Future Information Network as Large-Scaled Complex Adaptive Systems

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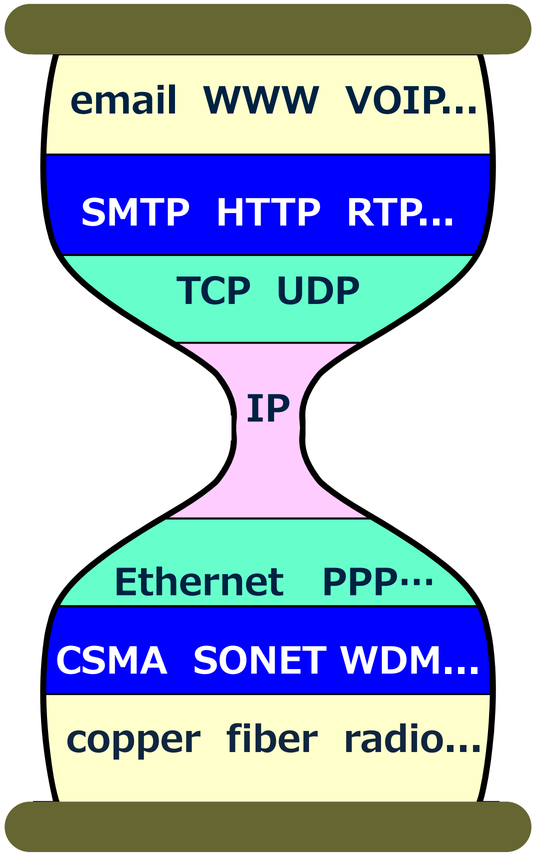
Content

- Why bio-inspired network control?
- Future trends of the information network and next ten years
  - Why we need bio-inspired approaches again?

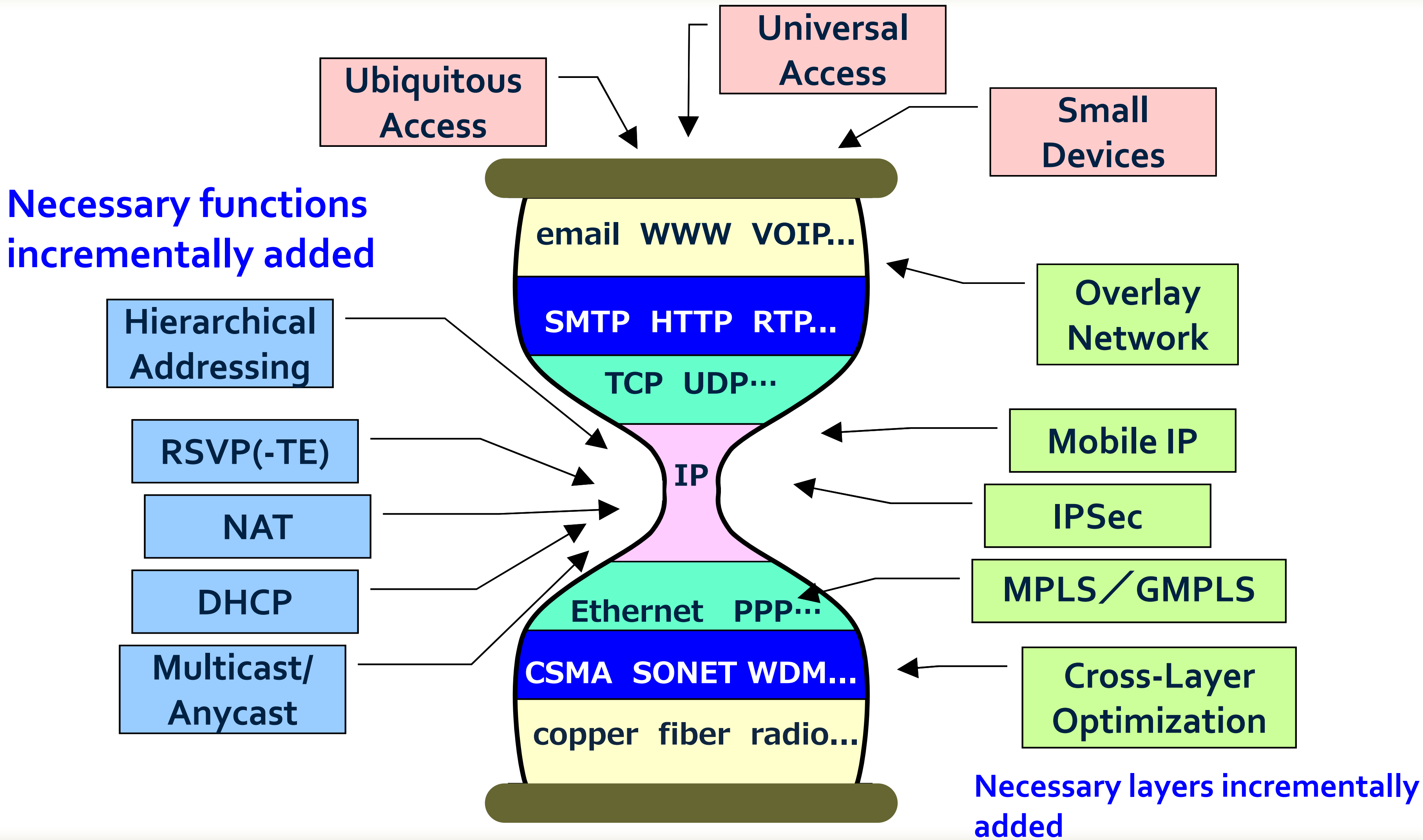
Why IP Succeeded?

- Hourglass Paradigm
  - Everything on IP, IP on Everything
- KISS Principle
  - "Keep It Simple, Stupid" by David S. Isenberg
  - Today's optimization is tomorrow's bottleneck
- Simple network layer: service is realized at the end-hosts
  - Reachability or connectivity
  - Adaptable to unpredictable new applications
  - Source of disruptive innovation

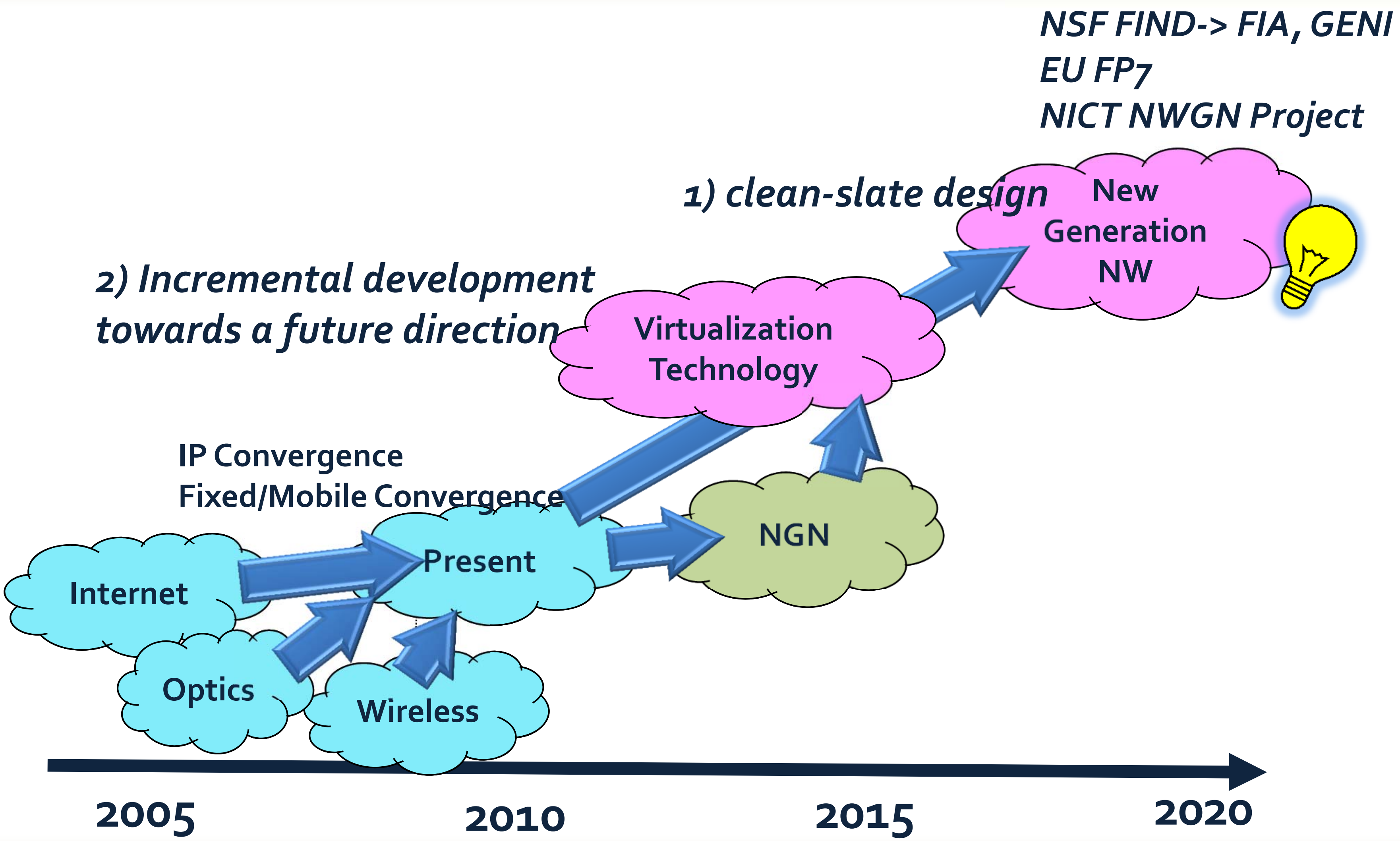


Hourglass Paradigm by Deering

IP is Really Simple?

