Controlled Potential-Based Routing for Large-Scale Wireless Sensor Networks

Daichi Kominami†, Masashi Sugano‡,
Masayuki Murata†, Takaaki Hatauchi#

†Osaka University
‡Osaka Prefecture University
#Fuji Electric Systems Co,. Ltd.

Outline

- Background of our research
  - Self-organization in wireless sensor networks
  - Controlled self-organization scheme
  - Potential-based routing
- Controlled potential-based routing
- Evaluation by computer simulation
- Conclusion and future work

Self Organization in Wireless Sensor Networks

Challenges in Wireless Sensor Networks

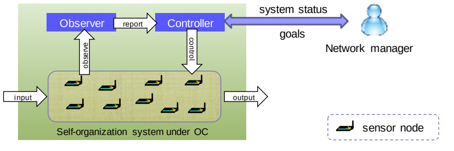
- Scalability improvement
  - To control an enormous number of sensor nodes
    - High message overheads and heavy traffic load for relay
- Robustness improvement
  - To maintain performance against environmental variations in a network
    - Frequent wireless channel fluctuations
    - Failure proneness and battery depletion of sensor nodes

Self Organization

- Globally coherent pattern appears from the "local interaction" between composition elements of the system
  - Pros : High scalability and good robustness
  - Cons : Difficulty in guaranteeing an optimal operation
    Difficulty in confirming an operation on the entire network

Controlled Self Organization

- Introduction of "Observer/Controller (OC) Architecture" into a self-organized system to make sure it does not result in unanticipated and undesired behavior [1]



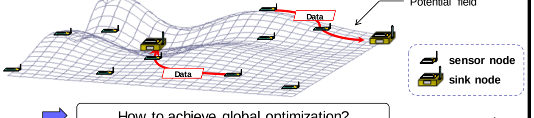
- We adopt a potential-based routing as one of self-organized routings and apply OC architecture to it

Goal: achieving global optimal operation of the network

[1] C. Muller-Schloer, H. Schmeck, and T. Ungerer, *Organic Computing - A Paradigm Shift for Complex Systems*. Birkhauser, 2011.

Potential-Based Routing

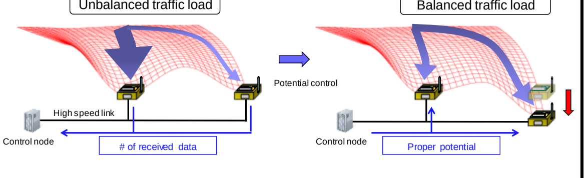
- Routing using a potential (scalar value) assigned to every sensor nodes
  1. Construction of a potential field
     - Each node calculates its own potential in a self-organized manner
     - More suitable nodes as a next hop have a smaller potential
       - *Sink nodes have the minimal potential*
  2. Data forwarding through the gradient of the field
     - A node forwards data to one of its neighbor nodes with the smallest potential



⇨ How to achieve global optimization?

Global Optimization with Global Potential Control

- Observer and controller construct a globally optimal potential field
  - Observer: sink nodes collect network information
  - Controller: control node sets potentials of sink nodes to proper value
- E.g., load balancing of sink nodes



Global Potential Control Algorithm

- Simple strategy for controlling sink nodes' potentials

$$\Phi(d,t+1) = \begin{cases} \Phi(d,t) * (1-\theta \frac{m(d)-\bar{m}}{\bar{m}}) & (m(d) \ge \bar{m}) \\ \Phi(d,t) * (1+\theta \frac{\bar{m}-m(d)}{\bar{m}}) & (m(d) < \bar{m}) \end{cases}$$

Φ	:	potential
d	:	sink node
t	:	time
θ	:	constant
m	:	metric value
$\bar{m}$	:	average of m

- Control node changes sink nodes' potentials periodically
- Proper m is selected for control purpose
  - E.g. load balancing of sink nodes
    - *m: the number of received data at each sink node*
  - E.g. prolonging reachability to sink nodes
    - *m:* the decrease rate of the total remaining energy among the neighbor nodes of each sink node

⇨ How can the effect of the potential changes in sink nodes be diffused around the entire network?

