IoT and 5G as Enablers for Networked Human-Cyber-Physical Systems

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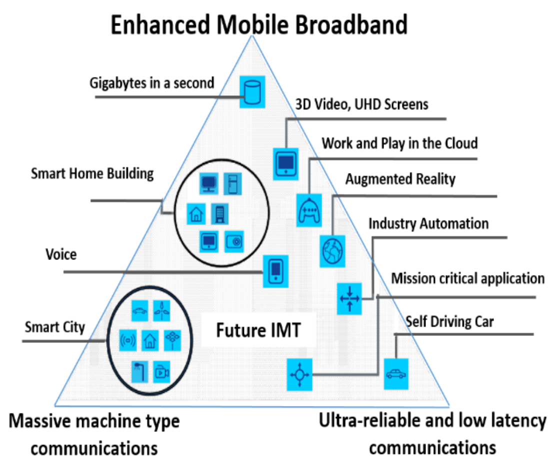
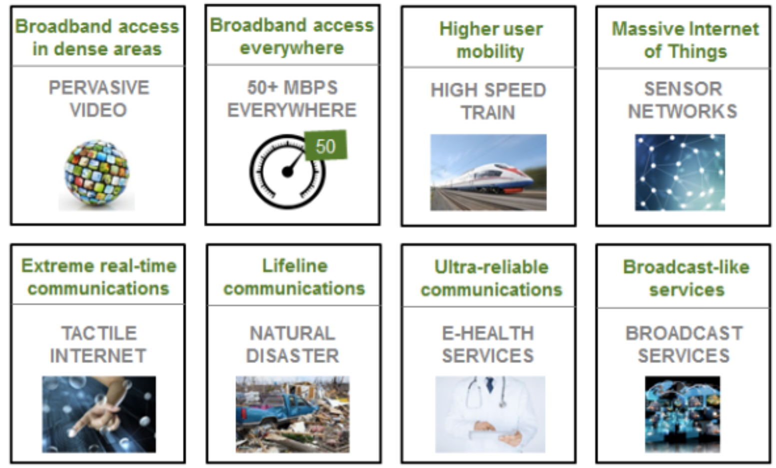
Outline

- 5G – Overview and technologies
- IoT – Overview, relation to 5G and trends
- CPS, Net-CPS, Net-HCPS
  - Overview and examples
  - Multiple interacting coevolving multigraphs
  - Enabling Technologies, challenges and benefits
- Resource allocation problems in virtualized infrastructures

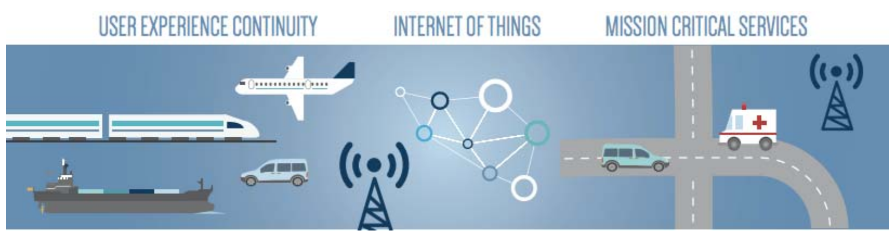
5G Use Cases



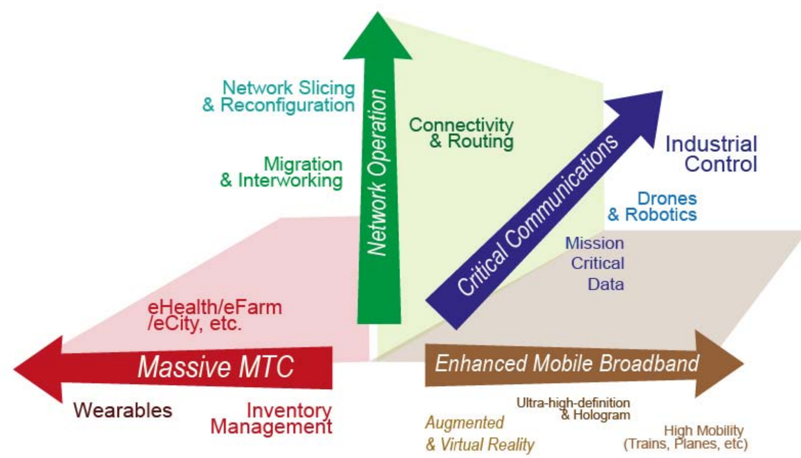
SRC: ITU-R



SRC: NGMN



SRC: 5G PPP



SRC: 3GPP

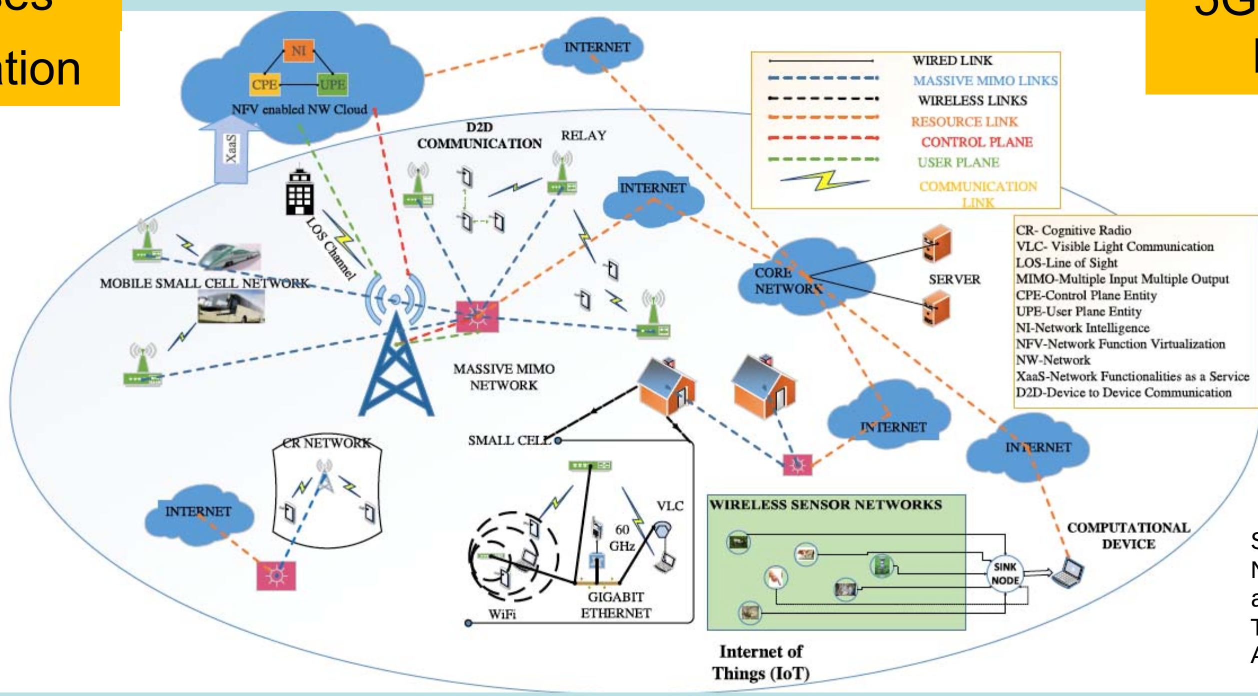
5G Vision

End-to-end ecosystem to enable a fully mobile and connected society
Value creation towards customers and partners, with existing and emerging use cases
Delivered with consistent experience
Enabled by sustainable business models

5G Use Cases

5G Value Creation

5G Business Models

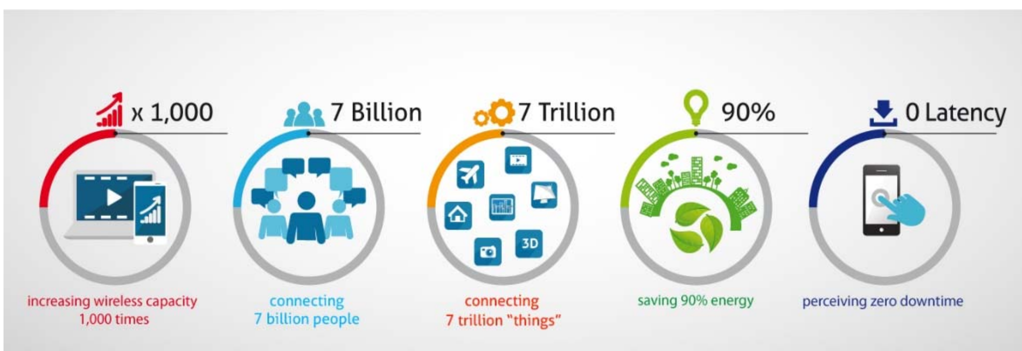


SRC: A Survey of 5G Network: Architecture and Emerging Technologies, IEEE Access, 2015

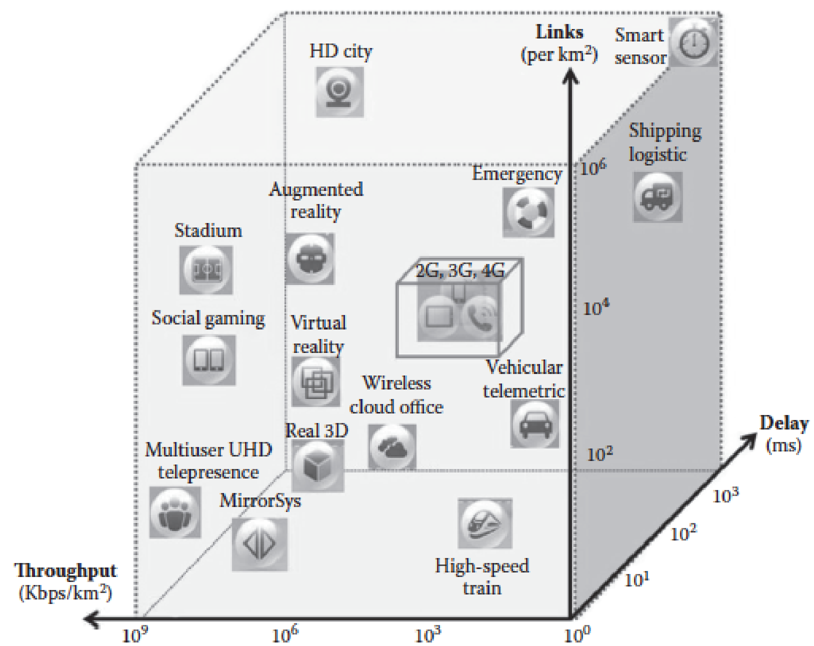
Network of networks,'' i.e., a heterogeneous system comprising a variety of air interfaces, protocols, frequency bands, access node classes, and network types

