Networked Cyber-Physical Systems (Net-CPS) and the Internet of Things (IoT)

John S. Baras

Institute for Systems Research, University of Maryland, USA
ACCESS Linnaeus Center, Royal Institute of Technology, Sweden
Institute for Advanced Study, Technical University of Munich, Germany

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Networked Cyber-Physical Systems

Infrastructure / Communication Networks

Internet / WWW
MANET
Sensor Nets
Robotic Nets
Hybrid Nets: Comm, Sensor, Robotic and Human Nets

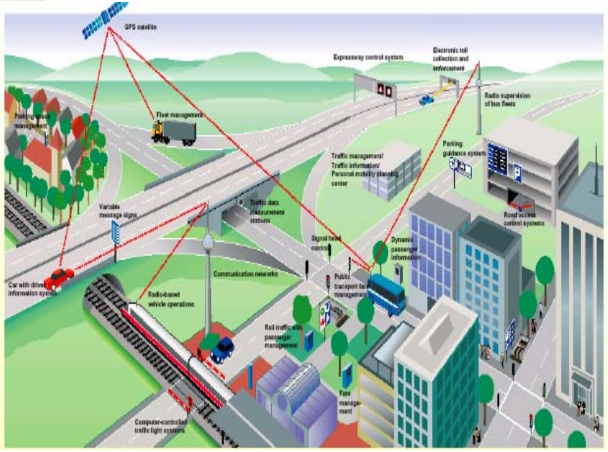
Social / Economic Networtks

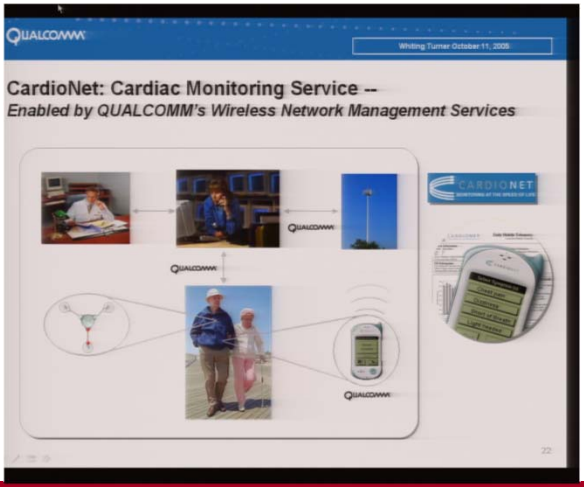
Social Interactions
Collaboration
Social Filtering
Economic Alliances
Web-based social systems

Biological Networks

Community
Epiddemic
Cellular and
Sub-cellular
Neural
Insects
Animal Flocks

Net-CPS: Wireless and Networked Embedded Systems



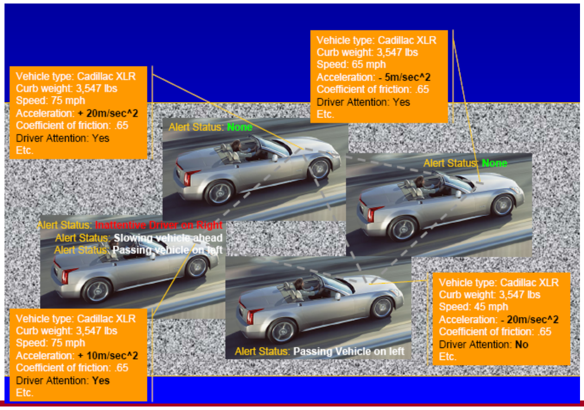


QUALCOMM

Whiting Turner October 11, 2005

CardioNet: Cardiac Monitoring Service --

Enabled by QUALCOMM's Wireless Network Management Services



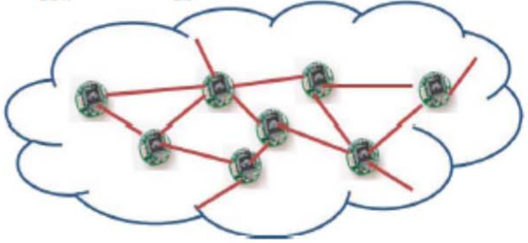
Future "Smart" Homes and Cities

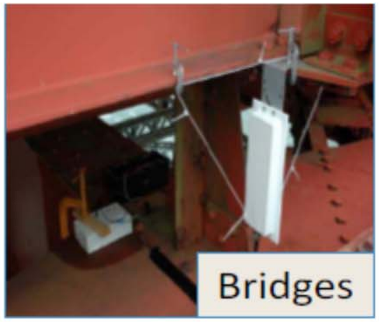
- UI for "Everything"
  - Devices with Computing Capabilities & Interfaces
- Network Communication
  - Devices Connected to Home Network
- Media: Physical to Digital
  - MP3, Netflix, Kindle eBooks, Flickr Photos
- Smart Phones
  - Universal Controller in a Smart Home
- Smart Meters & Grids
  - Demand/Response System for "Power Grid"
- Wireless Medical Devices
  - Portable & Wireless for Real-Time Monitoring

Net-CPS: Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage




Bridges


Snowpack

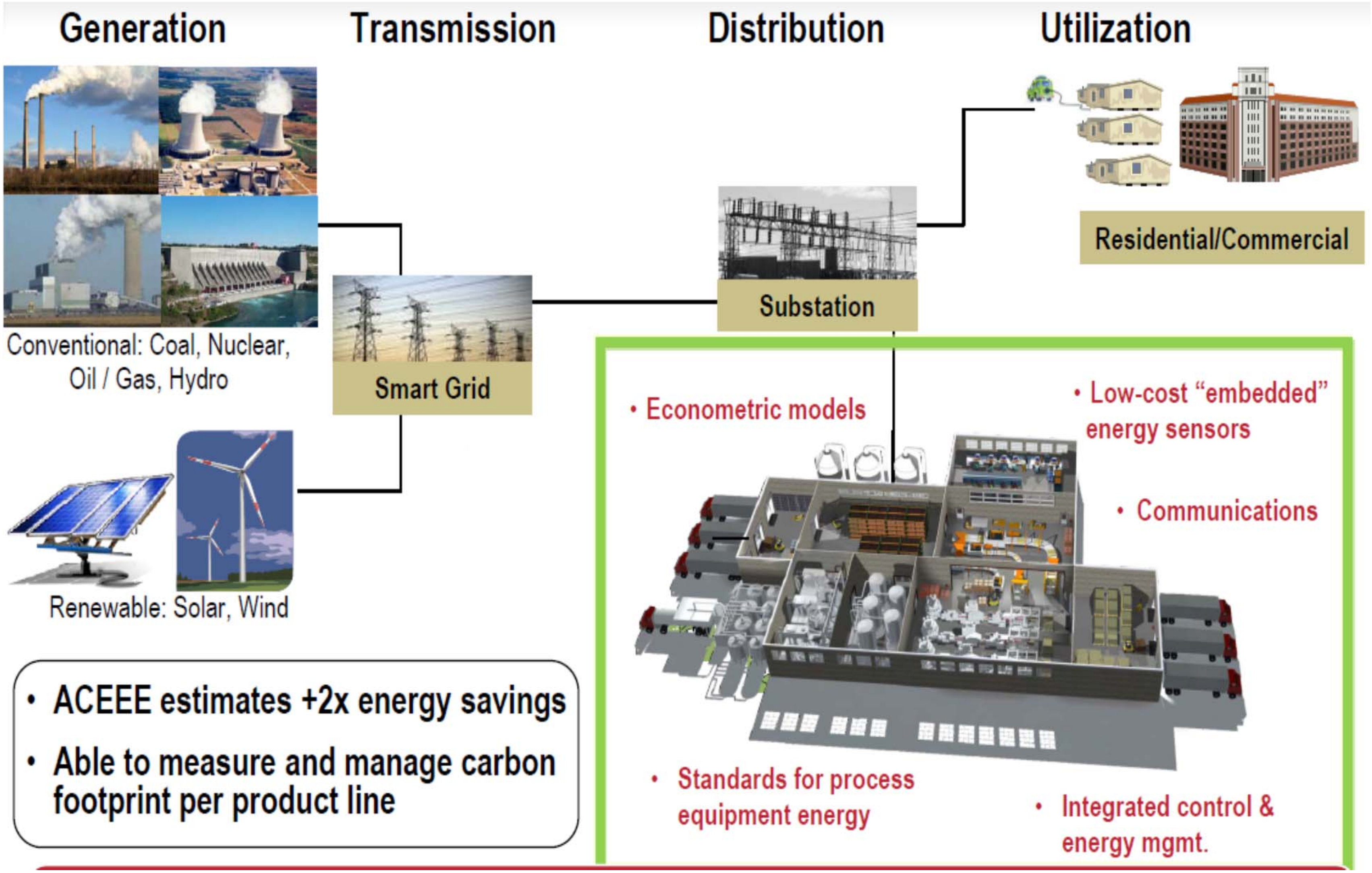

Soil liquefaction


Smart buildings


Traffic


Vineyards

Net-CPS: Smart Grids



- Econometric models
- Low-cost "embedded" energy sensors
- Communications
- Standards for process equipment energy
- Integrated control & energy mgmt.

- ACEEE estimates +2x energy savings
- Able to measure and manage carbon footprint per product line

Net-CPS: Collaborative Autonomy

- Component-based Architectures
- Communication vs Performance Tradeoffs
- Net-HCPS … human behavior
- Distributed asynchronous
- Fundamental limits

Net-HCPS: Social and Economic Networks over the Web

- We are much more “social” than ever before
  - Online social networks (SNS) permeate our lives
  - Such new Life style gives birth to new markets
- Monetize the value of social network
  - Advertising - major source of income for SNS
  - Joining fee, donation etc.
  - …
- Need to know the common features of social networks

CPS, Net-CPS, Net-HCPS

- **CPS**: Technological systems where physical and cyber components are tightly integrated
- **Examples**: smart phones, smart sensors, smart homes, smart cars, smart power grids, smart manufacturing, smart transportation systems, human robotic teams, …
- **Most of modern CPS are actually networked**: via the Internet or the cloud, or via special logical or physical networks
- **Examples**: modern factories, Industrie 4.0, modern enterprises, heterogeneous wireless networks, sensor networks, social networks over the Internet, Industrial Internet (IIC), the Internet of Things (IoT), …

CPS, Net-CPS, Net-HCPS

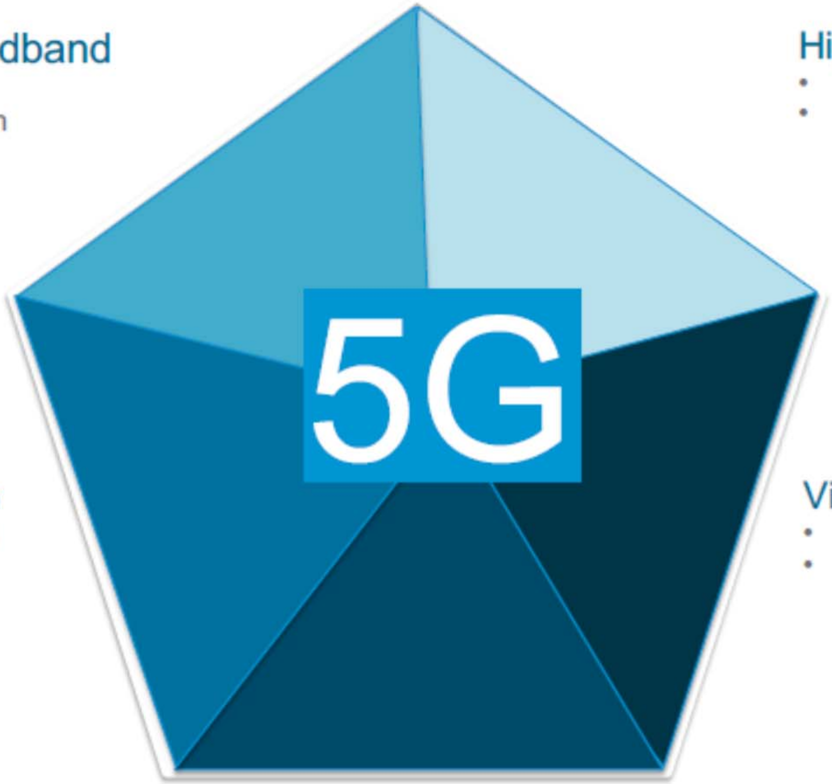
- With networks new fundamental challenges emerge: network semantics and characteristics
- Fundamental challenges on two fronts:
  - (a) on the interface between cyber and physical components and their joint design and performance;
  - (b) on the implications of the networked interfaces and the collaborative aspects of these systems and their design and performance.
- Networked Cyber-Physical Systems (Net-CPS)
- Additional challenge: incorporation of humans in Net-HCPS, as system components from start

IoT – Challenges and Opportunities

IoT opens up opportunities across multiple verticals

5G – What is it? Relation to IoT

Evolution to 5G Networks



High Speed Broadband
- Gigabit Data
- High Band Spectrum

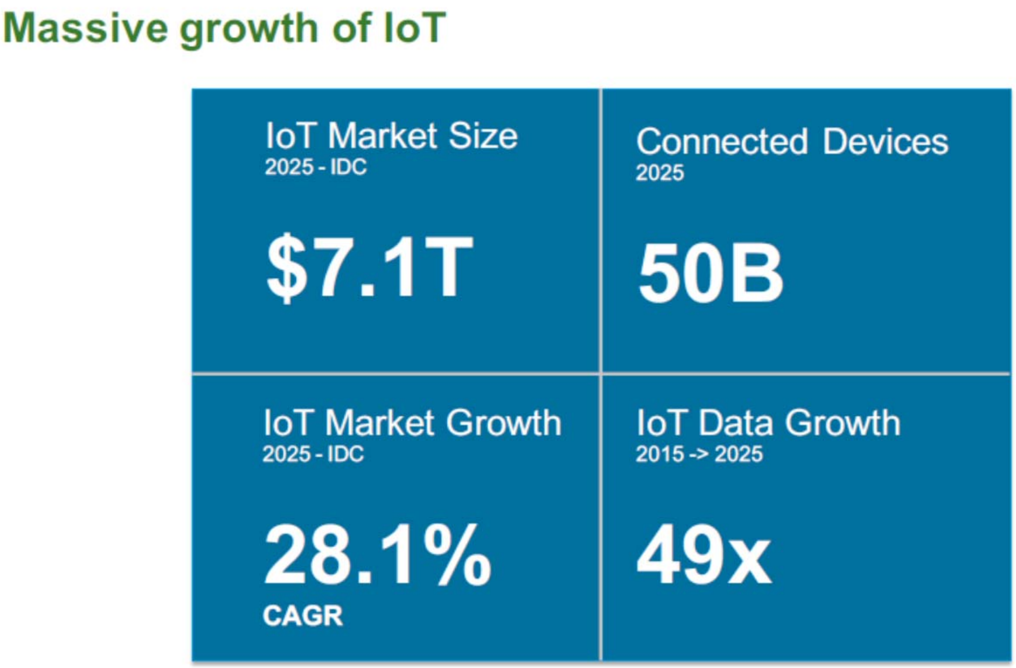
High Performance Networks
- Low Latency
- High Availability

Internet of Things
- Billions of connected devices

Virtualized Infrastructure
- Software-Defined Networks
- Network Function Virtualization (NFV)

