複雑系数理モデル学に基づく
通信システム最適化への新しいアプローチ

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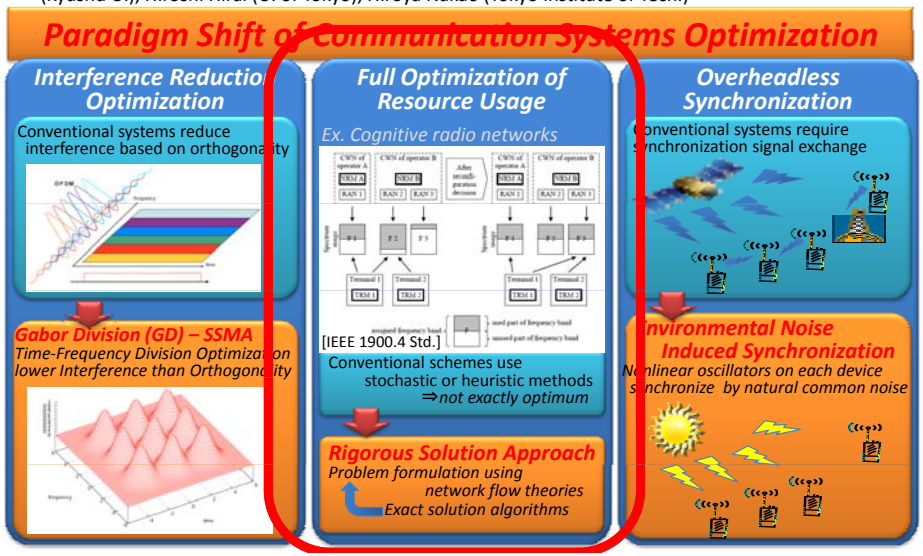
FIRST合原最先端数理モデルプロジェクト



Introduction

- Increasing demand for wireless communications/ capacity, bit rate, etc…
- Increasing of advanced wireless systems, cellular, WiFi, WiMAX, etc.…
- Scarcity of radio resources suitable for mobile communications

  ⇒ *Optimization of radio resource usage is an important issue*

Cognitive Radio Technology

- Spectrum sharing type cognitive radio
- ***Heterogeneous type cognitive radio***

- Radio resource usage optimization approaches in cognitive radio
  - *Fully distributed scheme*
  - *Cooperatively distributed scheme*
  - *Centralized scheme*

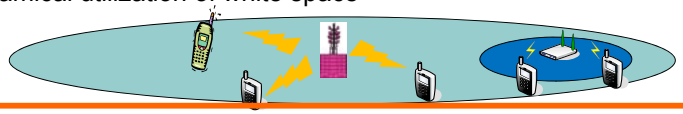
- *Optimization Techniques for cognitive wireless cloud*
  - *IEEE 1900.4 supported*
  - *Learning based / Distributed optimization method / Rigorous optimization method*

Two optimization approaches of Cognitive Radio

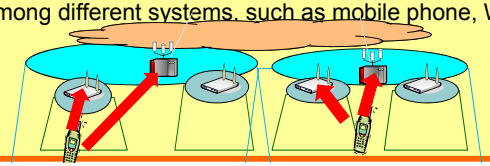
(H. Harada et al., Research and Development on Heterogeneous Type and Spectrum Sharing Type Cognitive Radio Systems, *CROWNCOM*, 2009.)

- Cognitive radio : radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly by collaborating wireless and wired networks

- Spectrum sharing type cognitive radio
  - Dynamical utilization of white space

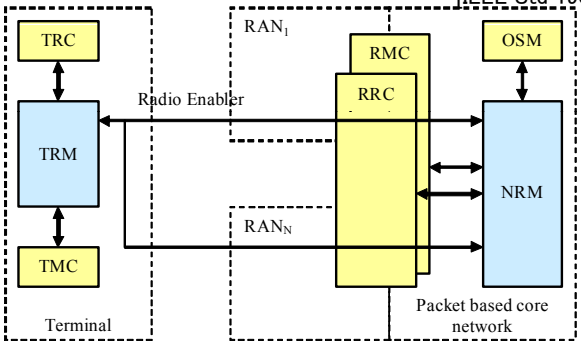


- Heterogeneous type cognitive radio
  - Dynamic optimization of usage of available legacy RANs by selecting most appropriate one, for optimizing QoS, load balancing, ..
    - switching among different systems, such as mobile phone, WLAN, WiMAX …



Cognitive Radio Network Architecture for radio resource usage optimization

- IEEE1900.4
  - Various context information for radio resource usage optimization can be exchanged among the networks and terminals [IEEE Std 1900.4TM–2009]



TRM – Terminal Reconfiguration Manager
TRC – Terminal Reconfiguration Controller
TMC – Terminal Measurement Collector
OSM – Operator Spectrum Manager
NRM – Network Reconfiguration Manager
RRC – RAN Reconfiguration Controller
RMC – RAN Measurement Collector
RAN – Radio Access Network