5G Requirements

SRC: NGMN

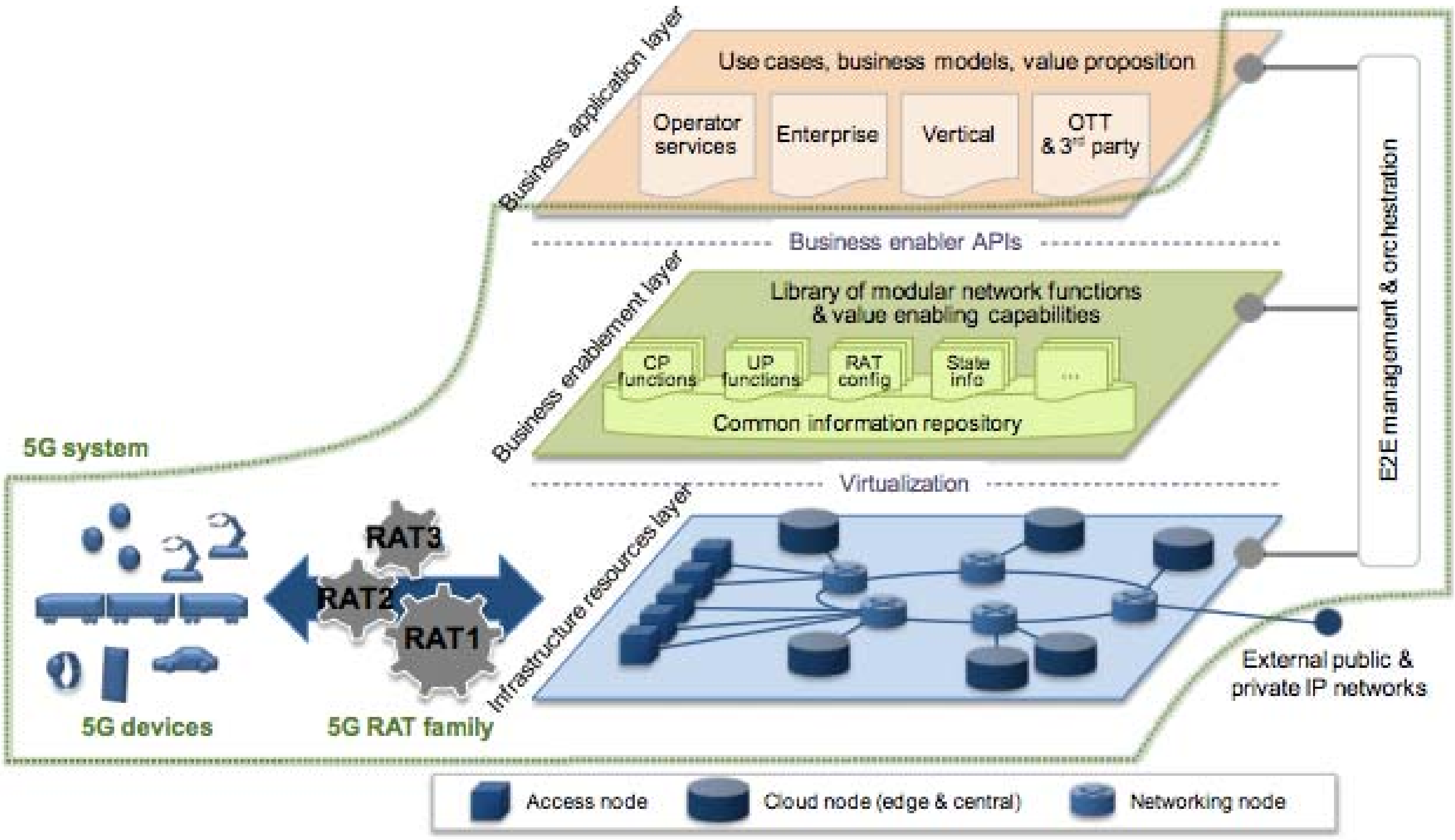


SRC: 5G PPP



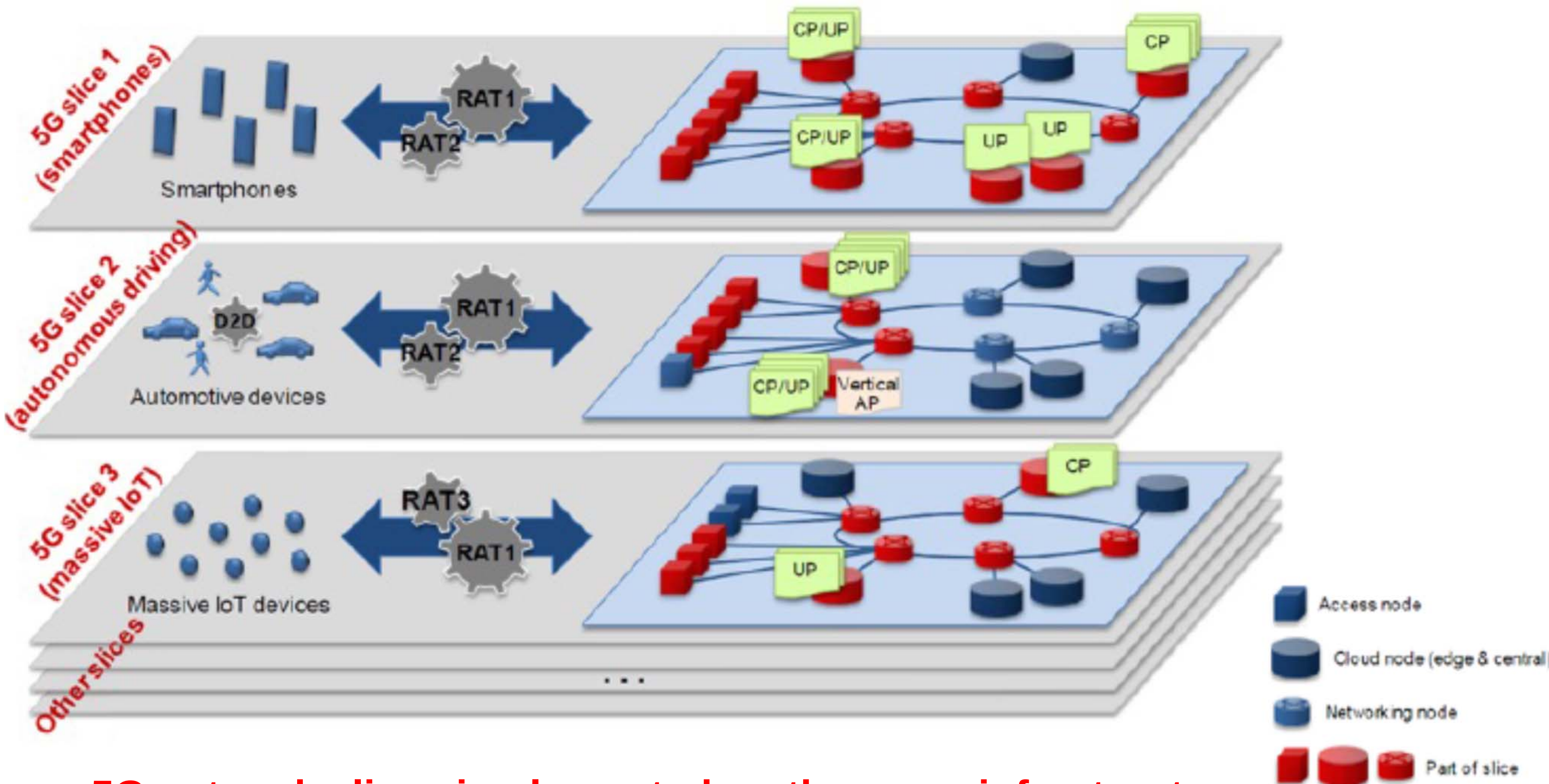
SRC: **Opportunities in 5G Networks:** A Research and Development Perspective, CRC press

5G Architecture



SRC: NGMN

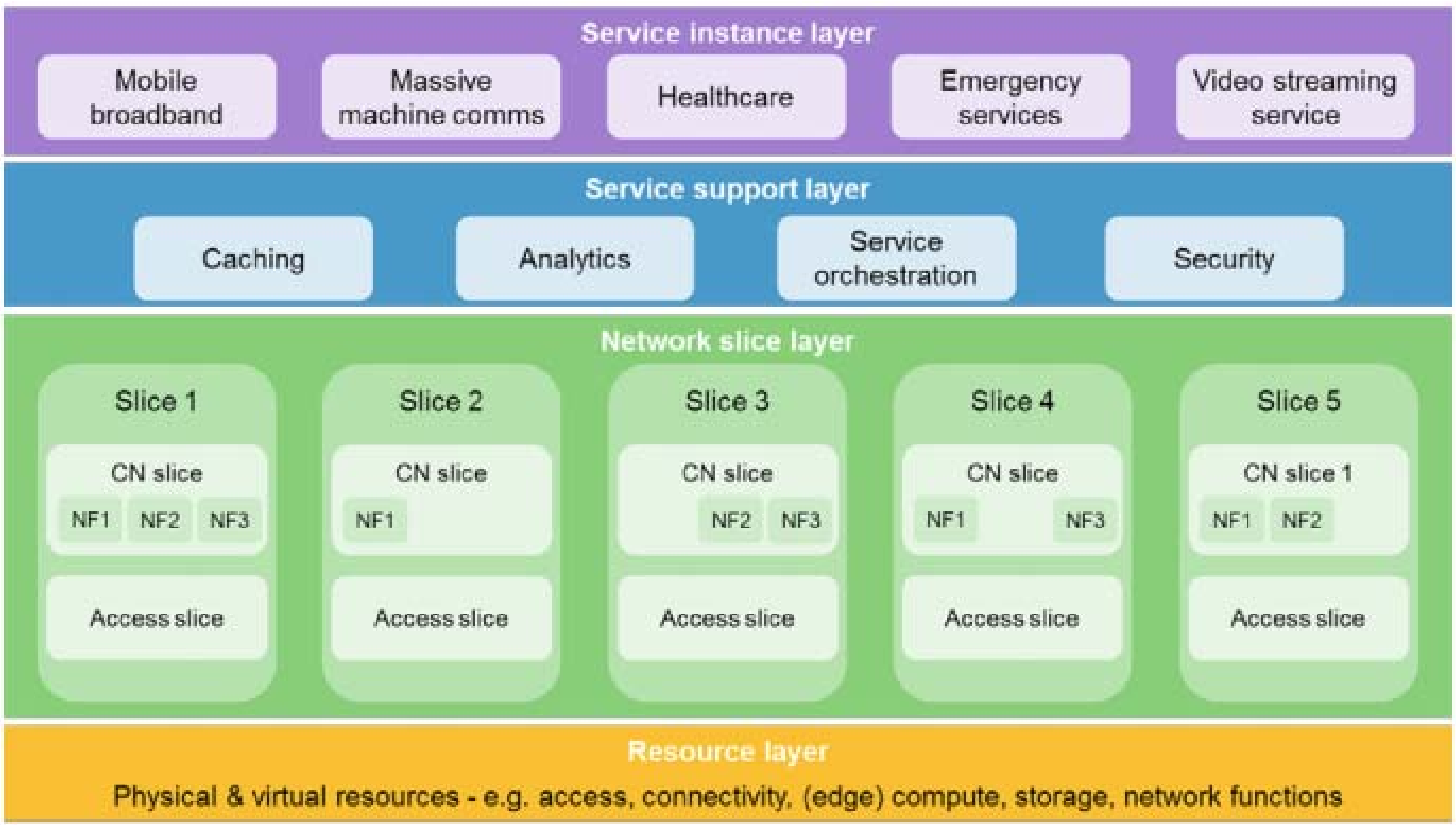
Network Slicing



5G network slices implemented on the same infrastructure

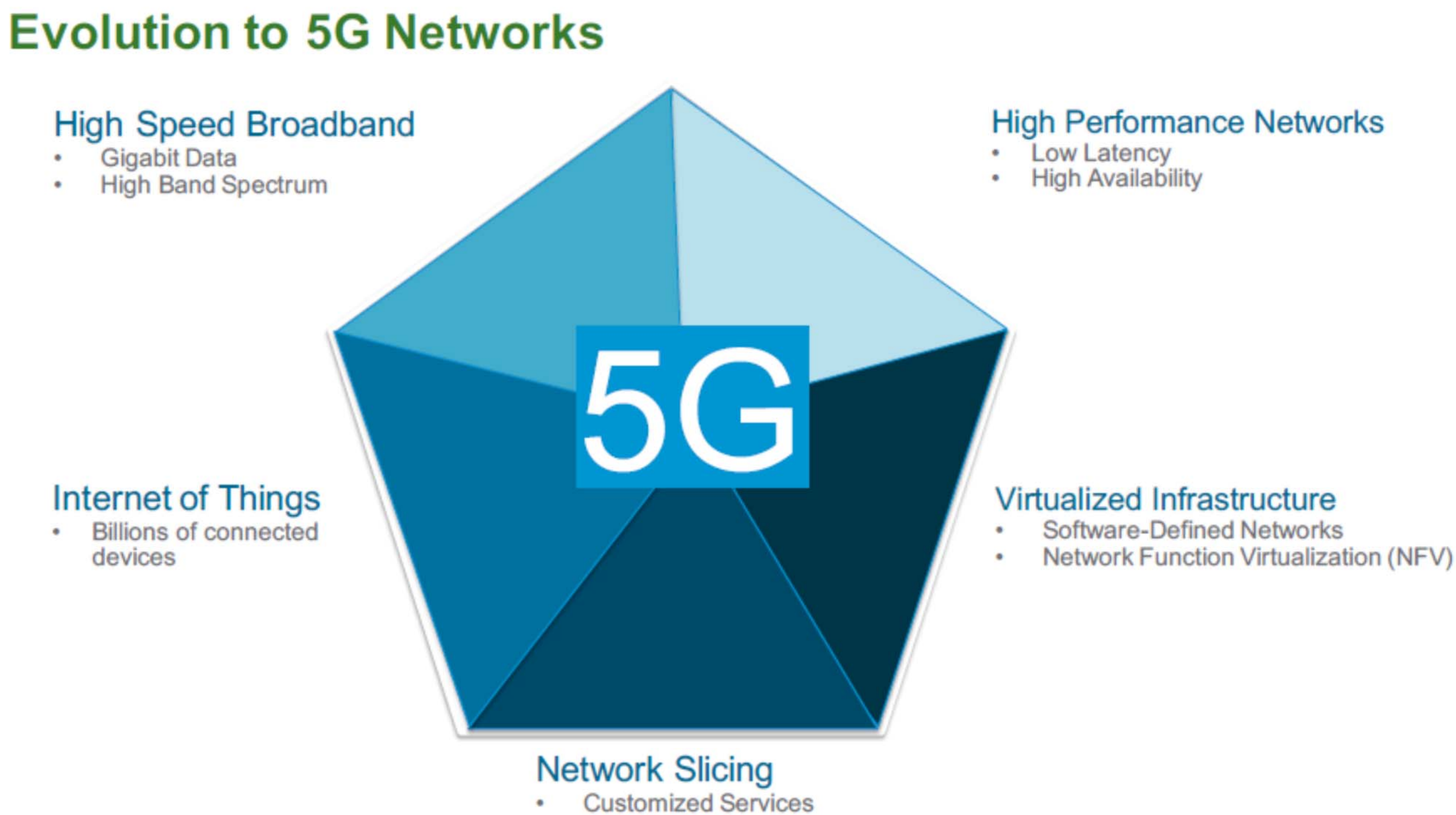
SRC: NGMN

5G Network Slicing (cont.)