Network Slicing
- Customized Services

IoT & 5G: Growth and Characteristics



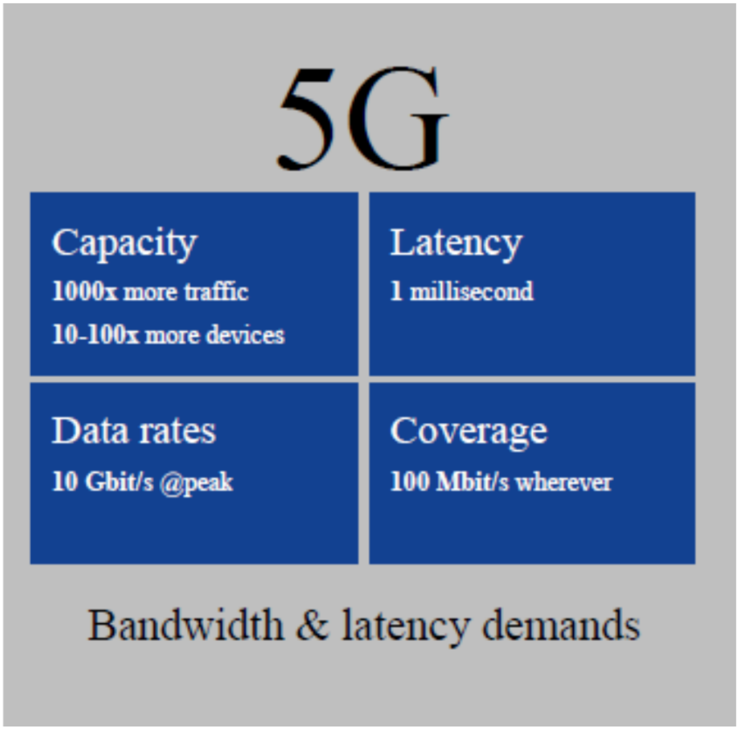
Massive growth of IoT

IoT Market Size
2025 - IDC
$7.1T

Connected Devices
2025
50B

IoT Market Growth
2025 - IDC
28.1%
CAGR

IoT Data Growth
2015 -> 2025
49x



5G

Capacity
1000x more traffic
10-100x more devices

Latency
1 millisecond

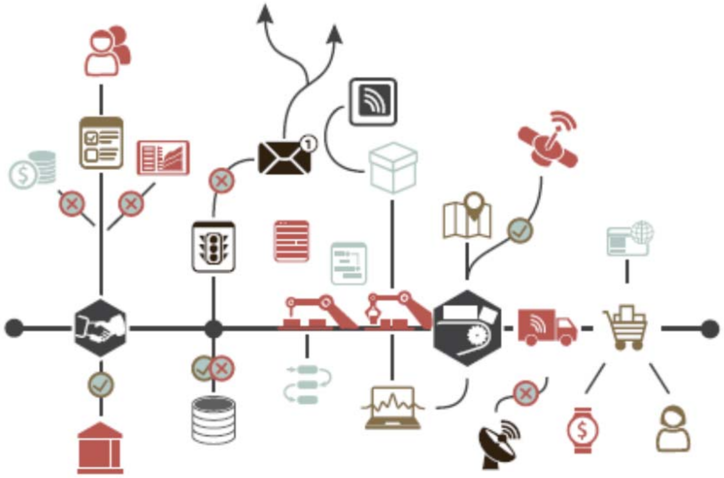
Data rates
10 Gbit/s @peak

Coverage
100 Mbit/s wherever

Bandwidth & latency demands

Some IoT Trends

- Analytics automation
- Augmented reality
- Industrial IoT – Smart Factory
- Thing Identity and Management Services
- IoT Governance and Exchange Services
- Edge computing

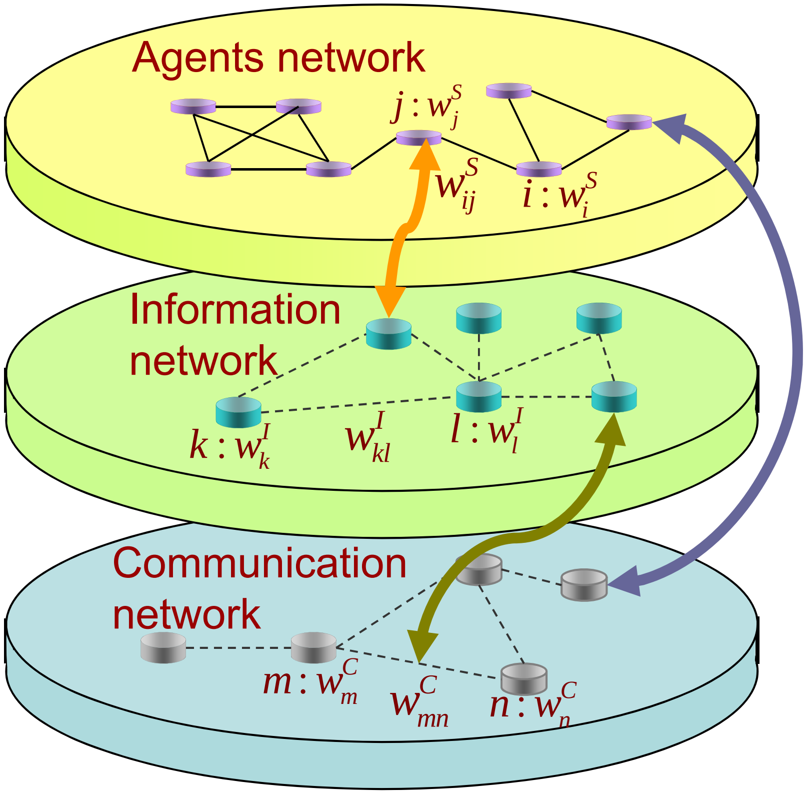


Outline

- Multiple interacting coevolving multigraphs – three challenges
- Graph Topology Matters
- Networks and Collaboration – Constrained Coalitional Games
- IoT and 5G – the enablers
- SDWN and NFV – SD Architecture for Net-CPS and implications for Net-HCPS
- Conclusions

Multiple Coevolving Multigraphs

- Multiple Interacting Graphs
  - *Nodes*: agents, individuals, groups, organizations
  - Directed graphs
  - *Links*: ties, relationships
  - Weights on links : value (strength, significance) of tie
  - Weights on nodes : importance of node (agent)
- **Value directed graphs with weighted nodes**
- **Real-life problems: Dynamic, time varying graphs, relations, weights, policies**



Networked System architecture & operation

Three Fundamental Challenges

- **Multiple interacting coevolving multigraphs involved**
  - ***Collaboration multigraph***: who collaborates with whom and when.
  - ***Communication multigraph***: who communicates with whom and when
- **Effects of connectivity topologies**:
  Find graph topologies with favorable tradeoff between performance improvement (**benefit**) of collaborative behaviors *vs* **cost** of collaboration
  - **Small word graphs** achieve such **tradeoff**
  - **Two level algorithm** to provide efficient communication
- Human group behavior and cognition need **different probability models** – the classical Kolmogorov model is **not correct**
  - Probability models over logics (independence friendly logic) and timed structures (constrained event algebras)
  - Logic of projections in Hilbert spaces – not the Boolean of subsets

Distributed Algorithms in Networked Systems and Topologies

- Distributed algorithms are essential
  - Agents **communicate with neighbors,** share/process information
  - Agents **perform local** actions
  - **Emergence** of global behaviors
- **Effectiveness** of distributed algorithms
  - The **speed** of convergence
  - **Robustness** to agent/connection failures
  - Energy/ communication **efficiency**
- **Design problem**:

  Find graph topologies with favorable tradeoff between performance improvement (**benefit**) *vs* **cost** of collaboration
- **Example: Small Word graphs** in consensus problems

An Example problem of the Interaction between the Control Graph and the Communication Graph

Expander Graphs

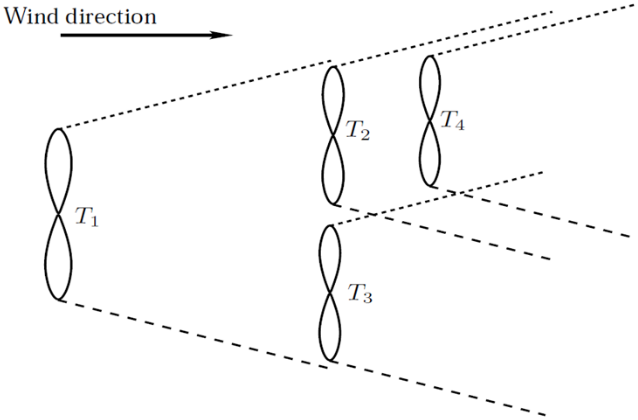
- First defined by Bassalygo and Pinsker -- 1973
- Fast synchronization of a network of oscillators
- Network where any node is “nearby” any other
- Fast ‘diffusion’ of information in a network
- Fast convergence of consensus
- Decide connectivity with smallest memory
- Random walks converge rapidly
- Easy to construct, even in a distributed way (ZigZag graph product)
- Graph G, ***Cheeger constant $h(G)$***
  - All partitions of G to S and S^c ,

    $h(G)$=min (#edges connecting S and S^c) / (#nodes in smallest of S and S^c)
- (k , N, ε) **expander** **:** $h(G) > \varepsilon$; **sparse but locally well connected** **(1-*SLEM*(G) increases as $h(G)^2$)**

Interaction Between Control and Communication Graphs: Agents Learn What is Best for the Team

Example: Maximizing Power Production of a Wind Farm

Horns Rev 1. Photographer Christian Steiness



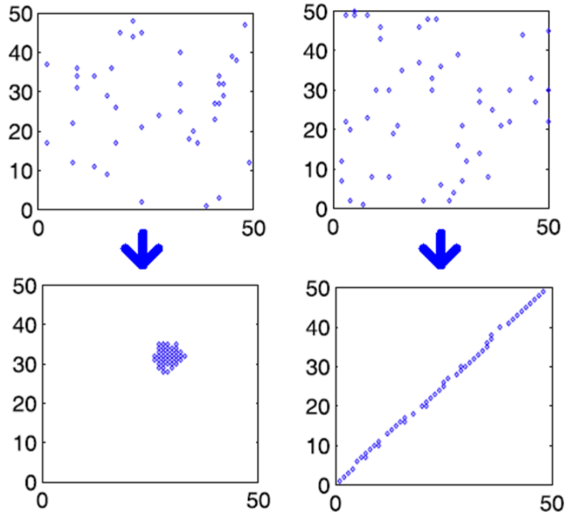
Schematic representation of a wind farm depicting individual turbine wake regions.

- Aerodynamic interaction between different turbines is not well understood.
- Need on-line decentralized optimization algorithms to maximize total power production.

Assign individual utility
$u_i(t) =$ power produced by turbine *i* at time *t*
such that maximizing $\sum_i u_i(t)$ leads to desirable behavior.

Interaction Between Control and Communication Graphs

Example: Formation Control of Robotic Swarms



Simulation results demonstrating rendezvous and gathering along a line[2]

- Deploy a robotic swarm in unknown environment: obstacles, targets etc. have to be discovered.[3]
- The swarm must form a prescribed geometric formation.
- Robots have limited sensing and communication capabilities.

For rendezvous, design individual utility

$$u_i(s_i) = \frac{1}{|\{s_j \in S : ||s_i - s_j|| < r\}|} - \alpha\, dist_r(s_i, obstacle),$$

such that minimizing $\sum_i u_i(t)$ leads to desirable behavior.

The Fundamental Trade-off

- The nodes **gain** from collaborating
- But collaboration has **costs** (e.g. **communications)**
- **Trade-off: gain from collaboration *vs* cost of collaboration**

  Vector metrics involved typically

➡ **Constrained Coalitional Games**

- **Example 1**: **Network Formation** -- Effects on Topology
- **Example 2**: **Collaborative robotics, communications**
- **Example 3**: **Web-based social networks and services**
- **Example 4**: **Groups of cancer tumor or virus cells**

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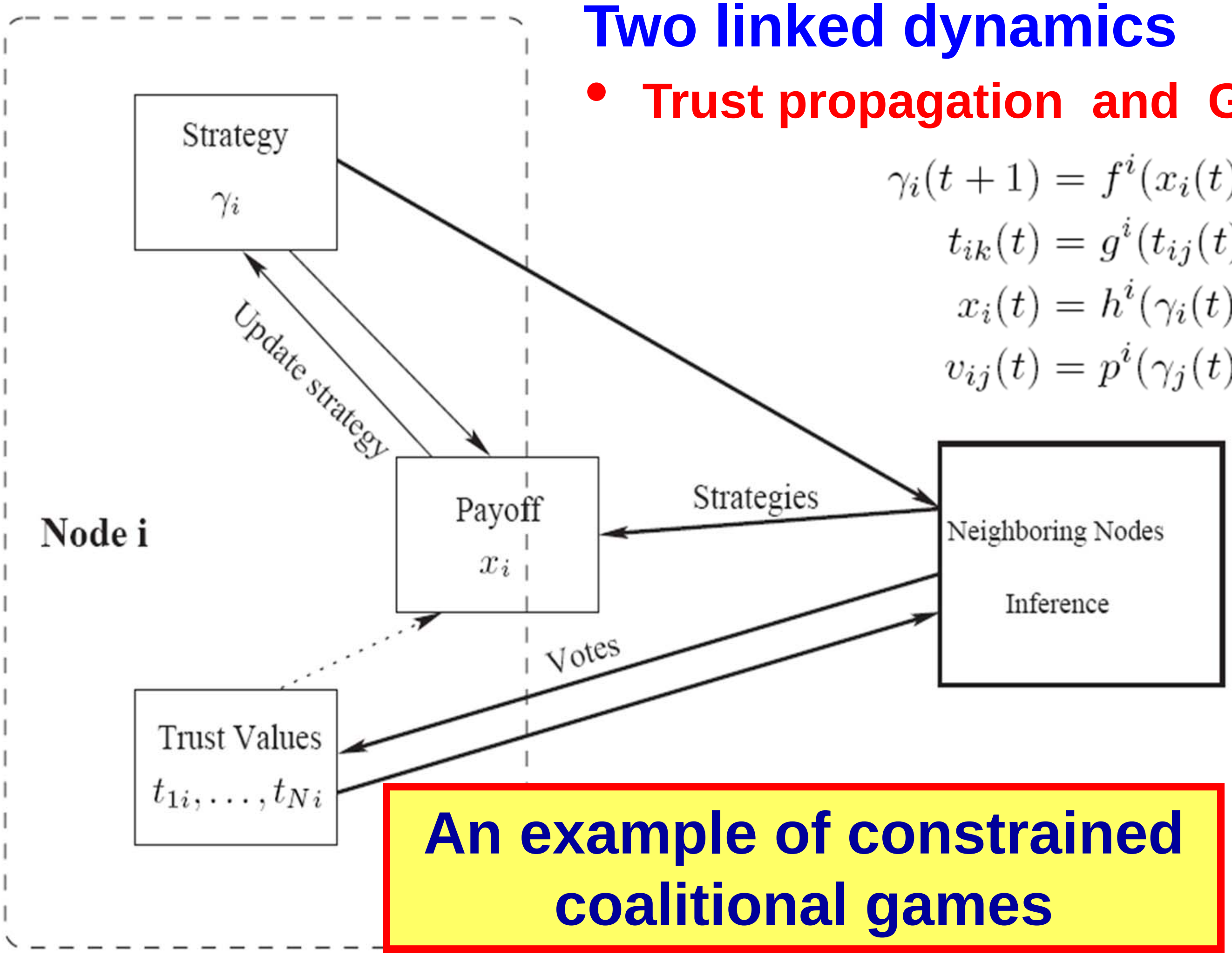
Dynamic Coalition Formation