RAN selection optimization in DRRUO use case of IEEE 1900.4

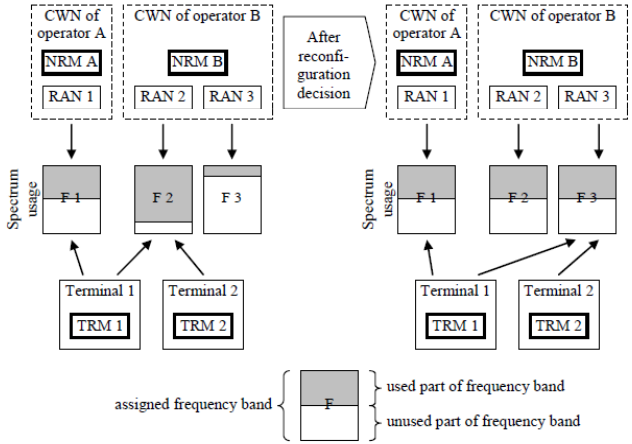
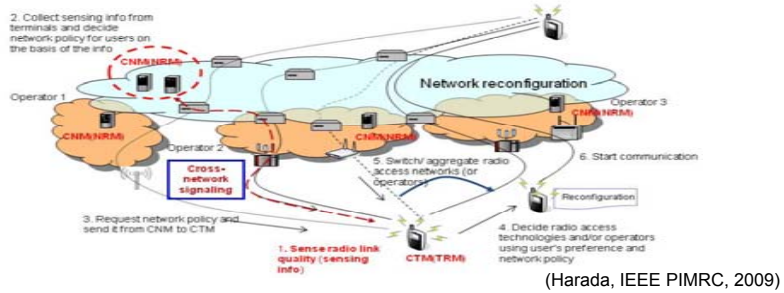


Figure A.7—Distributed radio resource usage optimization
[IEEE Std 1900.4TM–2009]

Heterogeneous type cognitive radio

Cognitive Wireless Cloud (NICT)



(Harada, IEEE PIMRC, 2009)

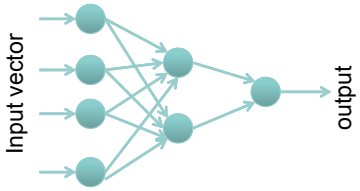
- Distributed Cognitive Radio Network Architecture
  - Signaling network for exchanging various context information
    - Supporting IEEE 1900.4
  - Cross-Network Handover / Heterogeneous Wireless Network Aggregation
- Radio resource usage optimization across various radio access networks
- Feasibility study in Fujisawa, Japan, using 500 cognitive wireless routers

Optimization approaches

- Fully distributed scheme ← NEURAL NETWORK LEARNING
  (no information exchange among terminals)
  - Optimization only by each terminal's decision
    ⇒Optimization of each terminal QoS
  - Optimization of entire networks is not possible
- *Cooperatively distributed scheme* ← NEURAL NETWORK OPTIMIZATION
  (with context information exchang
  - Optimization by terminal decisions with collaborative information exchange
    ⇒*Optimization of entire network's utility is possible (by NN)*
  - Rigorous optimization of entire network is not possible
- *Centralized scheme*
  - Optimization at centralized manager.
    ⇒*Optimization of entire network utility is possible*
  - ***Rigorous optimization of entire network is possible by proposal***

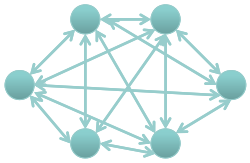
Applications of neural networks for cognitive radio network optimization

- **Learning**
  - Perceptron
  - Back Propagation



Modify connection weights to obtain correct output using training samples

  - SVM
  - SVR
- **Optimization**
  - Hopfield-Tank Neural Network
    - Mutually connected



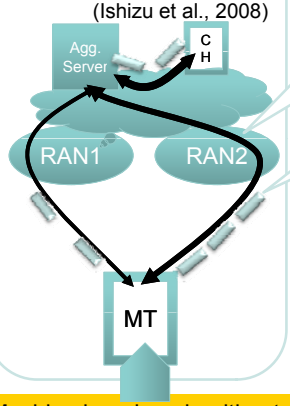
Energy function always decrease by distributed neuron updates

  - Higher-order NN

Throughput maximization by machine learning on Cognitive Wireless Cloud

(Kon, Hasegawa, Ishizu & Harada, IEICE Trans., 2012)

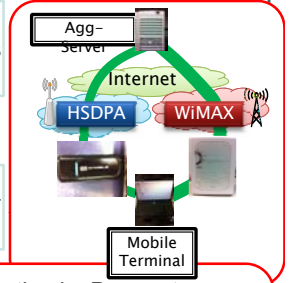
Network aggregation of Cognitive Wireless Cloud (Ishizu et al., 2008)



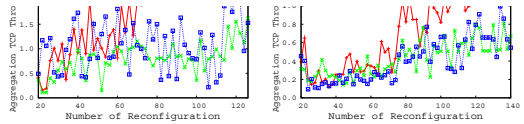
Machine learning algorithm to estimate optimum parameters

