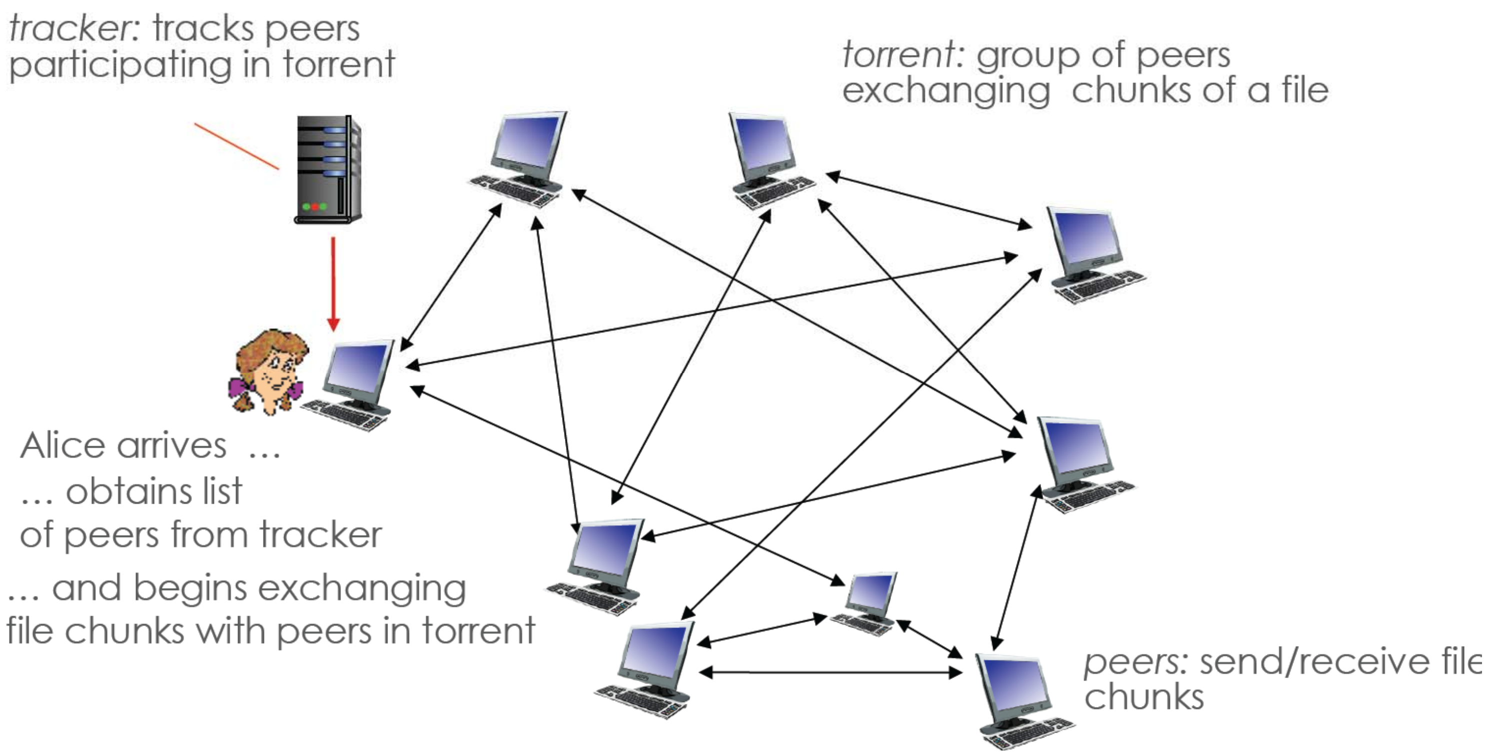
(b) Example configuration

Overlay Networks

- Mostly application layer overlays
- Nodes are end hosts (running applications)
- Links are end-2-end physical paths (through the Internet) between end hosts
- Creates a virtual topology on top of a physical network
- Usages
    - Application layer multicasting
    - P2P file sharing networks
    - Tor anonymity network
    - …

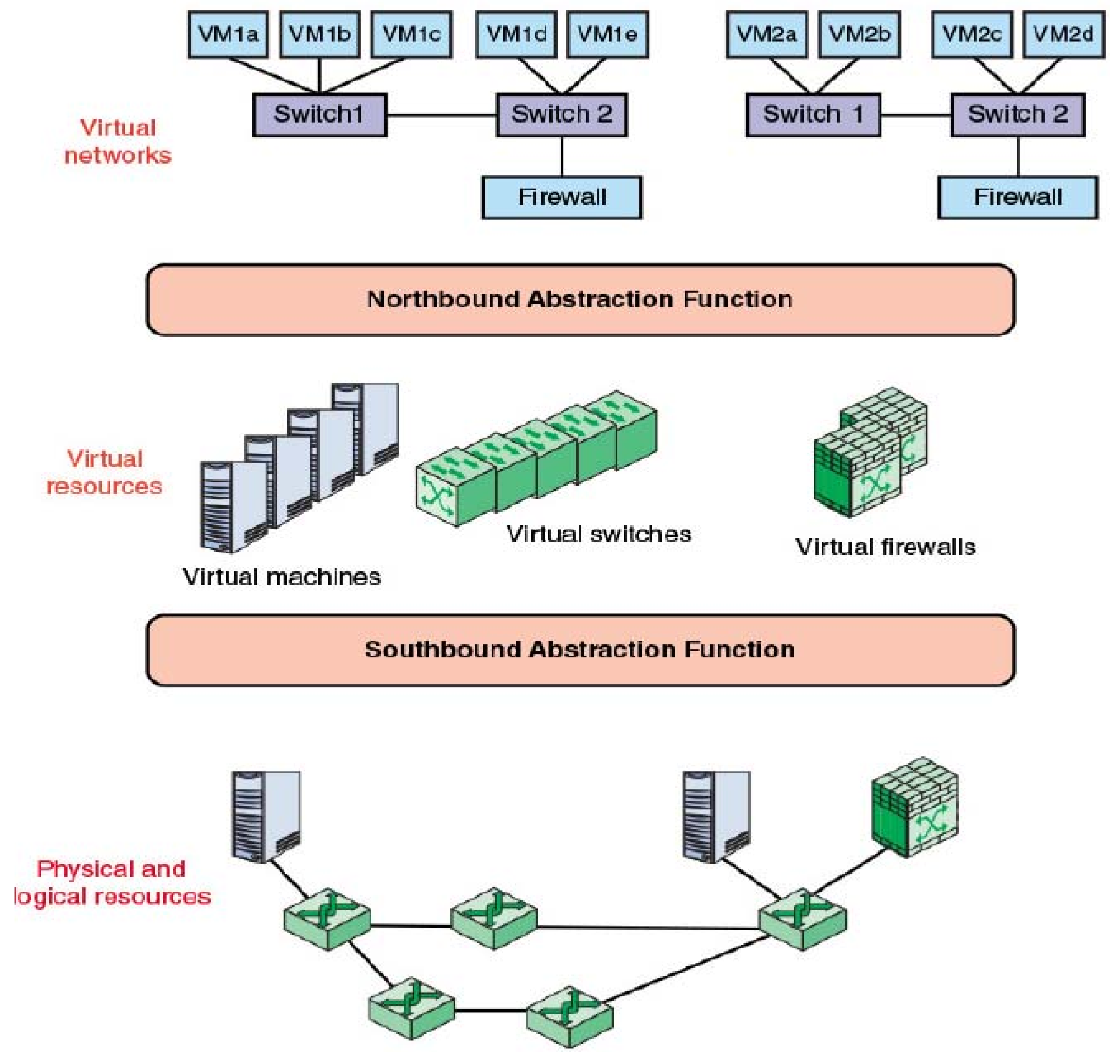


BitTorrent file distribution network

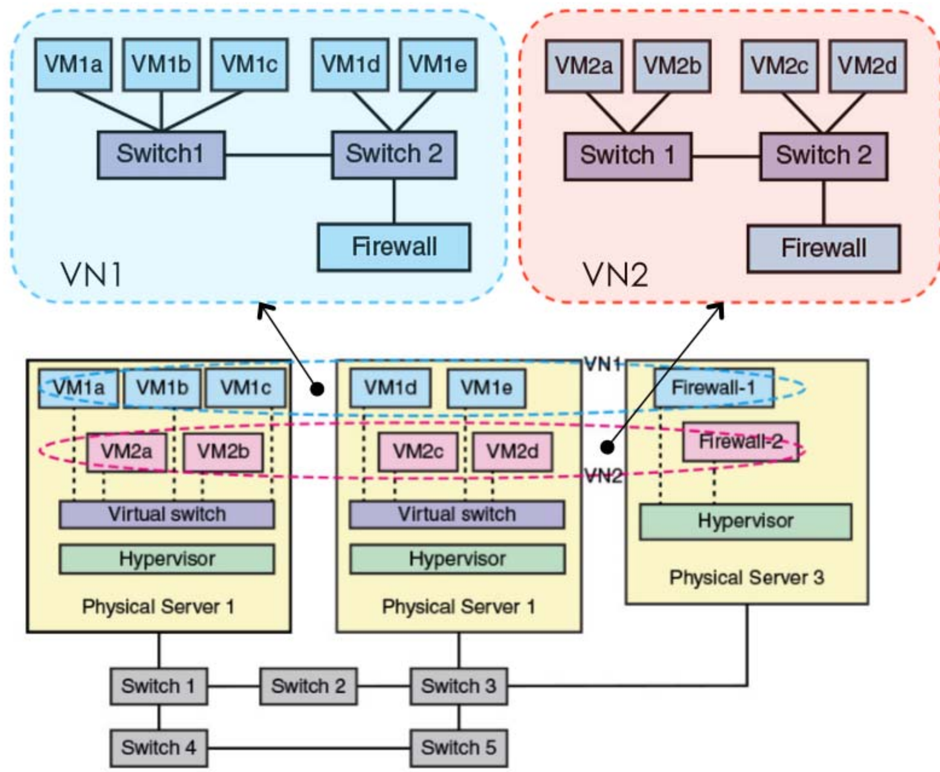


Network Virtualization

- Enables the creation of an entire virtual network including switching, routing, and value-added services, e.g., firewalling, load balancing, etc.
- Virtual Network
    - o vRouters, vSwicthes, vLinks, vNICs, VMs
    - o vLAN connecting multiple VMs using vSwitches
    - o vWAN connecting multiple vLANs using vRouters



Example Data Centre VN



Physical Data Center Network

Why We Need NFV?