Two linked dynamics

- **Trust propagation and Game evolution**

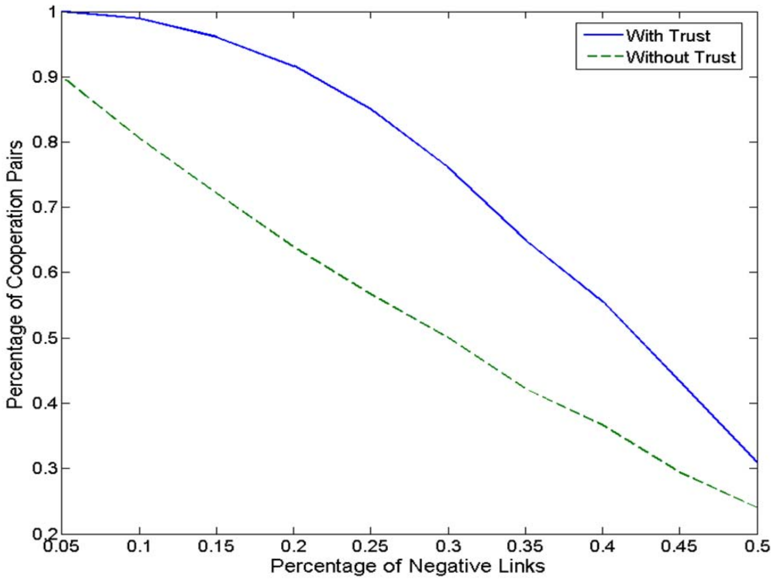
$$
\begin{aligned}
\gamma_i(t+1) &= f^i(x_i(t), \gamma_i(t), \gamma_j(t), t_{ij}(t)) \\
t_{ik}(t) &= g^i(t_{ij}(t), v_{jk}(t)) \quad \forall k \in N \\
x_i(t) &= h^i(\gamma_i(t), \gamma_j(t)) \\
v_{ij}(t) &= p^i(\gamma_j(t), t_{ji}(t))
\end{aligned}
$$

An example of constrained coalitional games

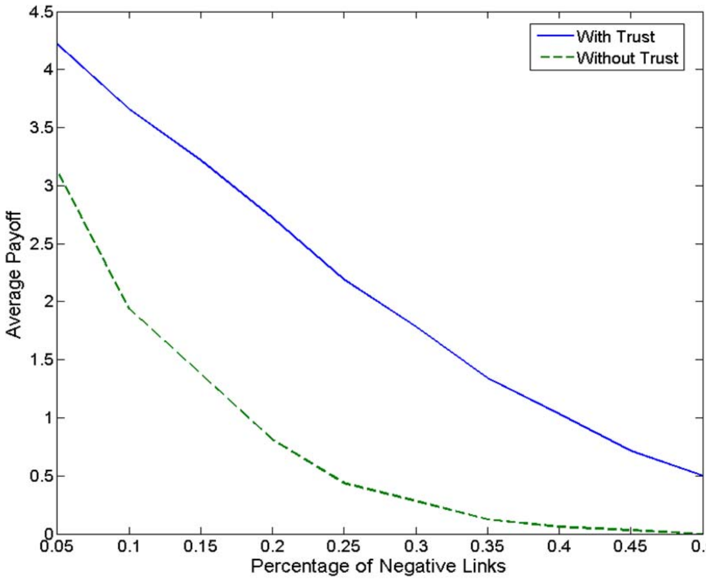
Stability of
dynamic
coalition
Nash equilibrium

Results of Game Evolution

- **Theorem**: $\forall i \in N_i$ and $x_i = \sum_{j\in N_i} J_{ij}$, there exists τ_0, such that for a reestablishing period $\tau > \tau_0$ *(Baras-Jiang 05, 09, 10)*
  - terated game converges to Nash equilibrium;
  - In the Nash equilibrium, all nodes cooperate with all their neighbors.
- Compare games with (without) trust mechanism, strategy update:



Percentage of cooperating pairs *vs* negative links

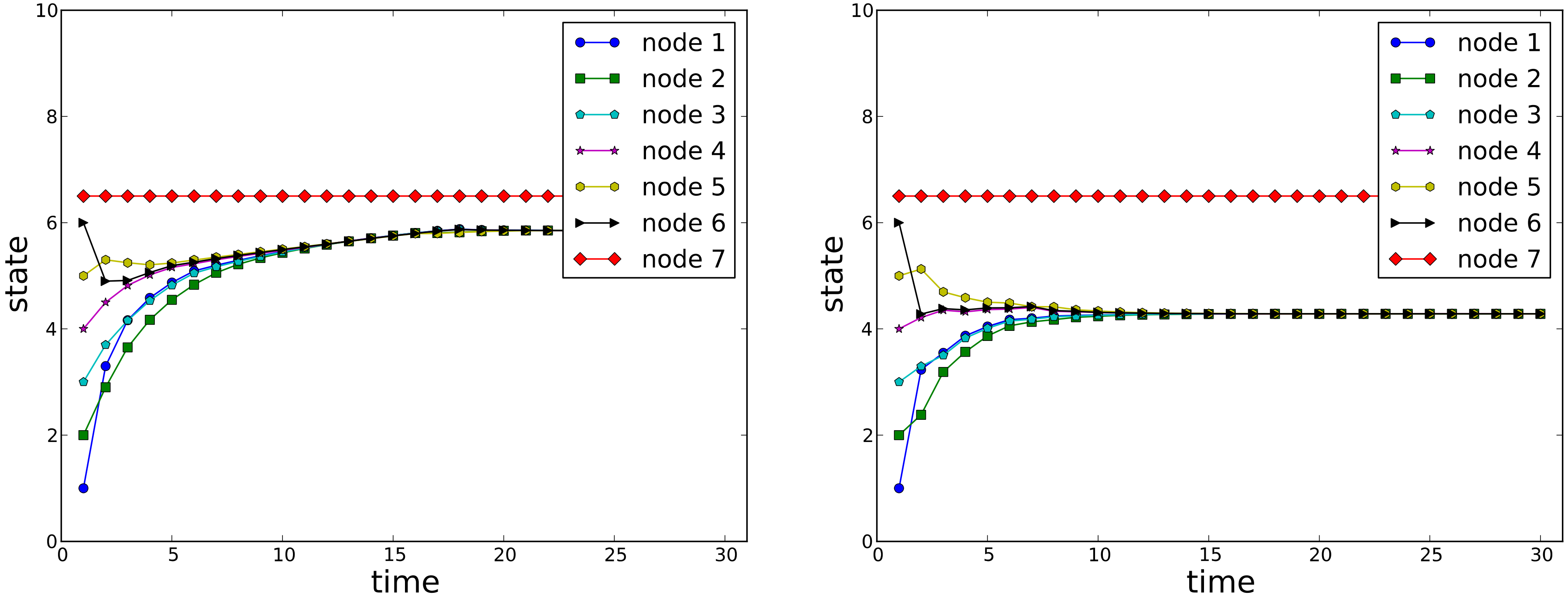


Average payoffs *vs* negative links

Consensus with Adversaries

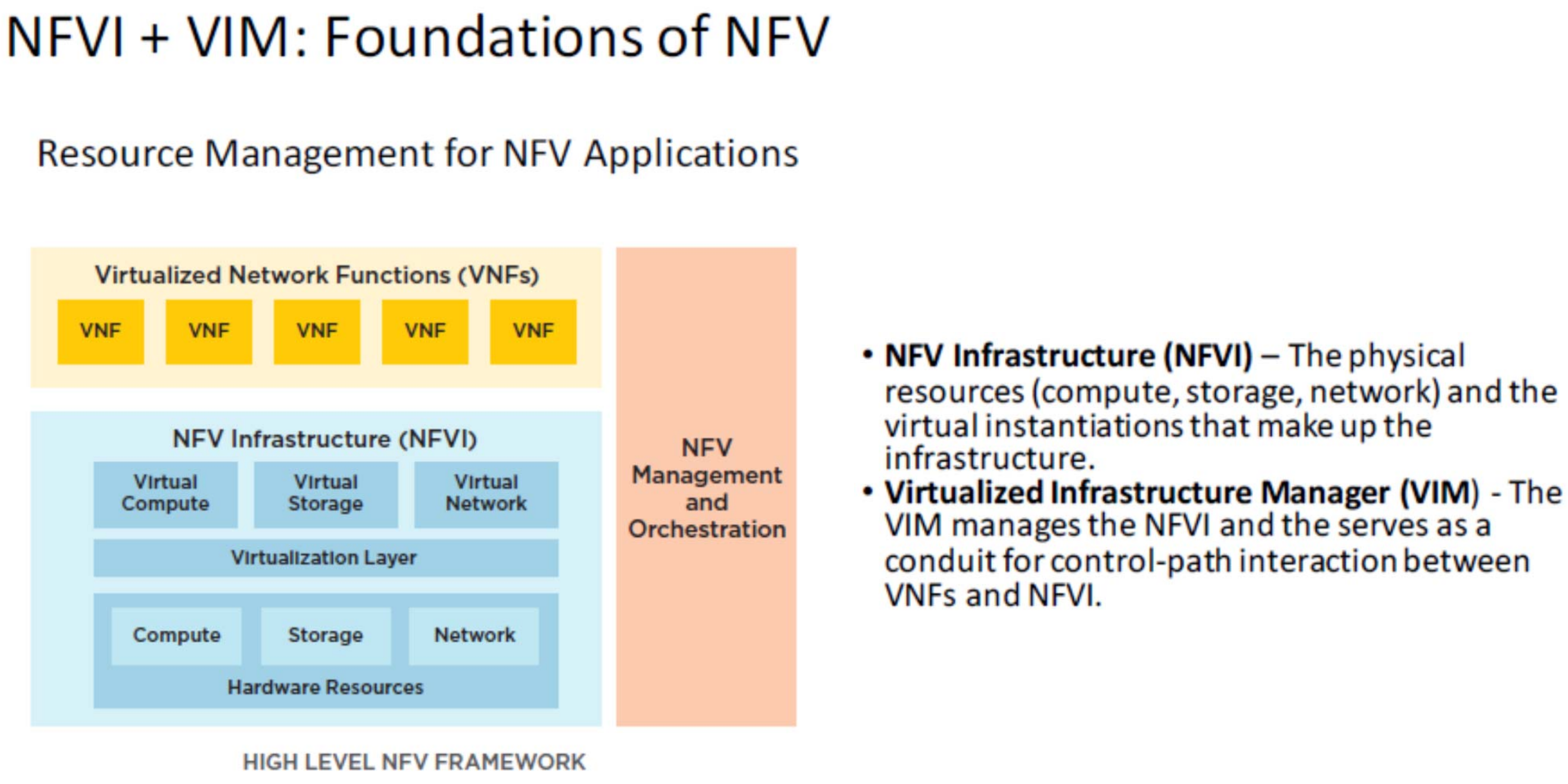
- Solve the problem via detecting adversaries in networks of low connectivity.
- We integrate a trust evaluation mechanism into our consensus algorithm, and propose a two-layer hierarchical framework.
    - Trust is established via headers (aka trusted nodes)
    - The top layer is a super-step running a **vectorized consensus algorithm**
    - The bottom layer is a sub-step executing our **parallel vectorized voting scheme**.
    - Information is exchanged between the two layers – they **collaborate**
- We demonstrate via examples solvable by our approach but not otherwise
- We also derive an upper bound on the number of adversaries that our algorithm can resist in each super-step

Simulations



Adversary outputs constant message. Figure on the left has no trust propagation. Figure on the right has trust propagation.

Conquering Heterogeneity -- NFVI & VIM



NFVI + VIM: Foundations of NFV

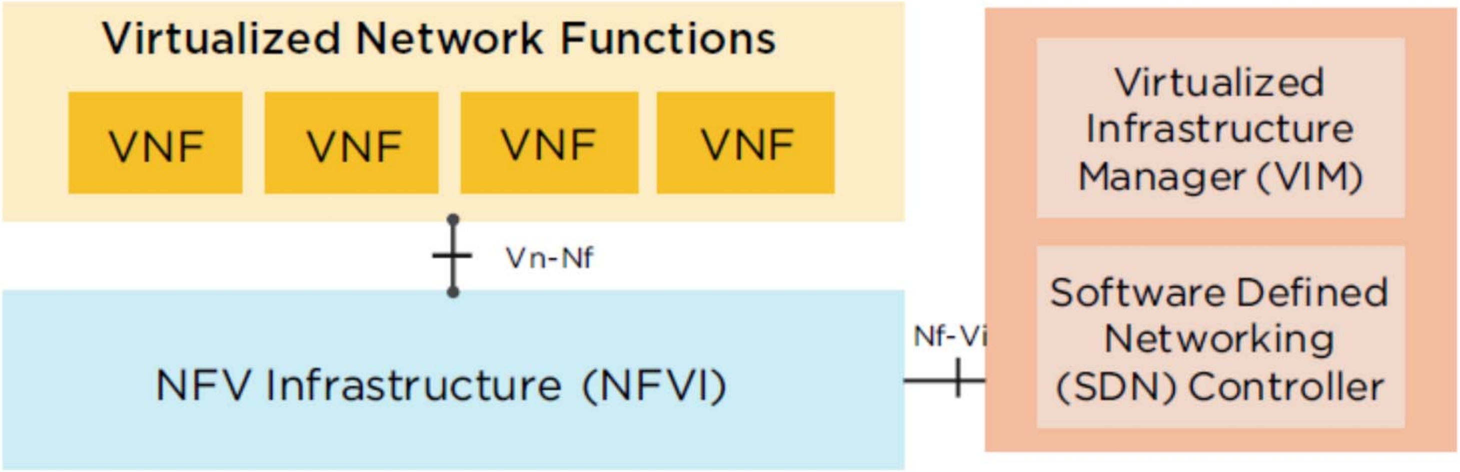
Resource Management for NFV Applications

HIGH LEVEL NFV FRAMEWORK

- **NFV Infrastructure (NFVI)** – The physical resources (compute, storage, network) and the virtual instantiations that make up the infrastructure.
- **Virtualized Infrastructure Manager (VIM)** - The VIM manages the NFVI and the serves as a conduit for control-path interaction between VNFs and NFVI.