Each RAN's QoS is different from others in heterogeneous wireless networks

Aggregation throughput depends on parameters of aggregation system



Throughput maximization by Parameter Optimization using Machine Learning Algorithms



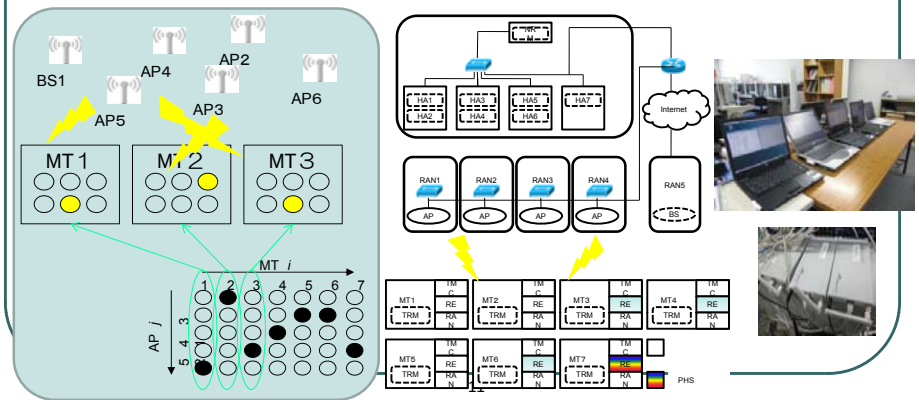
WCDMA + HSDPA WCDMA + WiMAX

Fairness Optimization by Hopfield-Tank Neural Net on Cognitive Wireless Cloud

(Hasegawa et al., IEICE Trans., 2008)

- Optimize entire network without any centralized computation
- Cooperation = exchange context information

Hopfield-Tank Neural Network approach
- Minimize energy function by distributed update of neurons



Optimization approaches

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Objective function for load balance

Minimization of throughput differences among user terminals

Objective function

$$F(\mathbf{L}) = \sum_{k=1}^{m} \frac{1}{T_k} = \sum_{k=1}^{m} \frac{N_{L(k)}}{C_{L(k)}}$$

$L(k)$: Base station, with which mobile terminal k is connecting

T_k : Available throughput for the mobile terminal k

c_j : Total throughput of the base station j

N_j : Number of mobile terminals connecting to base station j

Find optimum $\mathbf{L}$ to minimize $F(\mathbf{L})$

① Whole total of base station total throughput is constant
⇒ total of terminal throughputs is constant

$$\sum_{k=1}^{m} T_k = \sum_{j=1}^{n} C_j = C_{total}$$

② Each base station shares radio resources equally to terminals

$$T_k = \frac{C_{L(k)}}{N_{L(k)}}$$

Increase of the numbers of MT m and BS n, ⇒ combinatorial explosion m^n

Heuristic algorithms
→Not exact optimum

Proposal
Rigorous algorithm

Proposed rigorous optimization scheme for RAN selection [Matsui, **Hasegawa**, et al., 2012 in FIRST P.]

RAN selection problem = combinatorial explosion

Combinatorial optimization problem finding $L(k)$
⇒ Network flow problem find $N(j)$

Modeling the problem as the *minimum cost flow problem*

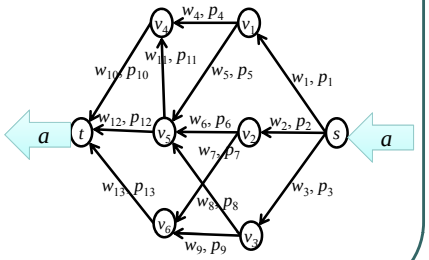
Exactly solvable
[eg. Goldberg, 1997.]

Applying exact algorithm
and rigorous solution of RAN selection can be obtained

Minimum cost flow problem

Given cost of each edge, w_e,
capacity of each edge, p_e, and
amount of flow a, which should be transmitted from s to t,
Minimize $F_{\mathrm{MCF}}(\mathrm{x})$, by finding optimal flow for each edge, $0 \le x_e \le p_e$

$$F_{\mathrm{MCF}}(\mathrm{x}) = \sum_{e \in E(G)} w_e x_e$$



Rigorous solutions can be obtained by,
- RELAX
- NETFLO
- RNET
- **CS** [A .V. Goldberg , J. Algorithms, 22, 1, 1997.]