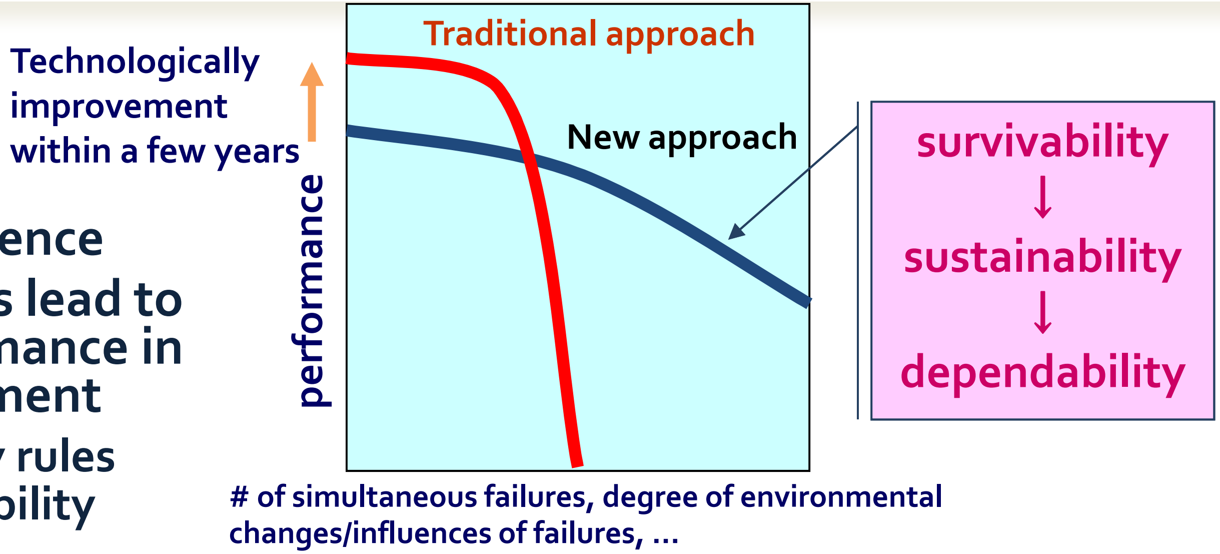


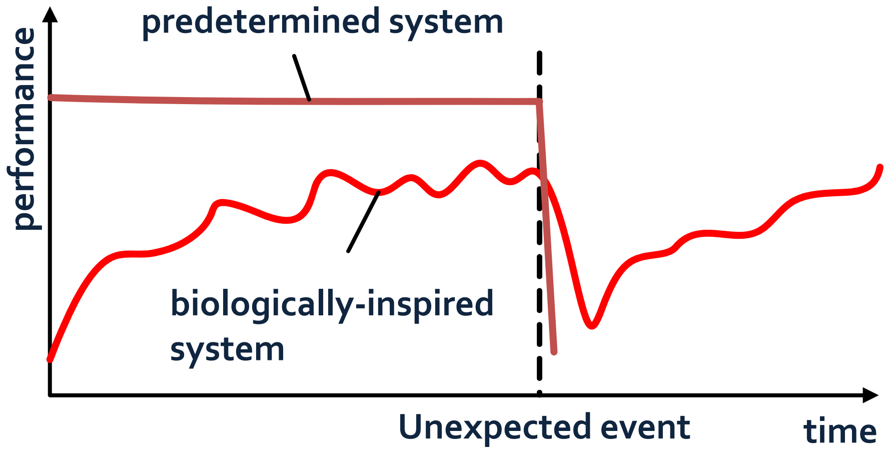
How to Reach "New Generation Network"



New Design Principle: Bio-Inspired Approach

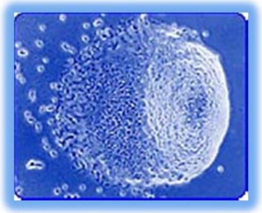
- Robustness and resilience
- Preprogrammed rules lead to more optimal performance in an expected environment
  - However: too many rules easily cause a scalability problem
- Self-organized methods inspired from biology can improve the performance even when unexpected events occur





Bio-inspired Examples based on Swarm Intelligence and Others

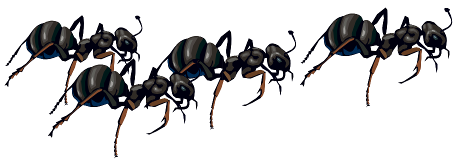
- Swarm Intelligence
  - A group exhibits an intelligent and organized behavior without any centralized control, but with local and mutual interactions among individuals
  - The behavior is adaptive to changes in the environment
  - A group keeps working even if a part fails



Symbiosis of different cells, organisms, groups, and species
overlay network symbiosis

Synchronized flashes in a group of fireflies
→ Pulse-coupled oscillator model
→Waveform synchronized data gathering in sensor networks

pattern formation on an emperor angelfish
→Reaction-diffusion model
→congestion control for video transmission



Foraging behavior of ants
→Scalable ant-based routing scheme

Lotka-Voltera model based on ecosystems
→Scalable congestion control for transport layer protocol

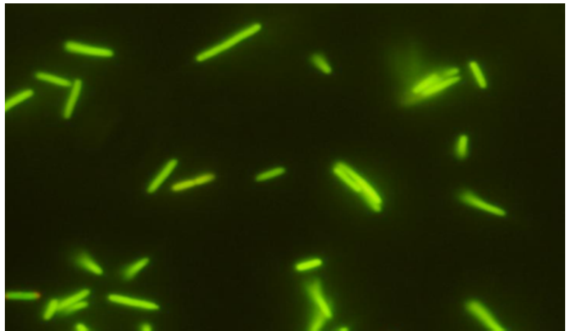
Division of labor
→Response threshold model
→Adaptive task allocation

Adaptive response of E.Coli cells to the availability of a nutrient
→Attractor selection model
→multipath routing, cognitive networks, IP over WDM networks, manet routing

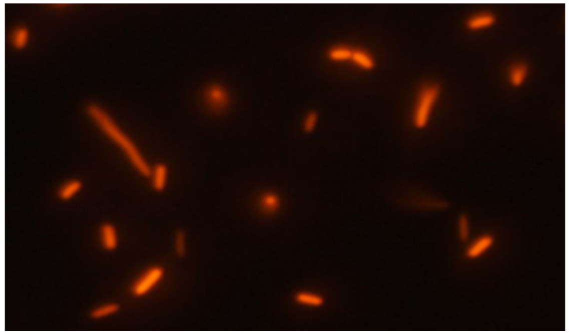
For detailed information, visit at http://www.anarg.jp/

Adaptation to Environment by Thermal Fluctuation in Gene Expression (Cell level *Yuragi*)

Environment1 ← Environmental change ← Original environment → Environmental change → **Environment2**



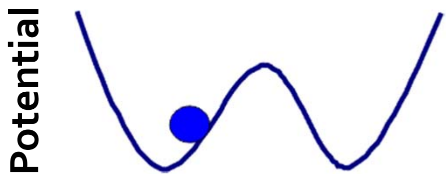
Glutamine deficiency



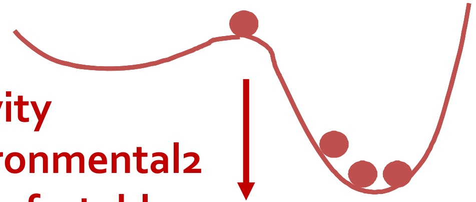
Tetrahydrofolate deficiency

Activity
Enviornemnt1
is comfortable

Attractor1



Attactor1 Attrator2



Activity
Environmental2
is comfortable

Attractor2

Attractor Selection or *Yuragi (fluctuation-based)* formula

$$\frac{d}{dt}x = f(x)\cdot activity + \eta\,, \quad \text{where } f(x) = -\frac{dU}{dx}$$

- **Selects the best situation (attractor) by maximizing activity (*Yuragi* search) in the gene expression**

A. Kashiwagi, I. Urabe, K. Kaneko and T. Yomo, "Adaptive Response of a Gene Network to Environmental Changes by Fitness-induced Attractor Selection," *Plos ONE, vol. 1, no. 1, e46*, Dec. 2006.