NFVI & VIM

VIM + NFVI



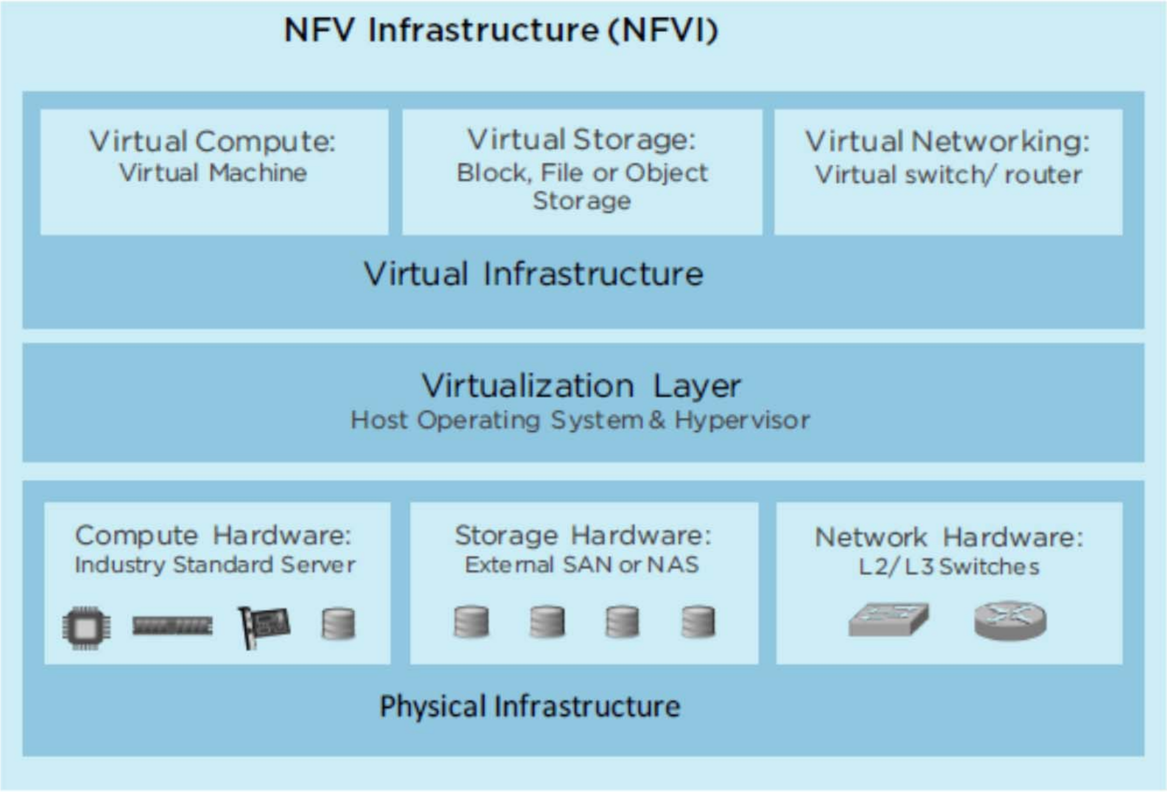
VIM's role in resource management is more closely tied with the NFVI infrastructure. Similarly SDN Controller is key to resource management of the networking layer (virtual or physical)

NFVI

NFVI – Not a Monolithic Component

Key Sub-Components Play Important Roles

Strong virtualization layer, with important properties – hardware compatibility, I/O performance, robust and mature virtual capabilities are critical to a strong foundation



NFV Infrastructure (NFVI)

Virtual Compute:
Virtual Machine

Virtual Storage:
Block, File or Object Storage

Virtual Networking:
Virtual switch/ router

Virtual Infrastructure

Virtualization Layer
Host Operating System & Hypervisor

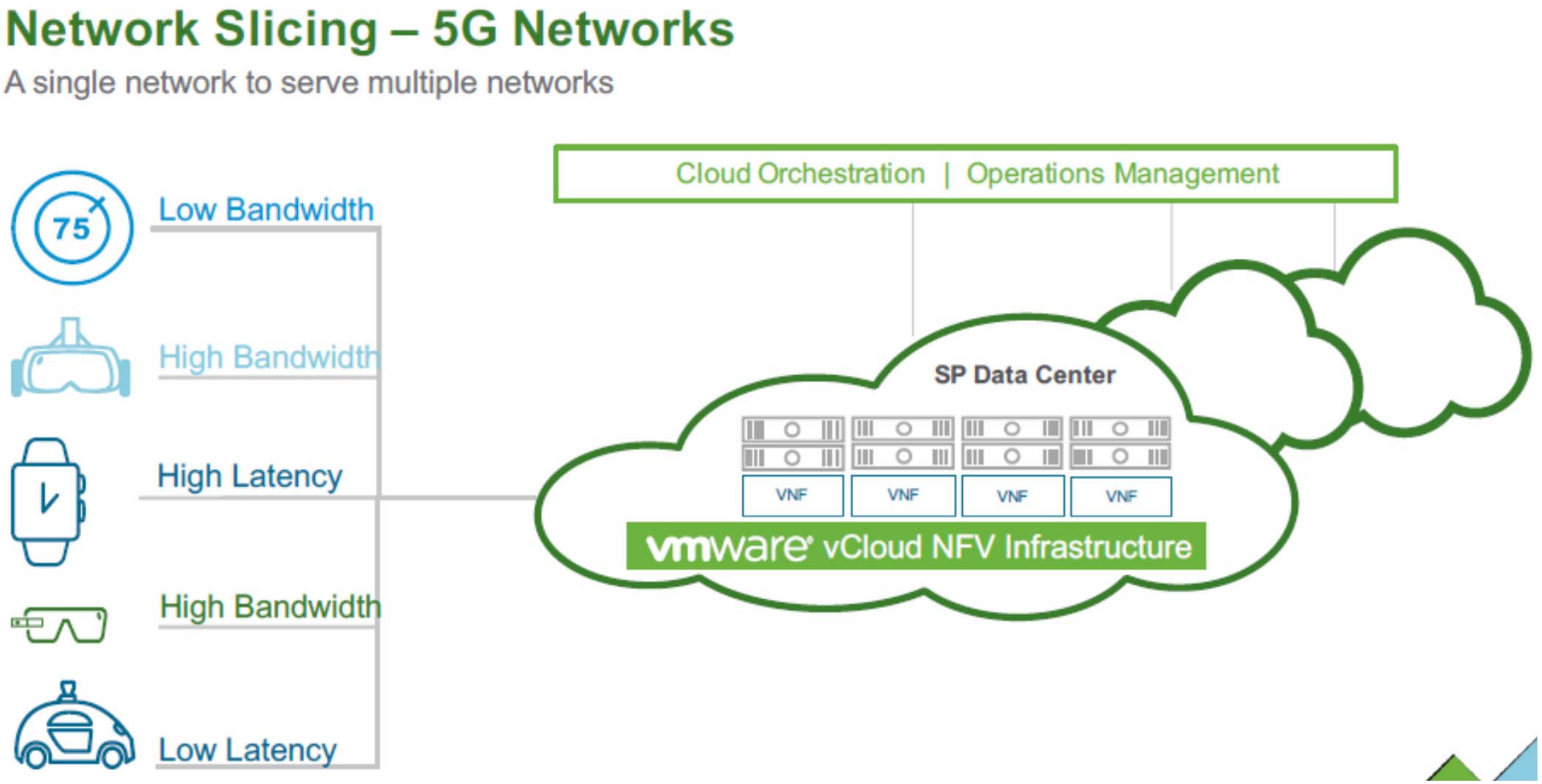
Compute Hardware:
Industry Standard Server

Storage Hardware:
External SAN or NAS

Network Hardware:
L2/ L3 Switches

Physical Infrastructure

Network Slicing

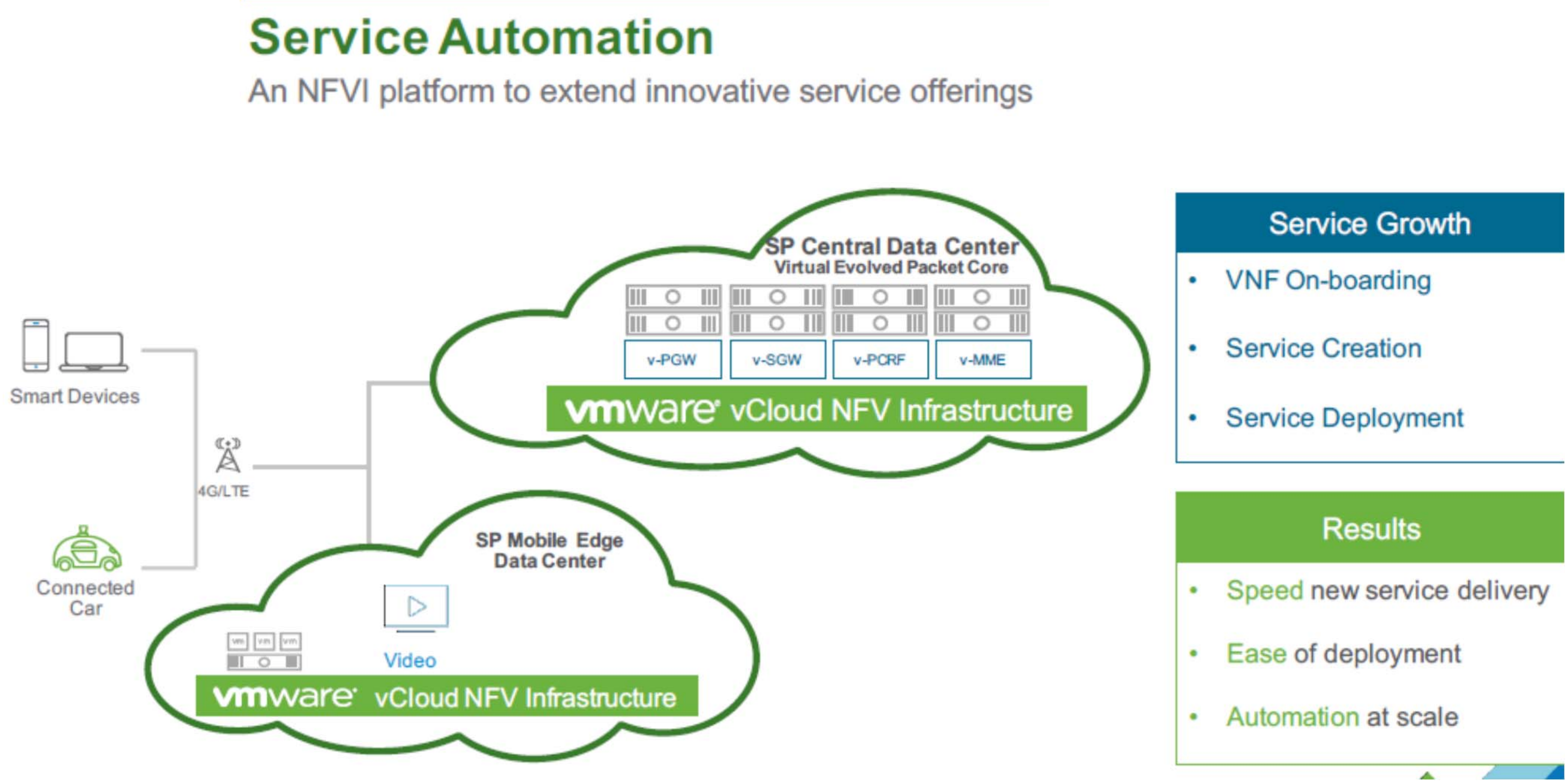


Network Slicing – 5G Networks

A single network to serve multiple networks

VMWARE

Service Automation



Service Automation

An NFVI platform to extend innovative service offerings

Service Growth

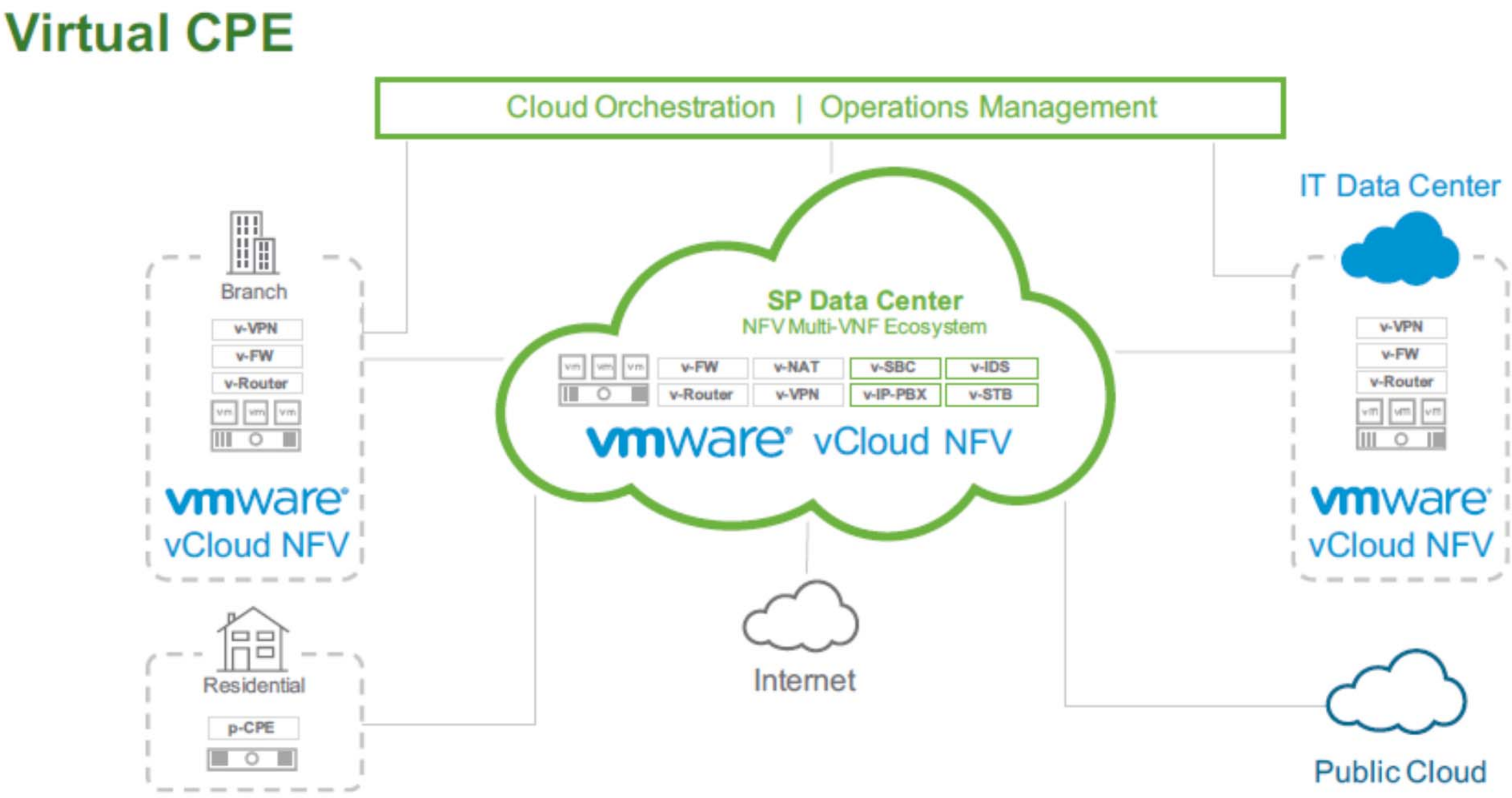
- VNF On-boarding
- Service Creation
- Service Deployment