Potential Field Construction from the Diffusion Equation

- Diffusion equation (heat equation)
  - provides magnitude ϕ of the diffusing quantity at time t at position $\boldsymbol{x}$

$$\frac{\partial \phi(\mathbf{x},t)}{\partial t} = D \triangle \phi(\mathbf{x},t)$$

Φ	:	heat or potential
x	:	position
t	:	time
D	:	diffusion constant
Δ	:	Laplacian
n	:	node
nb	:	set of neighbor node

⇩ discretize

$$\phi(n,t+1) = \phi(n,t) + D(n) \sum_{k \in nb(n)} \{\phi(k,t) - \phi(n,t)\} \quad (1)$$

- Potential field construction by local interaction
  - Each node broadcasts its potential to neighbor nodes periodically
  - Update its own potential based on equation (1) after the reception
    - *A neighbor node table is maintained by soft state*

Local Optimization by extending Diffusion Equation

- Local optimization from local information
  - By adding *ρ(n)* to RHS of the Diffusion Equation

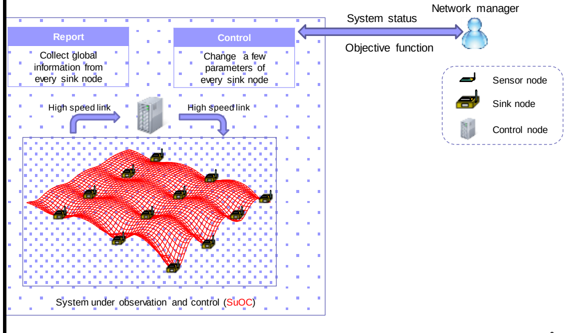
$$\phi(n,t+1) = \phi(n,t) + D(n) \sum_{k \in nb(n)} \{\phi(k,t) - \phi(n,t)\} + \rho(n)$$

  - ρ changes the probability of each node to be selected as a next hop
    - Decreasing ρ increases the probability
    - Increasing ρ decreases the probability

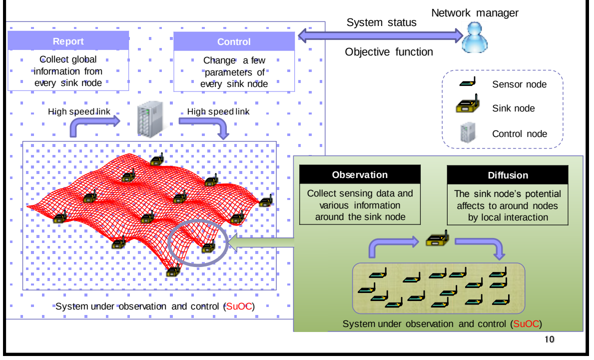
An example of using ρ

- Local load balancing based on the remaining energy
  - Comparing own residual energy with those of the neighbor nodes that have the same hop count
    - If own residual energy is more, decrease ρ
    - Else, increase ρ

Overview: Controlled Potential-Based Routing



Overview: Controlled Potential-Based Routing

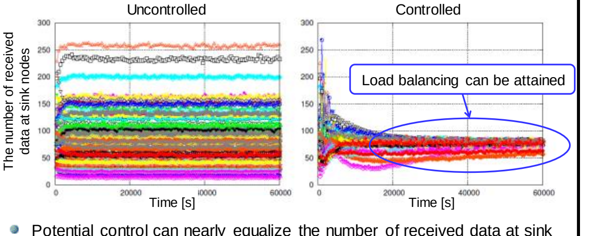


Simulation Results - Scalability -

Global Potential Control Works Well ?

Potential control to equalize the number of received data at 100 sink nodes

Potential broadcast interval:	100 s
Potential control interval:	500 s
The number of sensor:	5000
The number of sink:	100
Packet generation rate: 0.003 pkt/s/node	



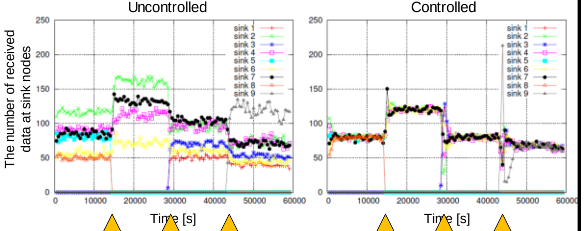
- Potential control can nearly equalize the number of received data at sink nodes over a 5000-node network

Simulation Results - Robustness -

Global Potential Control Has Good Robustness ?