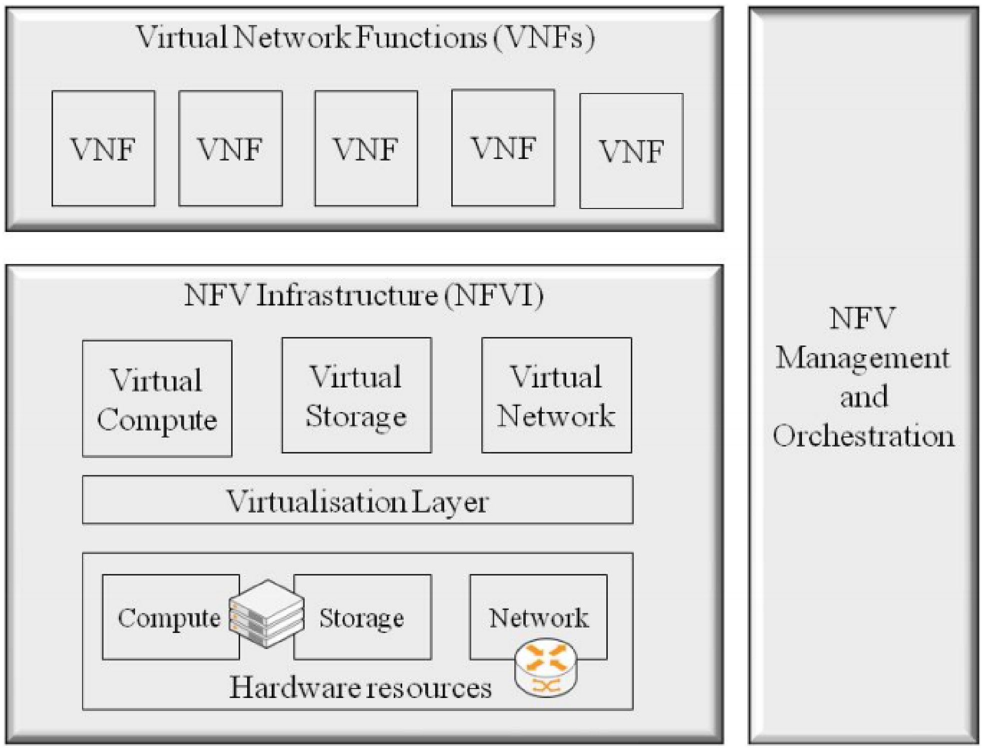
1) Virtualization: Use network resource without worrying about where it is physically located, how much it is, how it is organized, etc.
2) Orchestration: Manage thousands of devices
3) Programmable: Should be able to change behavior on the fly.
4) Dynamic Scaling: Should be able to change size, quantity Automation
5) Visibility: Monitor resources, connectivity
6) Performance: Optimize network device utilization Multi-tenancy
7) Service Integration
8) Openness: Full choice of Modular plug-ins Note: These are exactly the same reasons why we need SDN

NFV Concepts

- **Network Function (NF):** Functional building block with a well defined interfaces and well defined functional behavior
- **Virtualized Network Function (VNF):** Software implementation of NF that can be deployed in a virtualized infrastructure
- **VNF Set:** Connectivity between VNFs is not specified, e.g., residential gateways
- **VNF Forwarding Graph:** Service chain when network connectivity order is important, e.g., firewall, NAT, load balancer
- **NFV Infrastructure (NFVI):** Hardware and software required to deploy, mange and execute VNFs including computation, networking, and storage.

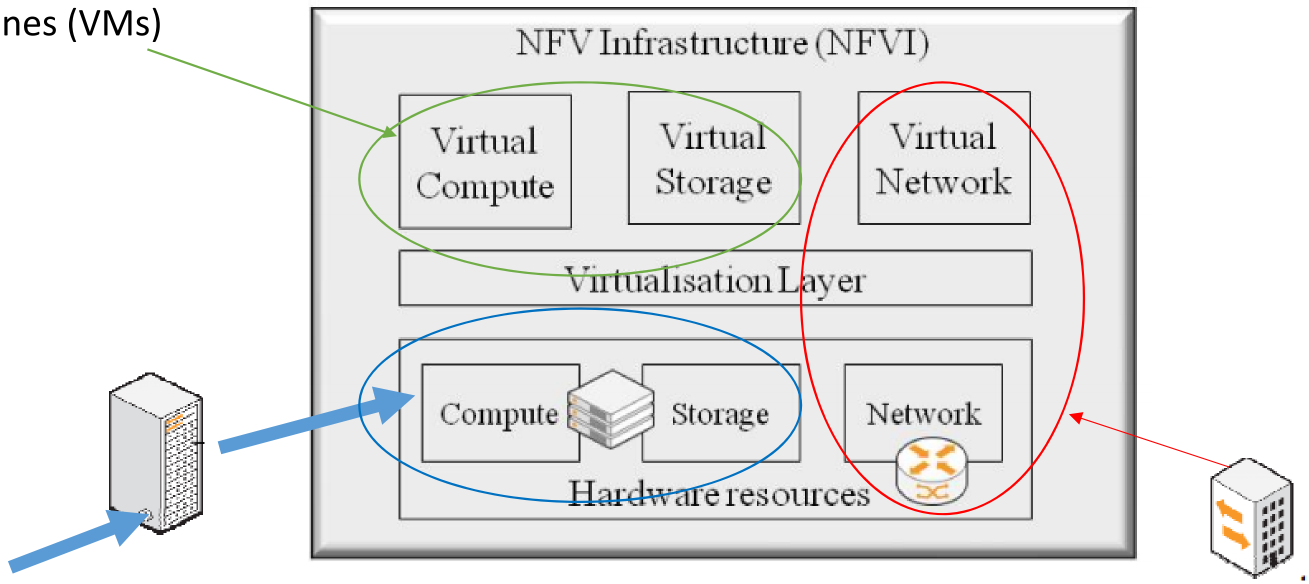
Ref: ETSI, "Architectural Framework," Oct 2013, http://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.01.01_60/gs_NFV002v010101p.pdf
ETSI, "NFV Terminology for Main Concepts in NFV," https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.03.01_60/gs_nfv003v010301p.pdf
W. Xu, et al., "Data Models for NFV," IETF Draft, Sep 2013, http://tools.ietf.org/html/draft-xjz-nfv-model-datamodel-00

High Level Architecture Framework of NFV



Focus on the NFV Infrastructure (NFVI)

Typically in the form of hypervisors and virtual machines (VMs)



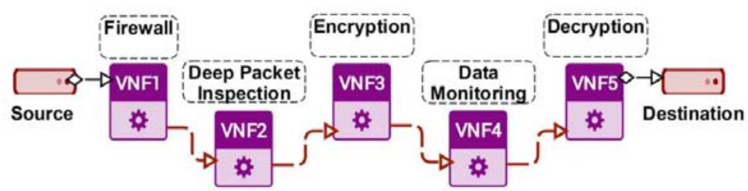
Based on general purpose processors (e.g. x86 or ARM-based)

Network resources provide connectivity between components of a VNF and/or between different VNF instances. Requires dynamic provision of many virtual networks

Focus on Presentation of Service

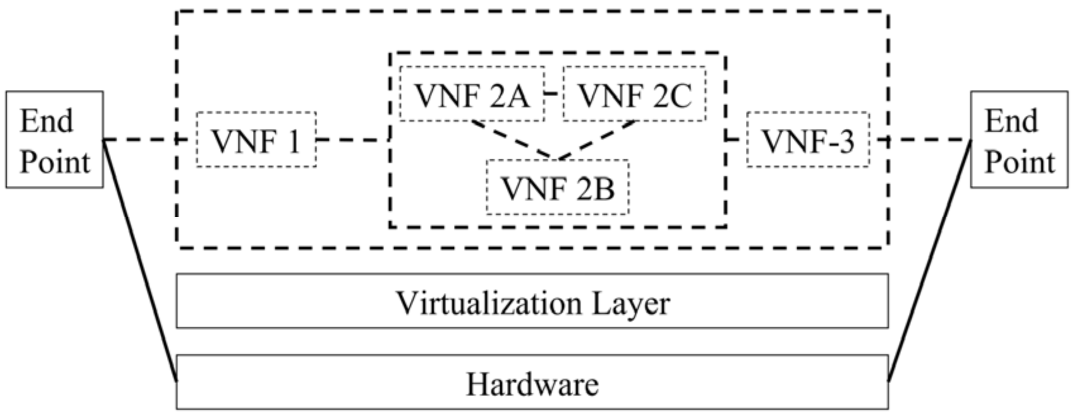
- Service Function Chain
  - A certain service provided by an operator can be viewed as a chain of network functions, called a service function chain (SFC).
  - Such an SFC is identified by the number and types of network functions included as well as their arrangement and the chronological order in which they need to be carried out
  - These virtual network functions (VNFs) can be easily installed in/removed from a server, or migrate from one server to another in order to accomplish the service requests' objectives in compliance with the requirements stipulated by service level agreement (SLA)

Service chain

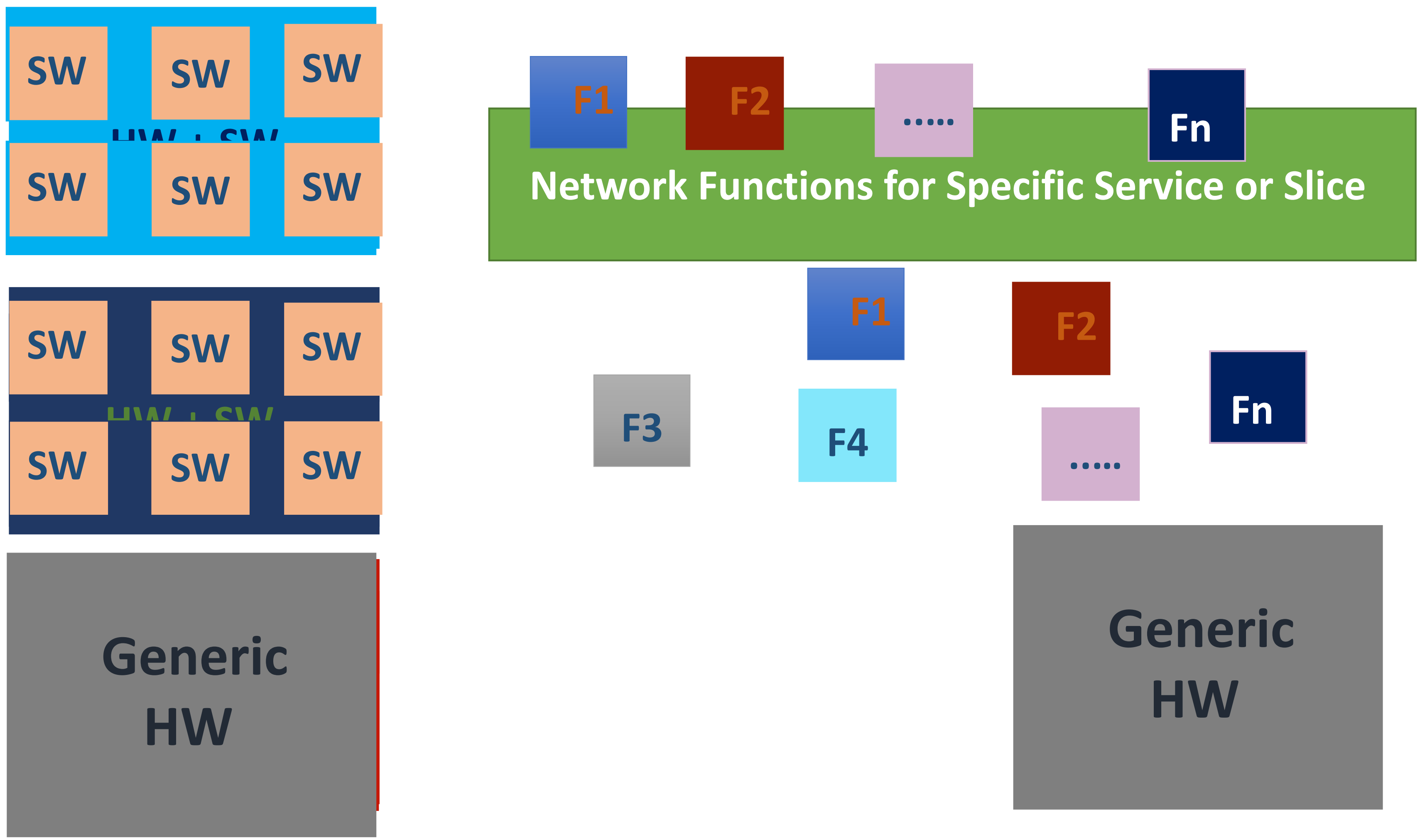


Focus on Service Function Chain

- Network Forwarding Graph
- An end-to-end service may include nested forwarding graphs