Results

- Speed new service delivery
- Ease of deployment
- Automation at scale

VMWARE

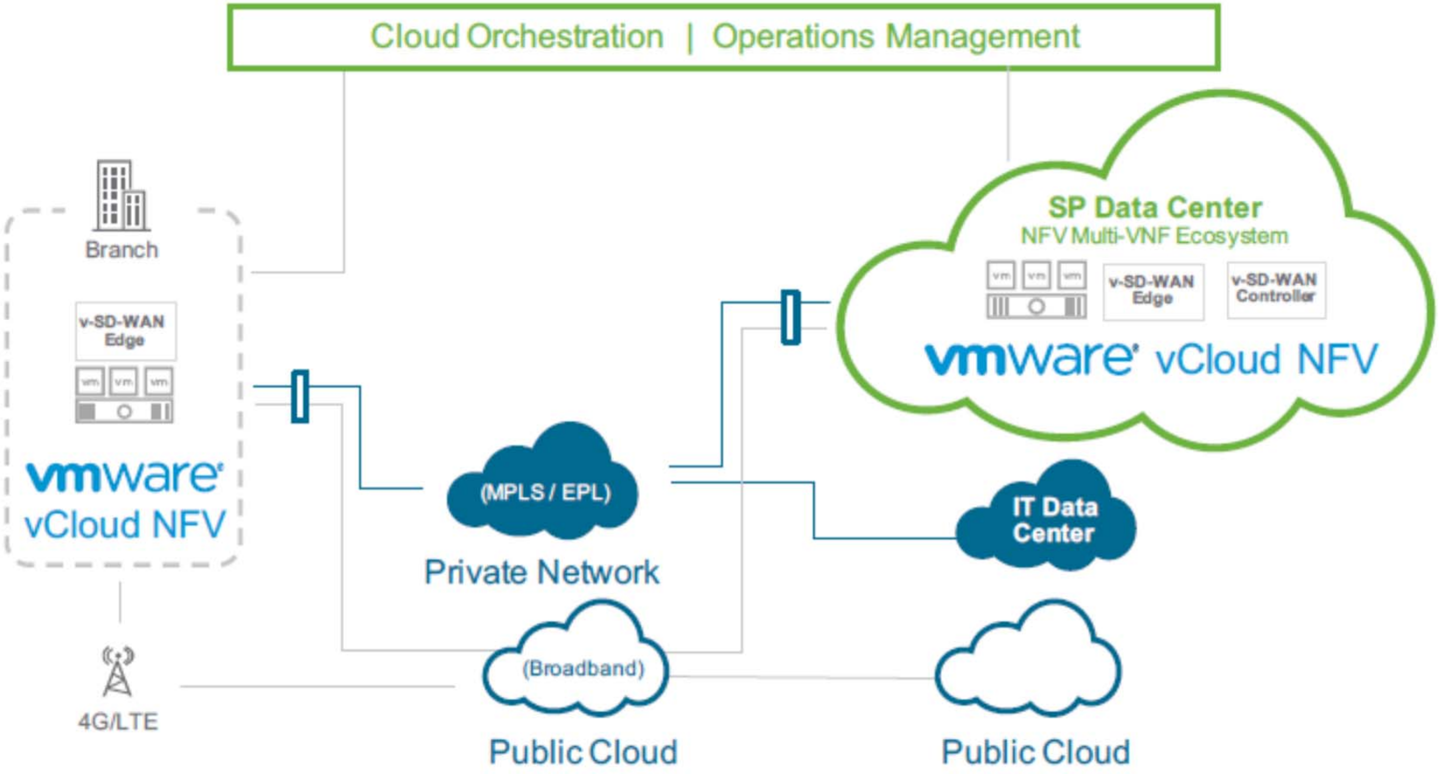
Use Case – Virtual CPE



VMWARE

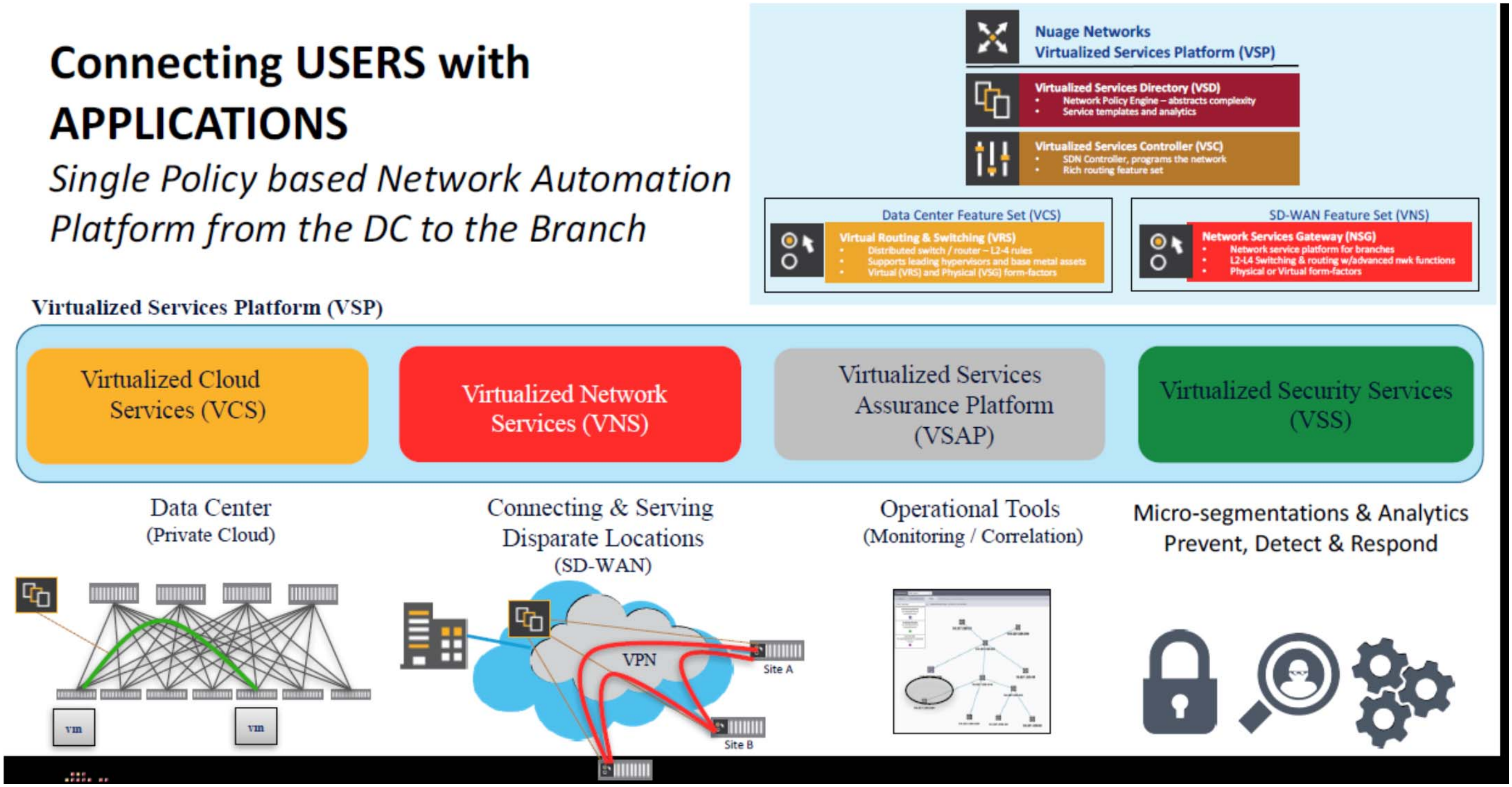
Use Case -- SDWAN

SD-WAN



VMWARE

Virtualizing the Network – Network as a Service (NaaS)?



Connecting USERS with APPLICATIONS

Single Policy based Network Automation Platform from the DC to the Branch

Nuage Networks Virtualized Services Platform (VSP)

Virtualized Services Directory (VSD)
- Network Policy Engine – abstracts complexity
- Service templates and analytics

Virtualized Services Controller (VSC)
- SDN Controller, programs the network
- Rich routing feature set

Data Center Feature Set (VCS)

Virtual Routing & Switching (VRS)
- Distributed switch / router – L2-4 rules
- Supports leading hypervisors and base metal assets
- Virtual (VRS) and Physical (VSG) form-factors

SD-WAN Feature Set (VNS)

Network Services Gateway (NSG)
- Network service platform for branches
- L2-L4 Switching & routing w/advanced nwk functions
- Physical or Virtual form-factors

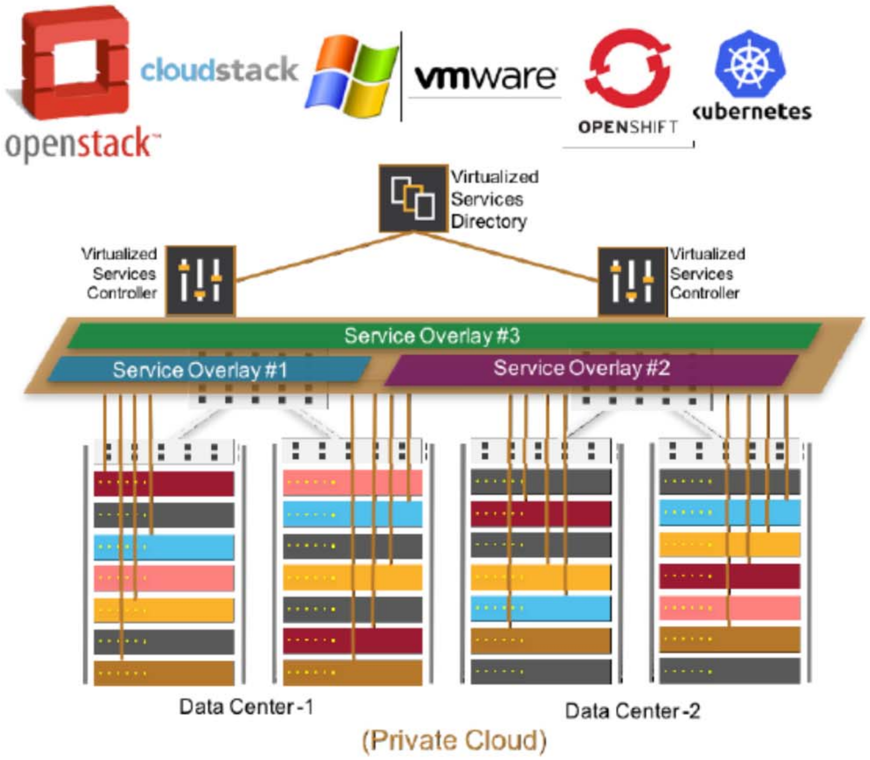
Virtualized Services Platform (VSP)

Virtualized Cloud Services (VCS)	Virtualized Network Services (VNS)	Virtualized Services Assurance Platform (VSAP)	Virtualized Security Services (VSS)
Data Center (Private Cloud)	Connecting & Serving Disparate Locations (SD-WAN)	Operational Tools (Monitoring / Correlation)	Micro-segmentations & Analytics Prevent, Detect & Respond

Ericsson

Virtualizing the Network

Final Picture : Datacenter to Cloud



Total Flexibility

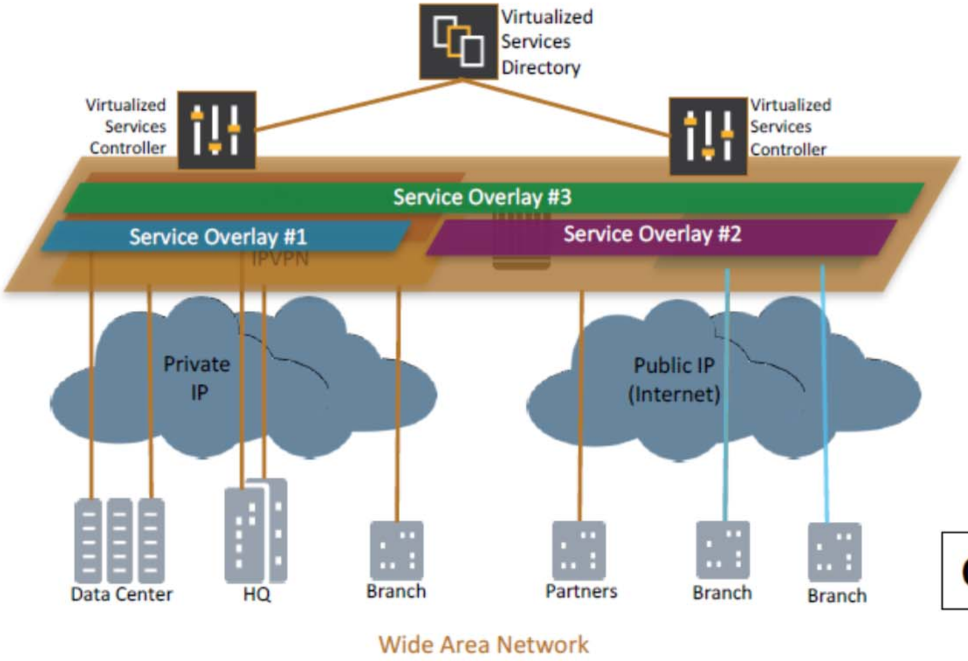
- Any Workload
- Any Hypervisor
- Any Orchestration
- Any Datacenter
- Any Network underlay
- Any Combination

Consistent Automation and Total control

Ericsson

Virtualizing the Network

SD-WAN: Over Private IP and Internet



Total Flexibility

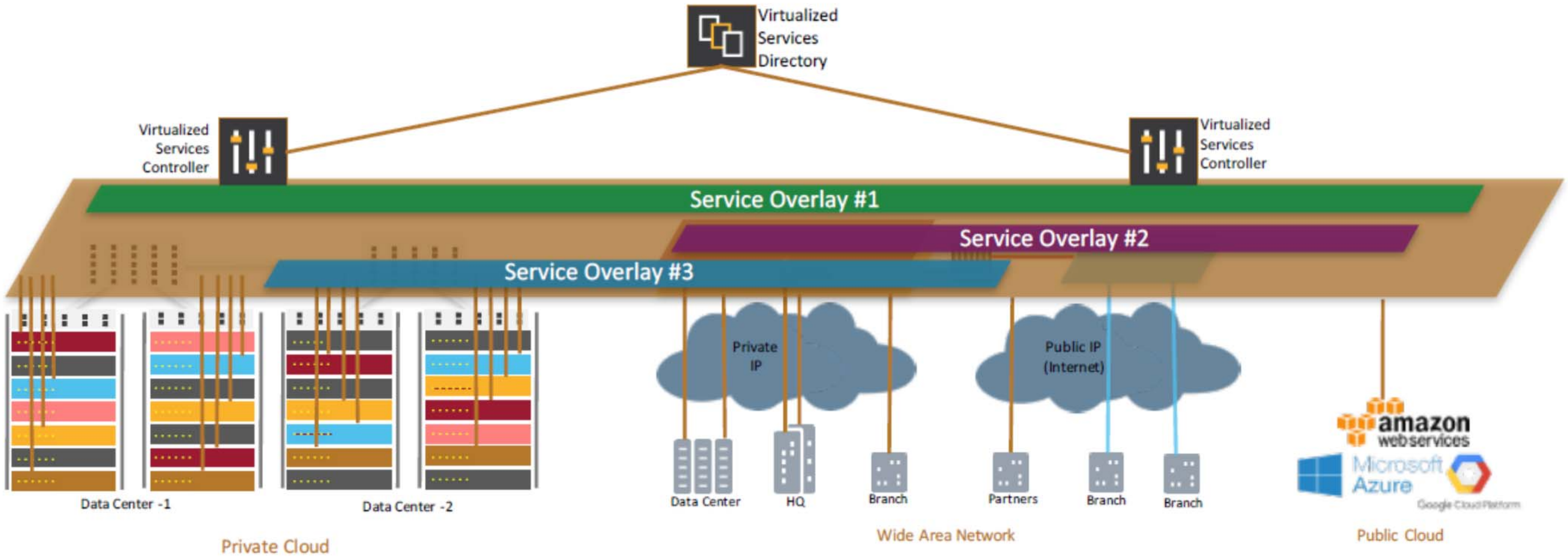
- Any Network
- Any Location
- Any Service ; L2 or L3
- Any Uplink
- Any X86 Platform
- All combinations