Self-organization Control

- Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components.
- The rules specifying the interactions among the system's constituent units are executed on the basis of purely local information, without reference to the global information.
- It is an emergent property of the system rather than a property imposed upon the system by an external ordering influence.

E. Bonabeau, M. Dorigo, G. Theraulaz, Swarm Intelligence: From Natural to Artificial Systems, Oxford University Press, 1999.

Four principles of self-organization

Positive feedback: permits evolution and promotes creation of structure (reinforcement)

Utilization of inherent randomness and fluctuations

Direct or indirect interaction among individuals

Negative feedback: regulates influences from previous bad adaptations (saturation, competition)

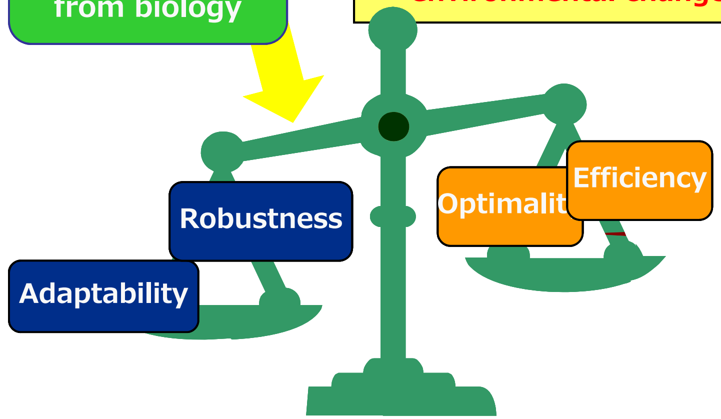
Characteristics of Information Networks

- Environmental changes
  - the # of users
  - Network resources
  - Traffic load

Self-organization inspired from biology

Conventional Approaches

- Predict future events and prepare an optimal solution for each environment
  →Optimal solution by centralized approach
  →Lead to explosion of states
- Meta-heuristic approaches
  GA (Genetic Algorithm), NN.
  SA (Simulated Annealing)
  →Use probability to escape from local optimum
  →Do not consider environmental changes



Network is still growing

- From ubiquitous to "network of things"
  - Ubiquitous network
    - "Anytime, Anywhere, Anyone"
    - Still developed in individual fields, including disaster treatment, healthcare, environment, transportation, life, entertainment, etc.
  - Network of things (or "Internet of Things"), or Network of Information
    - "Machine to machine communication"
    - Make "everything" have communication capability
- Content Centric Network (CCN) or Information Centric Network
  - NSF FIA Projects (Named Data Networking, Mobility First, Nebula, eXpressive Internet Architecture, Sept. 2010 – August 2013)
    - Destination address is "content name"
    - Contents are stored or cached near users
    - Network is adaptive to users' requirements

↓

    - Name based Routing, Storage Aware Routing, and/or In-Network Processing

CCN (Content Centric Network)

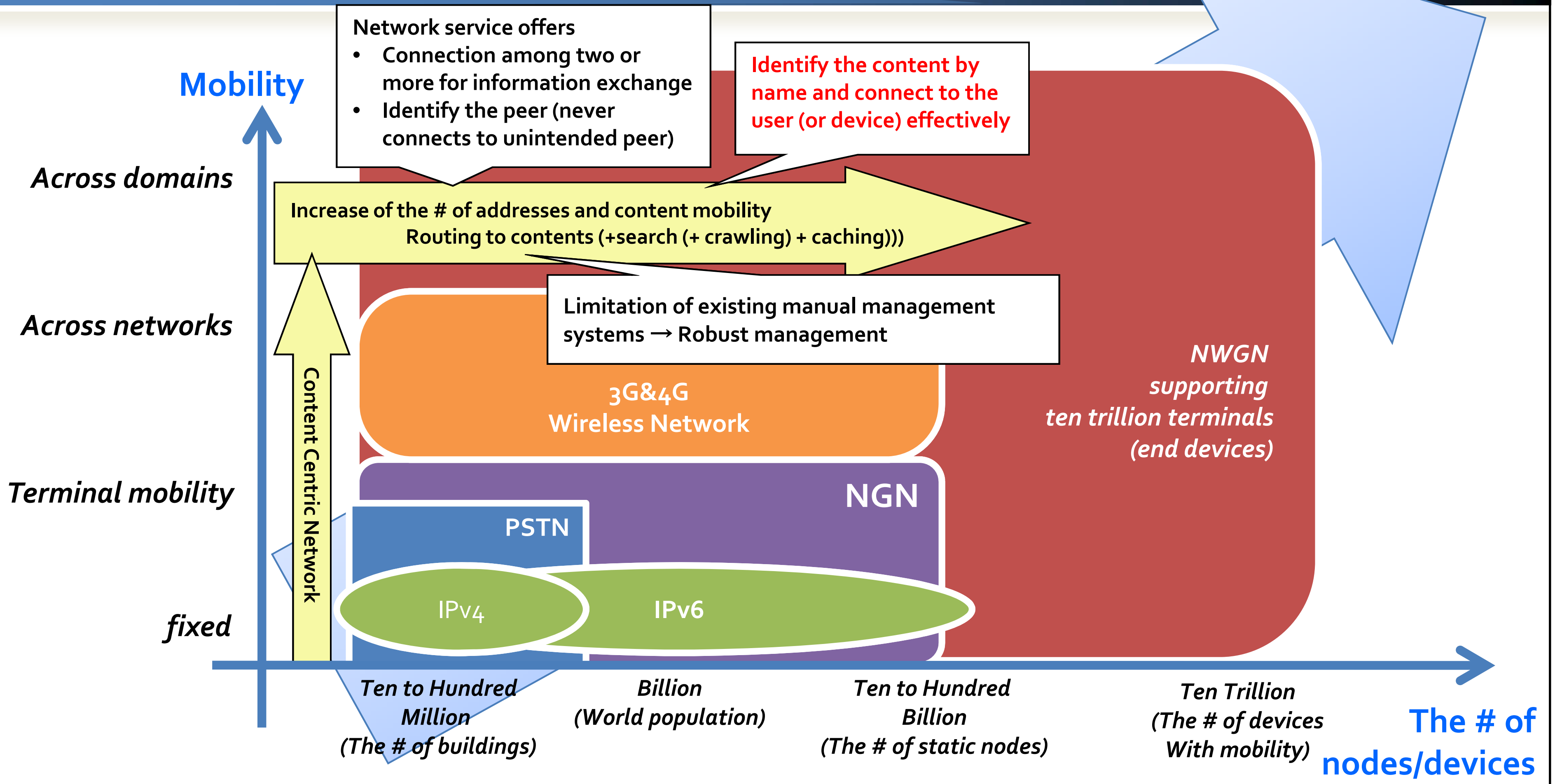
Design Principles
- Support multiple and new business models
- Simplicity
  - "Keep It Simple, Stupid" by David S. Isenberg

  →"Make everything as simple as possible, but not simpler," by Albert Einstein
- Sustainability, Scalability and Robustness
- Loose coupling
  - As things get larger they often exhibit increased interdependence between components

Merits
- Content could be stored/cached closer to the end users
- Routers could identify/analyze what content is flowing through them
- Network could dynamically identify what is the best path to the user
- Content could be interactively adapted
- Content could be selected and adapted to the context
- Content could be active instead of static

SRC: EC Future Content Networks Group, "Why do we need a Content-Centric Internet? Proposals towards Content-Centric Internet Architectures," White paper.

What will happen in 2020?



