Self-organizing Network Architecture
for Scalable, Adaptive, and Robust Networking

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New Generation Network

- Devices distributed/embedded in home/office/town
- Mobile devices on human/vehicles
- Tags and sensors attached to items/objects

- Explosion in the number of network devices
- Diversity and variation in traffic

- Higher scalability and adaptability than ever

- Fully-distributed and autonomous control without need for global information

- Higher robustness than ever

- Combination of simple functional modules

- New generation network architecture based on self-organization principle

- Self-adaptation of algorithm/function/parameter
Self-organization Network Architecture

Node-level self-organization
Node adapt to dynamically changing environment by using non-linear control modules, called SO (Self-Organization) engines

Network-level self-organization
Service overlay network/physical network are self-organized through direct/indirect interaction among nodes

System-level self-organization
Whole system is self-organized through inter-network/inter-layer interaction through mediation of common layer
Self-organization Network Architecture

Network architecture

Node architecture

- obtain information through local observation and message exchange
- non-linear control modules
- application
- overlay communication
- overlay routing
- mediation control
- physical routing
- topology control

- self-organizing network control

physical network

service overlay

Common layer (environment)

overlay node

physical node

local information

SO modules

operating environment

knowledge

communication

Node architecture
Self-organizing Network Architecture

Three layer model
- Service overlay network layer
- Common layer
- Physical network layer

Self-organizing network entities
- Node-level self-organization
- Network-level self-organization
- System-level self-organization

Self-organization by direct interaction among entities within layer
Self-organization by indirect interaction among entities within layer by common layer
Self-organization by interaction among entities between layers through common layer

In-layer
- small change → localized adaptation by nearby entities
- large-scale change → layer adaptation by interaction among entities

Inter-layer
- small physical change → adaptation of physical network
- large-scale physical change → system-level adaptation by inter-layer interaction
Self-organizing Network Control by SO Engines

- Pulse-coupled oscillator model – flashing fireflies
  - sleep scheduling and timing control
- Attractor selection model – no rule adaptation
  - routing
- Response threshold model – division of labor
  - adaptive task allocation
- Reaction-diffusion model – pattern on animal coat
  - congestion control
  - topology control
Pulse-coupled oscillator model

- synchronization of flashing fireflies
- heterogeneous oscillators reach synchronization

\[
\frac{d\phi_i}{dt} = \frac{1}{T_i} + \sum_{j \in N_i, \phi_j = 1.0} \delta(1 - \phi_j) \Delta(\phi_i) \delta(1 - \phi_i)
\]

\[
\Delta(\phi_i) = \left( e^{b_i \varepsilon_i(\phi_i)} - 1 \right) \left( \frac{1}{e^{b_i} - 1} + \phi_i \right)
\]

- timing control, sleep scheduling
- adaptive communication using travelling wave
- synchronized data gathering
- synchronization through local interaction among neighboring nodes
- entrainment to new synchronization
- scalability, adaptability, robustness
Reaction-diffusion model

Reaction-Diffusion Model
- emergence of periodic patterns on animal coats
- chemical interaction among activator and inhibitor

\[
\frac{\partial u}{\partial t} = F(u,v) + D_u \nabla^2 u, \quad \frac{\partial v}{\partial t} = G(u,v) + D_v \nabla^2 v
\]

activation reaction diffusion

- self-organizing cluster formation
- rate control in camera network
- pattern generation through interaction among neighbors
- scalability adaptability robustness

variety of patterns

energy delay

optimal random R-D clustering
Attractor Selection Model

- adaptation of biological systems to changing environment
- combination of deterministic and random control

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

routing, scheduling

MANET, WSN routing

MANET, WSN routing

overlay multipath routing

MANET, WSN routing

MANET, WSN routing
Combination of Multiple SO Engines

WSN of heterogeneous sensors
- periodic sensing and data gathering in usual condition
- application-oriented sensing adaptive to changes
  - heat: frequent sensing while temperature is changing
  - gas: frequent sensing while gas exists
- sufficient number of sensors should be engaged in sensing
- autonomous control based on local information

Energy-efficient scheduling by PCO model
synchronization of sleep timing

\[
\frac{d\phi_i}{dt} = 1 + \Delta(\phi_i) \delta(\phi_j)
\]
\[
\Delta(\phi_i) = a \sin \frac{\pi}{1-\tau} \phi_i + b(1-\tau-\phi_i)
\]

\(\phi_i\) phase \(\delta\) stimulus from neighbor
\(\Delta\) phase-response \(\tau\) inter-broadcasting period

Adaptive sensing by response threshold model
adaptation of number of sensing nodes in accordance with need for sensing

\[
s_{i,k} = \delta_{i,k}(t) - \alpha \frac{n_{i,k}(t)}{N_{i,k}(t)}
\]
\[
P(x_i = 0 \rightarrow 1) = \frac{s_{i,k}(t)}{s_{i,k}^2(t) + \theta_{i,k}^2(t)}
\]
\[
P(x_i = 1 \rightarrow 0) = p_{i,k}(t)
\]
\[
\frac{d\theta_i}{dt} = \begin{cases} -\xi & \text{if } i \text{ performs frequent sensing} \\ +\phi & \text{otherwise} \end{cases}
\]
\(s_{i,k}\) need for sensing
\(x_i = 1\) frequent sensing, =0 normal sensing
\(\theta_i\) threshold
Self-organization and Scalability/Adaptability/Robustness

**Self-organization**

Global pattern/behavior emerges from interaction among entities which behave in accordance with local information.

**Scalability**

Entities operate on local information; no overhead for global information.

**Adaptability**

Degree of adaptation depends on size/scale/degree of changes.

**Robustness**

Local error does not affect the whole; no dominant entity.

All SO engines are based on biological mathematical models.

Especially, the form of non-linear temporal evolution leads to self-organization.

Contrast between conventional system and self-organization system:
- Conventional system: sequential adaptation based on global information.
- Self-organization system: sequential adaptation based on local information.
Goal of Self-organizing Network Architecture

To establish network infrastructure scalable, adaptive, and robust to large, complex, and diverse network environment.
Thank you