Consistent Automation and Total control

Ericsson

Virtualizing the Network

Final Destination: Automated Networks without Borders



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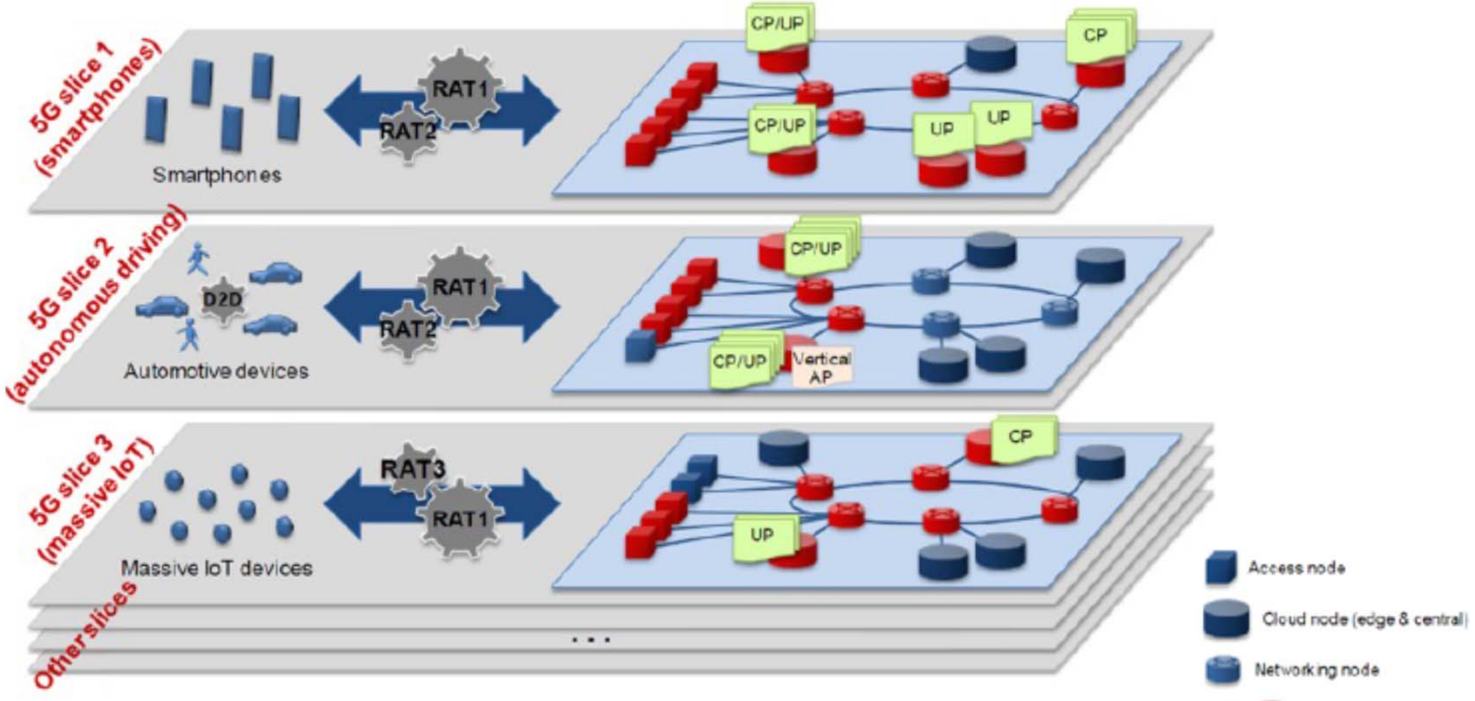
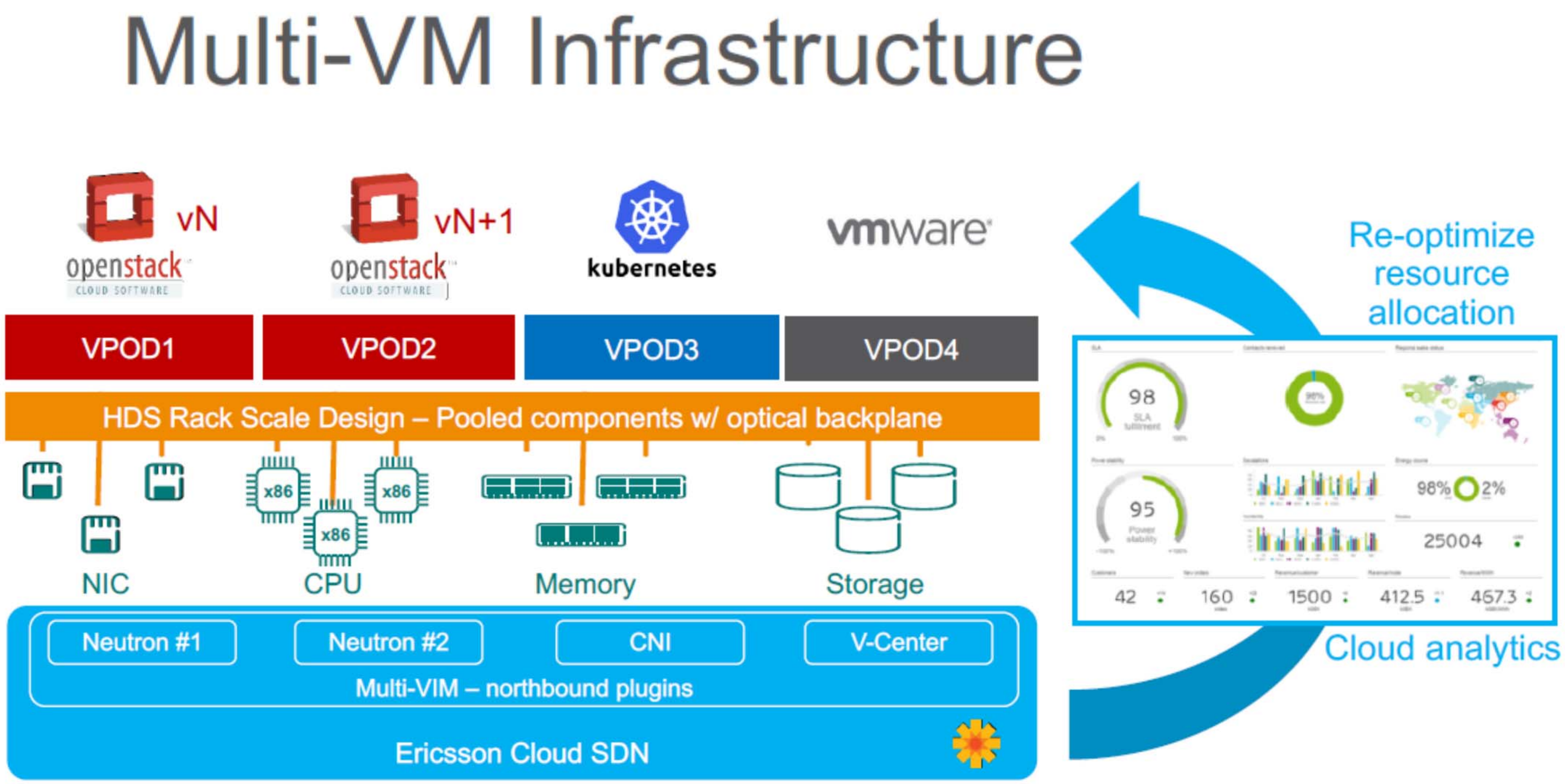
Application Delivery – Network Slicing



Network slicing and application delivery.