- Support several ten trillion moving devices; Mobile IP has a limitation
- Information itself may move; We cannot use a conventional crawling technique
- Routing by names of "information"

SRC: NICT New Generation Network R&D Project

In My View, Future Network Is …

Quite Huge

- In terms of # of users, end hosts, applications, and services
- Network of Things: No longer "hosts", but sensors and actuators are connected to the network

Complicated

- Wide variety of application/ service requirements
- M2M = Automatic control loop
- In-network processing

Diversified

- Wide variety of application/service requirements
- Wide variety of technologies

More Dynamic in Time and Space

Large-scaled Complex Information Networks

Complexity in time
- Deployments of various competing technologies
- Diversified application/services
- Mobility
- Information environments: Control loop from sensors to actuators

Complexity in space
- Various terminals
- The number of terminals/devices
- Various technologies
- Fast deployments of new services/applications
- Mobility
- From hosts to contents

- Traditional approach: Detailed analysis of composition of entire systems, and then component design
- New design principle apart from reductionism?

Complex adaptive systems
- Design the system including synthesis parts

Self-organized control
- Each element gets feedback from the entire system to emerge against the current environment autonomously.

For large-scaled complex adaptive systems

As science

- Interaction among network components?
- Interactions among different space and time scales?

As engineering

- New architecture, design methods, control methods for large-scaled networks?
- Control methods against not so different time scales and space changes?

Metrics

Adaptability (Sustainability)

- Adaptable to environments, services, …

Predictability

- Predictable to uncertain environments

Evolvability

- Evolvable to unpredictable growth

Scale-free/Small-world properties

The Internet is a distributed system; large-scaled and complex

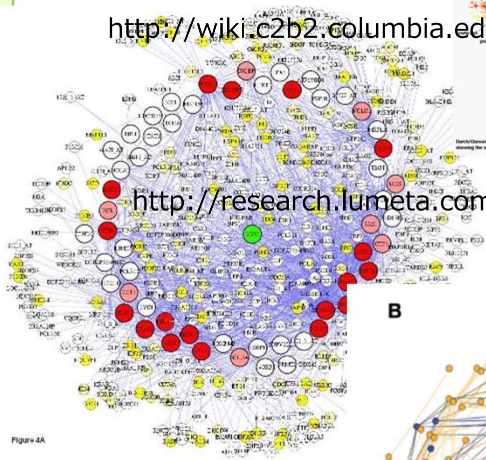
- We cannot say it is designed based on basic researches
- "The Internet is now far from the system that we can design and control."
- Still, it is managed and operated anyway
- Nevertheless, it follows the power-law
- Is it just a phenomenon or logical consequence?

Spatial property

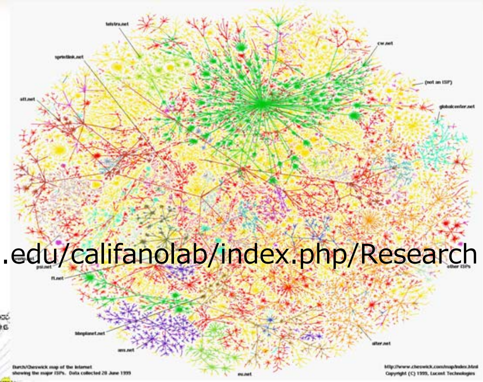
- Scale-freeness or small-world
- Structural analysis -> Engineering

Time property

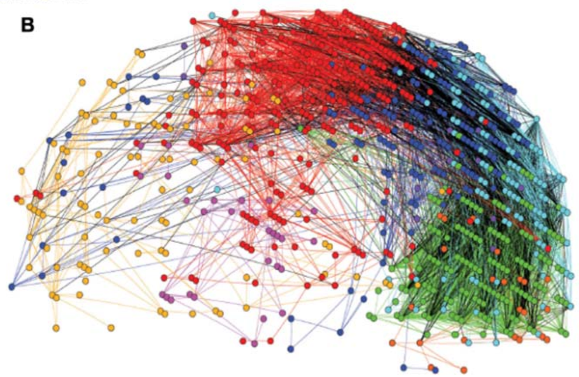
- So-called system dynamics
- Evolution based on attractor (basin) theory
- Information flow control



http://wiki.c2b2.columbia.edu/califanolab/index.php/Research

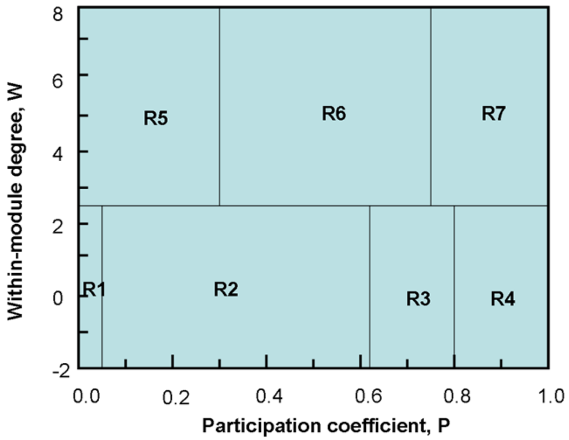


http://research.lumeta.com/ches/map/gallery/index.html



by David Meunier, et a
Brain Functional Netw
neuroinformatics (200

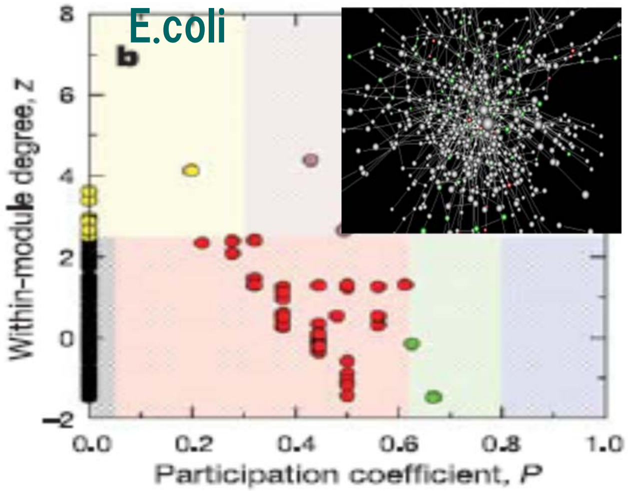
Characteristics of Biological Networks



R1: Ultra peripheral
R2: Peripheral
R3: Non-hub connectors
R4: Kinless nonhub
R5: Provincial hubs
R6: Connector hubs
R7: Kinless hubs

SRC: Guimera R, Luis LAN, "Functional cartography of complex metabolic networks," Nature, Vol. 433, No. 7028. (24 February 2005), pp. 895-900.

- Participation coefficient, *P* [0 ≤ *P* ≤ 1]
  - The ratio that a node is connected to the nodes within other modules.
- Within-module degree, *W*
  - The variance of the degree distribution of the module that a node belongs to



Brain functional network

Transcriptional network

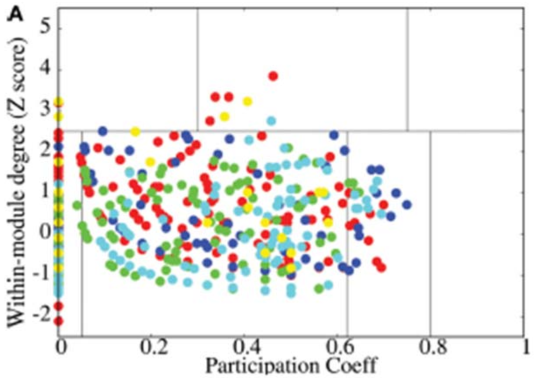
[Carro2010] M. Carro, et. al., "The transcriptional network for mesenchymal transformation of brain tumours," Nature, Jan. 2010.

[Bhardwaj2010] N. Bhardwaj, et. al., "Analysis of diverse regulatory networks in a hierarchical context shows consistent tendencies for collaboration in the middle levels," PNAS, April 2010.

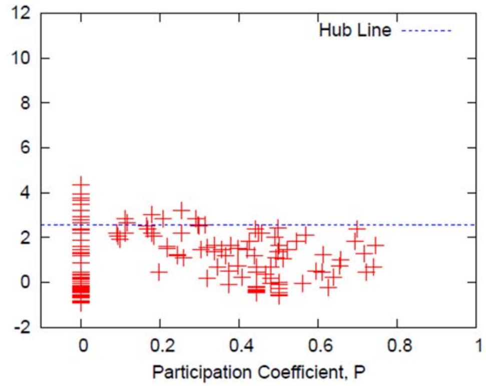
Topological Properties

SRC: Guimera R, Luis LAN, "Functional cartography of complex metabolic networks," Nature, Vol. 433, No. 7028. (24 February 2005), pp. 895-900.