SRC: TELCO 2.0. STL Partners- HP

5G – Relation to IoT

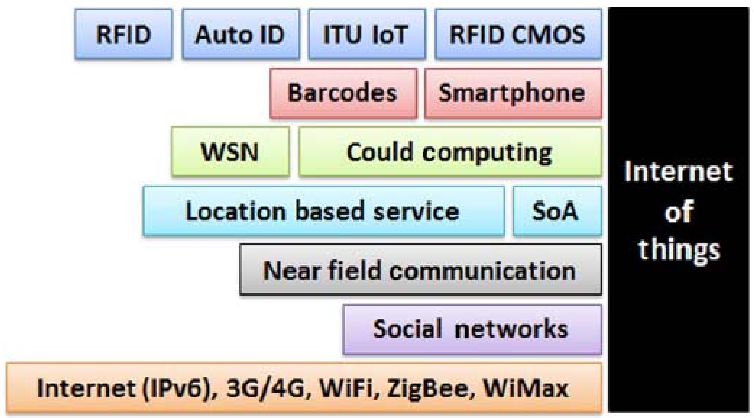


SRC: **vm**ware

Internet of Things

The Internet of Things represents a vision in which the Internet extends into the real world embracing everyday objects. Physical items are no longer disconnected from the virtual world, but can be controlled remotely and can act as physical access points to Internet services. [Mattern and Floerkemeier 2010]

A world where physical objects are seamlessly integrated into the information network, and where the physical objects can become active participants in business processes. Services are available to interact with these "smart objects„ over the Internet, query their state and any information associated with them, taking into account security and privacy issues [Haller et al. 2008]



SRC: Internet of Things in Industries: A Survey, IEEE Transactions on Industrial Informatics,2014.

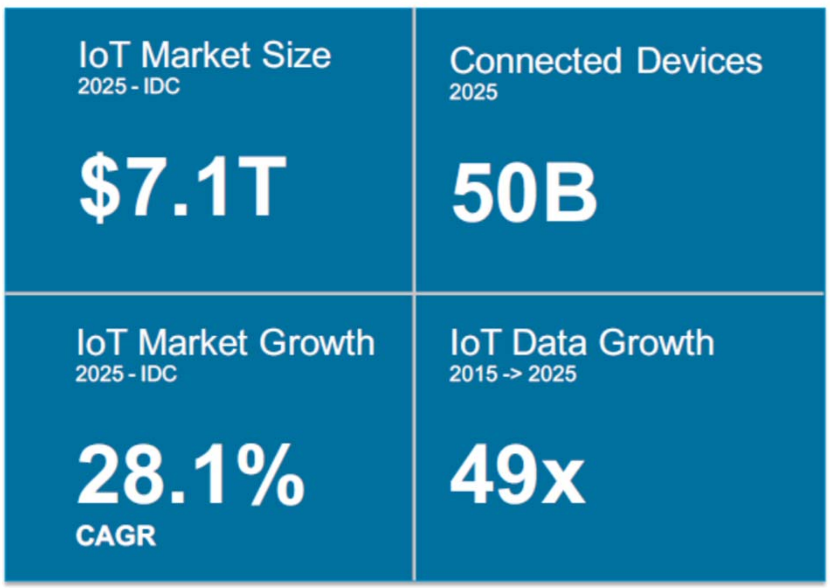
IoT – Challenges and Opportunities

IoT opens up opportunities across multiple verticals

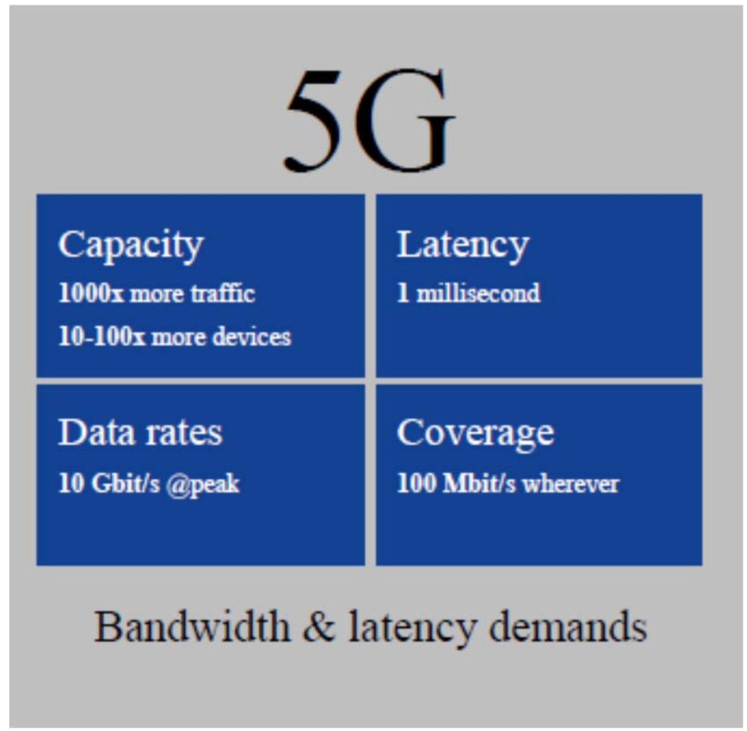
SRC: **vm**ware

IoT & 5G: Growth and Characteristics

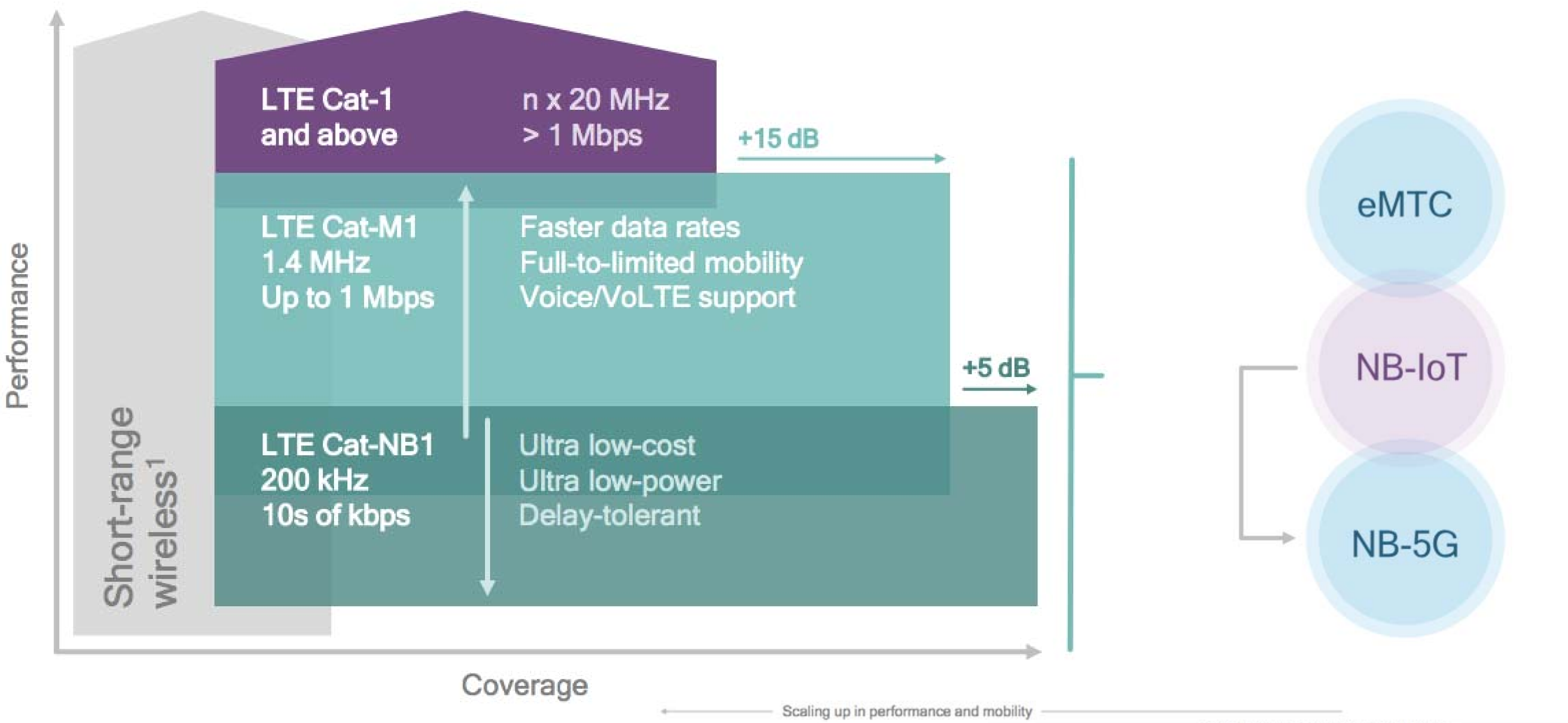
Massive growth of IoT

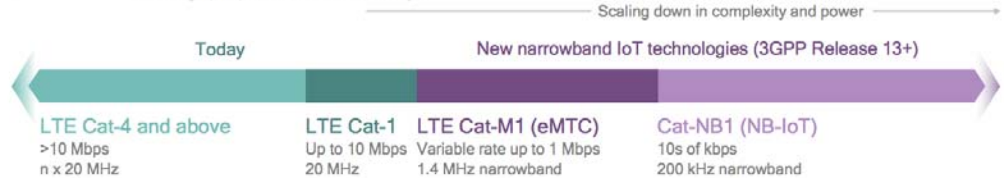


SRC: **vm**ware



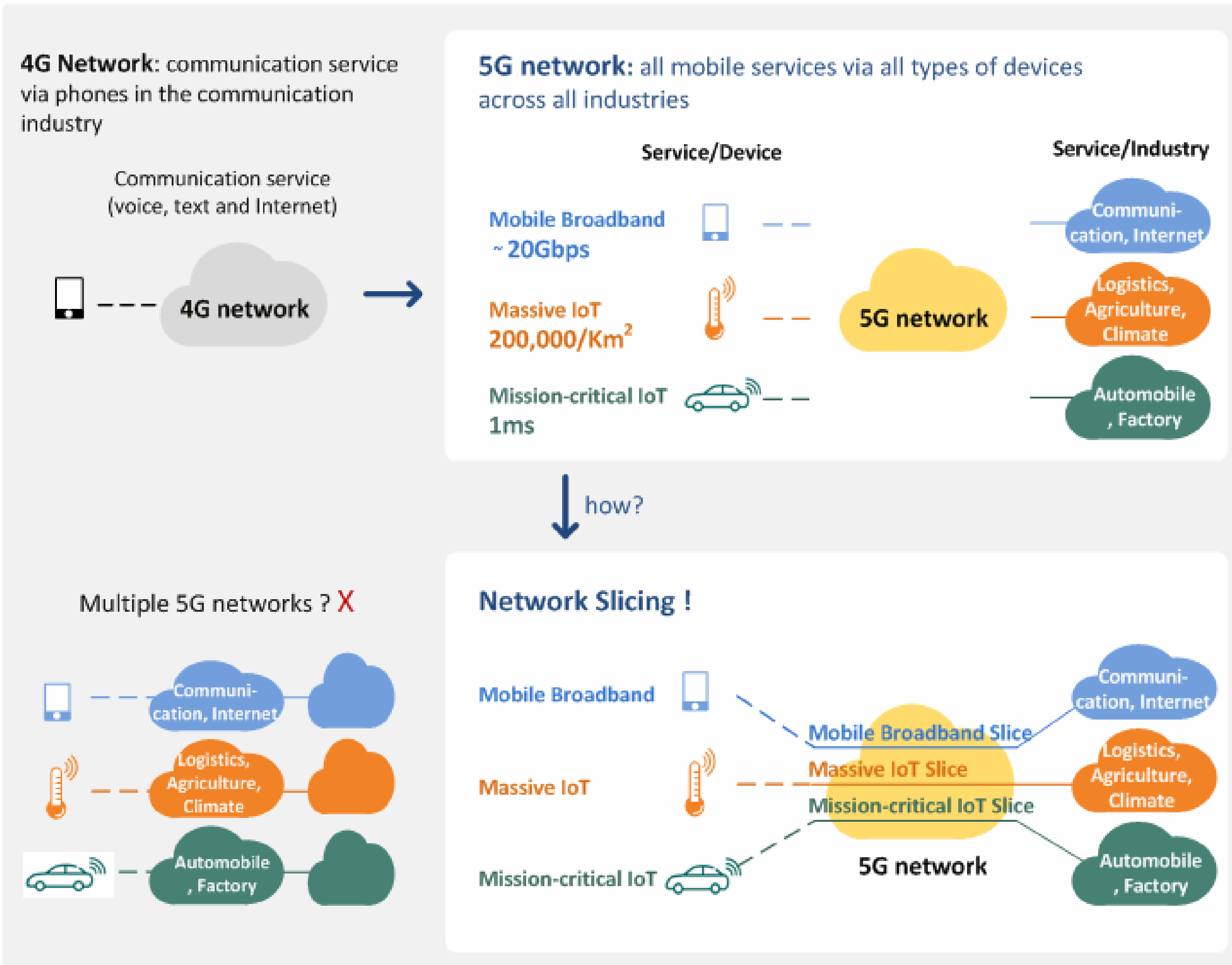
Paving the way to 5G





SRC: Paving the path to Narrowband 5G with LTE Internet of Things (IoT), Qualcomm, 2016

