Future Information Network as Large-Scaled Complex Adaptive Systems

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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?

Necessary functions incrementally added

- Ubiquitous Access
- Universal Access
- Small Devices

Necessary layers incrementally added

- Overlay Network
- Mobile IP
- IPSec
- MPLS/GMPLS
- Cross-Layer Optimization

Layers of the Internet Protocol (IP):

- TCP
- UDP
- Ethernet
- PPP
- CSMA
- SONET
- WDM
- copper fiber
- radio

Protocols:

- SMTP
- HTTP
- RTP

Specialized Protocols:

- RSVP
- TE
- NAT
- DHCP
- Multicast/Anycast

- Hierarchical Addressing

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How to Reach “New Generation Network”

1) clean-slate design

2) Incremental development towards a future direction

- Virtualization Technology
- NGN
- IP Convergence
- Fixed/Mobile Convergence
- Optics
- Wireless
- Present
- Internet

- NSF FIND -> FIA, GENI
- EU FP7
- NICT NWGN Project

2005 2010 2015 2020
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

The diagram illustrates the comparison between traditional and new approaches:

- Traditional approach: Technologically improvement within a few years leads to a decrease in survivability, sustainability, and dependability.
- New approach: A biologically-inspired system can maintain performance even when unexpected events occur.

The chart shows:
- Survivability, sustainability, and dependability decreasing over time for the traditional approach.
- Performance remaining relatively stable for the new approach even after an unexpected event.

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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-Volterra 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)

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

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

**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.


**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)

**Features of Information Networks**
- Environmental changes
  - \# 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
### 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?

Network service offers
- Connection among two or more for information exchange
- Identify the peer (never connects to unintended peer)

Increase of the # of addresses and content mobility
Routing to contents (+search (+ crawling) + caching))

Limitation of existing manual management systems → Robust management

Identify the content by name and connect to the user (or device) effectively

3G&4G Wireless Network

NGN

PSTN

IPv6

IPv4

Ten to Hundred Million
(The # of buildings)

Billion
(World population)

Ten to Hundred Billion
(The # of static nodes)

Ten Trillion
(The # of devices With mobility)

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
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?

- Adaptability (Sustainability)
  - Adaptable to environments, services, ...

- Predictability
  - Predictable to uncertain environments

- Evolvability
  - Evolvable to unpredictable growth
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

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Characteristics of Biological Networks

- Participation coefficient, $P \ [0 \leq P \leq 1]$
  - 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


Topological Properties

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?
  - brain has robustness, evolvability, energy-efficiency, ...

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


Modularity or Clustering?
Topological design robust against network growth?

Sustainability
Evolvability
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

Thank you for your attention

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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
- Resilient
- Dependability
- Sustainability
- Evolvability
- Predictability

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Estimated Broadband Traffic Volume in the World

Traffic Volume in Second: Tera (10\(^{12}\)) bps

TRUE?

Estimated Peak Values

Traffic volume in the human brain (500 Tbps)

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Estimated/Projected IP Traffic Volume in the World

Traffic Volume (Zeta Byte=10^{18})/Year

Interpretation of Yuragi Formula

\[ \frac{dx}{dt} = f(x) \cdot \text{activity} + \eta \]

The control structure that has attractors
Structure that accepts use of Yuragi
\( f(x) = -\frac{dU}{dx} \)

Condition of the system
Degree of comfortable feeling

Thermal fluctuation,
Spontaneous fluctuation
Structure of Yuragi

Potential \( U(x) \)
State variable \( x \)
Activity
Yuragi
Search
Selection

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Attractor
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

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

MANET/WSN routing

- determine resource \( x \)
- feedback of activity
- logical topology control
- cognitive network

- dynamically, adaptively, and autonomously share wireless media and spectrum

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Application to IP/Optical Integrated Networks

1) Measure network performance on an IP network
2) Calculate activity
3) Attractor Selection
4) Apply virtual topology

Construct virtual topology on a physical network (wavelength-routed optical network)

Construct new virtual topology by noise (Yuragi)
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

Emergence???
Self-organizing system
Self-organizing elements

Controller (Distributed or Centralized)
Observation
Control action
Self-organizing elements
Self-organizing system

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Managed SOS in IP/Optical Network

Traffic

 Observer

 Controller

 $\alpha$

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

 Target System

 IP Network

 Router

 Optical Network

 OXC

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Growth of the #’s of Information Devices in Japan

Share in Households

Mobile phones/PHS  
Fixed phones  
Personal computers  
FAX  
Car Navigation System  
Mobile phones with one segment broadcasting  
Game machines  
Internet TV

Interaction among Intra/Inter Layers

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

Sensor-overlay network

Logical topology control

\[
\frac{dx}{dt} = f(x) \cdot \alpha + \eta_i
\]

Physical topology control

\[
\frac{dy}{dt} = f(y) \cdot \alpha + \eta
\]

sync with green? orange? or unsync?

Cooperative overlay routing

\[
\frac{dx_j}{dt} = f(x_j) \cdot \alpha + \eta_j
\]

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