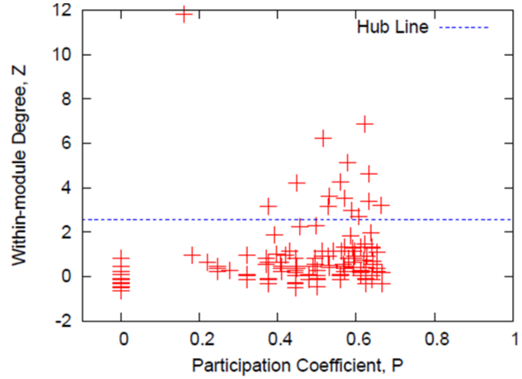
Brain functional network [Meunier2009]
modularity 0.5 - 0.6



AT&T router-level topology
Modularity 0.89



Artificial topology (BA)
Modularity 0.63



- Information networks have different values?

Modulairty or Clustering?

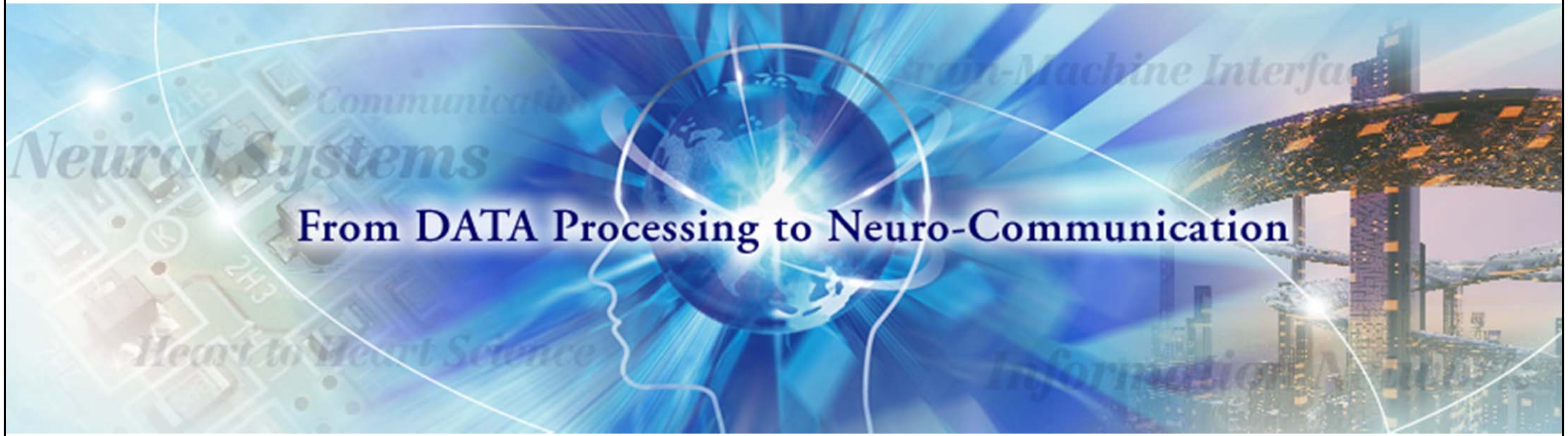
Topological design robust against network growth?

brain has robustness, evolvability, energy-efficiency, …

- The number of links having higher variability of packet flows can be reduced ← Sustainability
- How to build the topology for growing networks even with unpredictable traffic changes? ← Evolovability
- That is, how to determine the capacity against the traffic growth which is often unpredictable? ← Predictability

Center for Information and Neural Networks (CiNet)

- **Co-established by National Institute of Information and Communication Technologies, and Osaka University**
- **Measurement, HHS, BMI, and BFI**



http://cinet.jp/english/index.html

Thank you for your attention

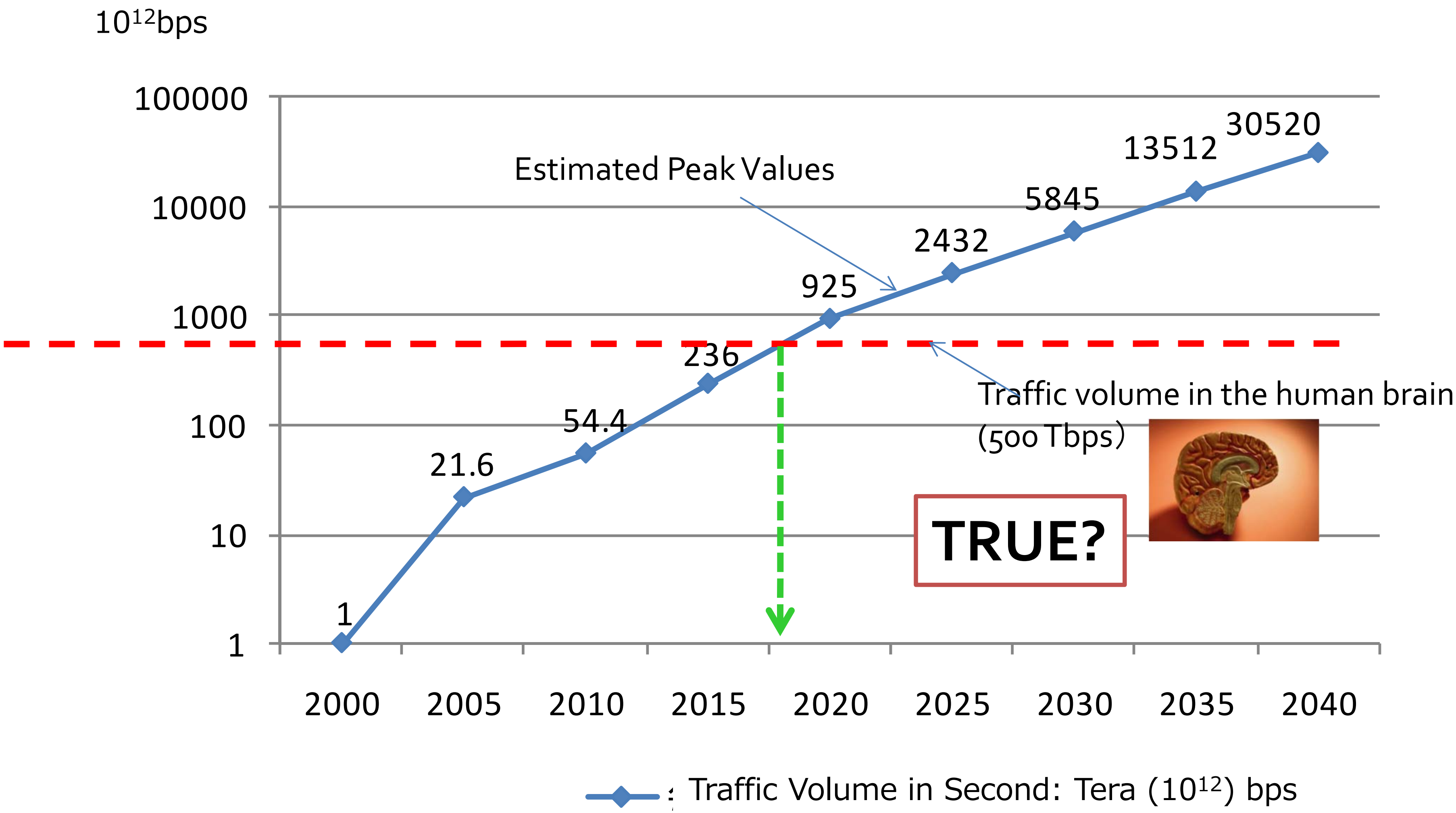
- Contact e-mail: murata@ist.osaka-u.ac.jp
- Related URLs
  - Advanced Network Architecture Lab., Osaka University
    - http://www.anarg.jp/

What are targets in future networks?