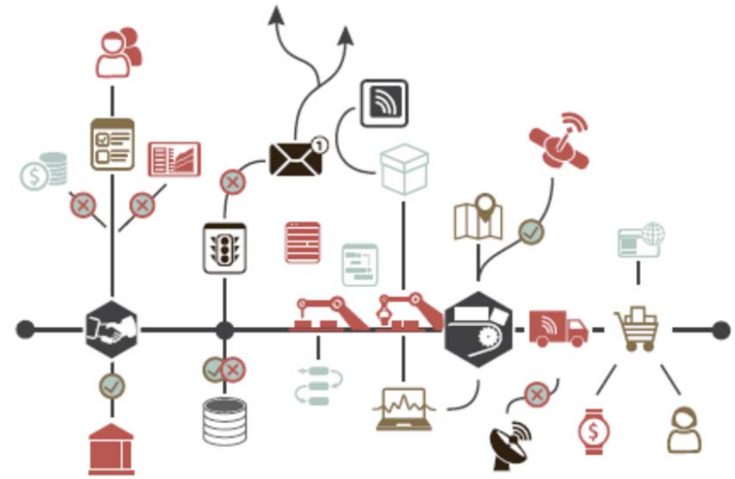
IoT and 5G Network Slicing

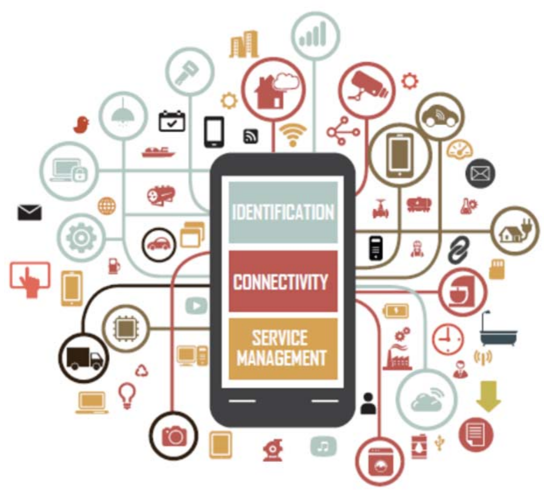


SRC: E2E Network Slicing, Netmanias

Some IoT Trends

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





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

Networked CPS are Ubiquitous

Infrastructure / Communication Networks

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

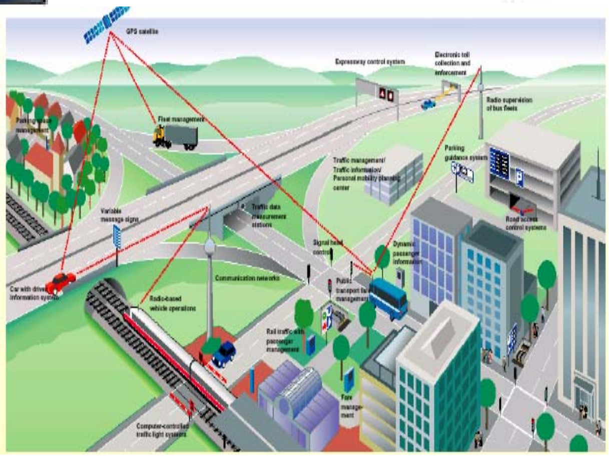
Social / Economic Networtks

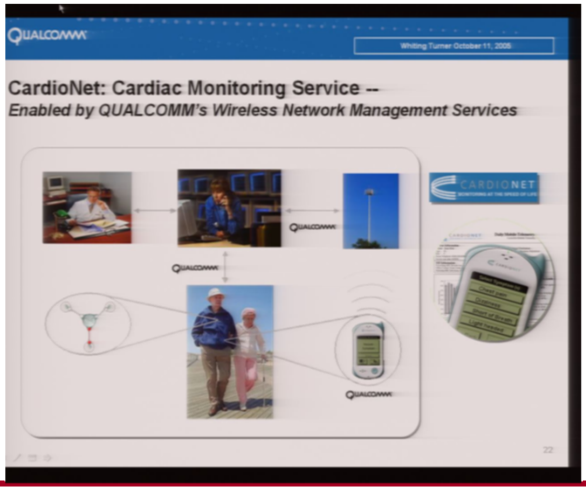
Social Interactions
Collaboration
Social Filtering
Economic Alliances
Web-based social systems

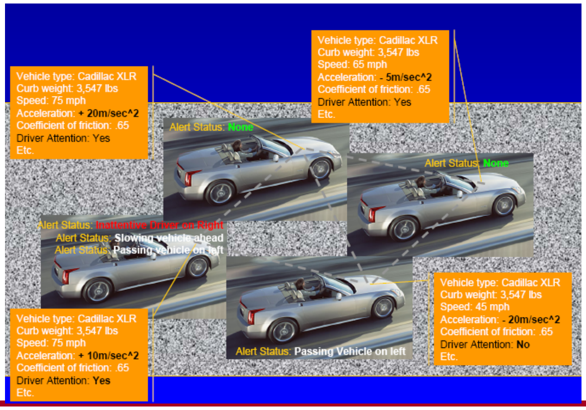
Biological Networks

Community
Epiddemic
Cellular and Sub-cellular
Neural
Insects
Animal Flocks

Net-CPS: Wireless and Networked Embedded Systems







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

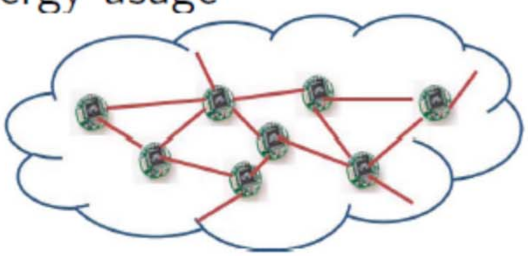




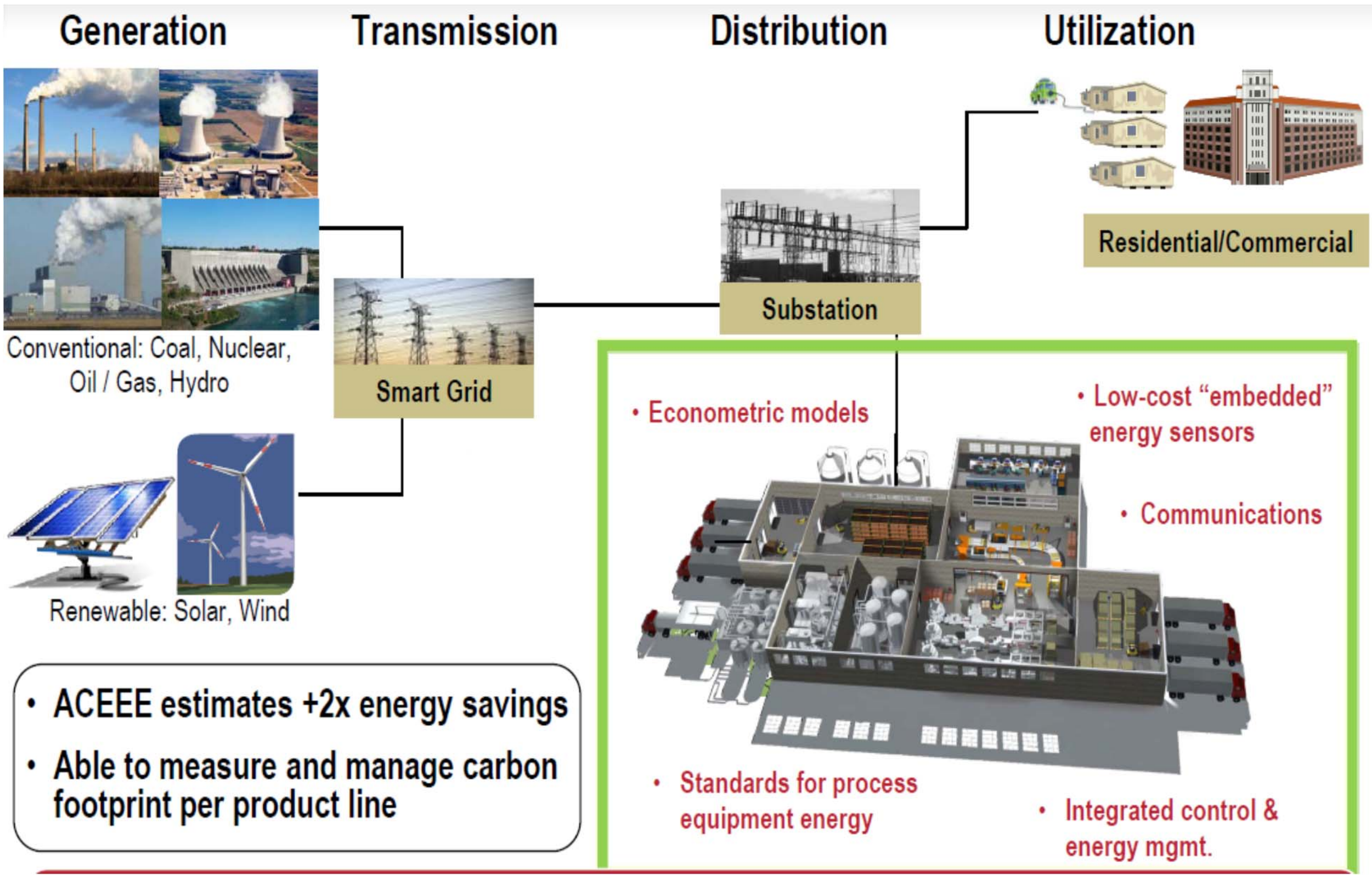
Net-CPS: Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

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



Net-CPS: Smart Grids



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

The Institute for Systems Research

Net-CPS: Collaborative Autonomy

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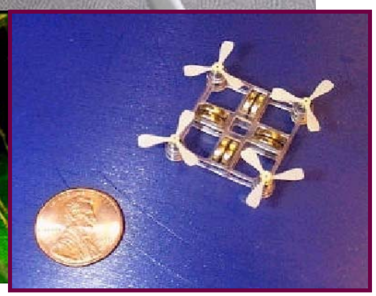
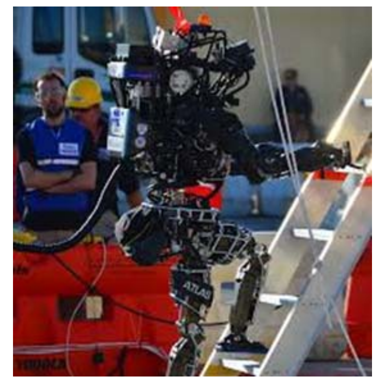
- Component-based Architectures
- Communication vs Performance Tradeoffs
- Net-HCPS … human behavior
- Distributed asynchronous
- Fundamental limits



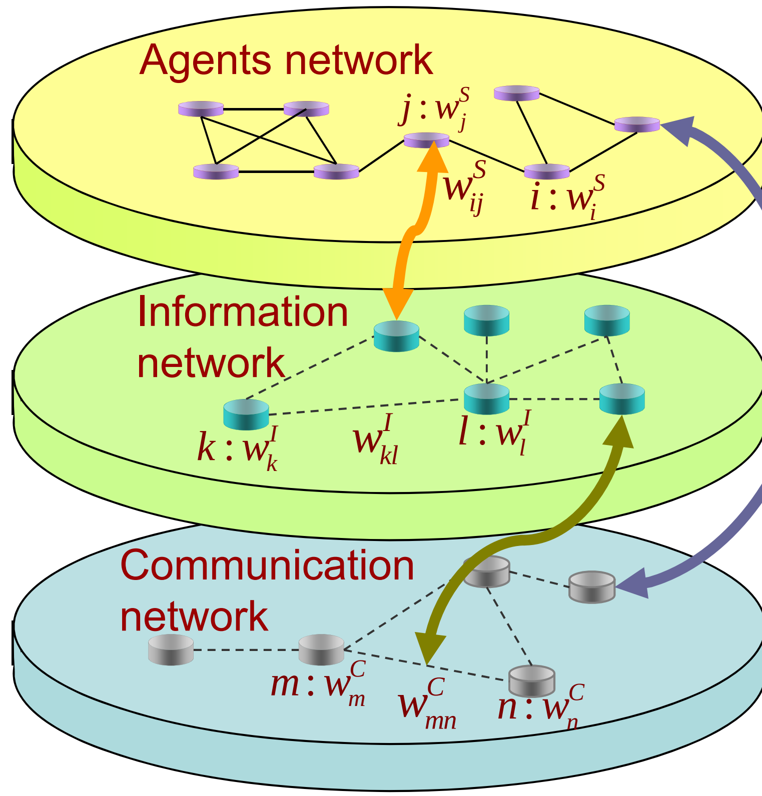


Net-HCPS: Social and Economic Networks over the Web

- 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

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

Fundamental Challenges

- **Multiple interacting 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
- Modeling human group behavior, cognition, decision making

Example: 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 Decision Making Graph and the Communication Graph

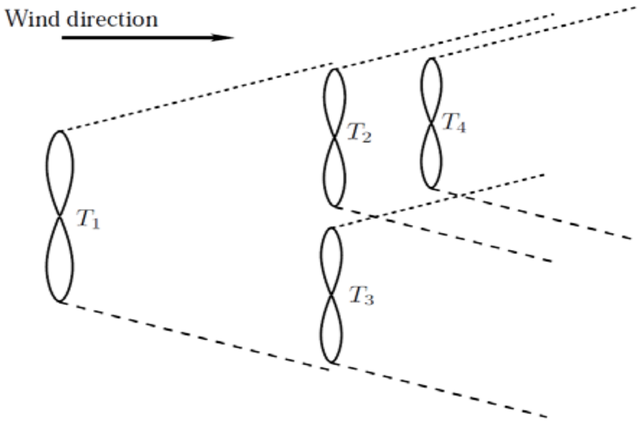
Baras, John S., Hovareshti, Pedram., "Efficient and Robust Communication Topologies for Distributed Decision Making in Networked Systems", *IEEE CDC*, 2009

Baras, John S., Hovareshti, Pedram., "Effects of Topology in Networked Systems: Stochastic Methods and Small Worlds", *IEEE CDC*, 2008

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



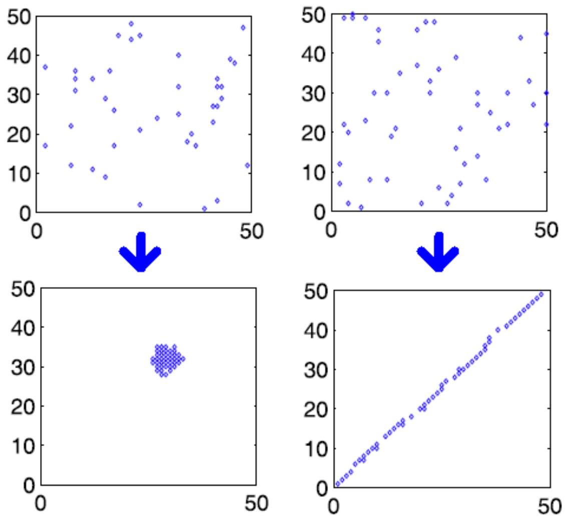
Schematic representation of a wind farm depicting individual turbine wake regions.