Ref: ETSI, "Architectural Framework," Oct 2013,
http://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.01.01_60/gs_NFV002v010101p.pdf


SW
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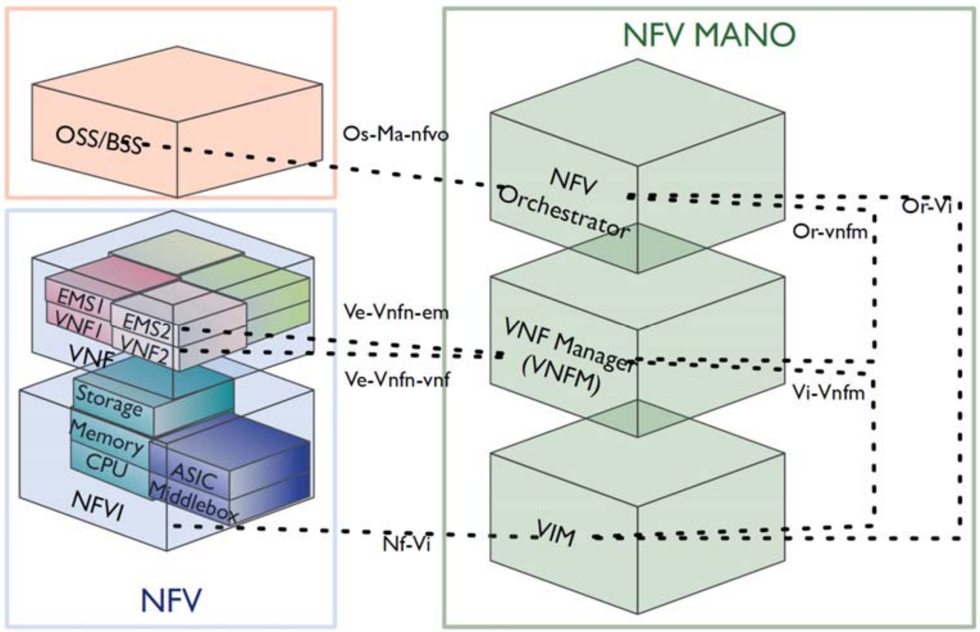
SW
SW
SW
SW
Generic HW
F1
F2
.....
Fn
Network Functions for Specific Service or Slice
F1
F2
F3
F4
.....
Fn
Generic HW

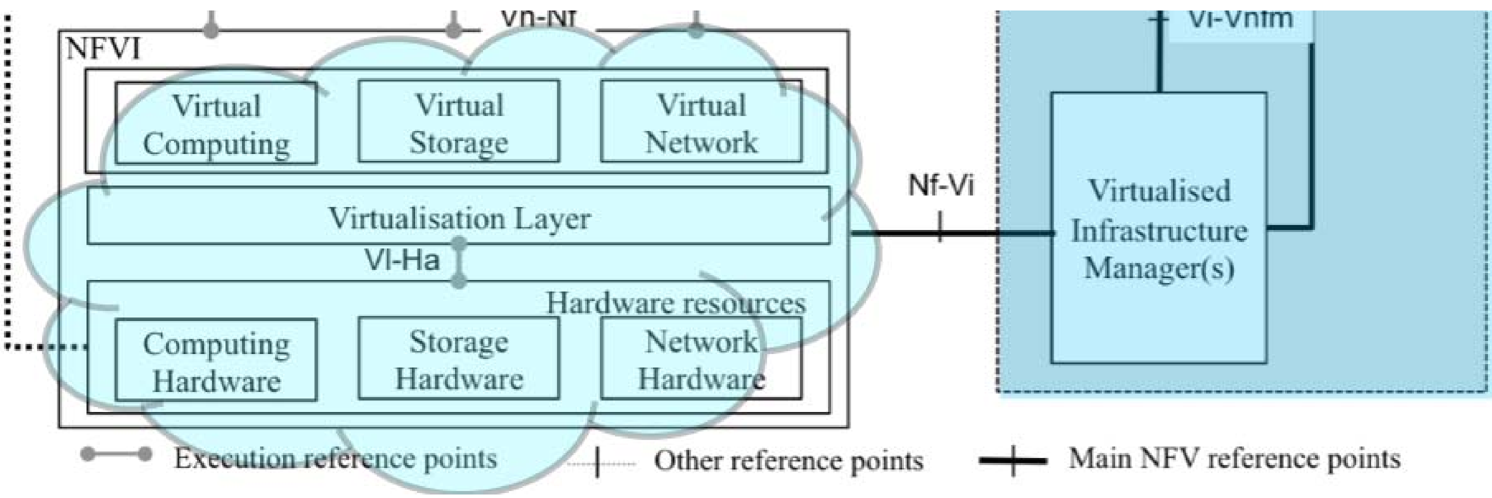
Focus on Management & Orchestration



ETSI NFV Management and Orchestration architecture

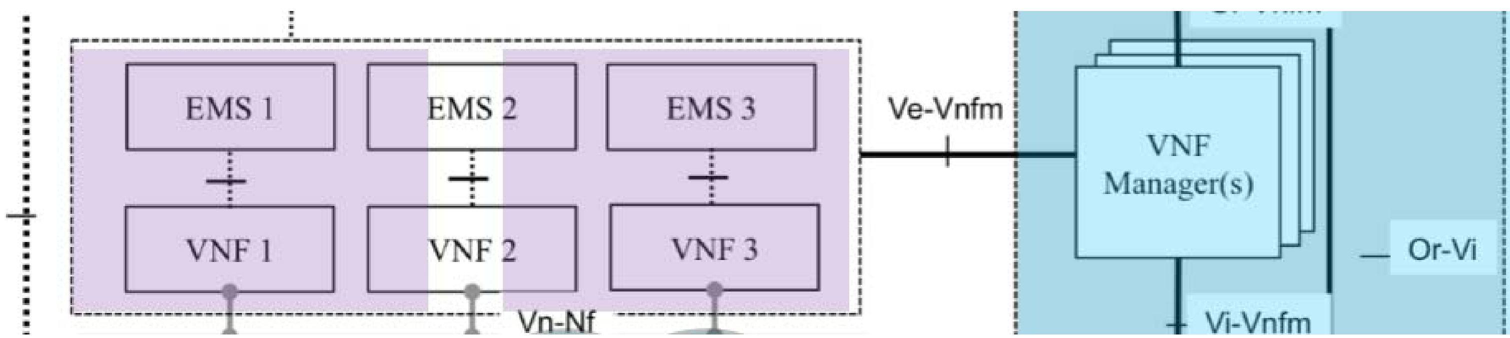
VIM

- Virtualised Infrastructure Manager (VIM):
  - controlling and managing the NFVI compute, storage and network resources, within one operator's infrastructure sub-domain
  - collection and forwarding of performance measurements and events



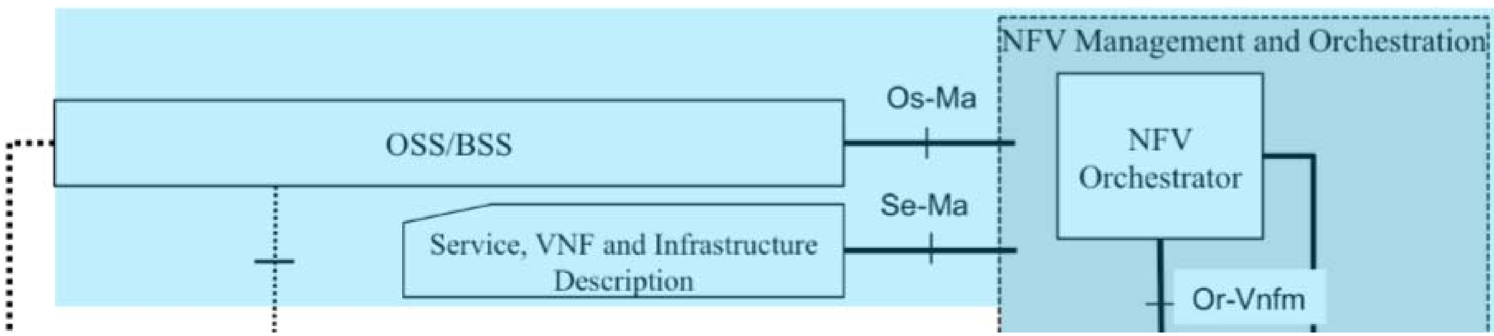
VNF Manager

- VNF Manager: – lifecycle management of VNF instances – overall coordination and adaptation role for configuration and event reporting between NFVI and the E/NMS

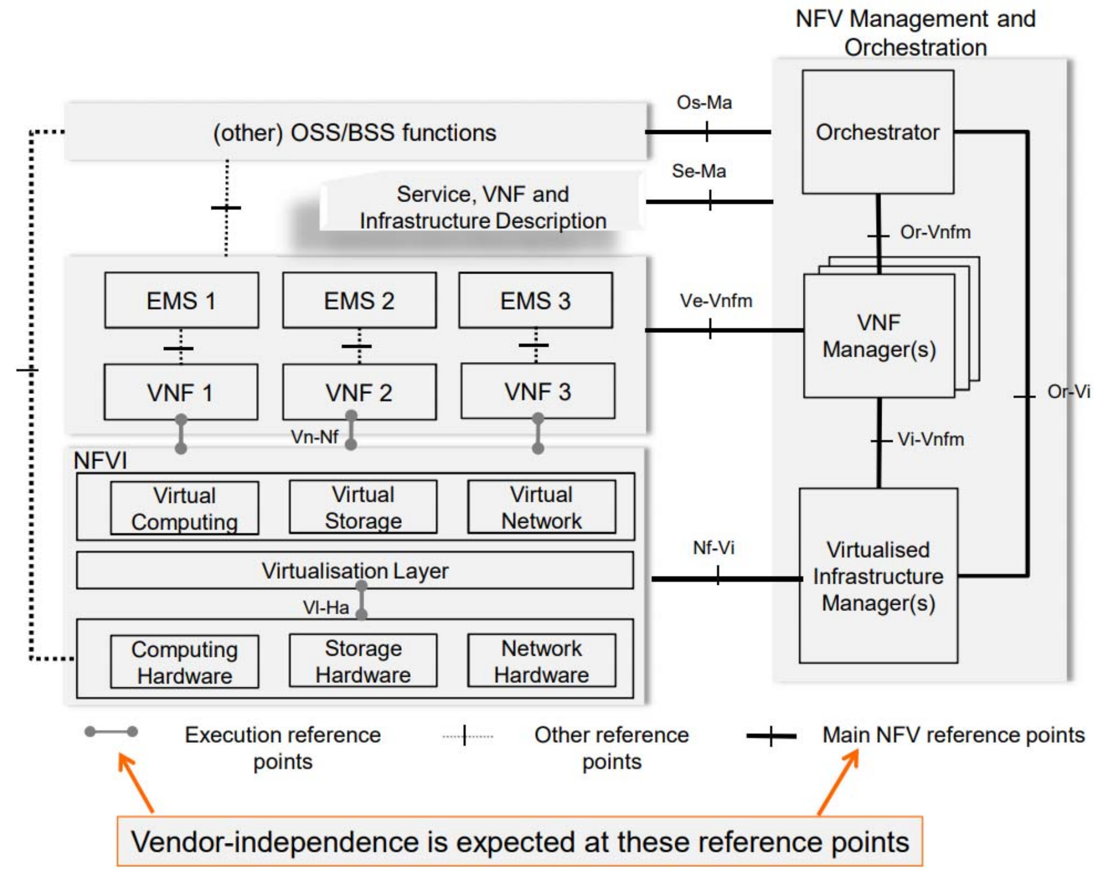


Orchestrator

- NFV Orchestrator: – on-boarding of new Network Service (NS), VNF-FG and VNF Packages – NS lifecycle management (including instantiation, scale-out/in, performance measurements, event correlation, termination) – global resource management, validation and authorization of NFVI resource requests – policy management for NS instances