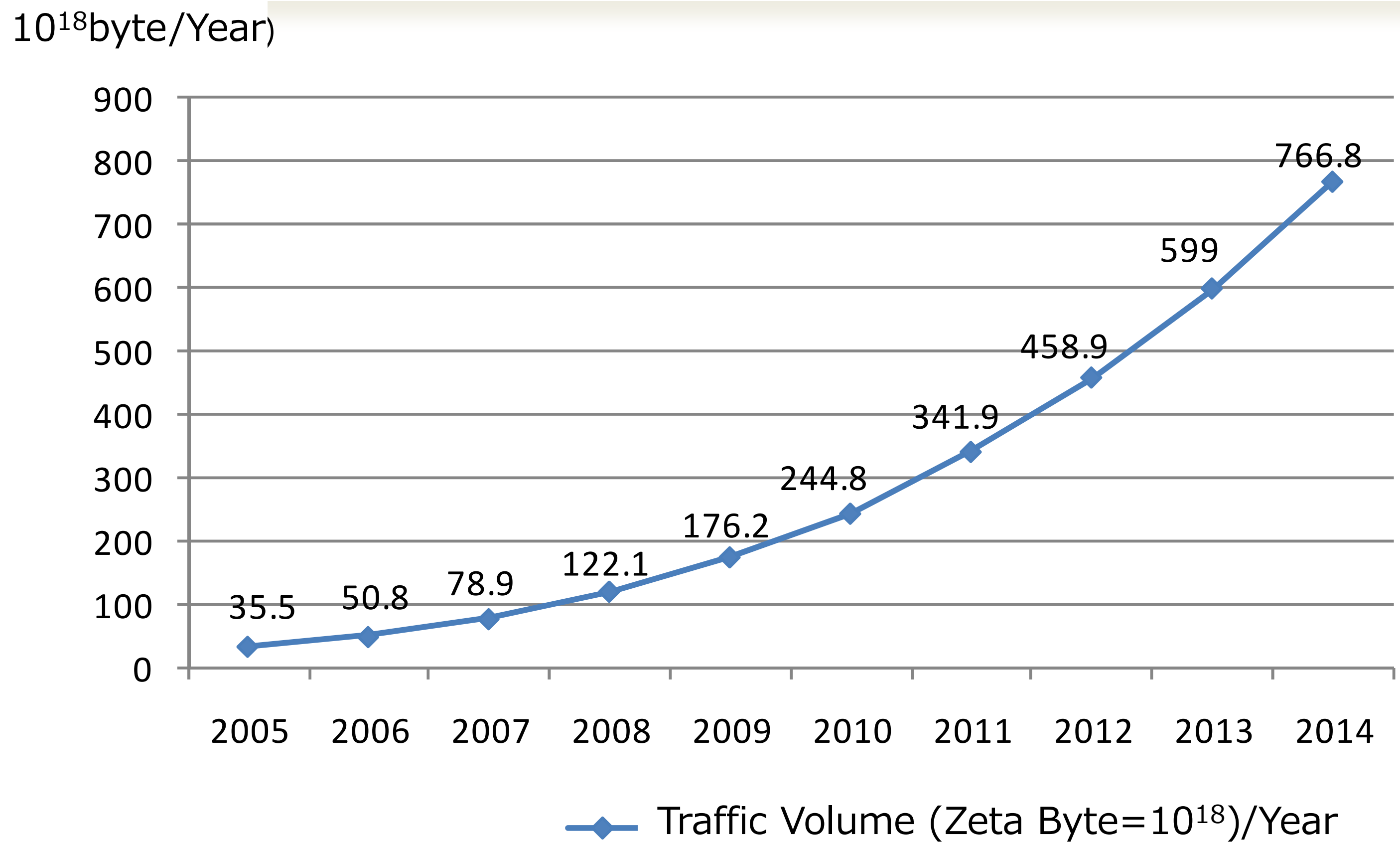
- From quantity to quality
  - At least, efficiency (throughput or link utilization) is not a target

- Manageability
- Availability
- Reconfigurability
- Adaptability
- Reliability
- Dependability
- Sustainability
- Resilient
- Predictability
- Evolvability

Estimated Broadband Traffic Volume in the World



Estimated/Projected IP Traffic Volume in the World



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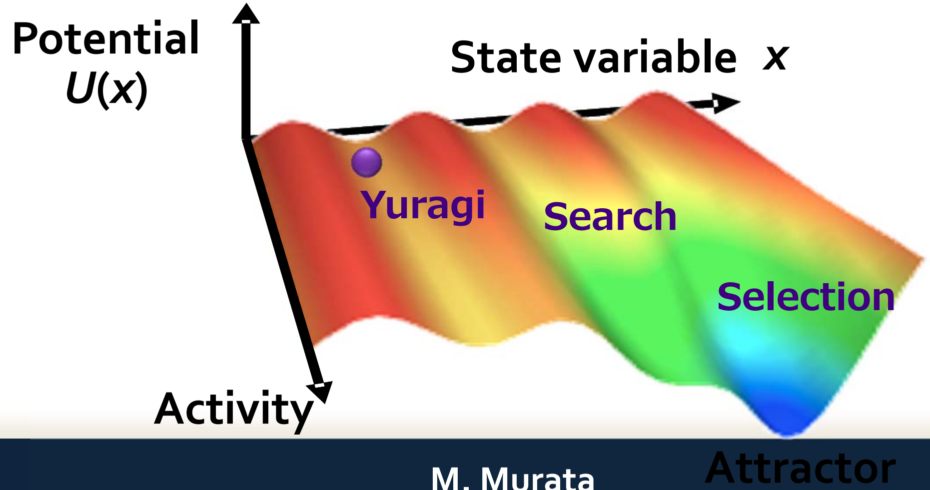
http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360.pdf より作成

Interpretation of *Yuragi* Formula

$$\frac{d}{dt}x = f(x)\cdot activity + \eta$$

The control structure that has attractors Structure that accepts use of Yuragi $f(x) = -dU/dx$	Condition of the system Degree of comfortable feeling	Thermal fluctuation, Spontaneous fluctuation Structure of Yuragi

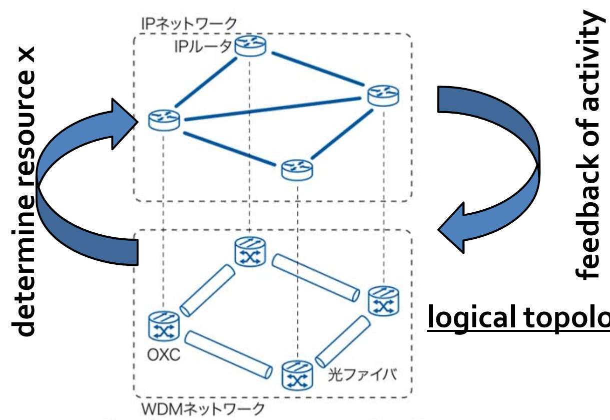


Applications of Attractor Selection Model

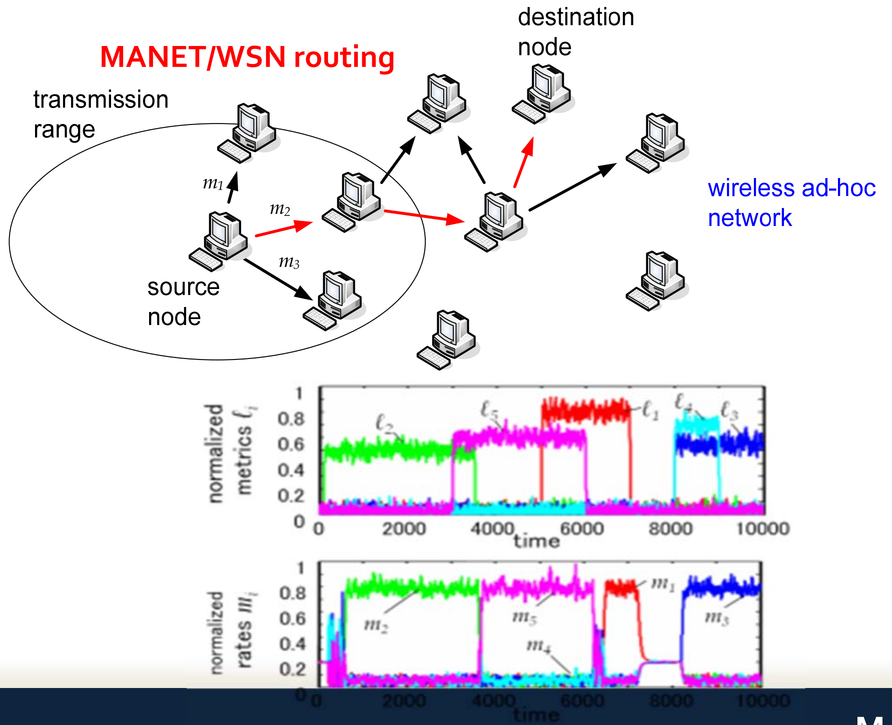
- Adaptable to dynamically changing environment without a priori knowledge and preprogrammed adaptation rule
- We only need to define
  - potential function to define attractors
  - activity to express the goodness of control