- 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**

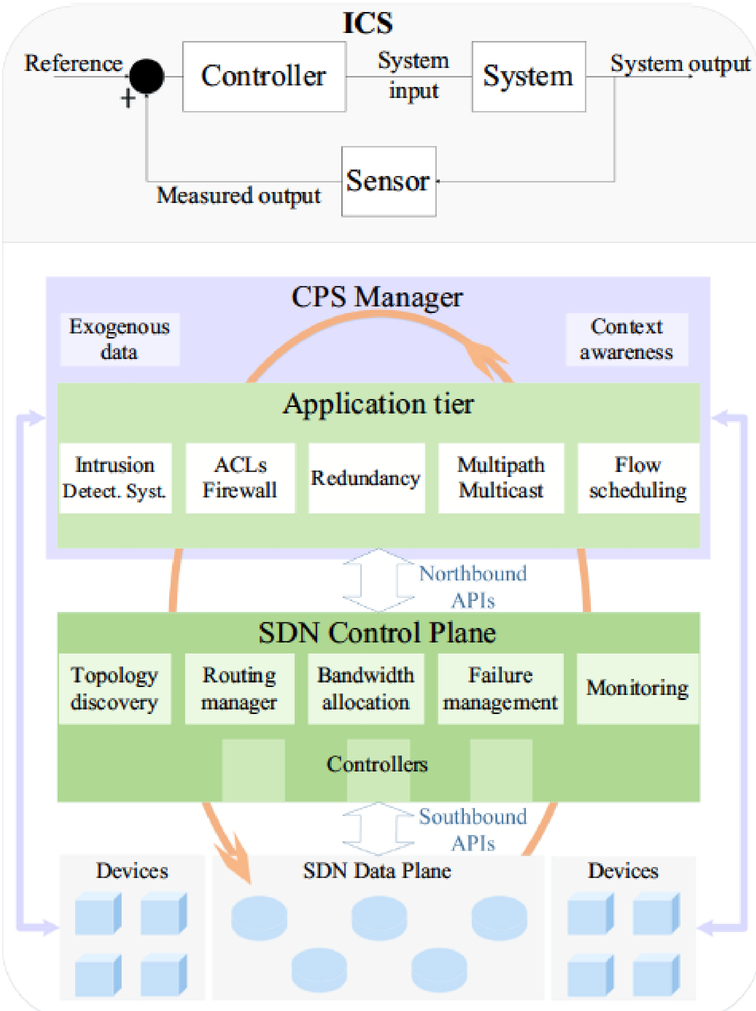
• • •

Example: 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

Liu, X. and Baras, J.S., "Using Trust in Distributed Consensus with Adversaries in Sensor and Other Networks," FUSION2014.

SDN-CPS



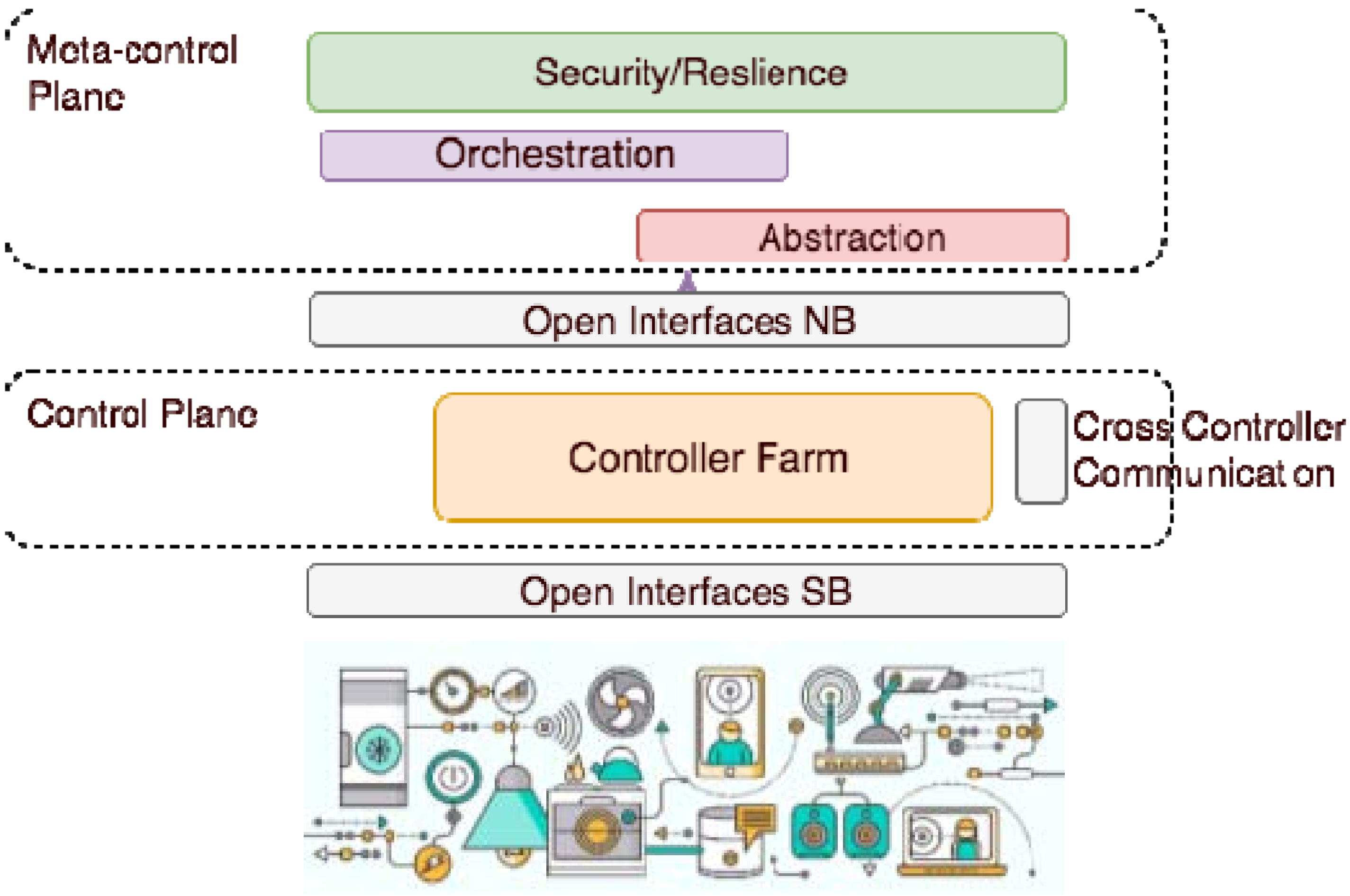
E. Molina and E. Jacob, "SDN in CPS: A Survey", 2017

- CPS, Net-CPS, Net-HCPS can be viewed as distributed partially asynchronous implementations of the sense-decide-actuate cycle in control systems
- The collaboration and information network in our multi-layer model of CPS, net-CPS and Net-HCPS impose requirements on the communication network including: priority, bandwidth constraints, predictability, timeliness, robustness, survivability, network securit
- The SDN paradigm and associated concepts such as Network Function Virtualization (NFV) can play a key role in meeting these requirements

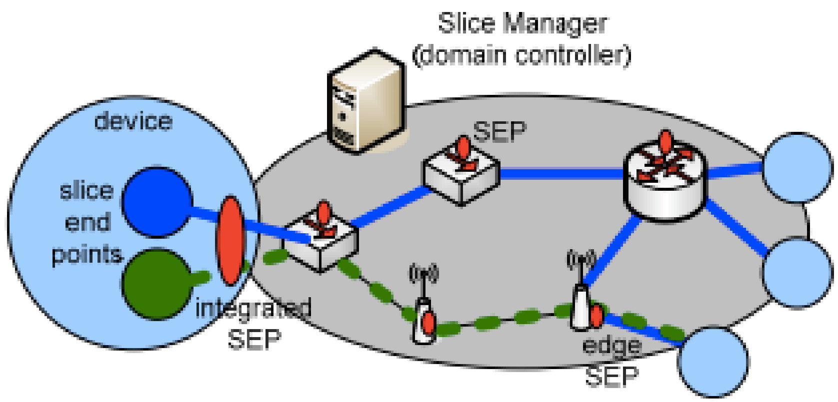
Challenges and Benefits

- ✓ Manageability
  - e.g., Automation, orchestration and network re-configuration
- ✓ Resource Allocation
- ✓ Real-time
- ✓ Reliability
  - e.g. failure detection and recovery
- ✓ Security
  - e.g. security policies applied on demand
- ✓ Interoperability
  - e.g., open standard interfaces

SD-CPS Architecture

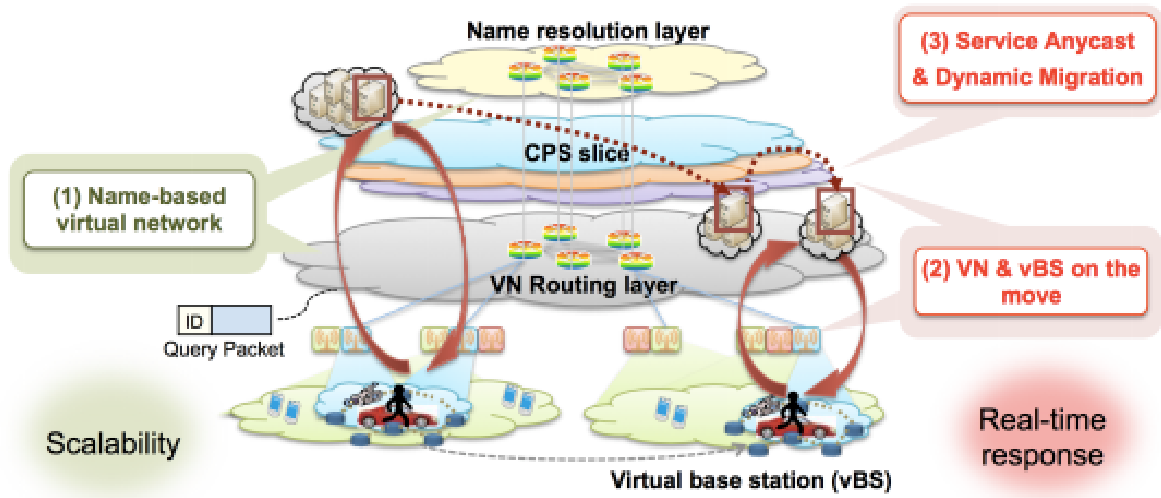


Network Slice for CPS

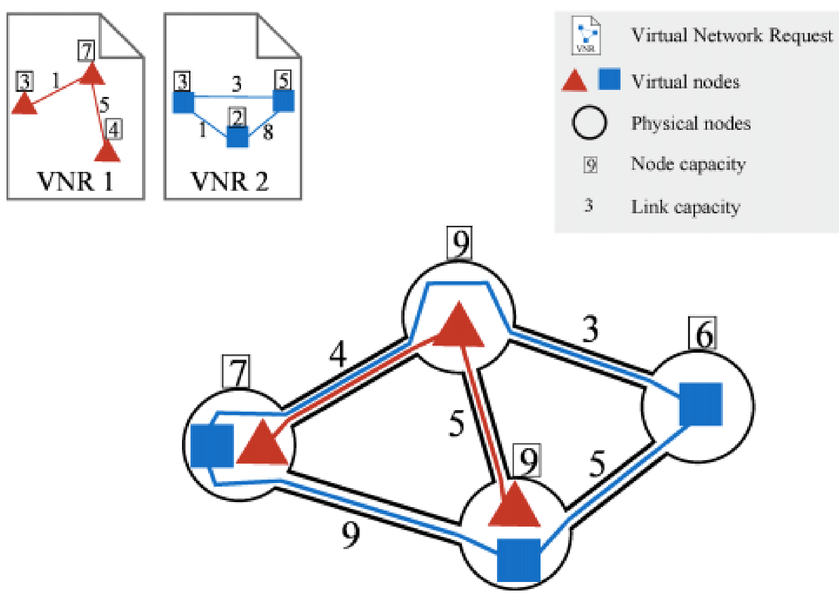


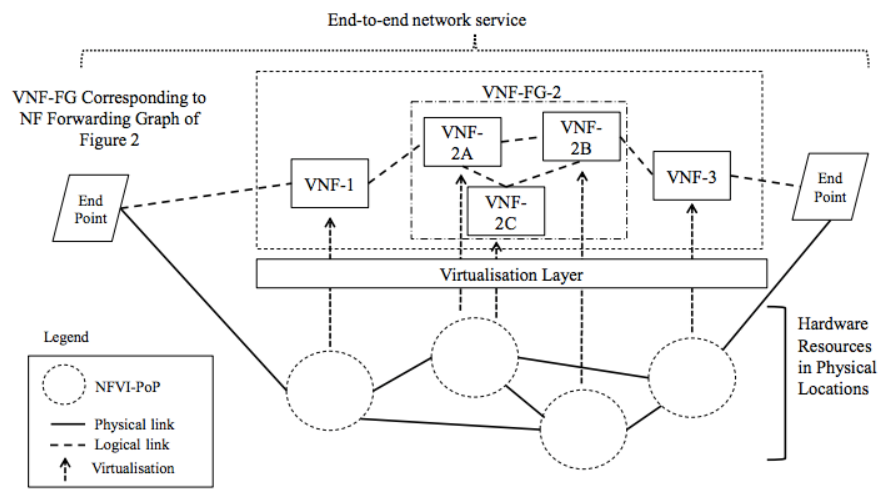
Resource-aware virtualization for industrial networks: A novel architecture combining resource management, policy control and network virtualization for networks in automation or supervisory control and data acquisition networks. *DCNET*, 2013.