Modeling RAN selection problem as minimum cost flow problem

Objective function of load balancing

$$F_{\mathrm{OBJ}}(\mathbf{L}) = \sum_{i=1}^{m} \frac{N_{L(i)}}{c_{L(i)}}$$

Find combination $\mathbf{L}$,
which minimize $F_{\mathrm{OBJ}}(\mathbf{L})$

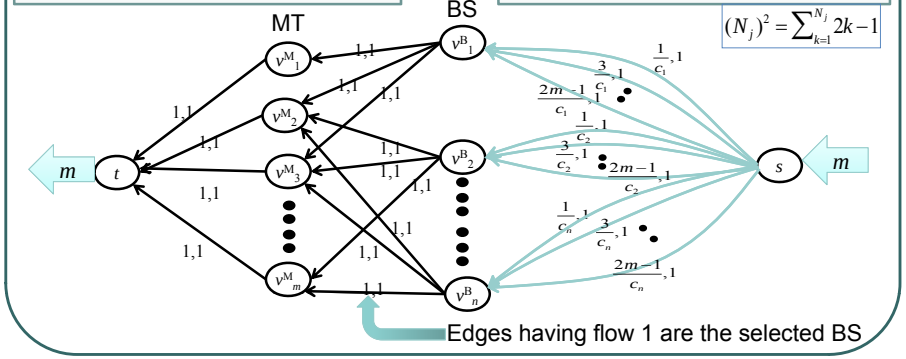
transform
BS shares throughput equally to terminals

Network flow problem

$$F_{\mathrm{OBJ}}(\mathbf{N}) = \sum_{j=1}^{n} \frac{N_j}{c_j} \bullet N_j = \sum_{j=1}^{n} \frac{(N_j)^2}{c_j}$$

Find flow $\mathbf{N}$ for each BS,
which minimize $F_{\mathrm{OBJ}}(\mathbf{N})$

$$(N_j)^2 = \sum_{k=1}^{N_j} 2k-1$$



Edges having flow 1 are the selected BS

Computational Complexity

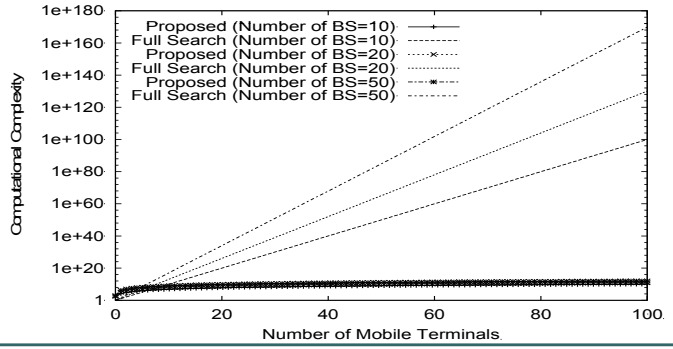
Full Search for obtaining rigorous solution

$$O\left(n^m\right)$$

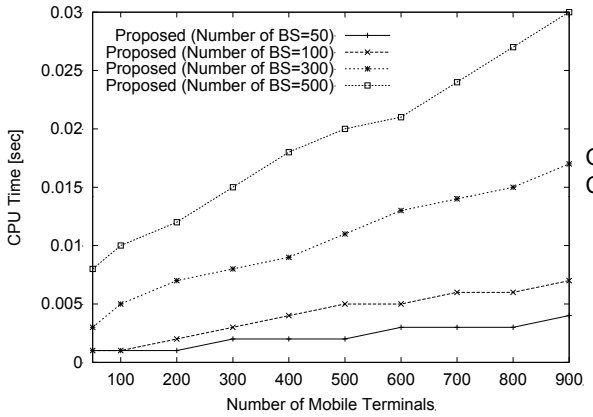
n: Number of base stations
m: number of mobile terminals

Proposed Scheme for obtaining rigorous solution (with Goldberg-Tarjan algorithm)

$$O\left(\left(n+m+2\right)^2\left(2nm+n\right)\log\left(n+m+2\right)\right)$$



CPU time for obtaining rigorous solutions of RAN selection



OS: Solaris 10
CPU: floating point processor 2926 MHz.

Only 0.03 seconds for rigorous solution
even for large-scale network with 500 BSs and 900 MTs

Conclusion

Optimization techniques in our research on cognitive wireless cloud for

- **Fully distributed Cognitive Wireless Networks**
  - Learning algorithm on Mobile Terminals / adaptation
- **Cooperatively distributed Cognitive Wireless Networks**
  - Distributed optimization of objective function of entire network
    - Hopfield-Tank Neural Networks
- **Fully centralized Cognitive Wireless Networks**
  - Optimization problem having Combinatorial Explosion can be rigorously solved
  - Transformation of combinatorial optimization problem to a minimum cost flow problem

Future works

- Design, implementation & testing on real wireless networks
- Applying this framework to other optimization problems

(G2) Engineering Applications of Modelling Complex Systems

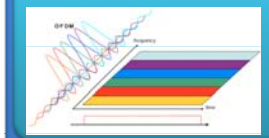
Complex Communication Network Group

Leader: Mikio Hasegawa (Tokyo U. of Science); Members: Tohru Kohda (Kyushu U.), Yutaka Jitsumatu (Kyushu U.), Hiroshi Hirai (U. of Tokyo), Hiroya Nakao (Tokyo Institute of Tech.)