$$\frac{d}{dt}x = f(x)\cdot\alpha + \eta$$

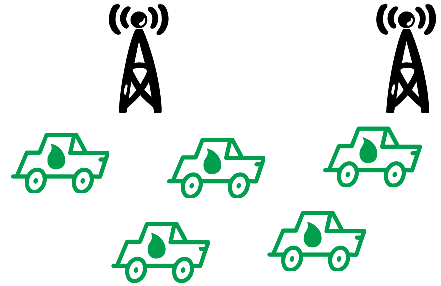
IP over WDM Network



MANET/WSN routing

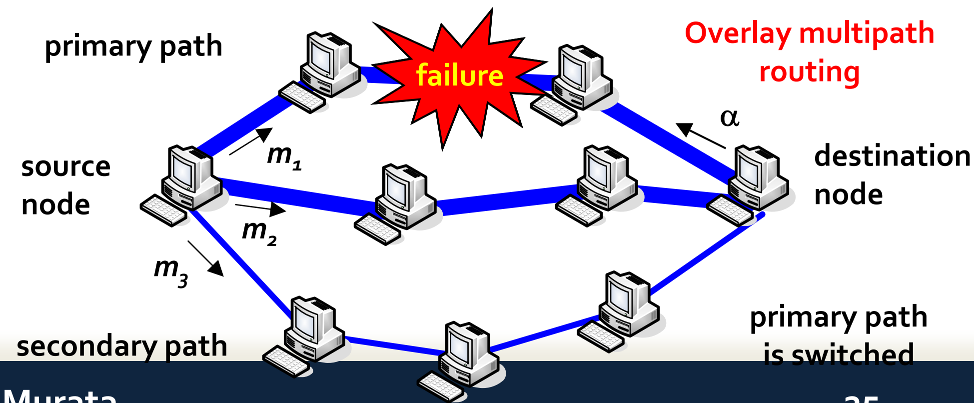


cognitive network

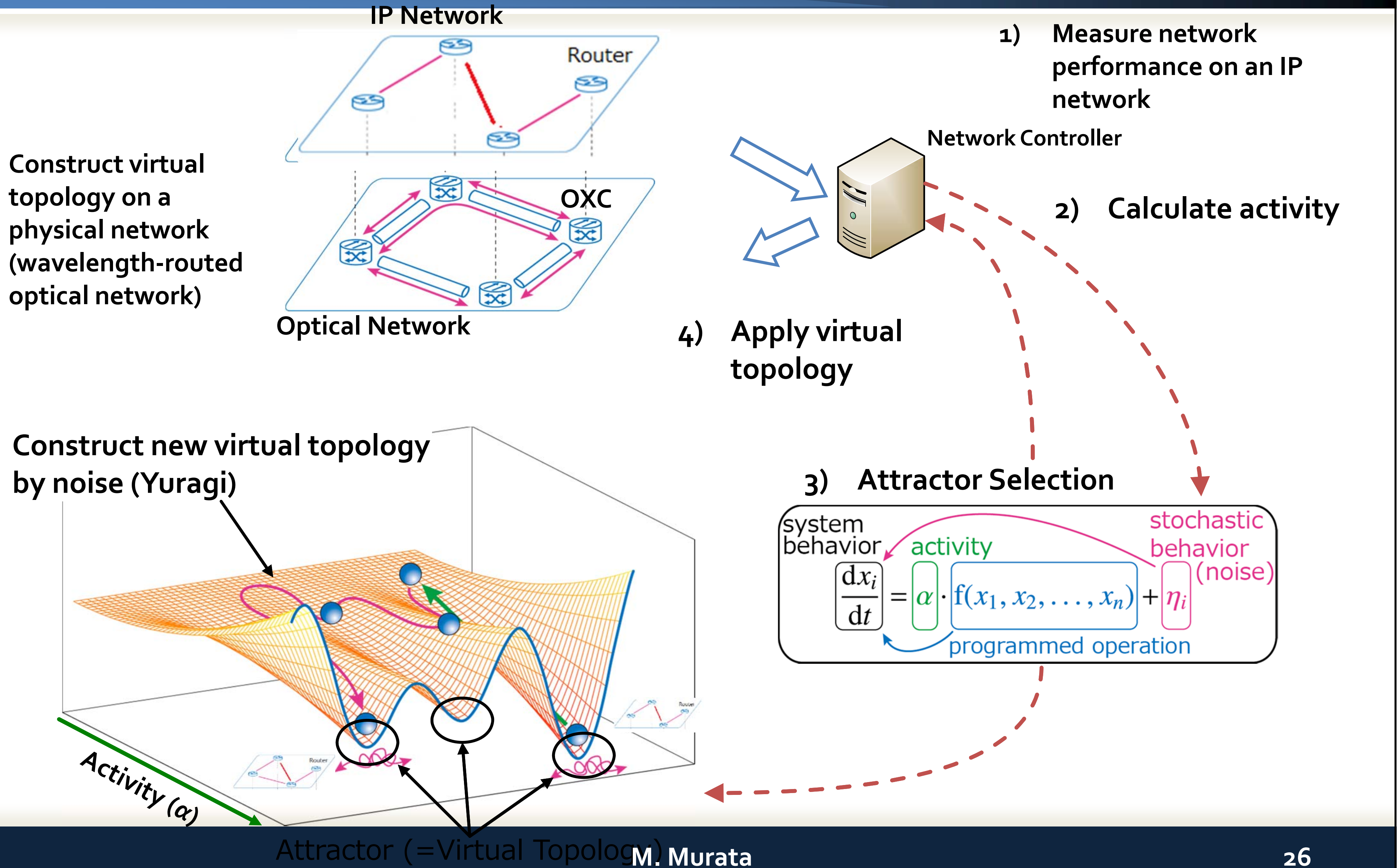


dynamically, adaptively, and autonomously share wireless media and spectrum

Overlay multipath routing



Application to IP/Optical Integrated Networks



Criticisms of Self-Organization

1. "Emergent behavior means that we cannot know the final result. It cannot be used in the operational system."
   - It is just a theory of reductionism.
   - More important is that we build the entire system
2. "We cannot use guaranteed system in business."
   - It is just an illusion that the real system is guaranteed.
   - Everything goes well if we don't have unexpected events.
3. "We need a manageable network."
   - Perhaps, they point out different time-scale issues.
   - But, we have an idea anyway.
4. "We need to have a evaluation method."
   - It's true. Currently, simulation is a only valid tool.
5. "We need to have a design methodology for the entire system.
   - Yes. Perhaps, we will have a layered system, but we have not yet known how to layer the system, how to combine those, etc.

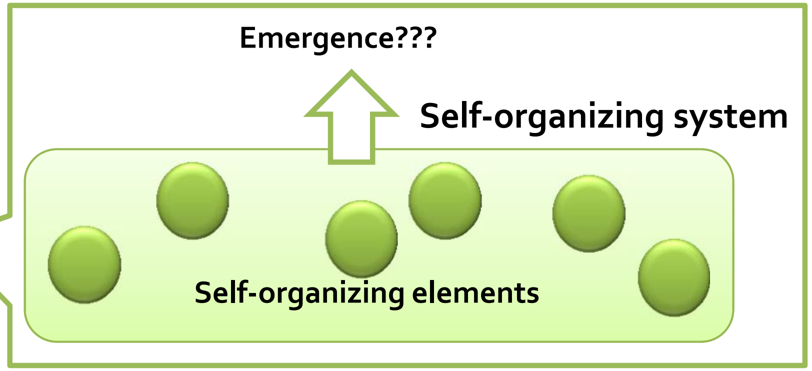
"Managed" Self-Organizing System

Autonomous System

The system can adapt to changing operating conditions and disturbances

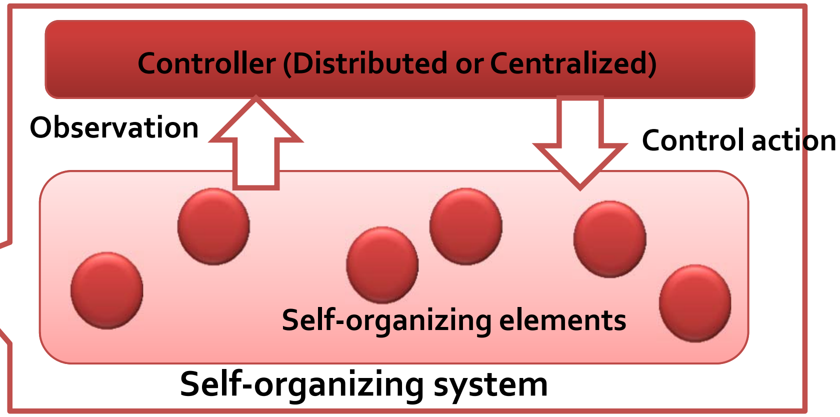
Self-Organizing System

Has an ability to operate in a dynamically changing environment without centralized control. We expect an "emergent behavior" which is often unpredictable