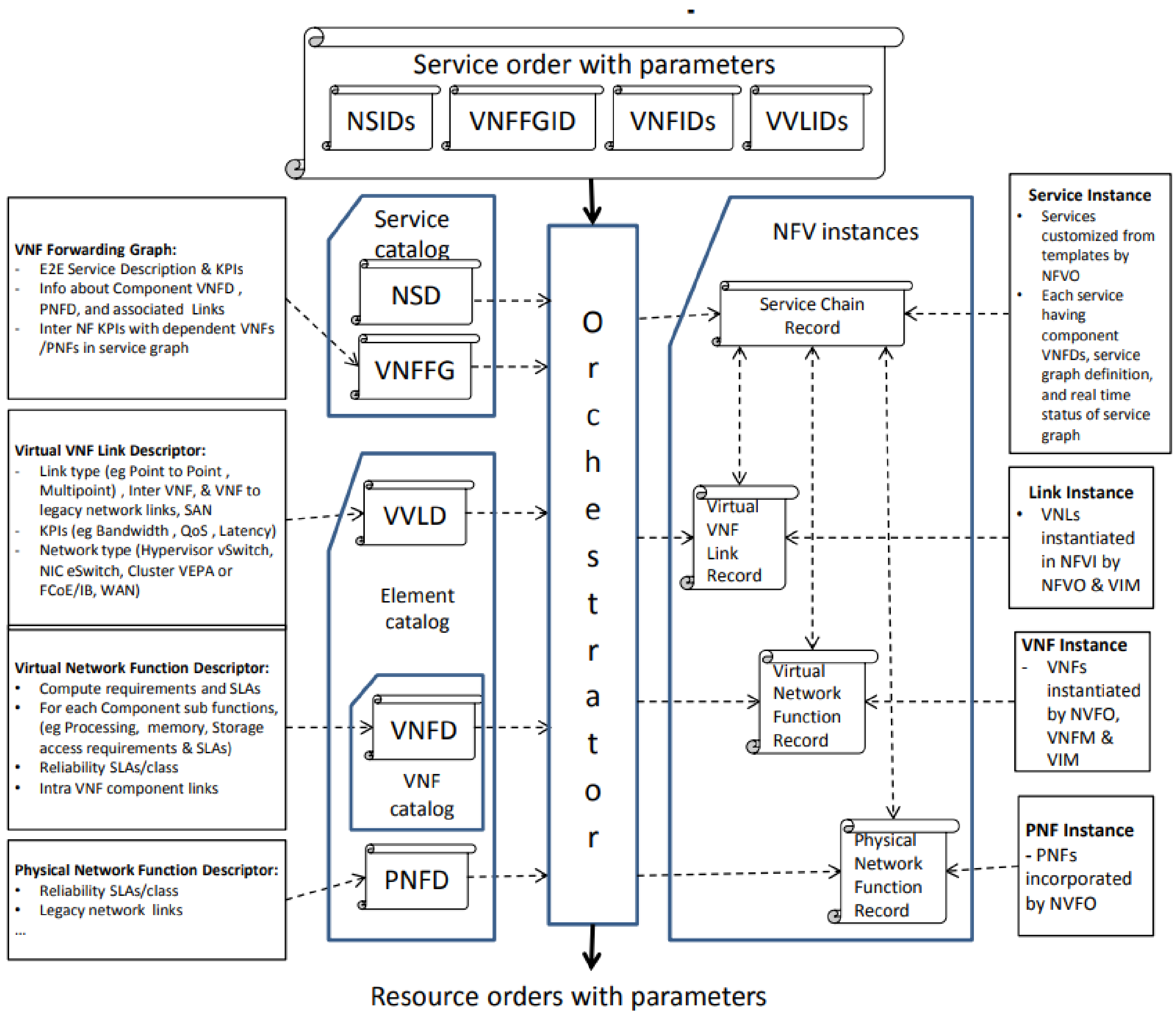


Detailed Architectural Framework

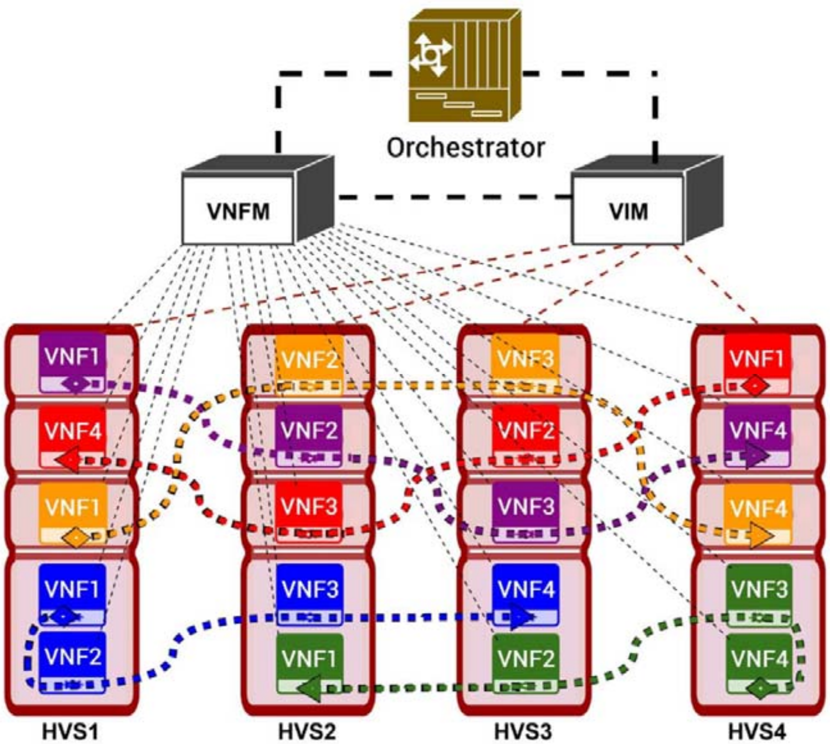


http://www.prism.uvsq.fr/~mogue/M2IRS/Cloud/WorkShop-SDN/Systematic-SDN%2526NFV-NFV-Orange-Chatras.pdf

Overview of MAN(
Descriptor Files



NFV Resource Allocation



❖ Resource definition in Core:

- ❑ Computation, storage devices
- ❑ Links and routs ….

❑ Within such a framework, one of the main problems to be considered is the problem of NFV resource allocation

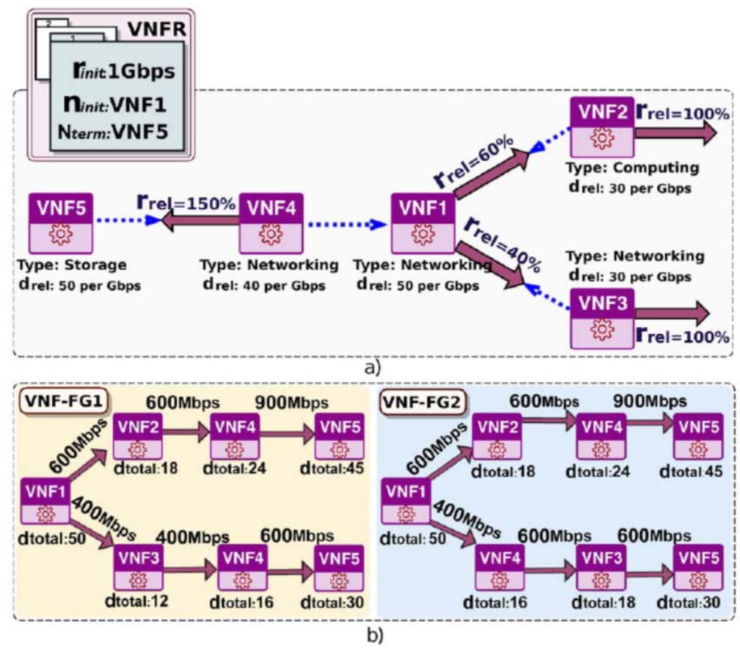
❖ Three stages of NFV resource allocation:

- ❑ VNFs Chain composition
- ❑ VNF Forwarding Graph Embedding
- ❑ VNFs Scheduling
- ❑ VNF Admission Control
- ❑ Chain recomposition

J. G. Herrera, etal, "Resource allocation in NFV: A comprehensive survey", IEEE Transactions on Network and Service Management, 2016.

VNFs Chain Composition (VNFs-CC)

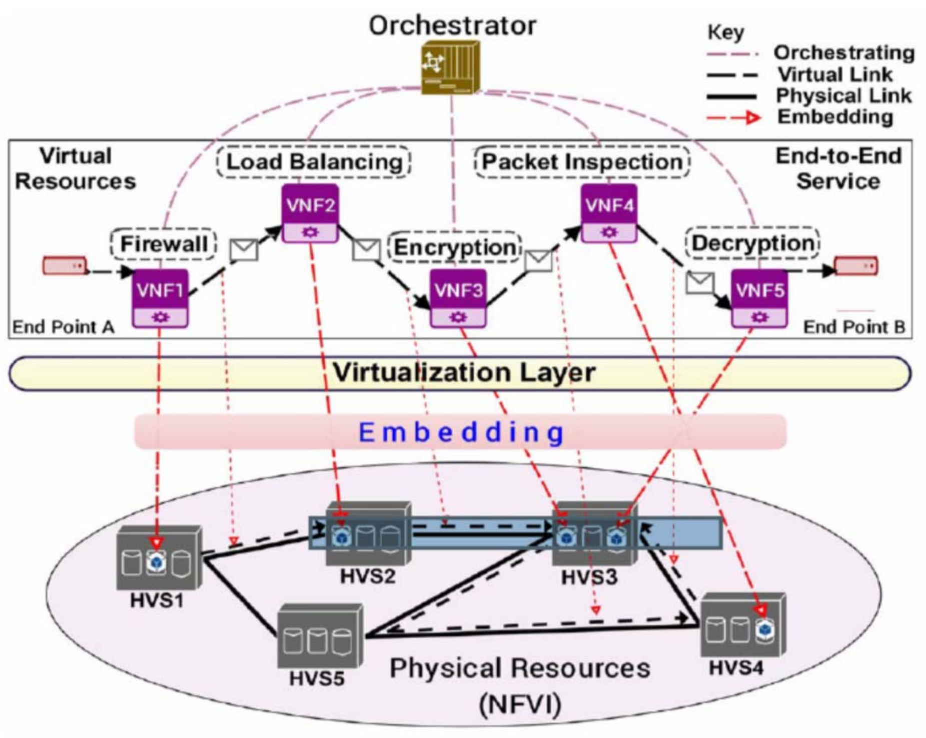
- VNFs chain composition (VNFs-CC), i.e. dealing with efficient ordering of a service's VNFs



J. G. Herrera, etal, "Resource allocation in NFV: A comprehensive survey", IEEE Transactions on Network and Service Management, 2016.