Ericsson

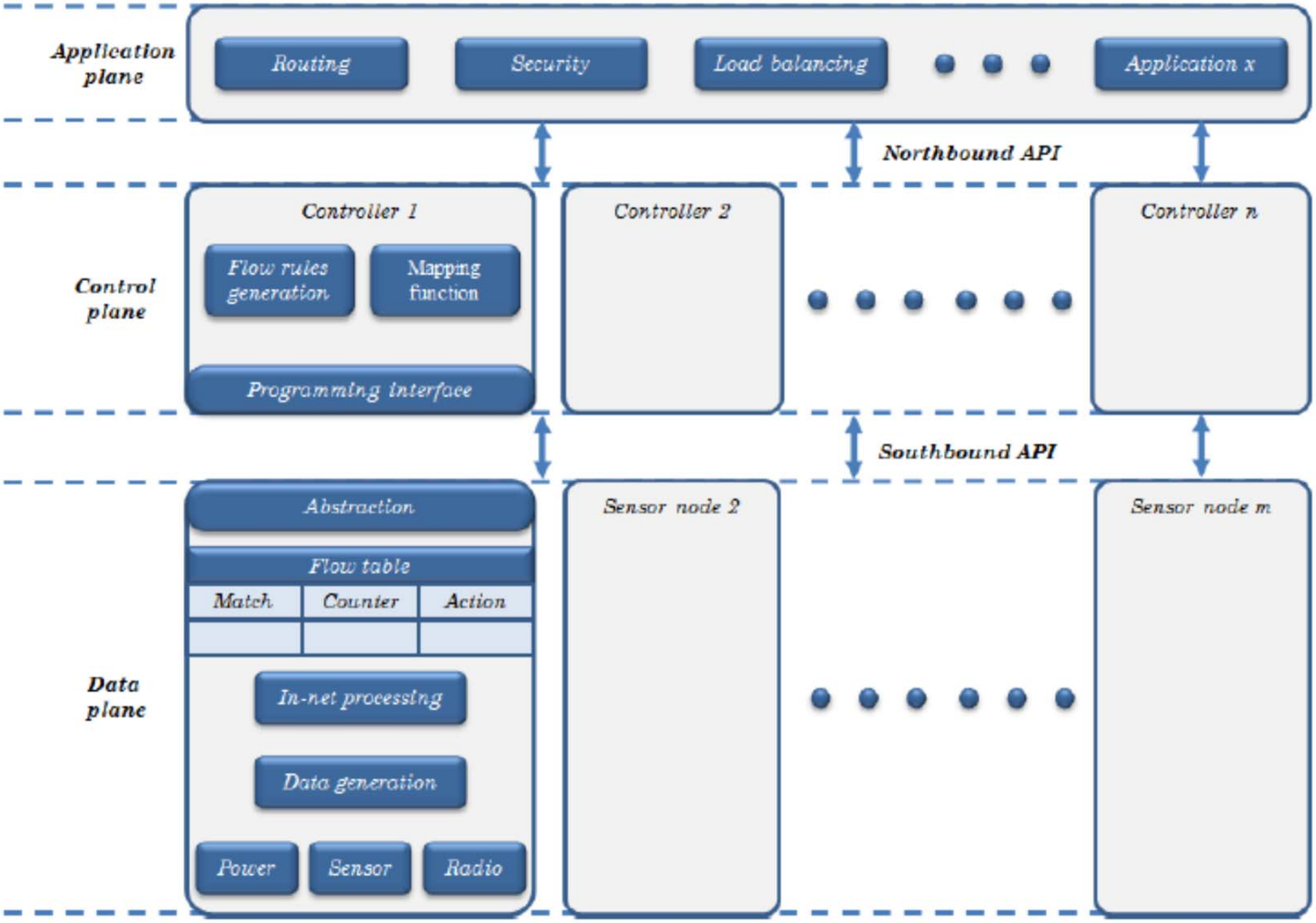
Supporting Multiple Virtualizations



Multi-VM Infrastructure

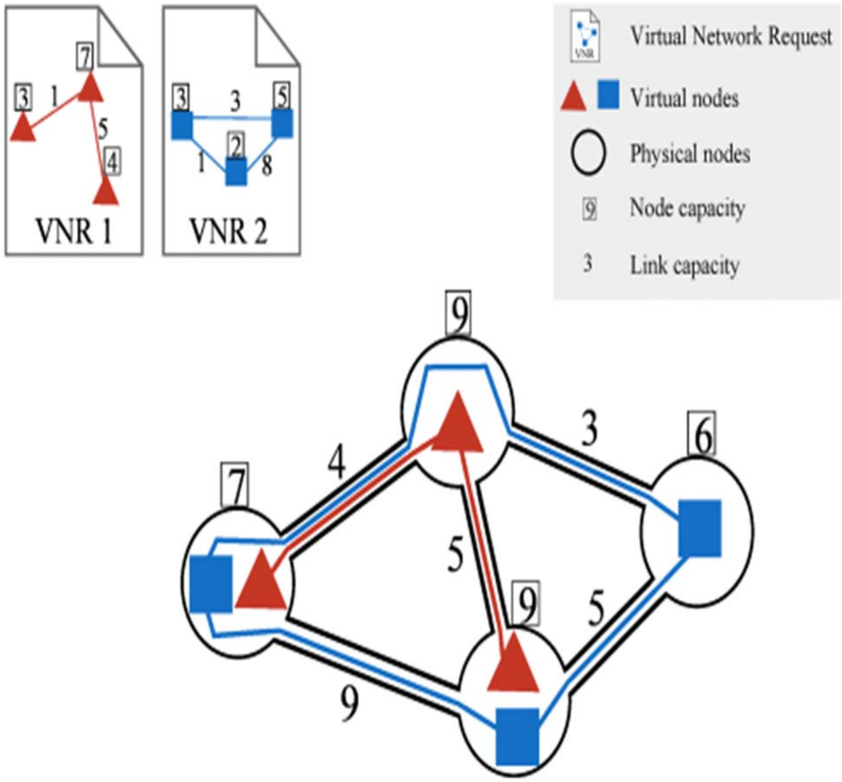
Ericsson

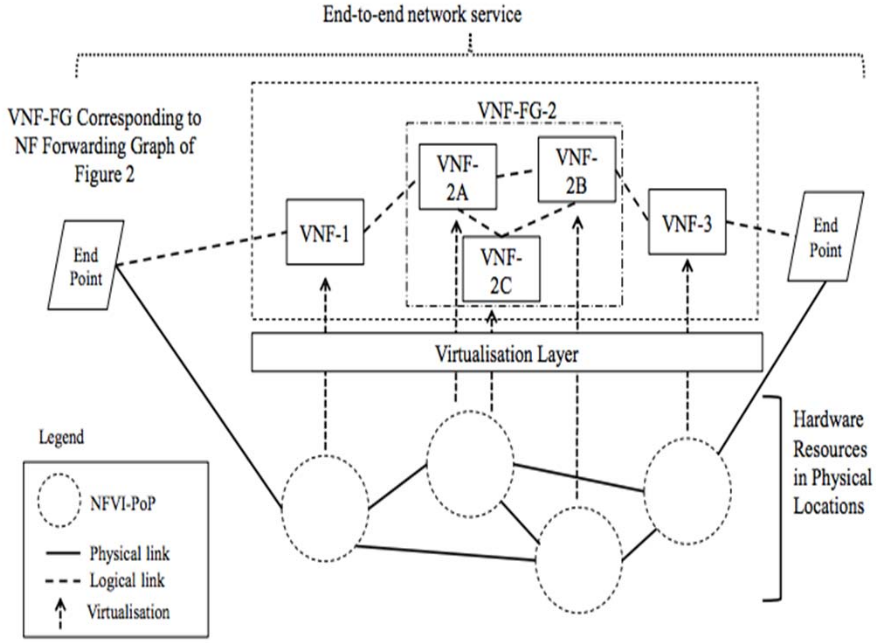
Basic SDWN Architecture



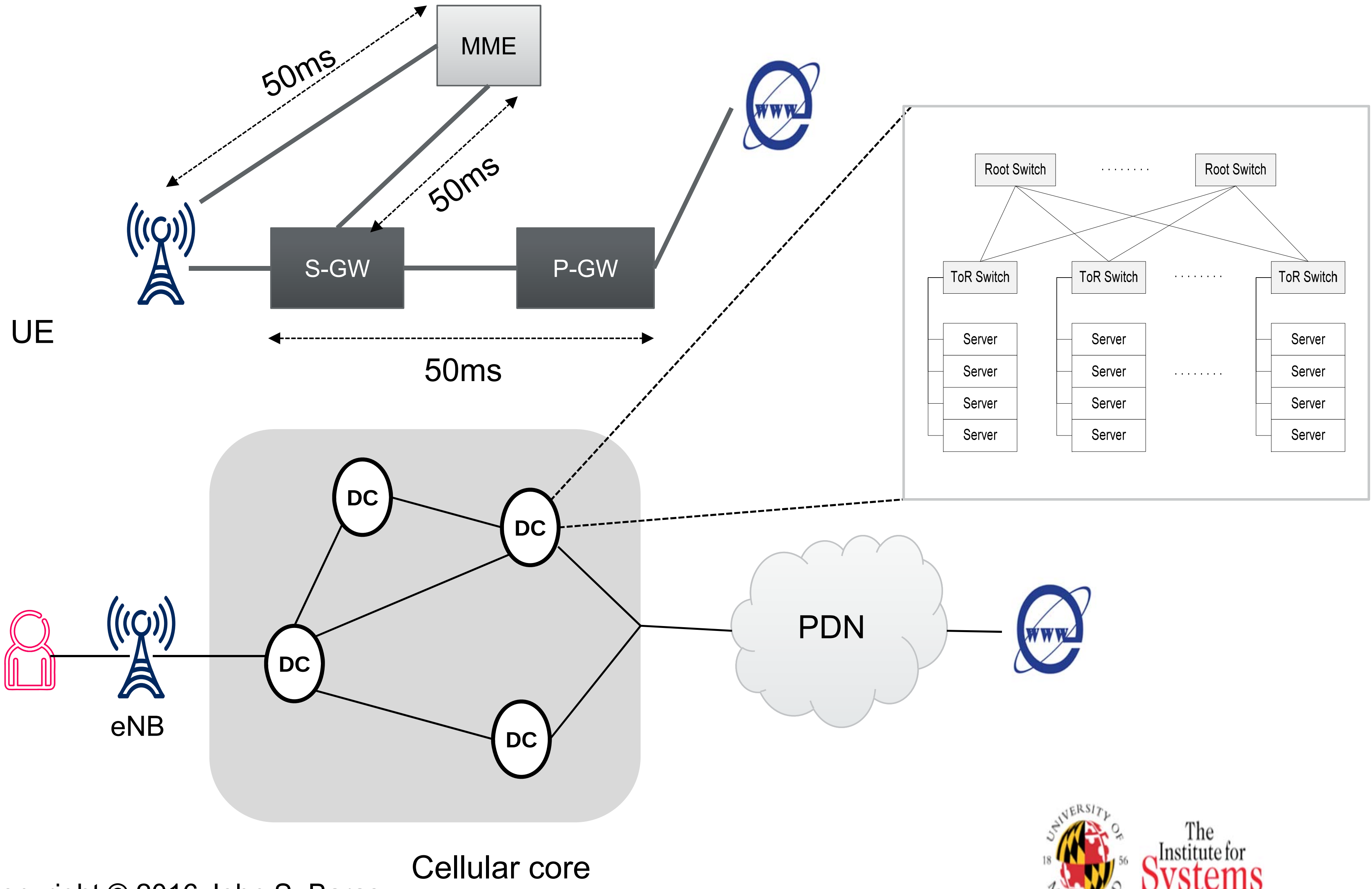
Different functionalities distributed along three planes