Paradigm Shift of Communication Systems Optimization

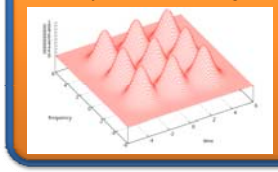
Interference Reduction Optimization

Conventional systems reduce interference based on orthogonality



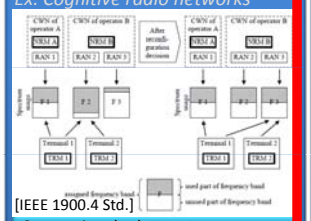
Gabor Division (GD) – SSMA

Time-Frequency Division Optimization lower Interference than Orthogonality



Full Optimization of Resource Usage

Ex. Cognitive radio networks



Conventional schemes use stochastic or heuristic methods ⇒*not exactly optimum*

Rigorous Solution Approach

Problem formulation using network flow theories

Exact solution algorithms

Overheadless Synchronization

Conventional systems require synchronization signal exchange

Environmental Noise Induced Synchronization

Nonlinear oscillators on each device synchronize by natural common noise

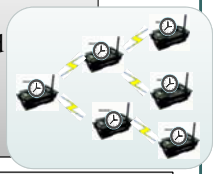
Introduction

Wireless Sensor Network

- Collection of various kinds of context information in real world

Reduction of the power consumption is important for extend lifetime
→ Intermittent packet exchange

- **Synchronization is necessary**



Synchronization using Natural Environmental Signals

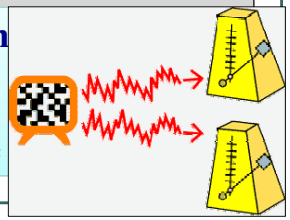
- **Without any packet exchange for synchronization**

Natural environment signals sensed at neighboring nodes have similar dynamics

Noise-induced Phase Synchronization

(Teramae et al., PRL, 2002; Nakao et al., PRL, 2009)

- Nonlinear oscillators synchronize by adding common noise

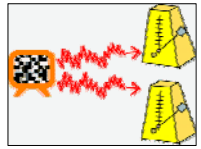


Noise-induced Phase Synchronization (NS) Phenomenon

(Teramae et al., 2002; Nakao et al., 2009)

- **Dynamics of the oscillator**

$$\dot{\mathbf{X}}(t) = \mathbf{F}(\mathbf{X})$$
$$\dot{\theta}(t) = \omega$$



- **Phase difference of nonlinear oscillators with common noise**

$$\dot{\mathbf{X}}_1(t) = \mathbf{F}(\mathbf{X}_1) + \xi(t) \quad \Rightarrow \quad \dot{\theta}_1(t) = \omega + Z(\theta_1)\xi(t)$$

$$\dot{\mathbf{X}}_2(t) = \mathbf{F}(\mathbf{X}_2) + \xi(t) \quad \Rightarrow \quad \dot{\theta}_2(t) = \omega + Z(\theta_2)\xi(t)$$

common noise

Phase sensitivity function
$Z(\theta) = grad_{\mathbf{X}}\theta(\mathbf{X})\big|_{\mathbf{X}=\mathbf{X}_0(\theta)}$

- **Analyzing the linear growth rate (Lyapunov exponent) of phase difference**

$$\phi = \theta_1 - \theta_2$$

$$\Lambda = \left\langle \frac{d}{dt}\ln|\phi(t)| \right\rangle = \varepsilon^2 \langle Z''(\theta(t))Z(\theta(t)) \rangle \cong \frac{\varepsilon^2}{2\pi}\int_0^{2\pi} Z''(\theta)Z(\theta)d\theta = -\frac{\varepsilon^2}{2\pi}\int_0^{2\pi}\{Z'(\theta)\}^2 d\theta \le 0$$

Linear growth rate is smaller than 0.

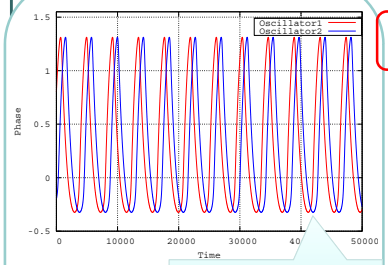
Phase difference converges to 0

Example

Oscillators : FitzHugh-Nagumo oscillator
Common noise : White Gaussian noise

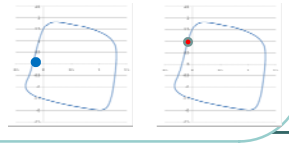
$$\frac{dx_1}{dt} = \varepsilon(y_1 + c - d * x_1) + \xi(t), \quad \frac{dy_1}{dt} = y_1 - \frac{y_1^3}{3} - x_1 + I$$
$$\frac{dx_2}{dt} = \varepsilon(y_2 + c - d * x_2) + \xi(t), \quad \frac{dy_2}{dt} = y_2 - \frac{y_2^3}{3} - x_2 + I$$