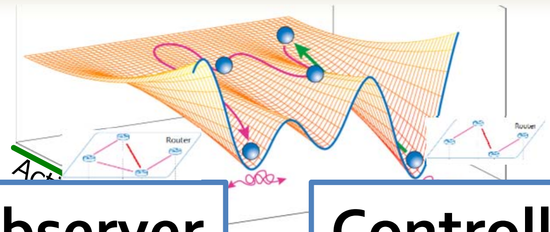


Managed Self-Organizing System

Provides a range of operating regime by an external control while allowing a self-organization property



Managed SOS in IP/Optical Network

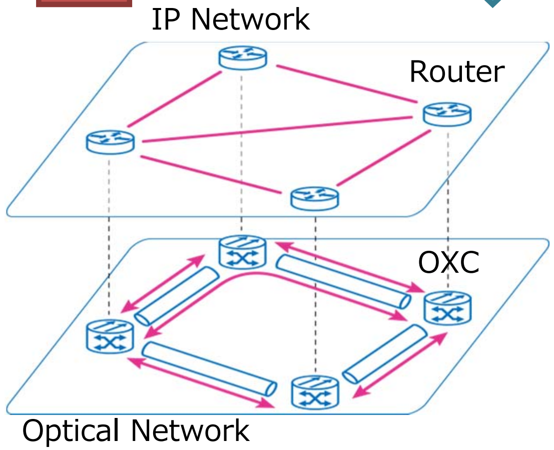


Observer **Controller**

α

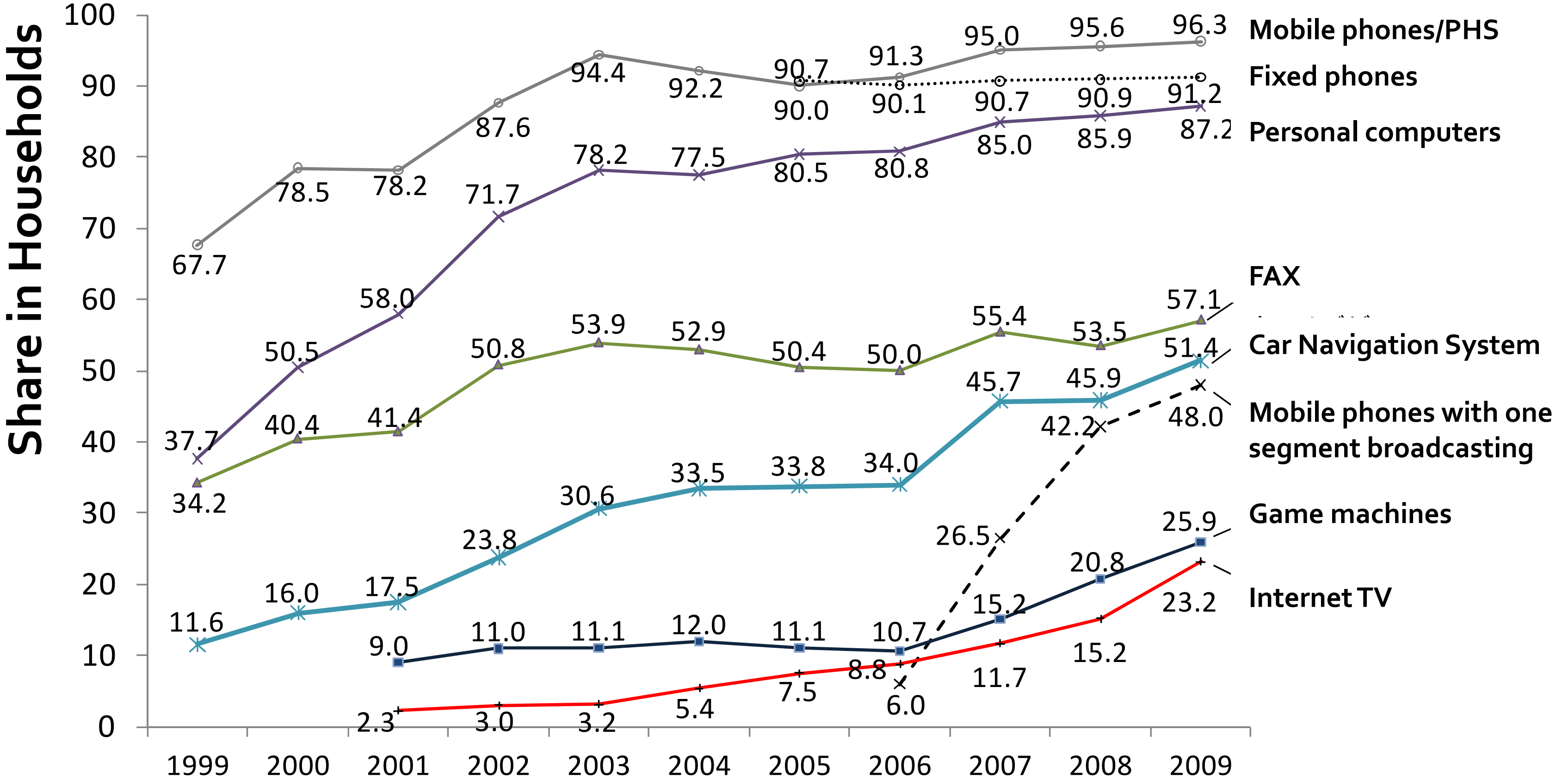
$$\frac{d}{dt}x = f(x)\cdot\alpha + \eta$$

Traffic



Target System

Growth of the #'s of Information Devices in Japan

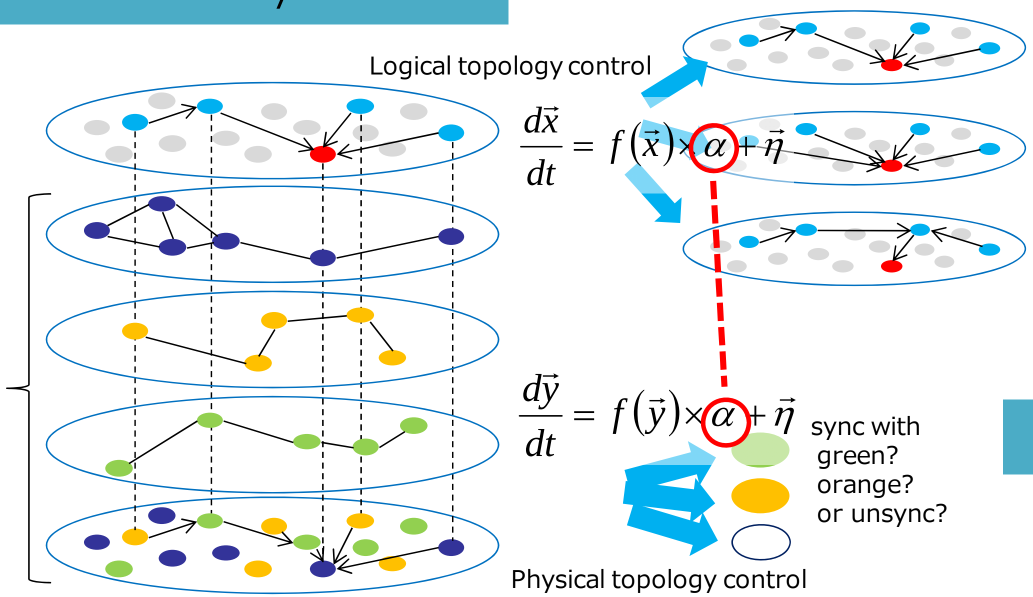


SRC: http://www.soumu.go.jp/main_content/000064217.pdf

Interaction among Intra/Inter Layers

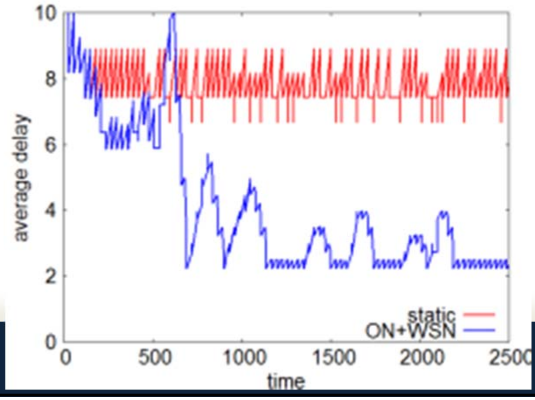
- **Multiple networks cooperative with each other to maximize global activity (share the same goal)**

Sensor-overlay network



$$\frac{d}{dt} x_i = f(x_i) \cdot \alpha + \eta_i$$

$$\frac{d}{dt} x_j = f(x_j) \cdot \alpha + \eta_j$$



Cooperative overlay routing