Potential control to equalize the number of received data at 4~7 sink nodes

Potential broadcast interval: 100 s
Potential control interval: 500 s
The number of sensor: 300
The number of sink: 4~7 (default 6)
Packet generation rate: 0.003 pkt/s/node



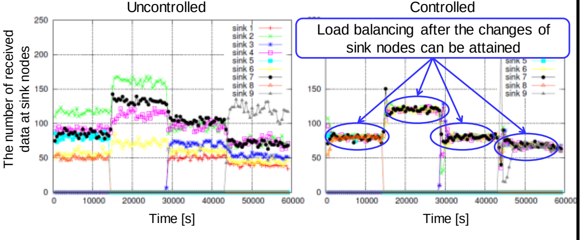
2 nodes failure | 2 nodes addition | 1 node addition

Simulation Results - Robustness -

Global Potential Control Has Good Robustness ?

Potential control to equalize the number of received data at 4~7 sink nodes

Potential broadcast interval: 100 s
Potential control interval: 500 s
The number of sensor: 300
The number of sink: 4~7 (default 6)
Packet generation rate: 0.003 pkt/s/node



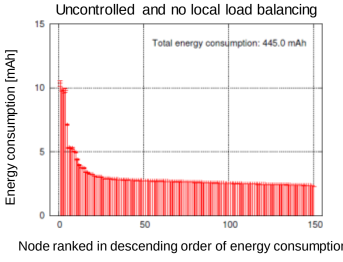
- Good robustness can be achieved against sink nodes' failure and addition
  - Potential control maintains the convergence after the events

Simulation Results - Network Lifetime -

Global Load Balancing for Reachability to Sink Nodes

Potential control to equalize the energy consumption of the neighbor nodes around sink nodes

Potential broadcast interval: 100 s
Potential control interval: 50 s
The number of sensor: 150
The number of sink: 3
Packet generation rate: 0.003 pkt/s/node
Simulation time: 6 hours

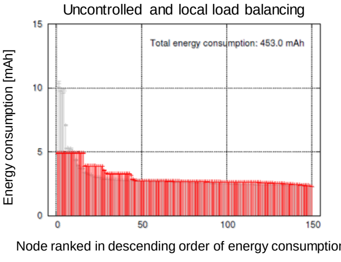


Simulation Results - Network Lifetime -

Global Load Balancing for Reachability to Sink Nodes

Potential control to equalize the energy consumption of the neighbor nodes around sink nodes

Potential broadcast interval: 100 s
Potential control interval: 50 s
The number of sensor: 150
The number of sink: 3
Packet generation rate: 0.003 pkt/s/node
Simulation time: 6 hours

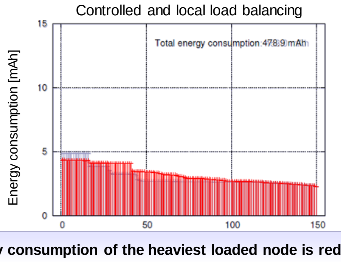


Simulation Results - Network Lifetime -

Global Load Balancing for Reachability to Sink Nodes

Potential control to equalize the energy consumption of the neighbor nodes around sink nodes

Potential broadcast interval: 100 s
Potential control interval: 50 s
The number of sensor: 150
The number of sink: 3
Packet generation rate: 0.003 pkt/s/node
Simulation time: 6 hours



Energy consumption of the heaviest loaded node is reduced by 58%

Conclusion and Future Work

- Conclusion
  - We show that global optimization can be achieved by controlled self-organization
  - We propose "controlled potential-based routing"
    - Global load balancing of sink nodes over a large-scale sensor network can be achieved
    - Good robustness can be obtained against network environmental changes caused by failures and additions of sink nodes
    - Global load balancing for reachability to sink nodes can reduce energy consumption of the heaviest loaded node by 58%
- Future work
  - Investigations into the variations in system behavior and convergence time as network size becomes increasingly large
  - Further evaluation on robustness and detailed study on the dependence on node density

Thank you