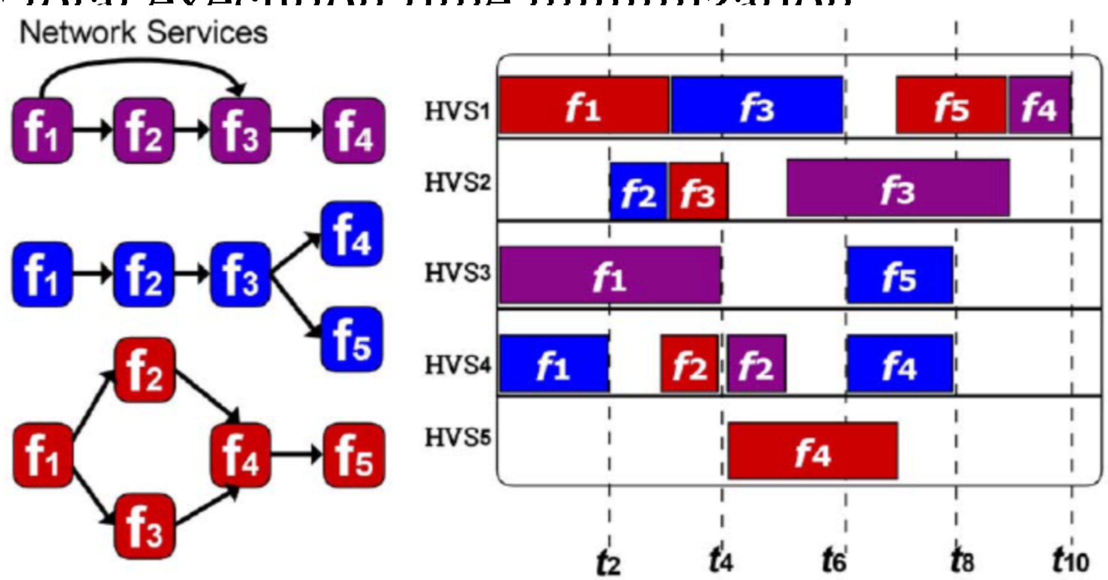
VNF Forwarding Graph Embedding (VNF-FGE)

- VNF forwarding graph embedding (VNF-FGE), i.e. seeking to embed VNFs in the substrate network, a problem commonly divided into two sub-problems of virtual node mapping and virtual link mapping



VNFs Scheduling (VNFs-SCH)

- VNFs scheduling (VNFs-SCH), i.e. time ordering the execution of VNFs, a problem arising when a resource, e.g. a server, is shared among several VNFs of different VNFRs over multiple time-slots and the time-slots allocated to execute each VNF should be determined, with some objectives such as total execution time minimization



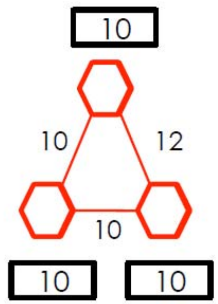
Joint Parameters Allocation

- Admission control (AC) is the process of deciding whether to accept a VNFR to be served in the network or reject it, with a set of aims such as complying with the constraints on network resources, meeting VNFRs' requirements, and optimizing some objective functions
- Re-composition of SFCs

Virtual Network Embedding (VNE)

- Mapping virtual network(s) onto a physical network
  - Map each virtual node to one physical node
  - Map each virtual link to one or more physical path(s)
- VNE is proven to be *NP-Hard*
  - No polynomial time optimal solution exists
  - Most solutions are heuristic-based
- Three versions of the problem
  - Offline: all the VN requests are known in advance
  - Online: VN requests arrive one at a time
  - Batch: Similar to online, but VN requests arrive in batches

VNE Example



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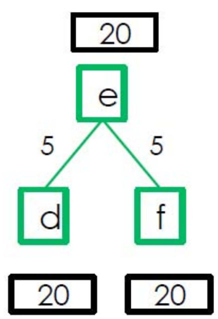

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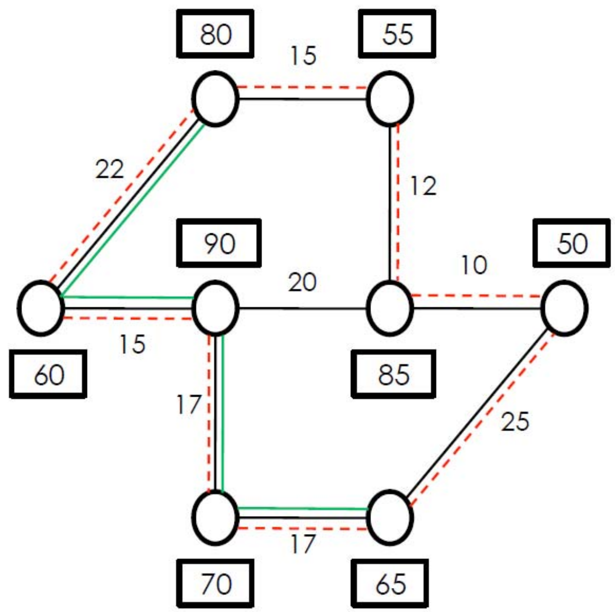

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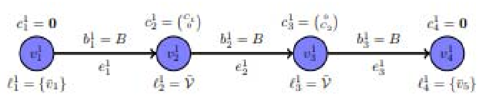
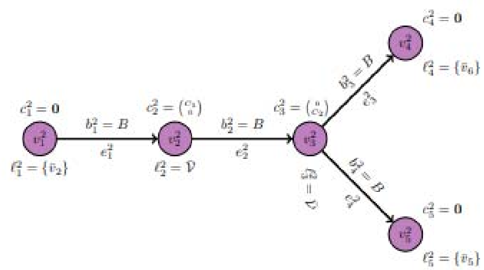
Optimal Solution Approach

- Optimal solution to VNE is modeled using Linear Programming
  - Multi-dimensional variables represent virtual node and link mapping
  - Linear constraints on variables represent physical constraints (e.g., no
  - Path splitting or no resource over-commitment)
  - Objective function is obtained from a linear combination of variables
- Example Constraints
  - Physical resource constraints
  - Technological constraints, e.g., wavelength contiguity constraint in
  - DWDM optical networks
- Example objective functions
  - Maximize acceptance ratio or revenue
  - Minimize the scheduling delay
  - Maximize physical resource utilization
  - Minimize energy costs

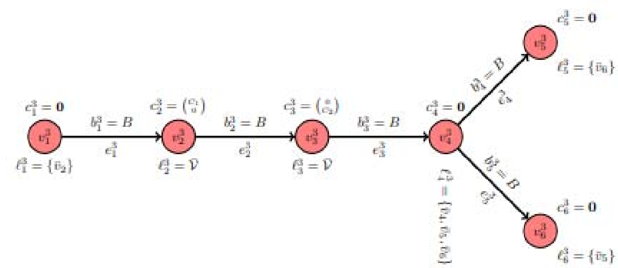
Example VNE: vSpace



(a) Directed graph $\mathcal{G}^1$ representing R_1, where the data flow has to pass through two VNFs of different types.



(b) Directed graph $\mathcal{G}^2$ representing R_2, where the same data flow, after being manipulated by certain VNFs, needs to be broadcast to two destination nodes.

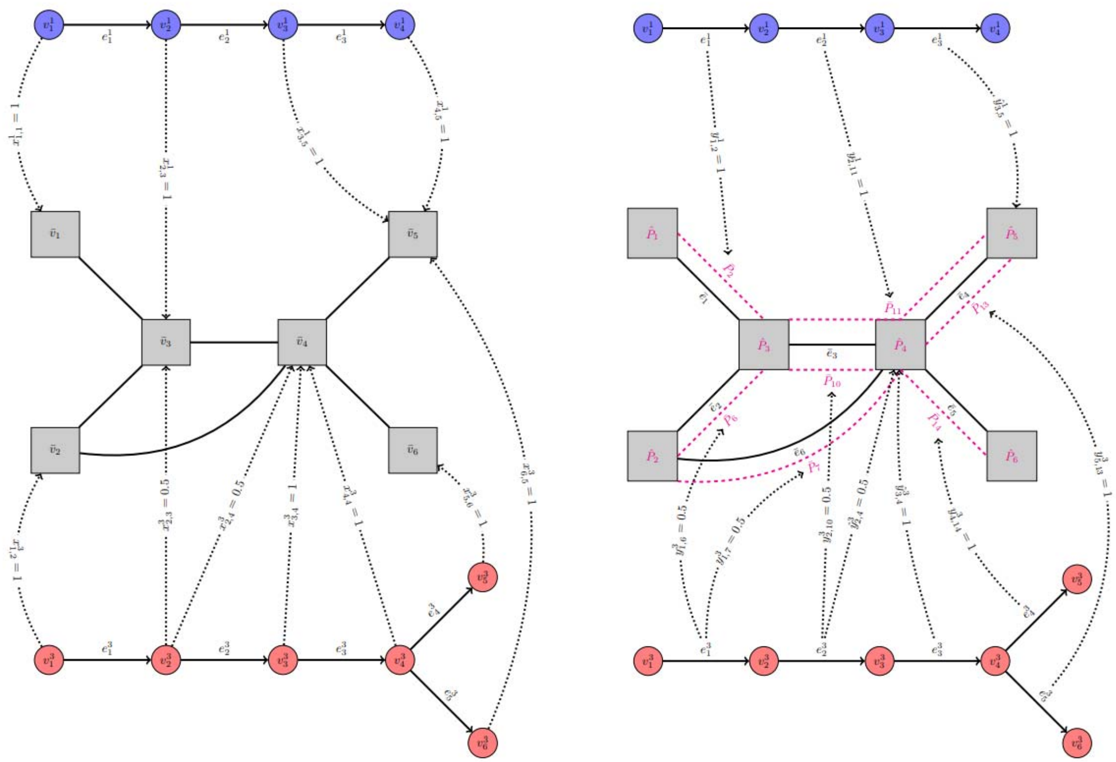


(c) Directed graph $\mathcal{G}^3$ representing R_3, where the to-be-broadcast manipulated data flow has to remain unsplit until having got close to destination zone.