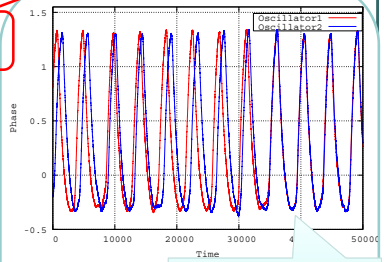
The common noise



Not Synchronize

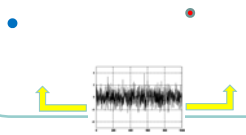
- Constant phase difference





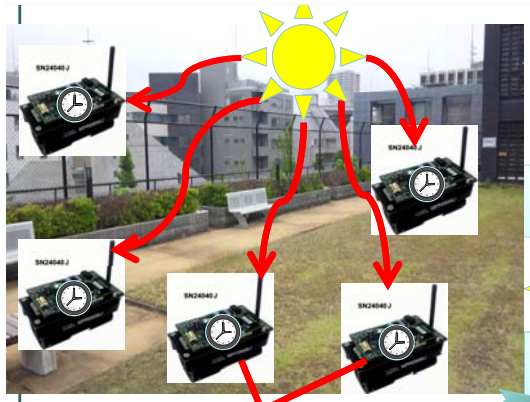
Synchronize

- Input the white Gaussian noise
- Phase difference is reduced.



Proposed synchronization scheme based on **Noise Induced Phase Synchronization Theory**

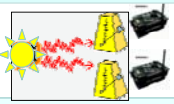
Synchronize wireless sensor nodes by natural signals sensed at each sensor



Time series of the natural environmental signals of neighboring nodes MAYBE similar

Every node runs a nonlinear limit cycle oscillator at each

Natural signals sensed at each sensor are added to oscillator independently



Oscillators will be synchronized by the Noise-induced phase synchronization phenomenon

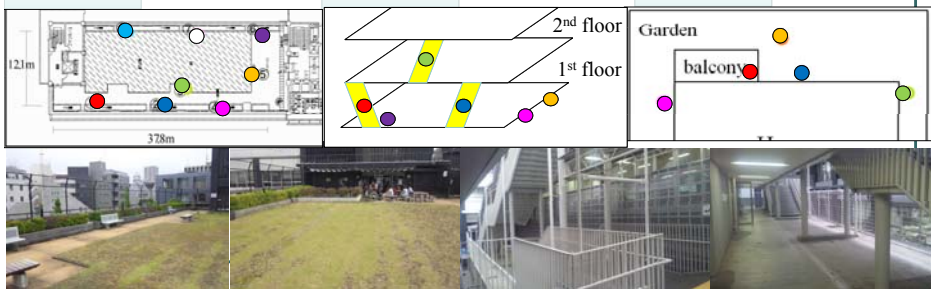
Adjusting clock of each node using phase of each oscillator

Experimental Analysis on data similarity

- Sensor nodes
  MICAz
  MICAz :
  Placed in less than 20m interval for low packet error rate
- Natural environmental signals
  Humidity, Temperature and Atmospheric pressure

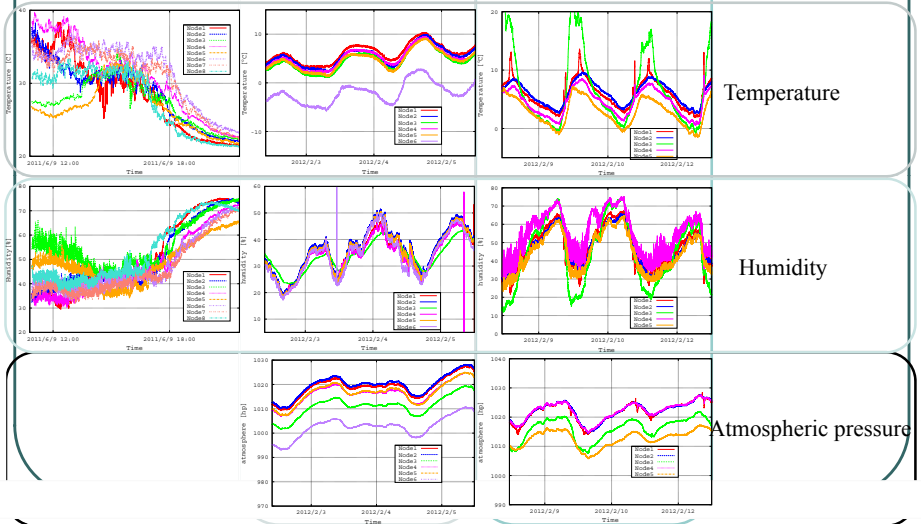
- Location 1: at rooftop garden of Kudan Building of TUS
- Location 2: at outdoor corridor of first and second floors of Kudan building of TUS
- Location 3: in a Garden of a house