Resource Allocation in Virtualized Environments

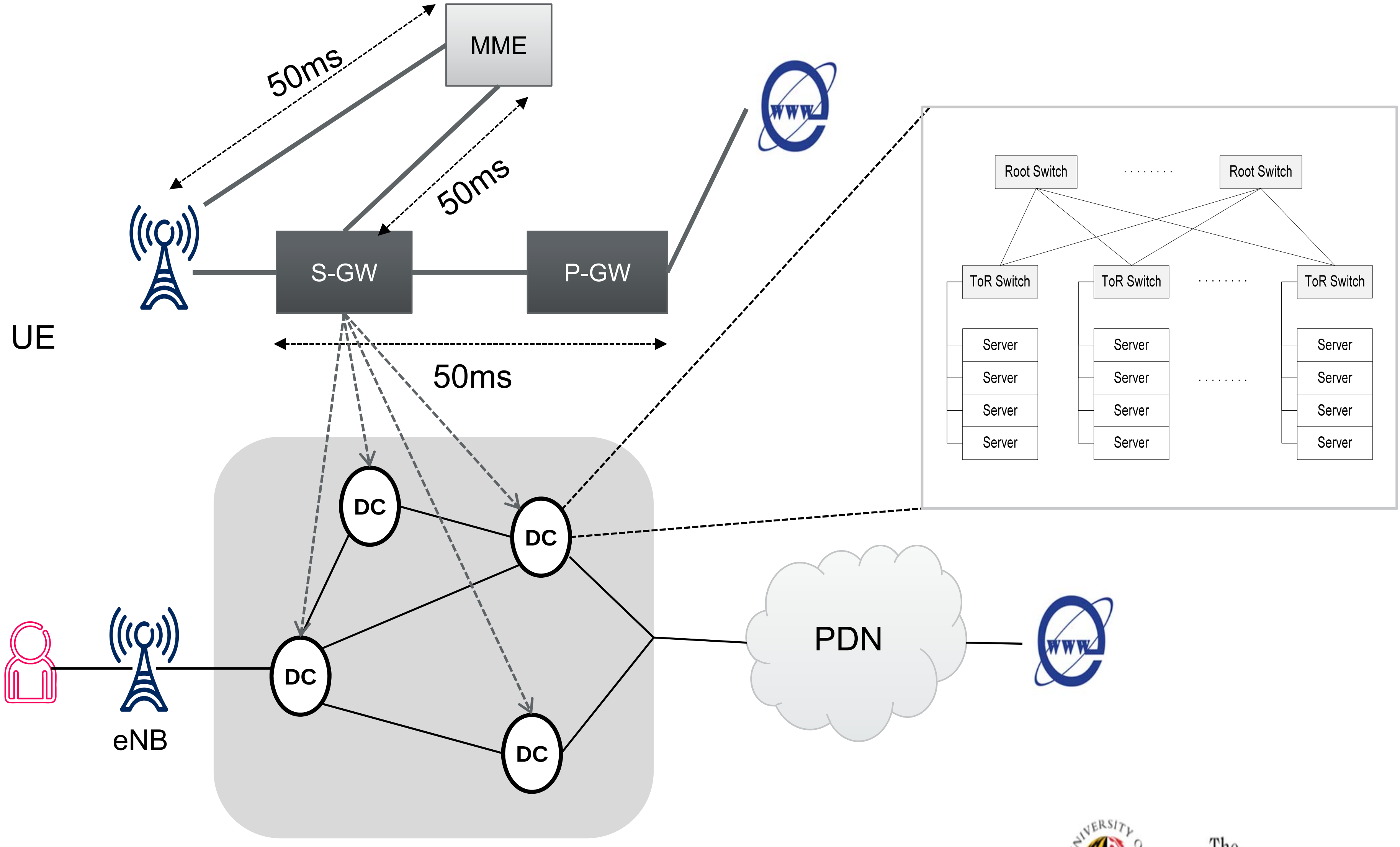




VEPC - NF PLACEMENT

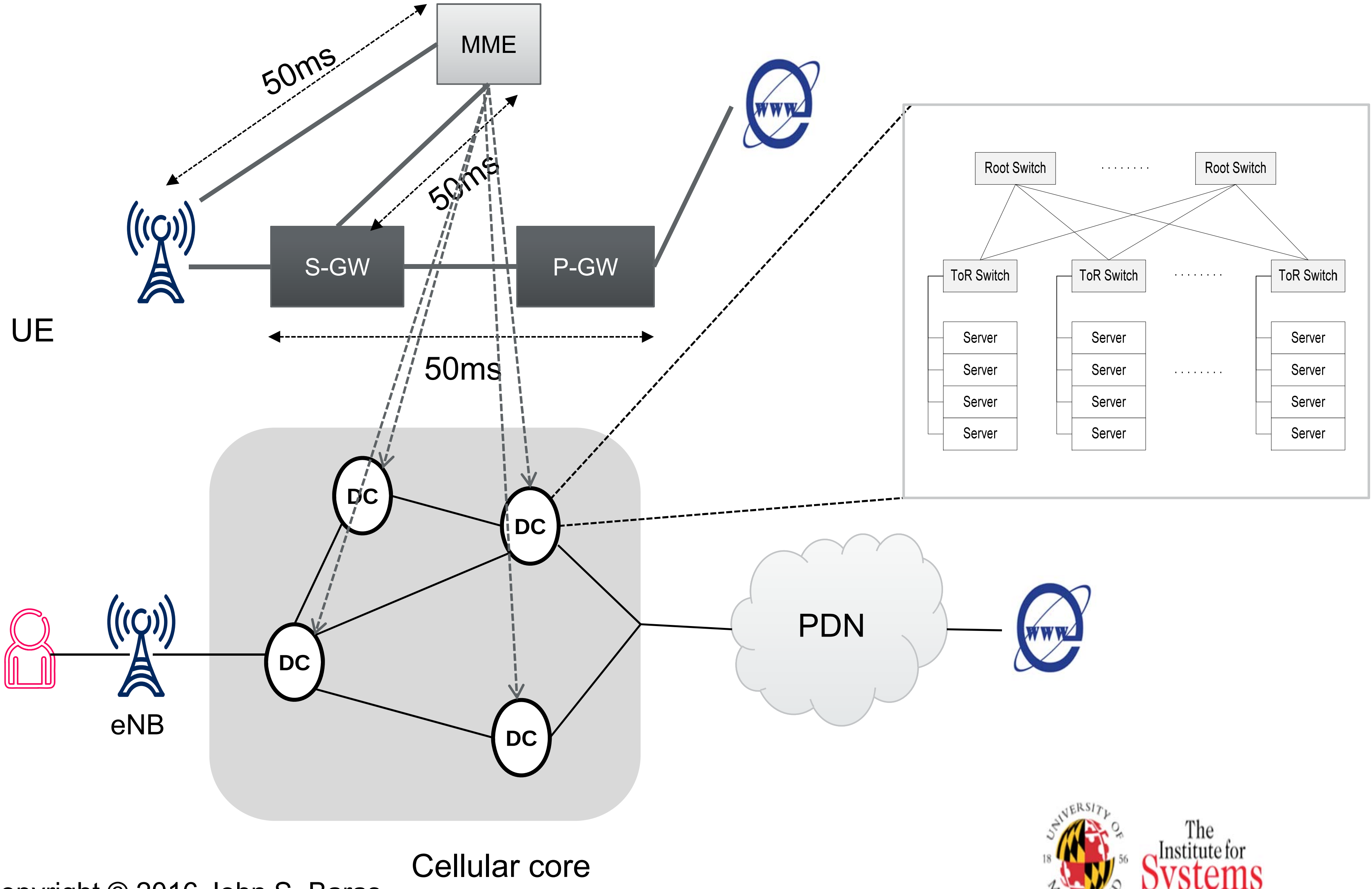


VEPC - NF PLACEMENT

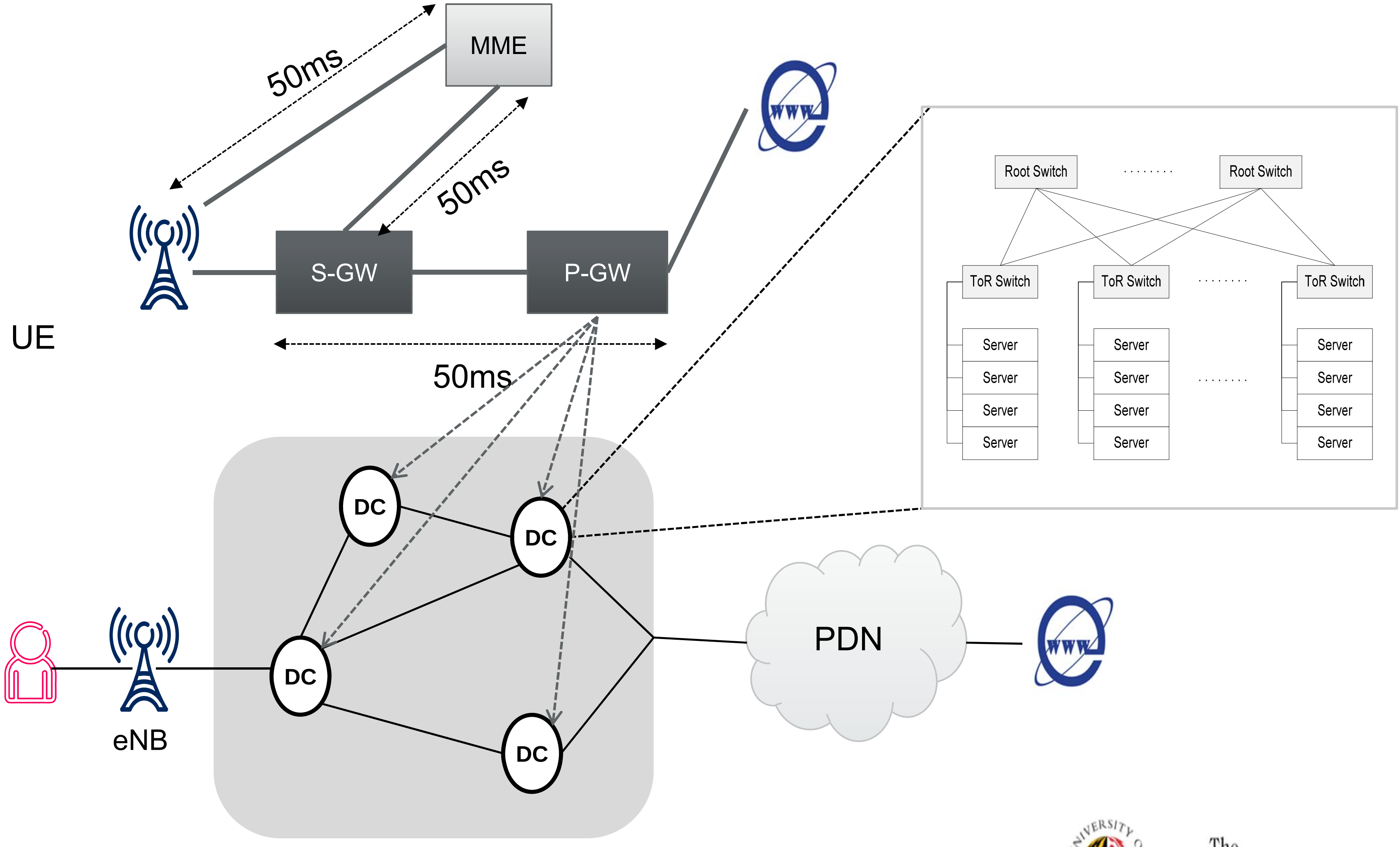


Cellular core

VEPC - NF PLACEMENT



VEPC - NF PLACEMENT



Cellular core

APPROACH

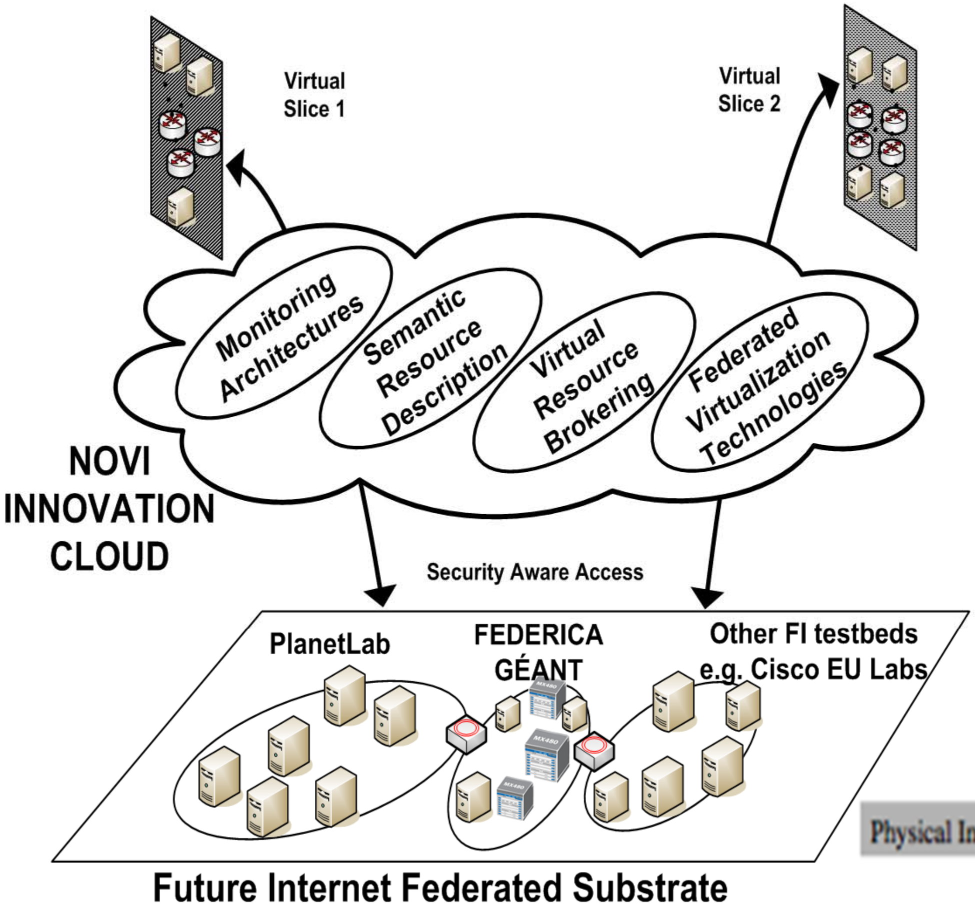
- Approach:
  - Single-stage solver
  - Cellular operator has network-wide view
- Main objective:
  - Load balancing across the cellular core
  - DCs close to eNBs are under heavy load (KLEIN [**SOSR 2016**])
- Assumptions:
  - Single S-GW and MME per UE (3GPP)

NF placement solvers:

Mixed Integer Linear Programming (MILP) formulation
- ✓ Optimality
- ✗ High time complexity

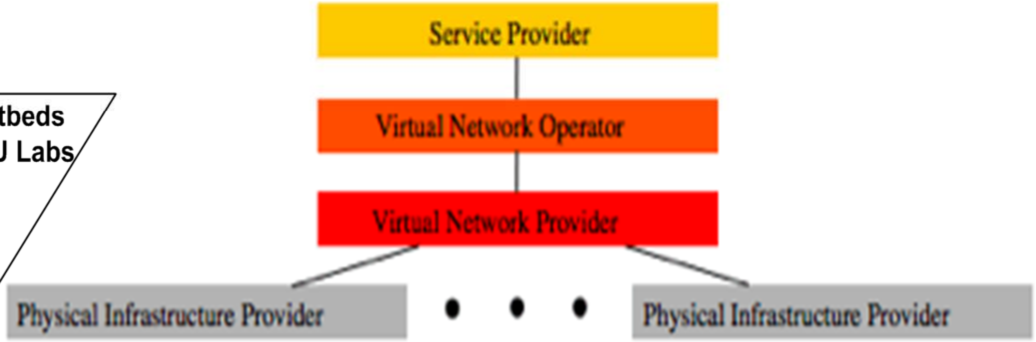
Linear Programming (LP) formulation
- ✓ Lower time complexity
- ✗ Optimality gap

MOTIVATION

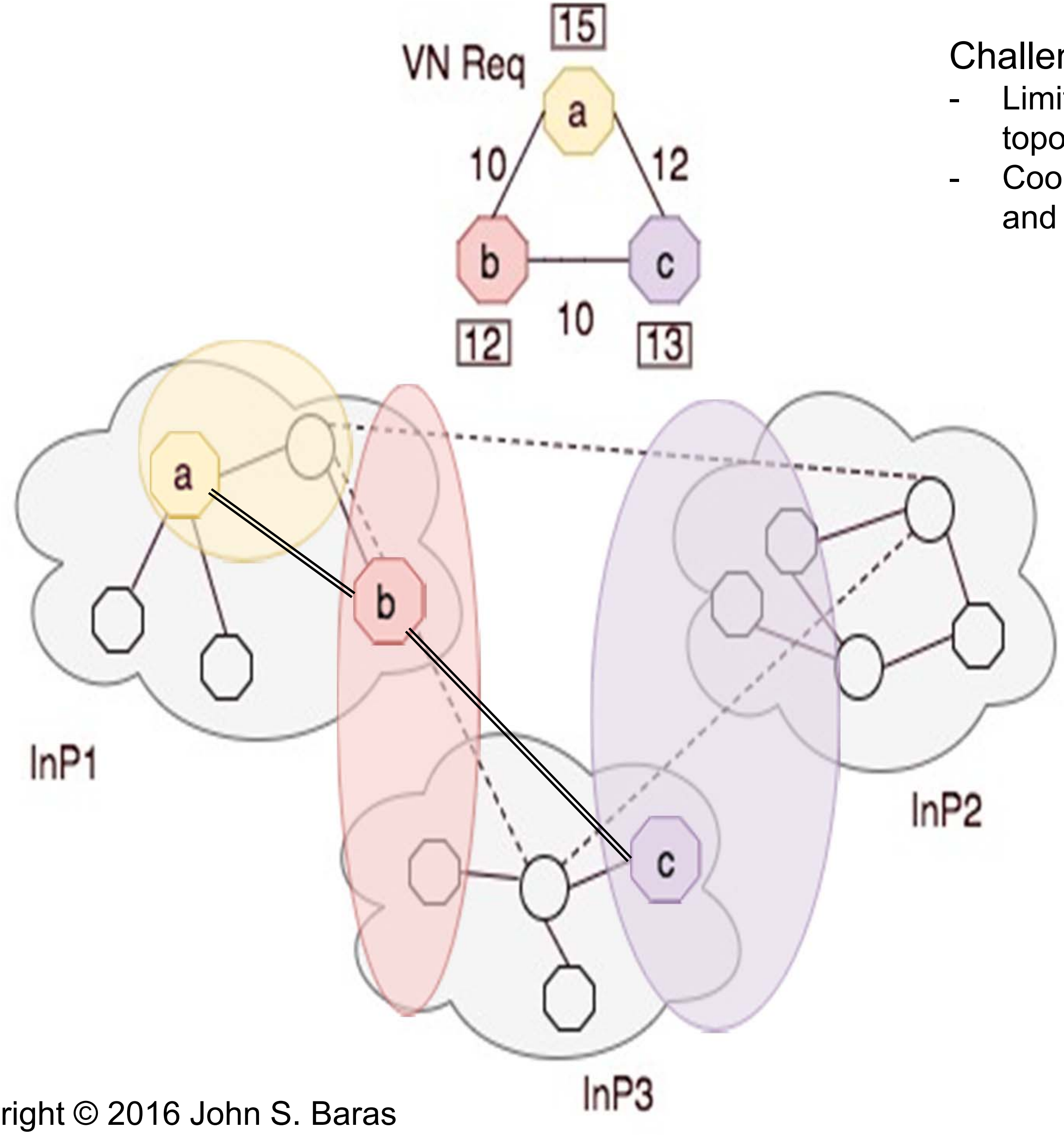


Multi-tenant network virtualization environments

- Sliceable infrastructures (e.g., FI testbeds)
- DCs



INTER-INP VIRTUAL NETWORK EMBEDDING

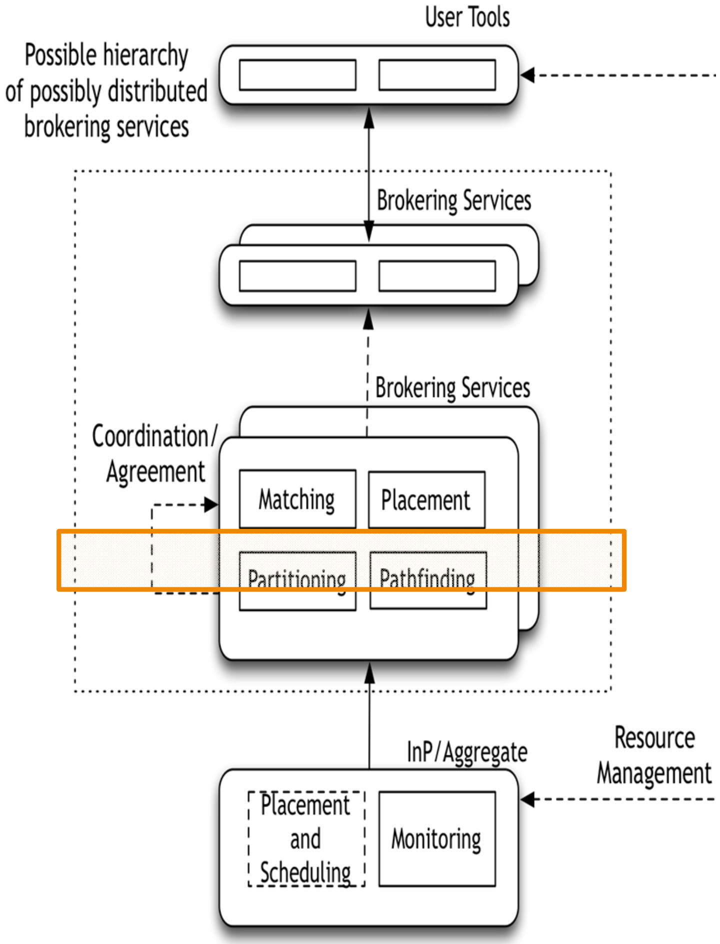


Challenges:
- Limited knowledge of substrate topology/resources
- Coordination between tenants tools and InPs

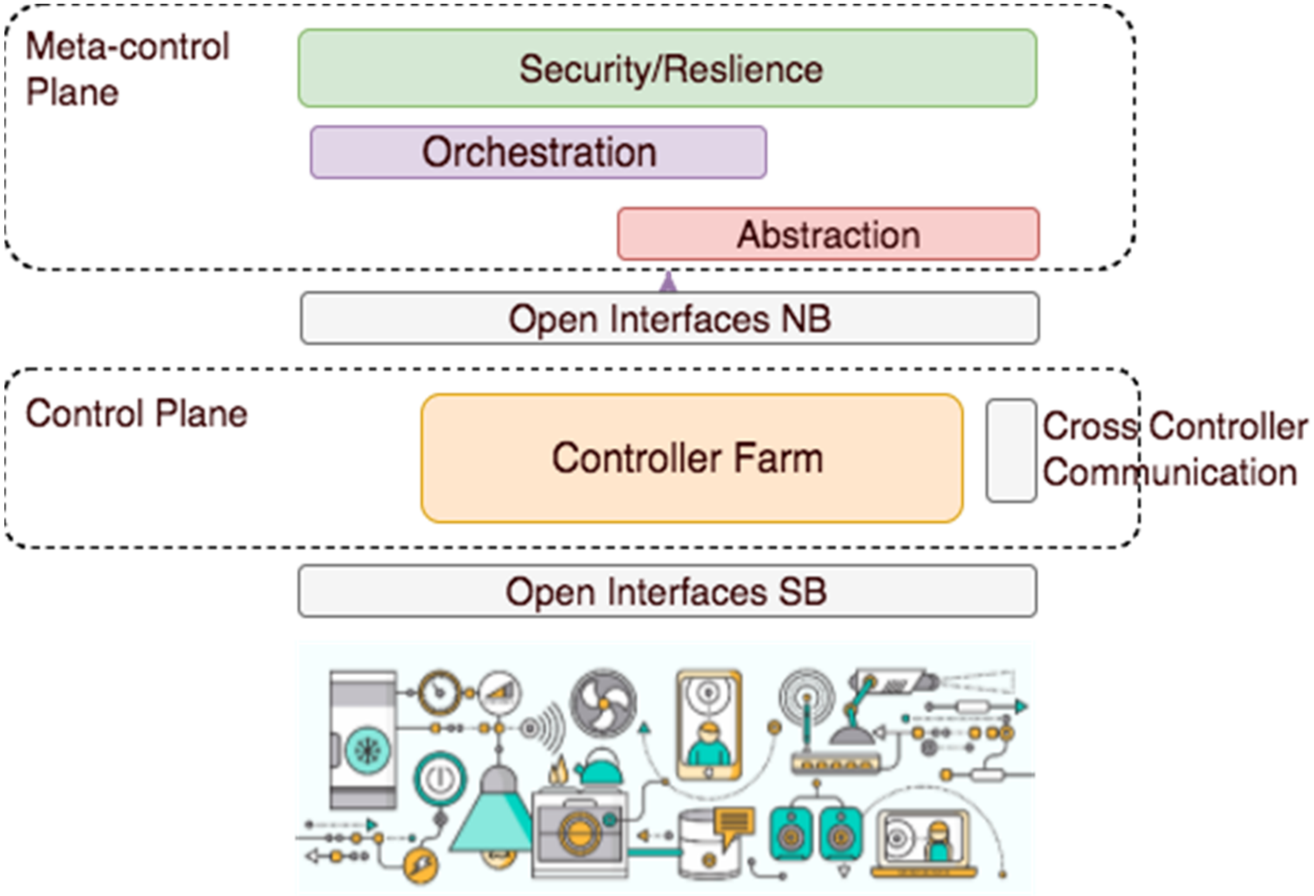
APPROACH

- Bird's eye view:
  - Two-stage solver
    1. Request Partitioning
       - Abstract view of substrate resources (multiple InPs)
    2. VN Embedding
       - InP has network-wide view of own resources
  - Establishing Interconnection

- Main objective:
  - Minimize embedding cost
  - Load balancing



SOFTWARE DEFINED CPS ARCHITECTURE



Meta-control Plane

Security/Reslience

Orchestration

Abstraction

Open Interfaces NB

Control Plane

Controller Farm

Cross Controller Communication

Open Interfaces SB

Summary and Conclusions

- Net-CPS model – dynamic multiple multigraphs
- Effects of topology on distributed algorithm performance
- Fundamental tradeoff between the benefit from collaboration and the cost for collaboration – constrained coalitional games
- IoT and 5G – the enablers
- SDWN and NFV key methods to address heterogeneity
- Extending UMD Model-Based Systems Engineering (MBSE) Framework to include Humans
- Challenges

Thank you!

baras@isr.umd.edu

301-405-6606

http://dev-baras.pantheonsite.io/

Questions?