vMCN: Virtual mobile cloud network for realizing scalable, real-time cyber physical systems, DCC 2016



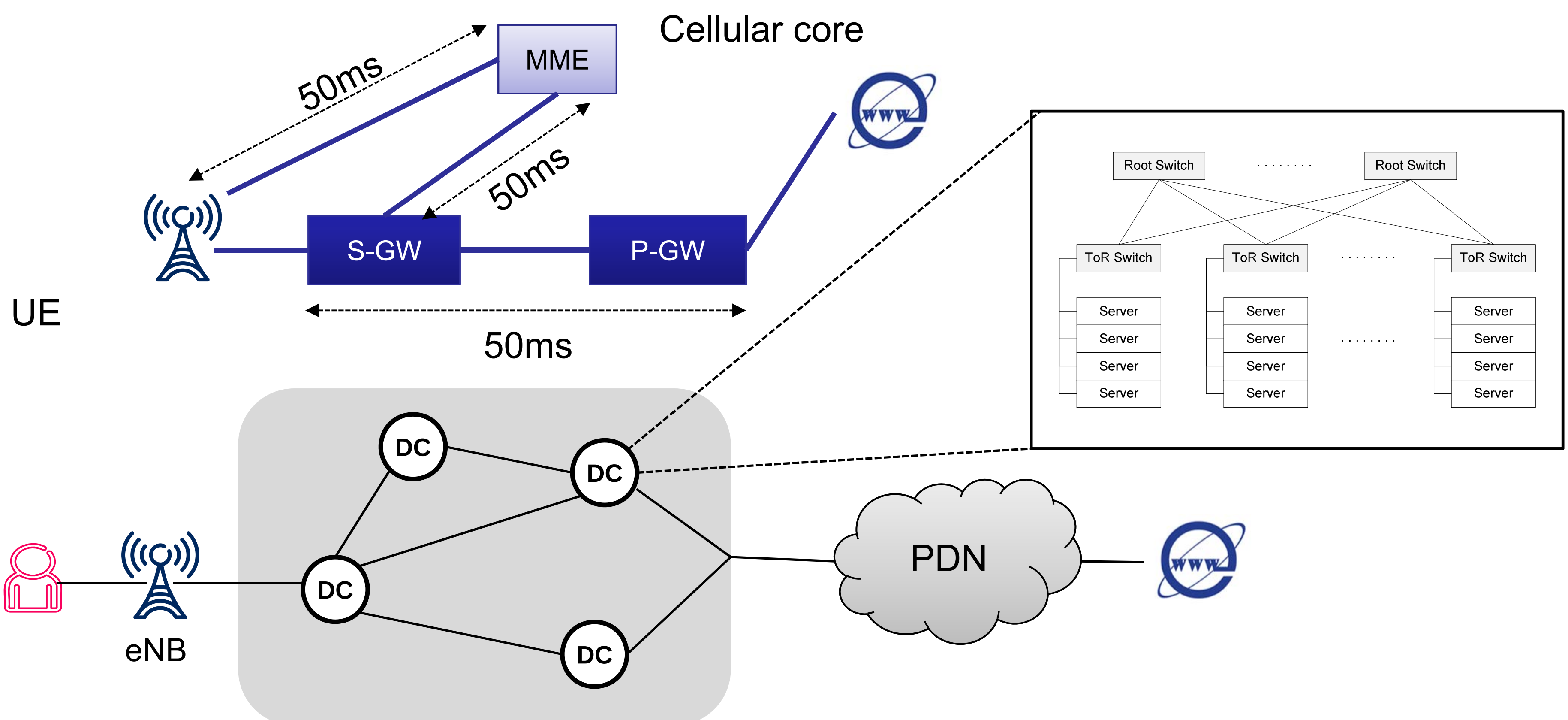
Resource allocation



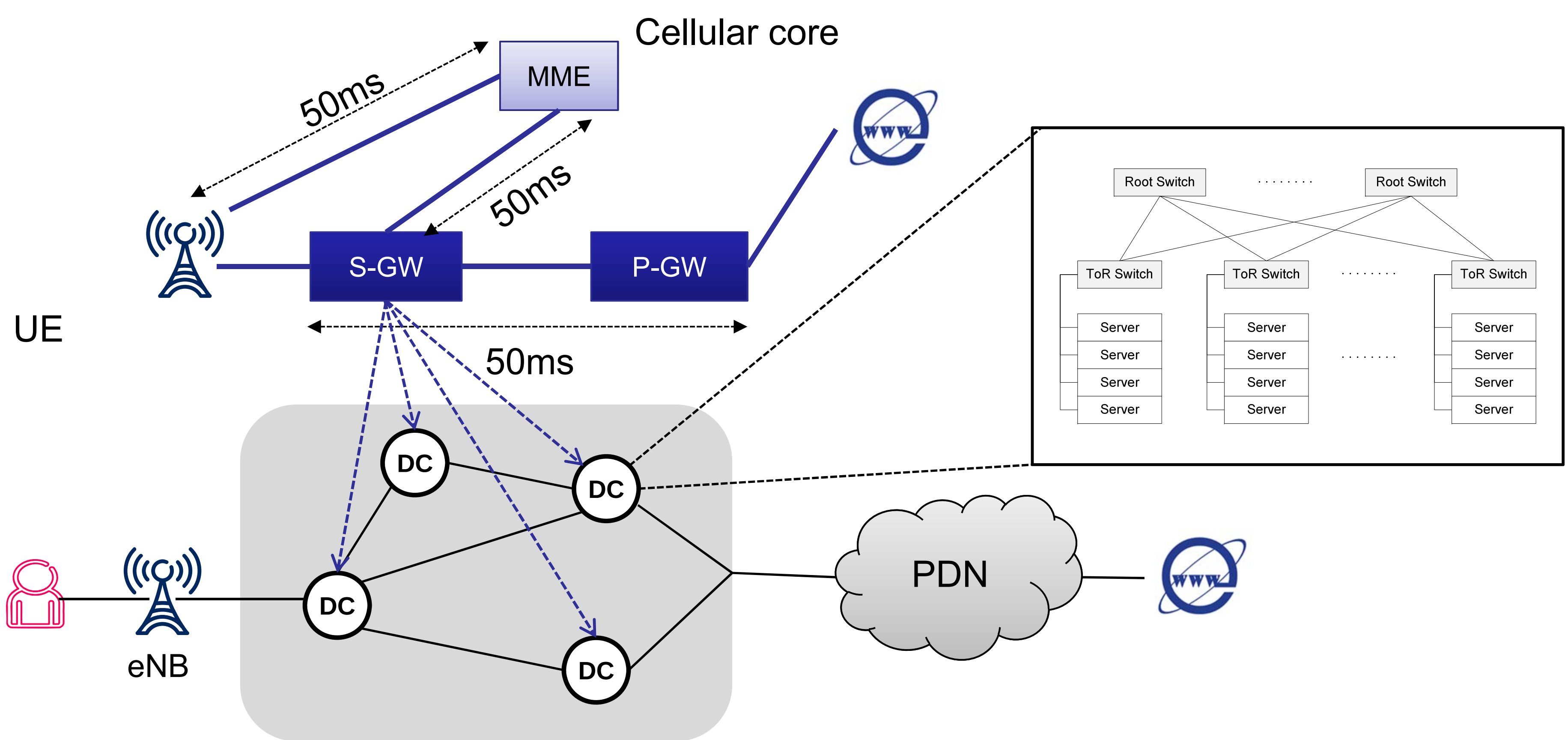


[FISCHER,2013] Fischer, Andreas, et al. "Virtual network embedding: A survey."Communications Surveys & Tutorials, IEEE 15.4 (2013)
[ETSI] http://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.01.01_60/gs_NFV002v010101p.pdf