Location 1 | Location 2 | Location 3



Collected data at three locations

Location 1 | Location 2 | Location 3

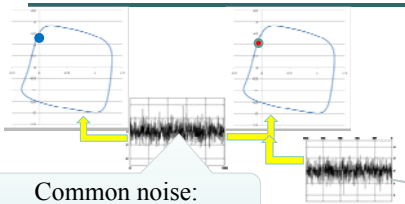


Temperature

Humidity

Atmospheric pressure

Analysis of necessary similarity for synchronization



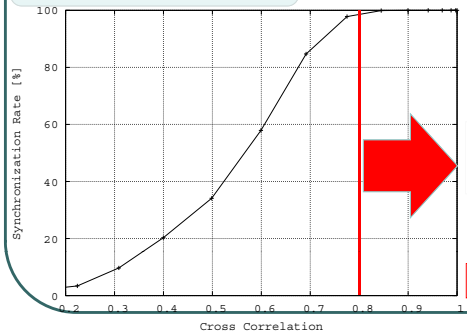
Oscillators : FitzHugh-Nagumo oscillator

$$\frac{dx_1}{dt} = \varepsilon(y_1 + c - d * x_1) + \xi_1(t), \frac{dy_1}{dt} = y_1 - \frac{y_1^3}{3} - x_1 + I$$

$$\frac{dx_2}{dt} = \varepsilon(y_2 + c - d * x_2) + \xi_2(t), \frac{dy_2}{dt} = y_2 - \frac{y_2^3}{3} - x_2 + I$$

Common noise:
Cross-correlation = 1

Additional noise reducing cross-correlation

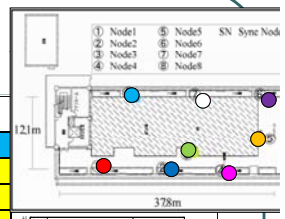


necessary cross-correlation for high synchronization rate is around 0.8<

Yasuda & Hasegawa., NLP, 2011

Cross-correlation of collected data

Location 2: At Rooftop garden of Kudan building of TUS



- Temperature

Node ID	2	3	4	5	6	7	8
1	**0.932**	0.613	**0.972**	0.467	**0.840**	**0.845**	**0.895**
2		0.718	**0.945**	0.623	**0.879**	**0.899**	**0.910**
3			0.624	**0.919**	**0.864**	**0.851**	**0.846**
4				0.482	**0.866**	**0.889**	**0.894**
5					0.754	0.727	0.749
6						**0.970**	**0.912**
7							**0.916**

- Humidity

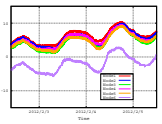
Node ID	2	3	4	5	6	7	8
1	**0.968**	0.785	**0.964**	0.764	**0.931**	**0.924**	**0.975**
2		**0.838**	**0.959**	**0.829**	**0.947**	**0.944**	**0.952**
3			0.781	**0.932**	**0.886**	**0.878**	**0.813**
4				0.742	**0.955**	**0.961**	**0.940**
5					**0.834**	**0.828**	**0.810**
6						**0.979**	**0.916**
7							**0.918**

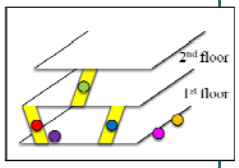
Cross-correlation of collected data

Location 2: at outdoor corridor first and second floors of Kudan building of TUS

- Temperature

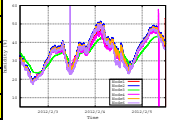
Node ID	2	3	4	5	6
1	0.9806	0.9918	0.9982	0.9876	0.8969
2		0.9903	0.9845	0.9891	0.8564
3			0.9930	0.9917	0.8868
4				0.9868	0.8840
5					0.9123





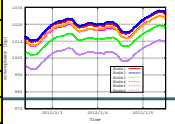
- Humidity

Node ID	2	3	4	5	6
1	0.9522	0.9326	0.9894	0.9914	0.9323
2		0.9515	0.9664	0.9635	0.8622
3			0.9383	0.9443	0.8402
4				0.9864	0.9201
5					0.9280



- Atmospheric pressure

Node ID	2	3	4	5	6
1	0.9959	0.9974	0.9991	0.9989	0.9938
2		0.9962	0.9973	0.9959	0.9877
3			0.9977	0.9957	0.9955
4				0.9989	0.9926
5					0.9910

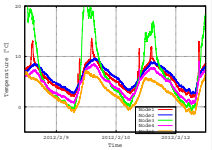


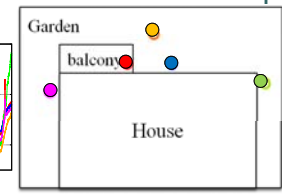
Cross-correlation of collected data

Location 3: In a Garden

- Temperature

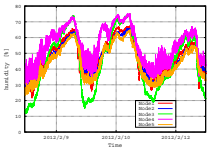
Node ID	2	3	4	5
1	0.8759	0.8546	0.9420	0.9148
2		0.6803	0.9622	0.8928
3			0.8345	0.9061
4				0.9608





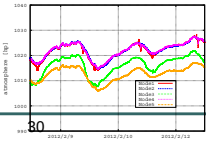
- Humidity

Node ID	2	3	4	5
1	0.9310	0.9688	0.9658	0.9802
2		0.8930	0.9335	0.9438
3			0.9423	0.9701
4				0.9685



- Atmospheric pressure

Node ID	2	3	4	5
1	0.9641	0.9620	0.9838	0.9636
2		0.8930	0.9922	0.9558
3			0.9345	0.9390
4				0.9707



Cross-correlation of collected data

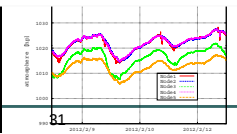
Location 3: In a Garden

For Noise-induced phase synchronization.
necessary cross-correlation is around 0.8 or higher

Cross-correlation between the time series of natural environmental signals sensed at the neighboring nodes are mostly higher than 0.8.