An example of the requests' set including three VNFRs.

M. A. Tahmasbi Nejad, S. Parsaeefard, M. A. Maddah-Ali, T. Mahmoodi and B. H. Khalaj, "vSPACE: VNF Simultaneous Placement, Admission Control and Embedding," in *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 3, pp. 542-557, March 2018.

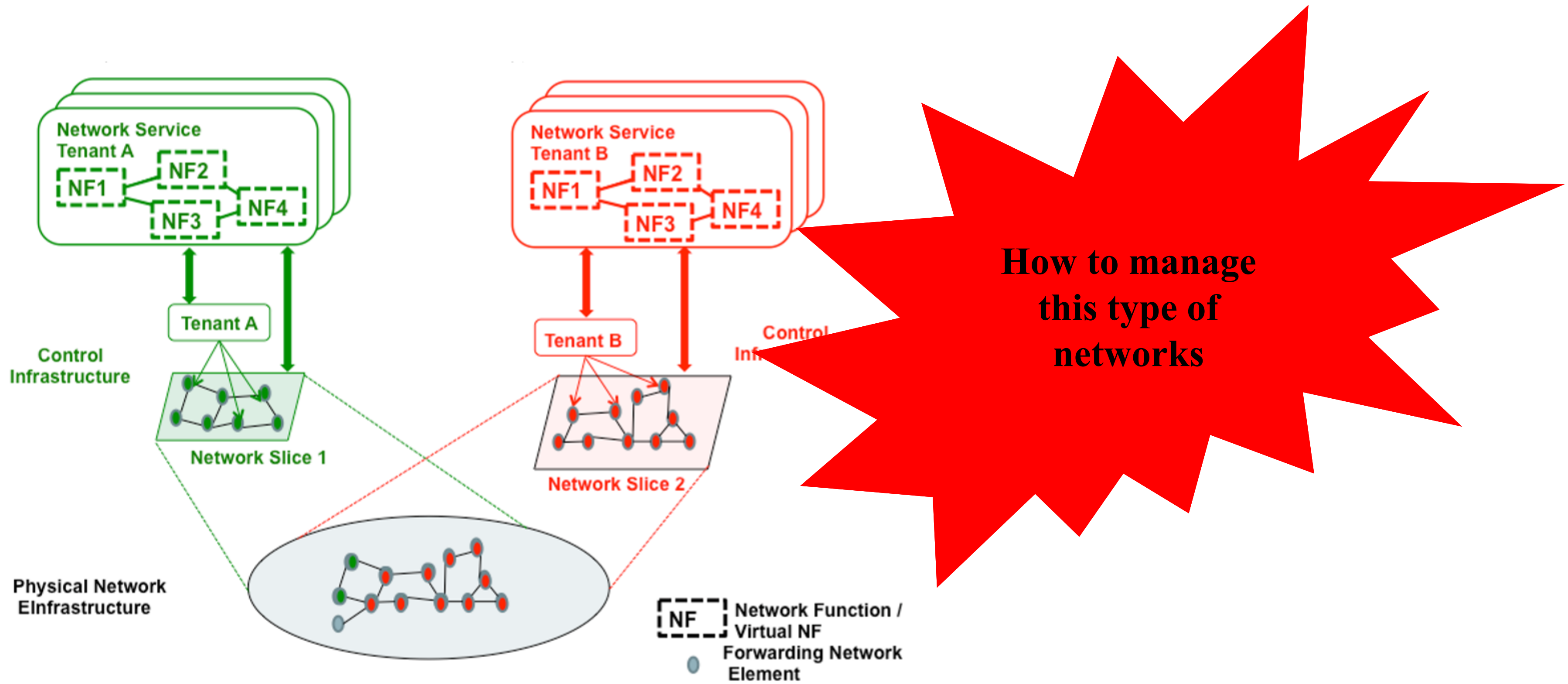
WNF Embedding Example



M. A. Tahmasbi Nejad, S. Parsaeefard, M. A. Maddah-Ali, T. Mahmoodi and B. H. Khalaj, "vSPACE: VNF Simultaneous Placement, Admission Control and Embedding," in *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 3, pp. 542-557, March 2018.

Complementary Concepts

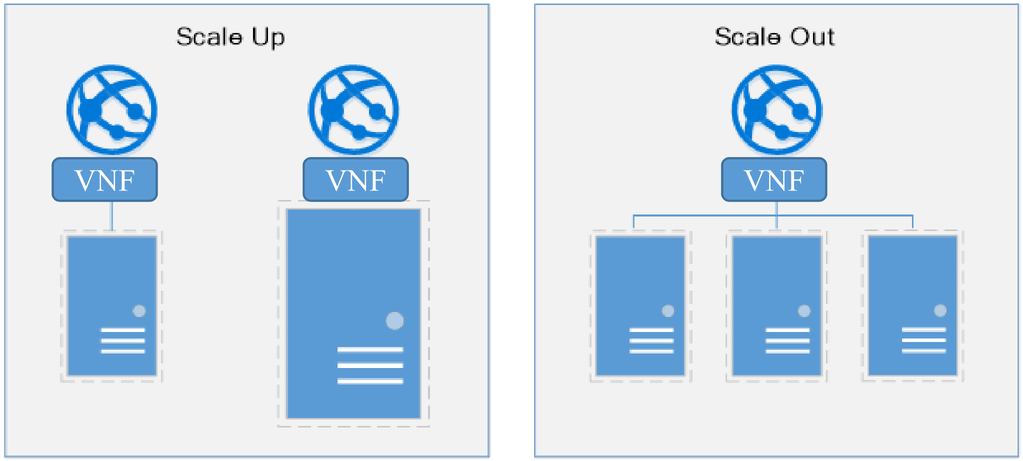
5G Logical and Physical Slice View



5G Network Slicing Representation in A. Galis, "Towards Slice Networking," presentation at IETF98 -, March 2017; https://github.com/netslices/IETF-NetSlice

VNF Scale up and Scale Down

- Scaling is growing an infrastructure (compute, storage, networking) larger so that the applications riding on that infrastructure can serve more people at a time.
  - Scaling out => adding more components in parallel to spread out a load.
  - Scaling up = making a component bigger or faster so that it can handle more load.

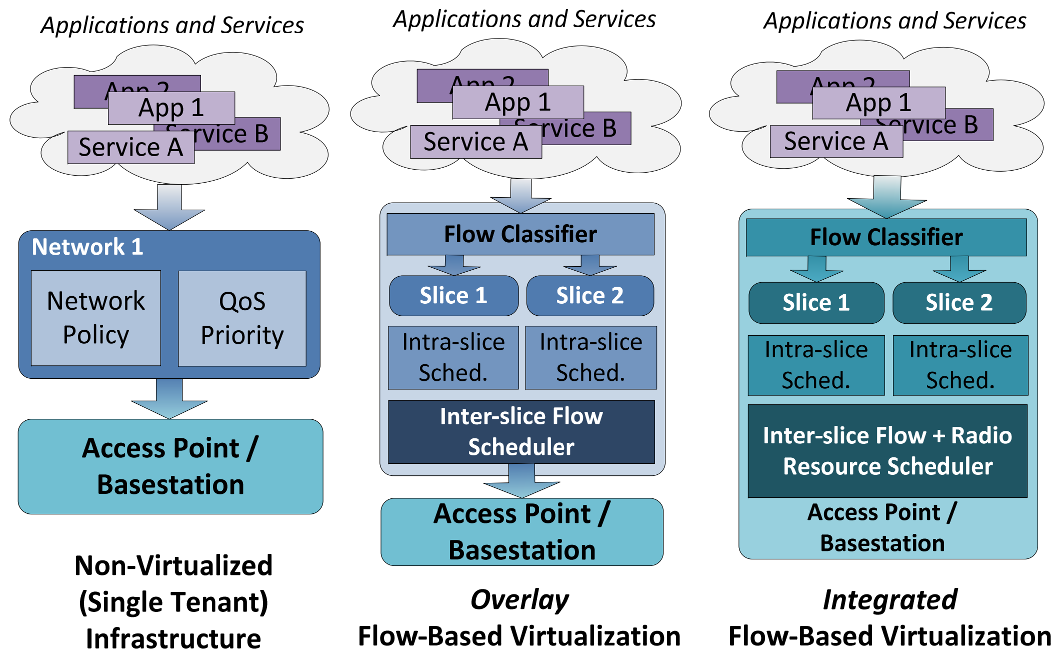


Types of Wireless Network Virtualization

- There exist three major categories:
  - **Flow based**
  - **Protocol based**
  - **Spectrum and RF Front-end Virtualization**
- They can also defined the depth of virtualization in the network

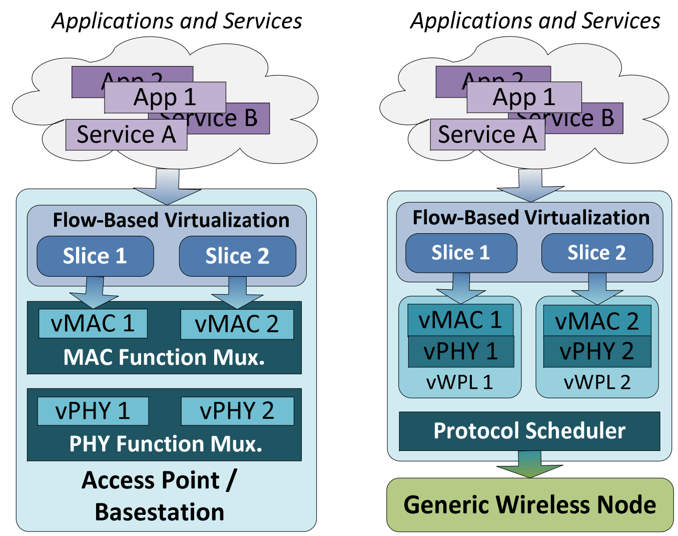
Flow-based Wireless Virtualization

- Main focus on isolation of the **transfer of data**
- Can be viewed as an extension of SDN and virtualization principles from network virtualization
- **Overlay** flow-based virtualization:
    - Virtualization layer is **external** to the physical hardware
- **Integrated** flow-based virtualization:
    - Virtualization layer **integrated** within the physical hardware



Protocol-based Wireless Virtualization

- supporting **virtualized wireless protocol stacks** on the same radio hardware (potentially simultaneously)
- Virtualization and abstraction of resources such as:
  - MAC opportunities to the channel
  - PHY processing resources
- **Partial** protocol-based virtualization
  - Virtual instances of the **same protocol stack** on the same physical hardware (different radio configuration profile)
- **Full** protocol-based virtualization
  - Virtual instances of **different wireless protocol stacks** on the same hardware (full functionalities)
- Can be achieved through the use of **SDR technologies**