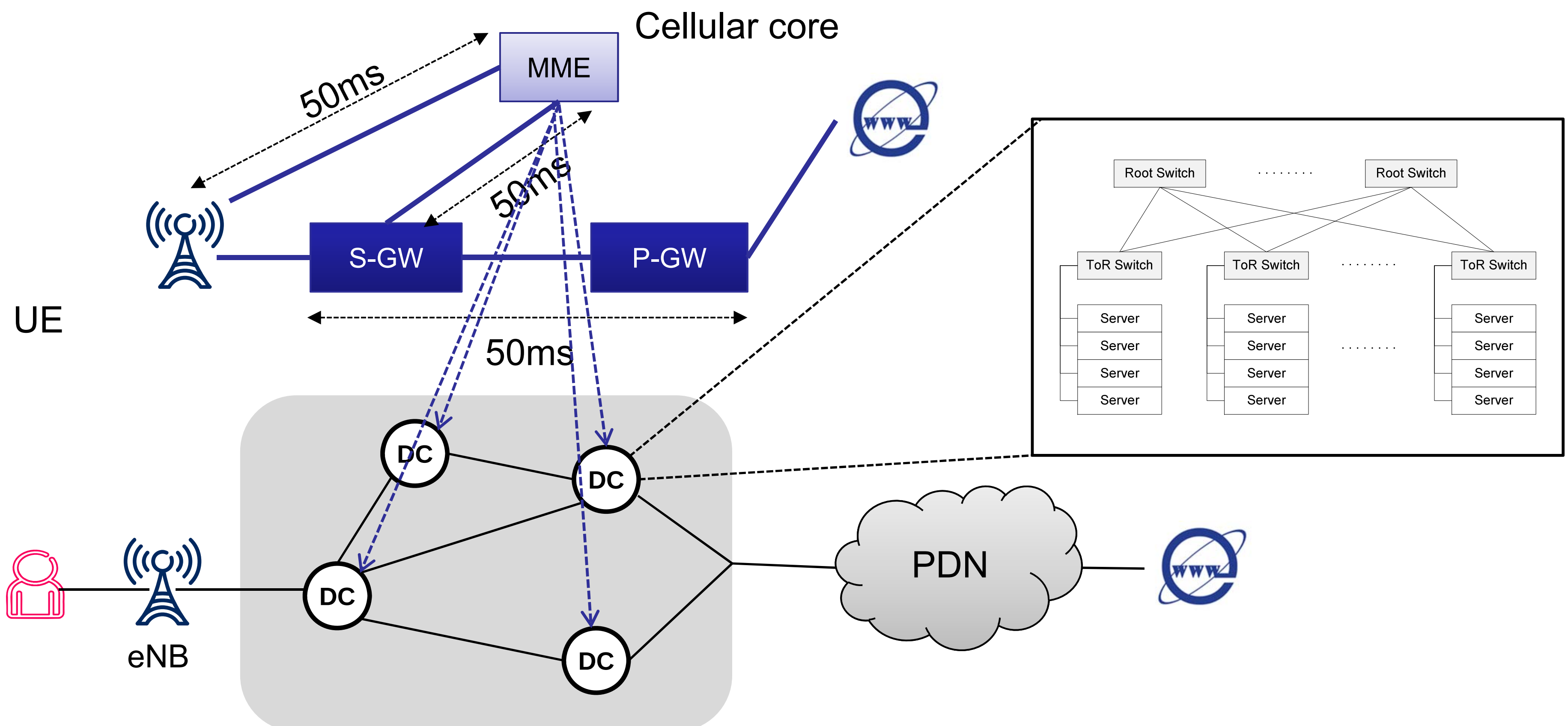
vEPC- SFC allocation



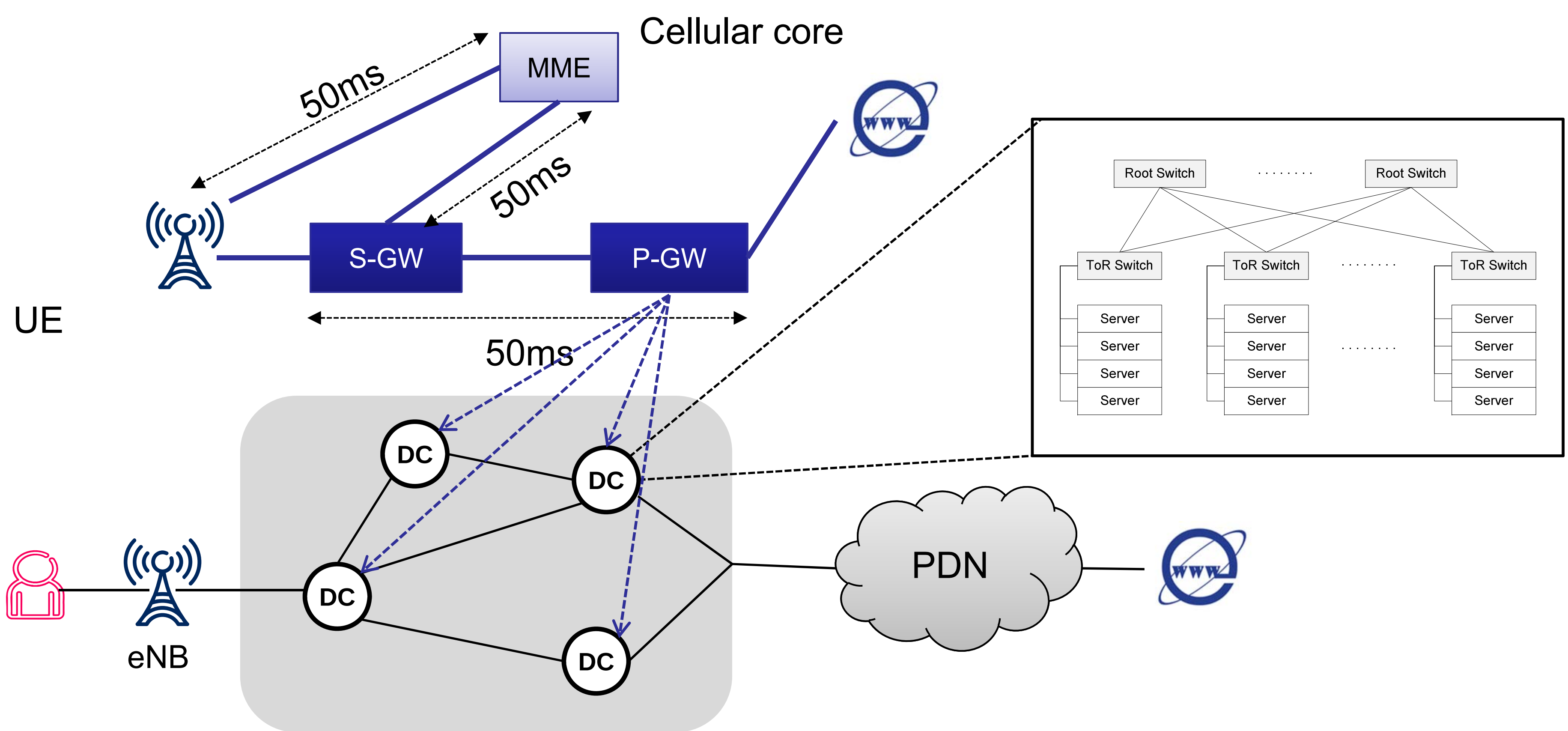
vEPC- SFC allocation



vEPC- SFC allocation



vEPC- SFC allocation



vEPC - NF placement

- Challenges:
  - Tight coupling between data and control plane elements
    - » Delay budgets among cellular core elements
  - Scale
    - » Large number of UEs and DCs in cellular networks

- Existing NF placement methods:
  - Optimize the placement of data-plane functions

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 [Qazi, 2016])
- Assumptions:
  - Single S-GW and MME per UE (3GPP)

NF placement solvers:

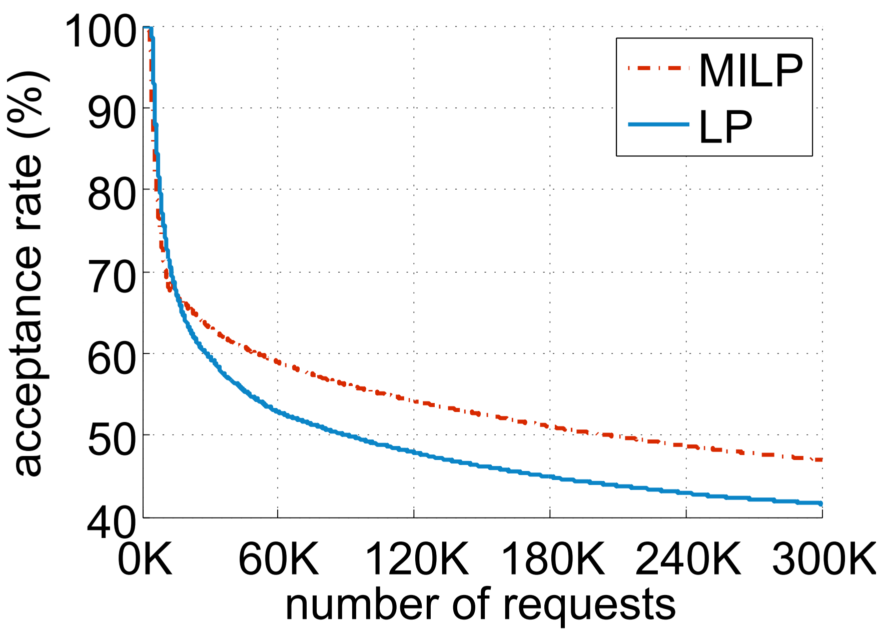
Mixed Integer Linear Programming (MILP) formulation
- ✓ Optimality
- ✗ High time complexity

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

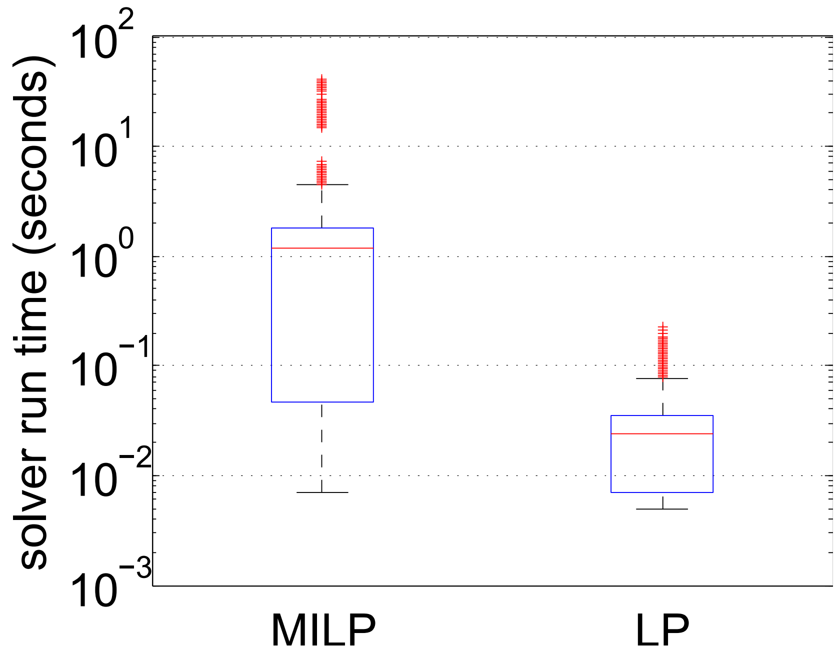
Dietrich, David., Papagianni, Chrysa. , Panagiotis, Papadimitriou., Baras, John S., "Network Function Placement on Virtualized Cellular Cores", *COMSNETS 2017.*