Noise-induced phase synchronization by natural environmental signal should be feasible.

Node ID	2	3	4	5
1	0.9641	0.9620	0.9838	0.9636
2		0.8930	0.9922	0.9558
3			0.9345	0.9390
4				0.9707



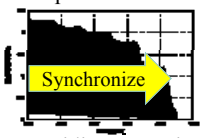
Noise Induced Phase Synchronization by Natural Environmental Signals

Oscillators : FitzHugh-Nagumo Oscillator

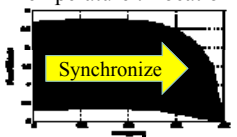
The natural environmental signals

$$\frac{dx_1}{dt} = \varepsilon(y_1 + c - d * x_1) + \xi_1(t), \quad \frac{dy_1}{dt} = y_1 - \frac{y_1^3}{3} - x_1 + I$$
$$\frac{dx_2}{dt} = \varepsilon(y_2 + c - d * x_2) + \xi_2(t), \quad \frac{dy_2}{dt} = y_2 - \frac{y_2^3}{3} - x_2 + I$$

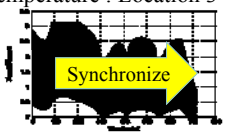
Temperature : Location 1



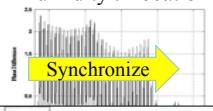
Temperature : Location 2



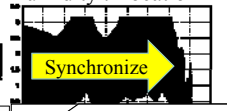
Temperature : Location 3



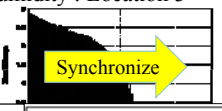
Humidity : Location 1

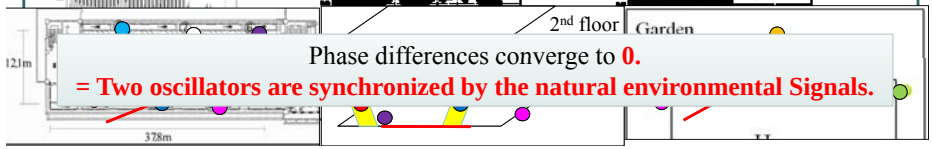


Humidity : Location 2



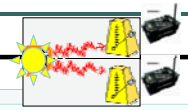
Humidity : Location 3





Phase differences converge to **0.**
= Two oscillators are synchronized by the natural environmental Signals.

Conclusion



Proposed method

Synchronization of Wireless Sensor Nodes
by natural environmental signals, such as temperature, humidity, etc.

Noise-induced Phase Synchronization Theory
nonlinear oscillators synchronize by adding common noise

Experimental using sensor nodes

Neighboring nodes independently collect highly correlated natural signal

Phase difference can be reduced to 0 by natural signals

Synchronization succeeded

(G2) Engineering Applications of Modelling Complex Systems

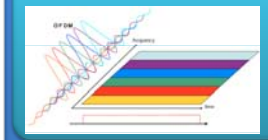
Complex Communication Network Group

Leader : Mikio Hasegawa (Tokyo U. of Science); Members: Tohru Kohda (Kyushu U.), Yutaka Jitsumatu (Kyushu U.), Hiroshi Hirai (U. of Tokyo), Hiroya Nakao (Tokyo Institute of Tech.)

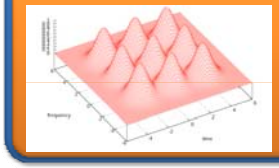
Paradigm Shift of Communication Systems Optimization

Interference Reduction Optimization

Conventional systems reduce interference based on orthogonality

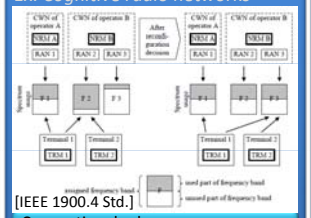


Gabor Division (GD) – SSMA
Time-Frequency Division Optimization lower Interference than Orthogonality



Full Optimization of Resource Usage

Ex. Cognitive radio networks



[IEEE 1900.4 Std.]

Conventional schemes use stochastic or heuristic methods
⇒*not exactly optimum*

Rigorous Solution Approach
Problem formulation using network flow theories
Exact solution algorithms

Overheadless Synchronization

Conventional systems require synchronization signal exchange

Environmental Noise Induced Synchronization
Nonlinear oscillators on each device synchronize by natural common noise