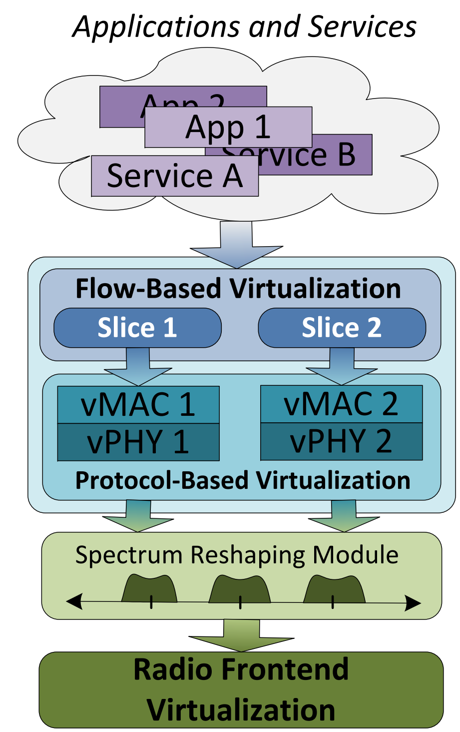


Partial
Protocol-Based Virtualization (Single Protocol Type)

Full
Protocol-Based Virtualization (Multiple Protocol Types)

Spectrum and RF Front-end Virtualization

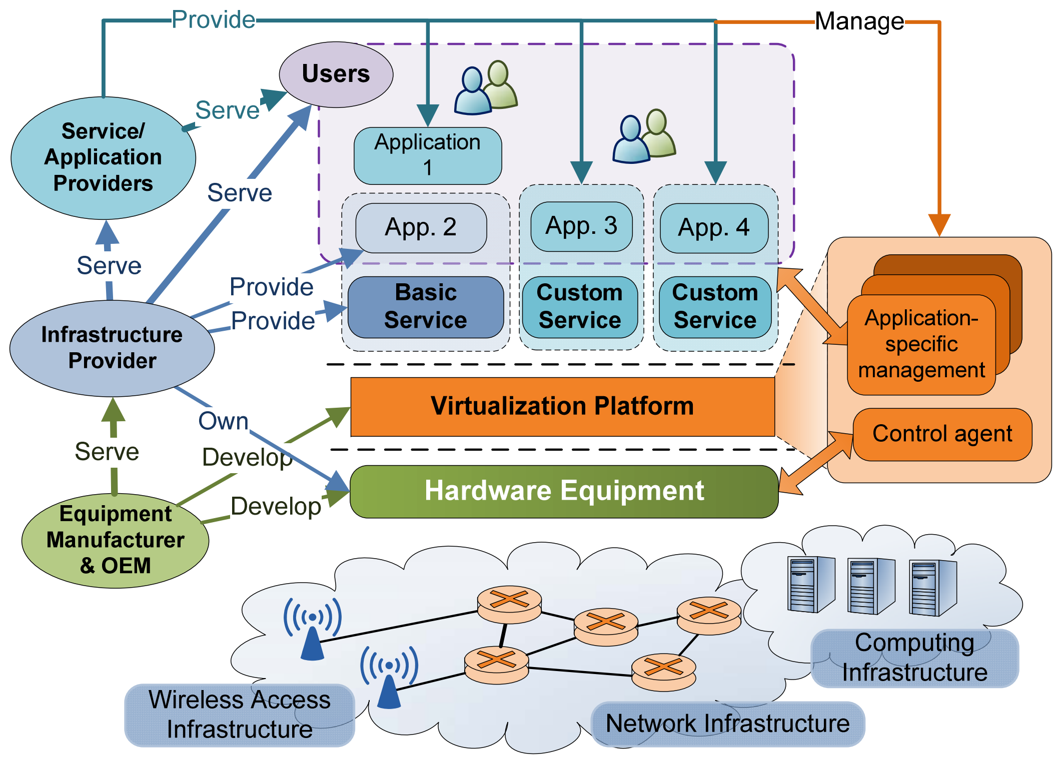
- Decouples the spectrum and RF frontend from the protocol stacks
- Can be applied to distributed antenna systems and cognitive radios
- Can further improve the flexibility and isolation of the virtualization framework



Spectrum-Based Virtualization

virtualization platform: Service-oriented Scenario

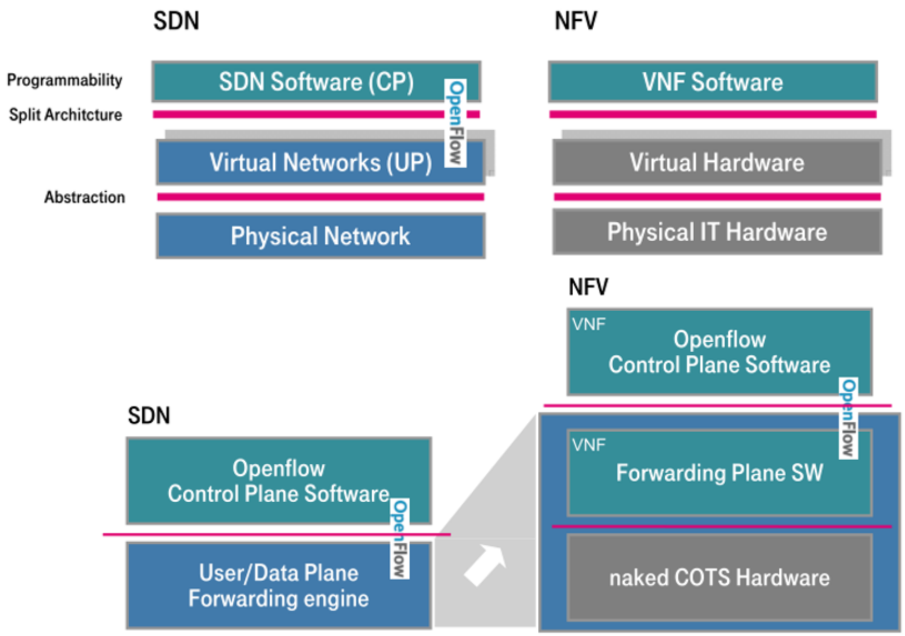
- Interplay of different domains (computer, network, wireless access)
- The equipment manufacturer and OEM can provide the APIs to access virtualization functions
- Development of **virtualization platform** as firmware/software
- Services on the infrastructure can be adjusted to different applications
- Full control of the virtualized infrastructure given to each tenants.



Virtualized Cloud Infrastructure

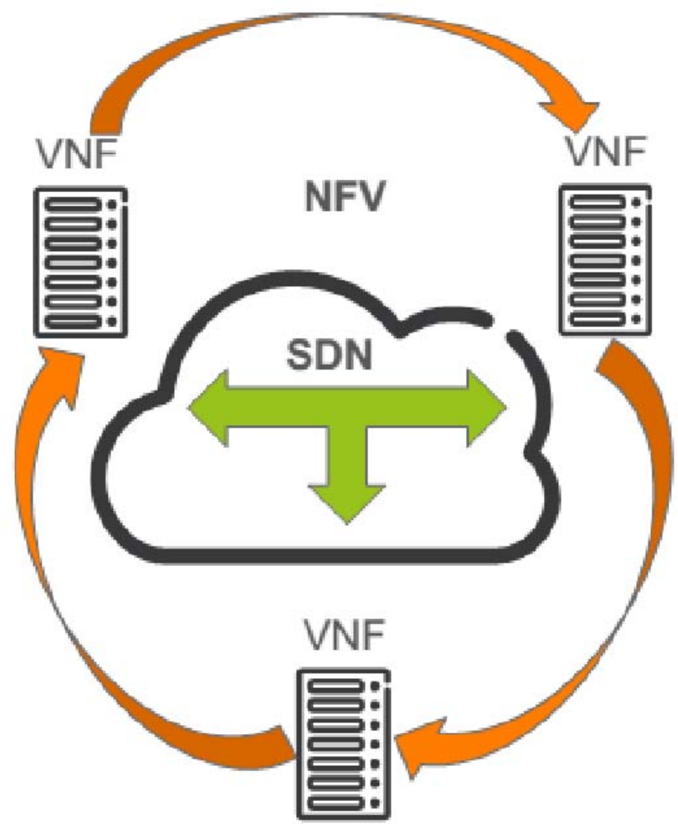
SDN and NFV

- Two complementary problem
- SDN and NFV do Not depend on each other



NFV vs SDN

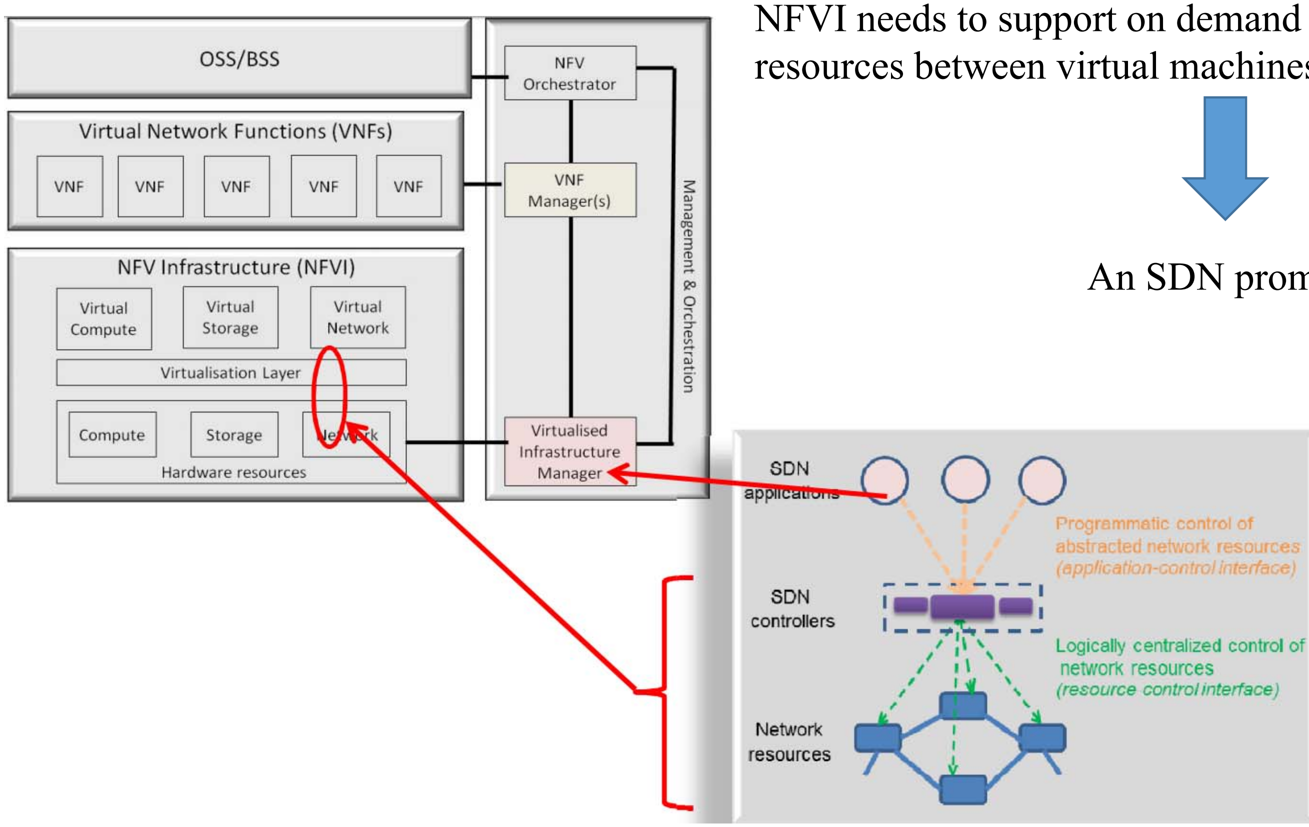
- SDN ››› flexible forwarding& steering of traffic in a physical or virtual network environment [Network Re-Architecture]
- NFV ››› flexible placement of virtualized network functions across the network [Appliance Re-Architecture]
- SDN & NFV are complementary tools for achieving full network programmability



