Self-organizing Wireless Sensor Networks Based on Biological Collective Decision Making for treating Information Uncertainty

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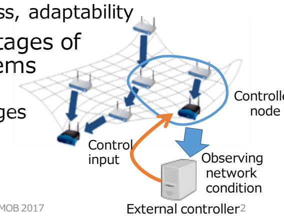
Our Previous Work

- Controlling self-organizing networks by introducing an external controller
- Advantages of self-organizing
  - Scalability, robustness, adaptability
- Overcome disadvantages of self-organizing systems
  - Fast adaptation to environmental changes
  - Global optimality



Problem of Network Control

- In large and complex networks

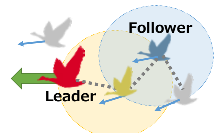
Information uncertainty

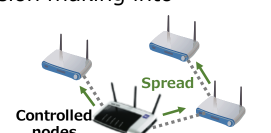
- **Dynamic** according to changing condition of nodes,
- **Incomplete** because of capacity limitation of nodes,
- **Ambiguous** because of estimation/communication errors

Nodes need to make decisions based on uncertain information

Approach

- Apply collective decision making into network control





Controlled directly and guide other nodes

Coordinated decision even with information uncertainty

Robust and adaptable control to information uncertainty

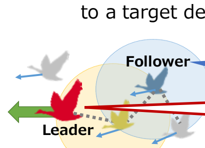
In this work

- A network control mechanism with collective decision making
- Simulation
  - How our mechanism behaves when applied collective decision making
    - Theoretically
    - In wireless sensor network environment
  - How the performance is with information uncertainty

Collective Decision Making

- In swarms (groups of insects, birds, etc.)
  - Some individuals (leaders) guide the others to a target destination

Followers decide their direction of move based only on local interaction among others in their observable range



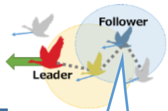
Leaders decide their direction of move based both on local interaction and their information of a destination

Leaders' decision spread through local interaction
→ Leaders guide whole group

Robust and adaptable to **information uncertainty**

Effective Leadership Model[1]

- A mathematical model of collective decision making



Followers (uninformed individuals)

- Only follow others in their observable range
- Make decision based only on local interaction
- $\boldsymbol{d}_i(t+\Delta t) = \sum_{j\in N_b(i,\rho)\setminus\{i\}} \frac{\boldsymbol{c}_j(t)-\boldsymbol{c}_i(t)}{|\boldsymbol{c}_j(t)-\boldsymbol{c}_i(t)|} + \sum_{j\in N_b(i,\rho)} \frac{\boldsymbol{v}_j(t)}{|\boldsymbol{v}_j(t)|}$

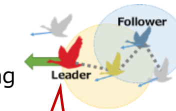
Averaging position — Averaging direction

Local interaction with other individuals

[1] I. D. Couzin, J. Krause, N. R. Franks, and S. A. Levin,
"Effective leadership and decision- making in animal groups on the move," Nature, vol. 433, pp. 513–516, Feb. 2005.

Effective Leadership Model[1]

- A mathematical model of collective decision making



Leaders (informed individuals)

- Have information of a destination
- Make decision based both on local interaction and their information
- $\boldsymbol{d}_i(t+\Delta t) = \frac{\hat{\boldsymbol{d}}_i(t+\Delta t)+\omega_0 \boldsymbol{g}_i}{|\hat{\boldsymbol{d}}_i(t+\Delta t)+\omega_0 \boldsymbol{g}_i|}$

g_i: target direction

Local interaction (same as followers)

[1] I. D. Couzin, J. Krause, N. R. Franks, and S. A. Levin,
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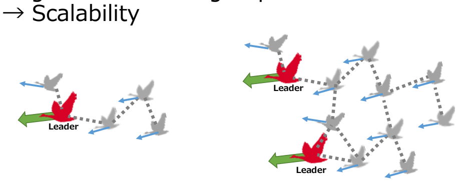
Effective Leadership Model[1]

- The larger the group (more individuals), **smaller proportion of leaders** needed to guide the whole group
  → Scalability



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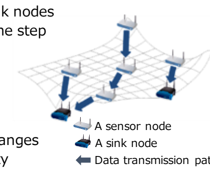
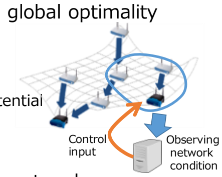
Potential-based Routing

- A self-organizing network control mechanism
- Routing according to **"potential"**
  - Each node has scalar potential
  - Closer to sink nodes, nodes have lower potential
  - Nodes transfer data to nodes with lower potential
  - Data packets are finally carried to sink nodes
  - Potential values are updated each time step based on neighbors' potential
- Advantages
  - Scalability, adaptability, robustness
- Disadvantages
  - Slow adaptation to environmental changes
  - Difficult to guarantee global optimality



Controlled Potential-based Routing[2]

- To achieve fast adaptation and global optimality
- An external controller
  - Input: potential information around sink nodes
  - Output: information of target potential to some **"controlled nodes"**
  - Control input is calculated based on H∞ control theory
- Control input spread whole the network
  → Controlled nodes guide the whole network

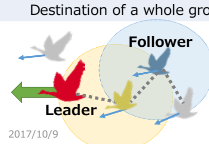


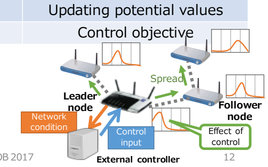
Controlled nodes: leaders in network

[2] N. Kuze, D. Kominami, K. Kashima, T. Hashimoto, and M. Murata, "Controlling large-scale self-organized networks with lightweight cost for fast adaptation to changing environments," ACM Transactions on Autonomous and Adaptive Systems (TAAS), vol. 11, no. 2, p. 9, 2016.