MILP vs LP

- LP yields substantially lower solver runtime and smaller acceptance rate



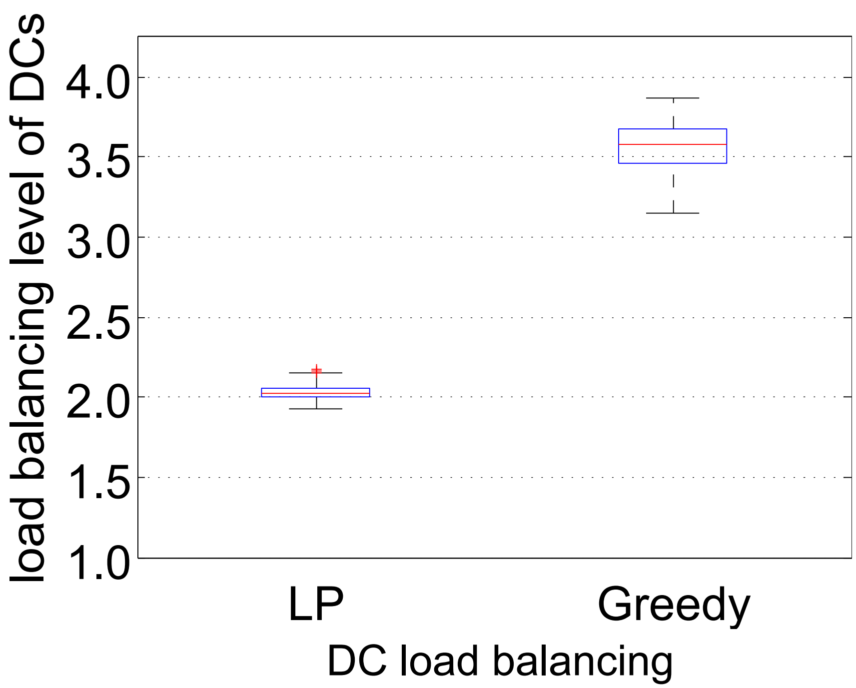
Acceptance Rate



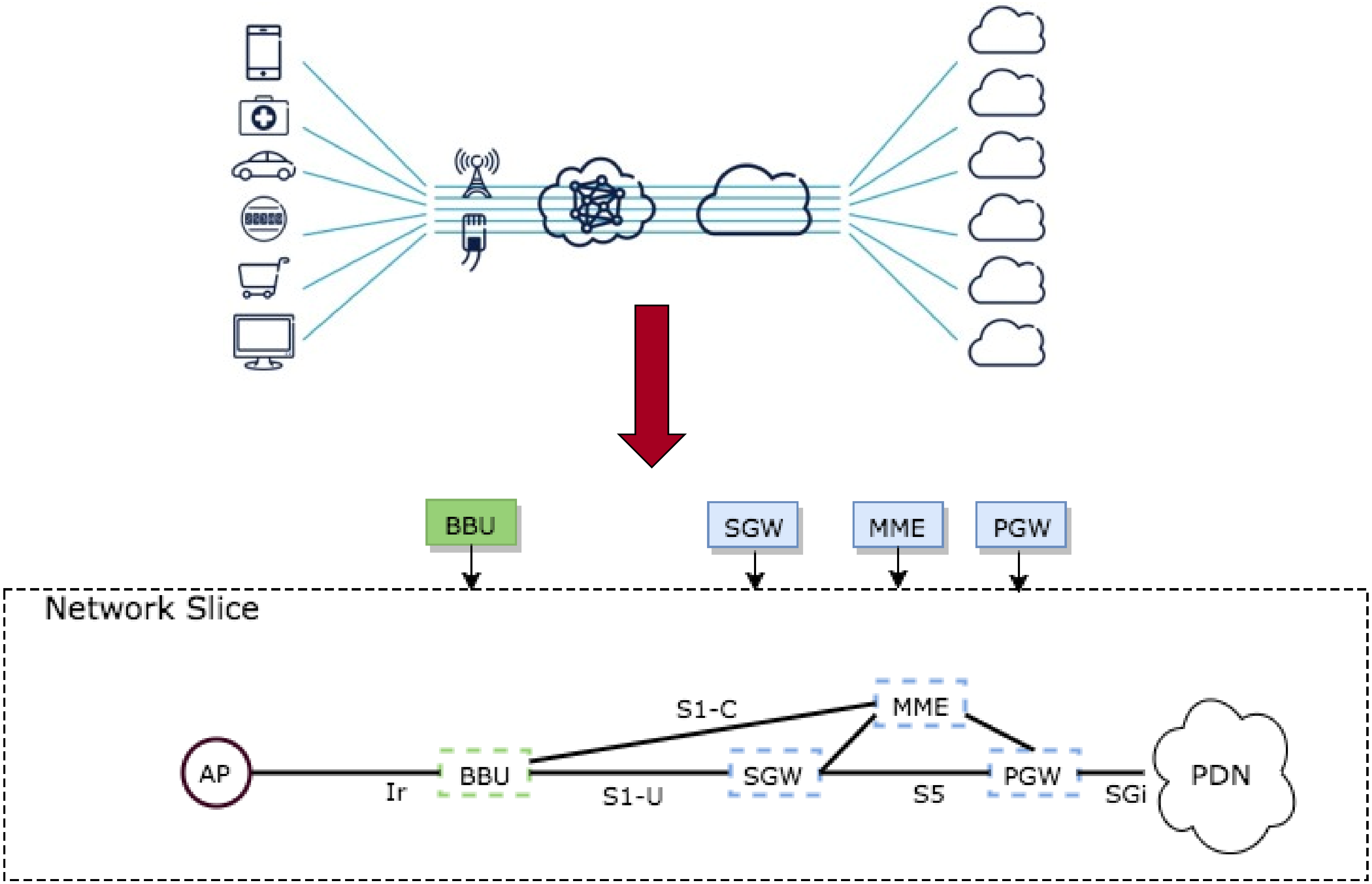
Solver Runtime

LP vs Greedy

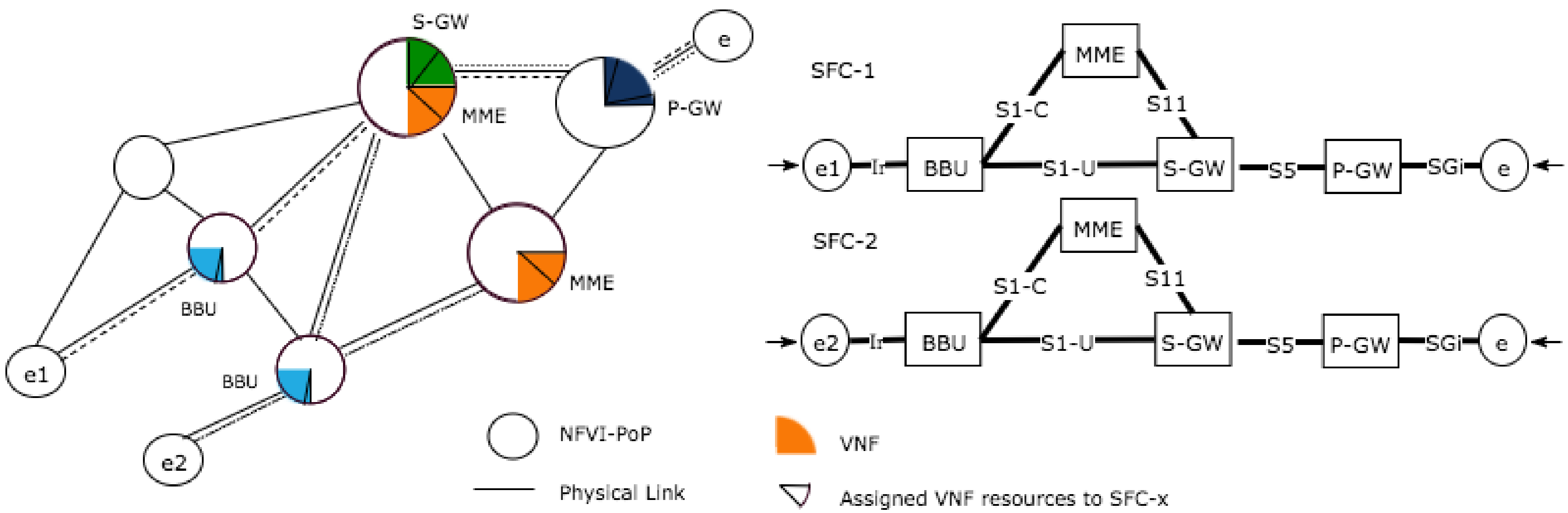
- LP yields much better load balancing across DCs



E2E Network Slicing – SFC allocation

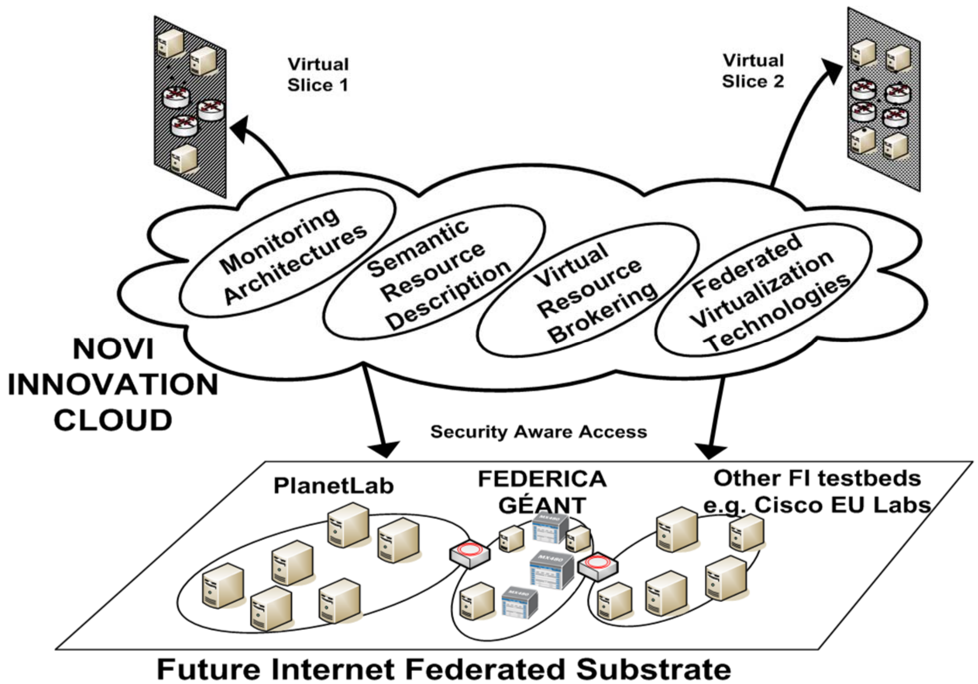


Approach – 2-level vs 1-level



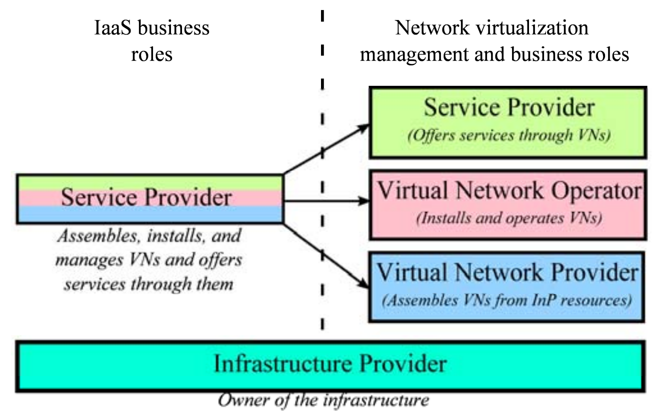
- ✓ Support different resource allocation policies for 5G network slicing
- ✓ Hybrid solutions may be employed

Virtual Network Embedding



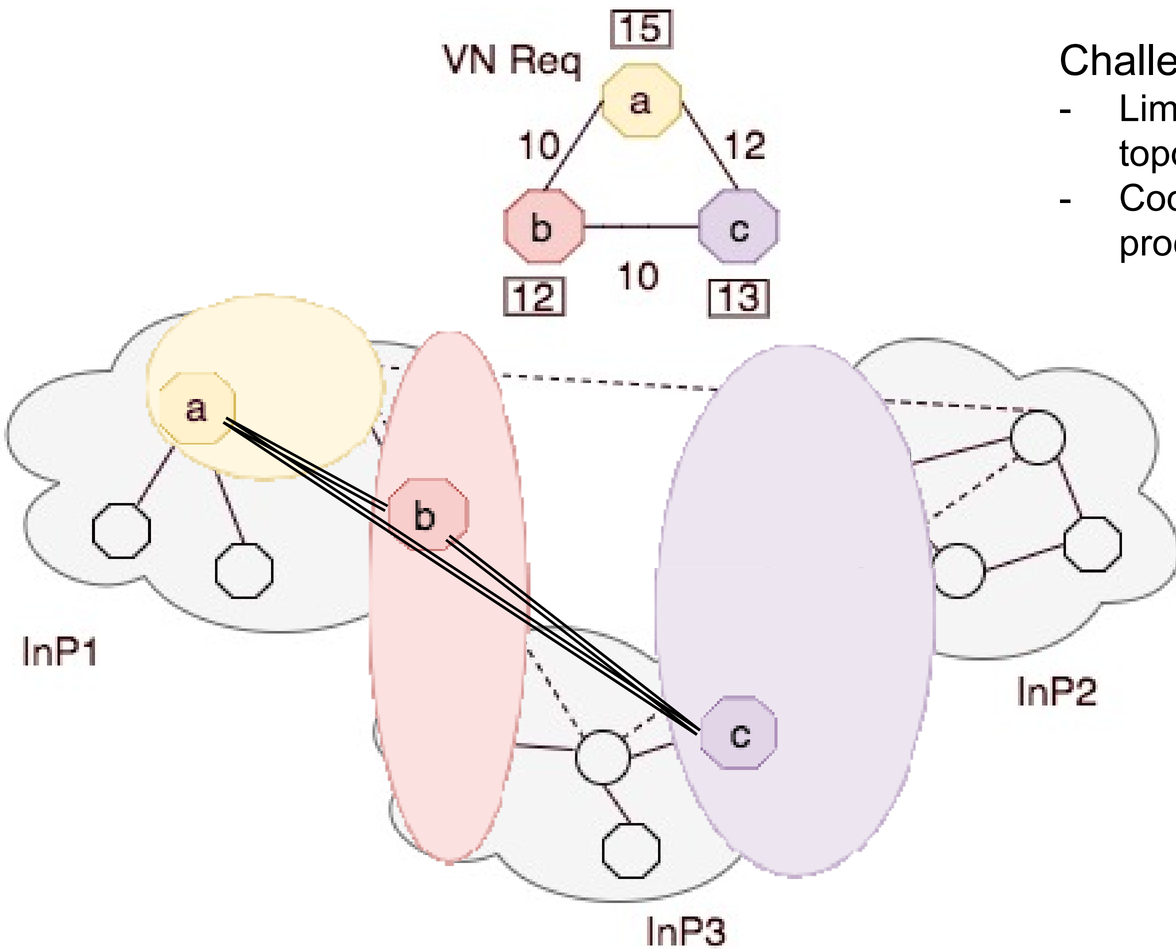
Multi-tenant network virtualization environments

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



[FISCHER,2013] A. Fischer, J. F. Botero, M. T. Beck, H. de Meer and X. Hesselbach, "Virtual Network Embedding: A Survey," in *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1888-1906, Fourth Quarter 2013

Inter-InP virtual network embedding

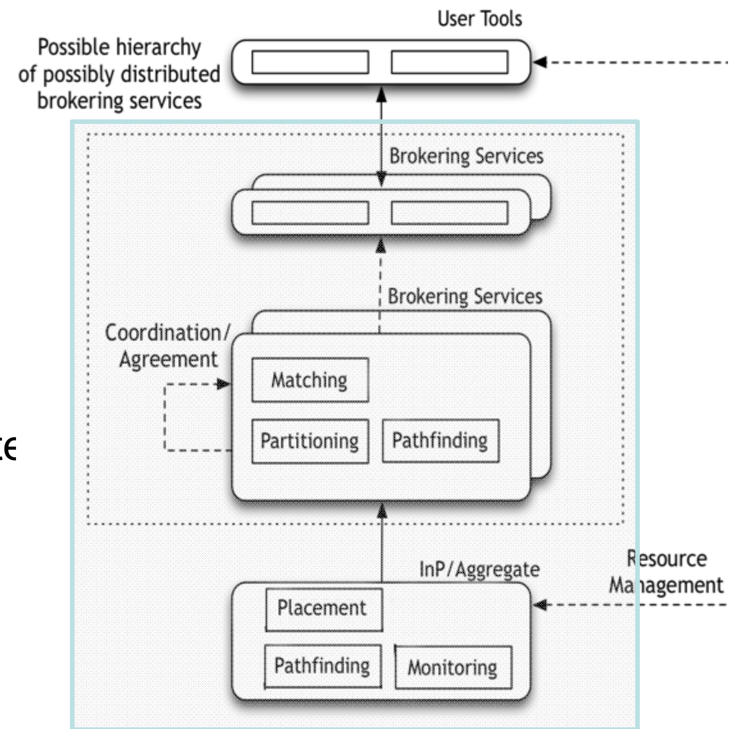


Challenges:

- Limited knowledge of substrate topology/resources
- Coordination of the embedding process

Approach

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



C . Papagianni, A. Leivadeas, S. Papavassiliou, V. Maglaris, C. Cervello-Pastor and A. Monje, "On the optimal allocation of virtual resources in cloud computing networks", IEEE TCC 2013.

A. Leivadeas, C. Papagianni and S. Papavassiliou, "Efficient Resource Mapping Framework over Networked Clouds via Iterated Local Search based Request Partitioning", IEEE TPDS 2013.

V. Maglaris, C. Papagianni, et al.., "Toward a holistic federated future internet experimentation environment: the experience of NOVI research and experimentation", IEEE Communications Magazine 2015.

S. Papavassiliou, C. Papagianni, I. Baldine, Y. Xin, Technical Report, Resource Management and Topology Embedding in Distributed Networked Infrastructure Environment, TR-2016, DOI: 10.13140/RG.2.1.4722.6961

Conclusion

- SDN / NFV key enabling technologies for 5G
- The evolution of 5G is linked to the emerging Internet of Things (IoT).
  - 5G will power the IoT
- 5G and IoT are essential for CPS, Net-CPS, Net-HPCS
  - Communication networks supporting Net-CPS should be flexible to changing operating conditions (5G and IoT will be used extensively)
  - SDN / NFV key enabling technologies
  - 5G can be the solution for many verticals like smart cities etc.
- Resource allocation facilitating network slicing in 5G and IoT is essential albeit challenging
  - Needs to meet the requirements of 5G use case scenarios

Thank you!

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Questions?