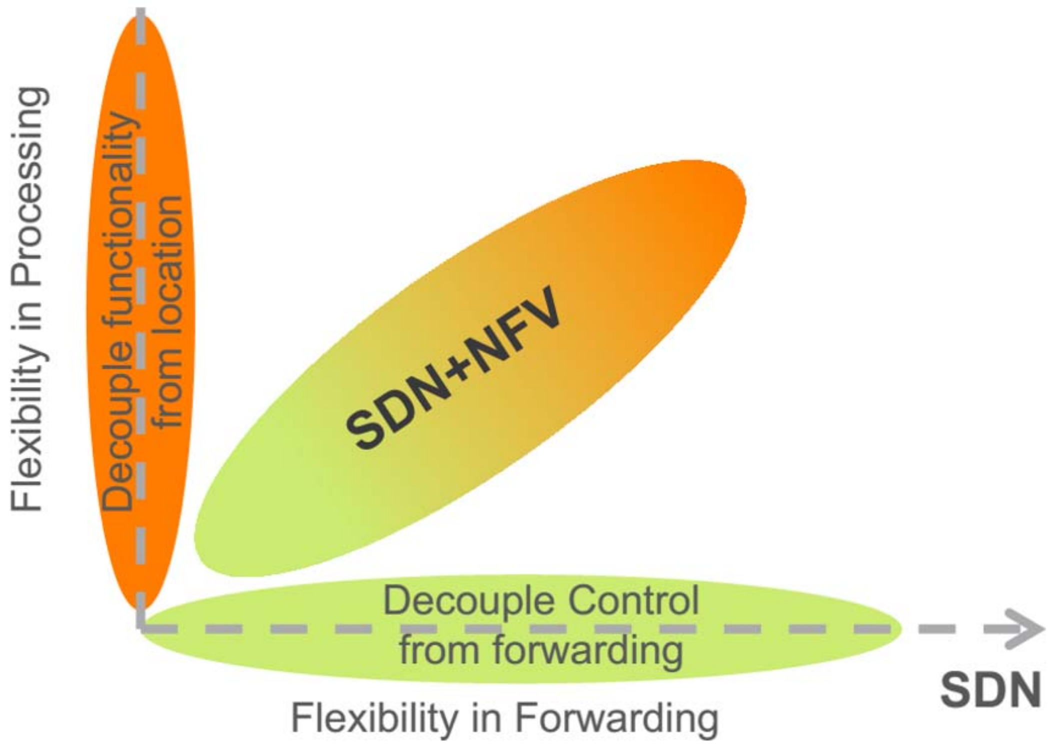
SDN in the NFV infrastructure

NFV promise: Reduce the time to deploy network functions => NFVI needs to support on demand provisioning of connectivity resources between virtual machines.

An SDN promise!



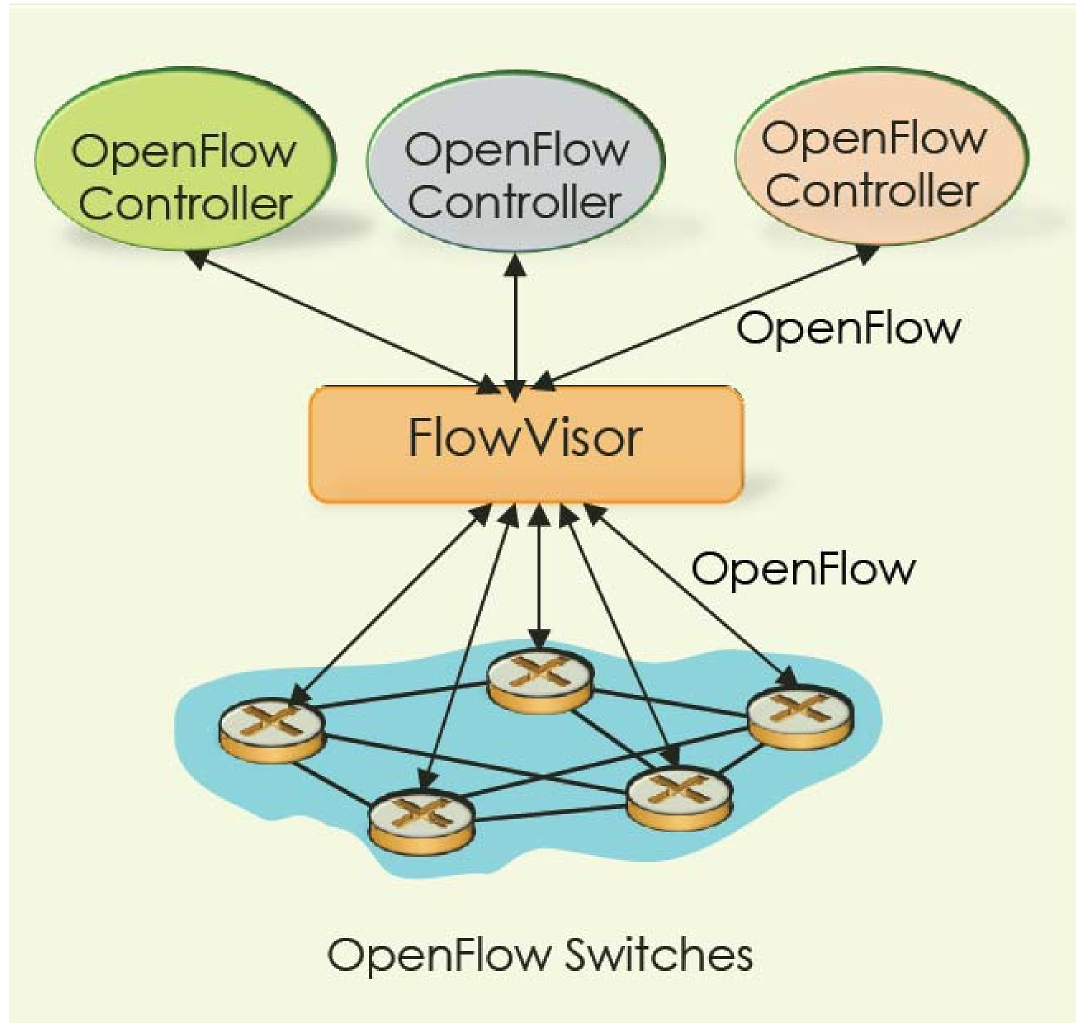
Flexibility with SDN & NFV



Source: Ahmad Rostami, Ericsson Research (Kista):
http://www.itc26.org/fileadmin/ITC26_files/ITC26-Tutorial-Rostami.pdf

FlowVisor

- An OpenFlow controller
  - Acts as a proxy between OpenFlow switches and multiple
- Controllers (one per slice)
  - Intercepts messages between controllers and switches
  - Isolate slices from each other
- Slices the flowspace based on OpenFlow match fields
  - switch port, MAC@, IP@, etc.
- Uses OpenFlow protocol to control underlying physical network and network slices



Research Challenges

- Virtual Network Embedding
  - What is the most efficient mapping of a VN on an InP's physical network?
- Admission Control and Usage Policing
  - How does an InP guarantee QoS for each VN with it's limited physical resources?
- Resource Scheduling
  - Maximize *degree of co-existence*
  - Schedule node resource and Link bandwidth
  - Energy efficiency

Research Challenges

- Orchestration
  - Reliability, delay and quality of service guarantee
  - Traffic and function monitoring,
  - Inter-operability and interfacing, programmability and Intelligence,
  - Distributed versus centralized management,
  - Combined management of cloud, SDN and NFV,
  - Autonomic (self) management technologies in NFV (e.g., processing of alarms)
- Security, Privacy, Trust

Network function virtualization: State-of-the-art and research challengesR Mijumbi, J Serrat, JL Gorricho, N Bouten, F De Turck, R Boutaba IEEE Communications Surveys & Tutorials 18 (1), 236-262

Standardization Body

SUMMARY OF NETWORK FUNCTION VIRTUALIZATION STANDARDIZATION EFFORTS

	Description	Focus Area	Description of NFV-Related Work
ETSI	Industry-led ETSI Standards Group	NFV	NFV architectural framework, infrastructure description, MANO, security and trust, resilience and service quality metrics.
3GPP SA5	3GPP's Telecom Management working group	Mobile Broadband	Working in liaison with the ETSI. Studying the management of virtualized 3GPP network functions.
IETF SFC WG	IETF Working Group	NFV	To propose a new approach to service delivery and operation, an architecture for service function chaining, management and security implications.
IRTF NFVRG	IRTF Research Group	NFV	Organizing NFV-related research activities in both academia and industry through workshops, research group meetings etc. at premier conferences.
ATIS NFV Forum	Industry-led Standards Group	NFV	Developing specifications for NFV, focusing on inter-carrier interoperability.
ONF	Industry-led consortium for standardization of OpenFlow	SDN	Standardizing the OpenFlow protocol and related technologies. Defines OpenFlow as the first standard communications interface defined between the control and forwarding layers of an SDN architecture.
DMTF OVF	Industry-led consortium	Cloud	DMTF's OVF and the CIM may be used as one option for capturing some or all of the VNF package and/or VDU [18] Descriptor.
BB Forum	Industry-led consortium that develops broadband network specifications	NFV in Broadband Networks	Collaborating with the ETSI to achieve a consistent approach and common architecture for the infrastructure needed to support VNFs.

Network function virtualization: State-of-the-art and research challengesR Mijumbi, J Serrat, JL Gorricho, N Bouten, F De Turck, R Boutaba IEEE Communications Surveys & Tutorials 18 (1), 236-262

SUMMARY OF NETWORK FUNCTION VIRTUALIZATION PROJECTS

	Project Type	Leader and/or Funding	Focus Areas	Main Objective
ZOOM	Association of SPs	TM Forum	NFV	Enable more rapid deployment of services by automating the provisioning process and modernizing OSS/BSS models.
OPNFV	Collaborative Project	Linux Foundation	NFV	Build an open source reference platform to advance the evolution of NFV.
OpenMANO	Vendor Project	Telefonica	SDN, NFV	Implementation of ETSI's MANO framework.
MCN	Research Project	European Union	SDN, NFV	Cloudify all components of a mobile network operation.
UNIFY	Research Project	European Union	NFV	Develop an automated, dynamic service creation platform, leveraging fine-granular service chaining.
T-NOVA	Research Project	European Union	SDN, NFV	Design and implement a MANO platform for NFV.
CONTENT	Research Project	European Union	Mobile Networks, Cloud	Providing a technology platform interconnecting geographically distributed computational resources that can support a variety of Cloud and mobile Cloud services.
OpenStack	Working Group	OpenStack Foundation	Cloud, NFV	Identify requirements needed to deploy, manage, and run telecom services on top of OpenStack.
OpenDaylight	Collaborative Project	Linux Foundation	SDN, NFV	Develop an open platform for SDN and NFV.

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