Correspondence

Collective decision making (Effective Leadership model)	**Network control** (Potential-based routing with external controller)
Informed individuals (**leaders**)	Controlled nodes (**leader nodes**)
Uninformed individuals (**followers**)	Nodes other than the controlled nodes (**follower nodes**)
Decision making of individuals	Updating potential values
Destination of a whole group	Control objective





Proposed mechanism

$\theta_n(t)$: potential of node n at time t
$f_n(t)$: flow rate
$\alpha, \beta, \sigma_n, \omega$: weighting constant
$N_b(n)$: neighbor nodes of node n

- **Follower nodes**
  - Update their potential to follow neighbor nodes through local interaction among nodes
  - $\theta_n(t) = (\alpha + 1)\theta_n(t-1) - \alpha\theta_n(t-2) + \beta\sigma_n(\Sigma_{k \in N_b(n)}\{\theta_k(t-1) - \theta_n(t-1)\} + f_n(t))$
- **Leader nodes**
  - Update their potential based both on local interaction and control input from the external controller
  - $\theta_n(t) = (1-\omega)\{(\alpha + 1)\theta_n(t-1) - \alpha\theta_n(t-2) + \beta\sigma_n(\Sigma_{k \in N_b(n)}\{\theta_k(t-1) - \theta_n(t-1)\} + f_n(t)\} + \omega\mathbf{g}_i$

Local interaction among nodes

Weighting parameter of control input against local interaction

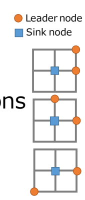
Target potential by external controller

Simulation Experiments

How our mechanism works with Effective Leadership model?

- Numerical simulation
  - Evaluate theoretical performance of controller
  - We found the low-cost way to select leaders
- Network simulation
  - Evaluate performance in wireless sensor network environment
  - Evaluate performance in case with uncertain information

MATLAB Simulation

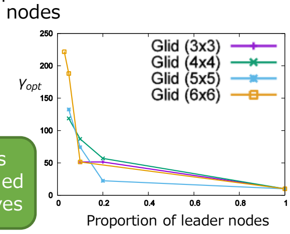


- Comparing all possible leader positions
  - Square lattice topology
    - 3×3, 4×4, 5×5, 6×6
  - Changing number of leader nodes
- Evaluation index γ_{opt}
  - indicator of H^∞ controller performance
  - Maximum value of closed loop norm of transfer function $||G||_\infty$
    - Calculate using *dhinflmi* function of MATLAB
  - The smaller γ_{opt}, the higher degree of contribution of the leader nodes
    (**Smaller γ_{opt} means better performance**)

Result of Evaluation

- Plot minimum γ_{opt} for all cases
  - The highest control performance at each proportion of leader nodes
- γ_{opt} decrease faster with more nodes in the network

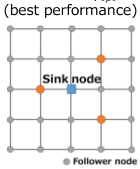
The more nodes, the less proportion of leaders needed to achieve control objectives



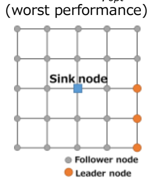
Position of Leaders

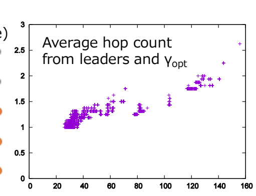
- We found correlation between average hop count from leaders and γ_{opt}

Minimum γ_{opt} (best performance)



Maximum γ_{opt} (worst performance)

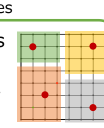


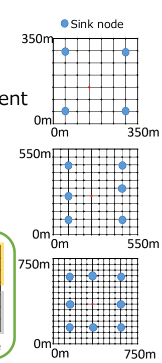


Network Simulation

- In wireless sensor network environment
- Topology
  - Square lattice topology
  - 64 nodes, 144 nodes, 256 nodes
- Proportion of leader nodes
  - About 1% - 11% to all nodes

Positions of leader nodes
- K-Means clustering
  - Leader node is set to be the center of each cluster
  - Less calculation cost than average hop count

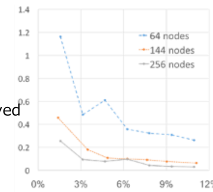




Result of Network Simulation

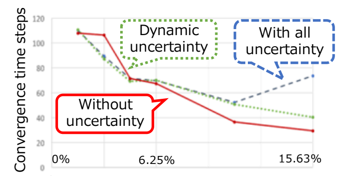
- Evaluation index
  - The ratio with/without control of convergence time after a traffic change (indicator of adaptation speed to unexpected environmental changes)
  - Smaller value means higher performance of controller
- Result
  - The more nodes in the network, higher performance can be achieved by smaller proportion of leaders → Scalability

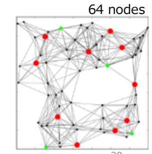
$$\frac{\text{Convergence time with control}}{\text{Convergence time without control}}$$



Information Uncertainty

- In case the controller have uncertain information
  - Dynamic (information including communication delay)
  - Incomplete (information of the nodes around sink nodes)
  - Ambiguous (information including estimation errors)





Conclusion

- Applied collective decision making to network control
  - Robust and adaptable to unexpected environmental changes and information uncertainty
- Proposed a way to select leader nodes
  - high control performance and low calculation cost
- More nodes in the network, control objective can be achieved with smaller proportion of leaders
- Our mechanism works even with uncertain information