Enhancing Convergence with Optimal Feedback for Controlled Self-organizing Networks

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Background

- Rapid growth of networks in scale and complexity
  - Limitation of conventional information systems based on central control or distributed control with global information
- Self-organizing systems
  - High scalability, adaptability, robustness
    - Components behave autonomously based on local information
    - Global pattern emerges through interactions among components
  - Disadvantage of self-organizing systems
    - Global optimality is not guaranteed
    - Long time is needed for emergence
      → Adaptation to environmental changes is slow

We introduce **controlled self-organization** where the self-organizing system is controlled through some constraints

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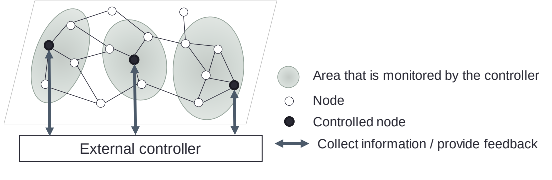
Objective

- Our target is to enhance the convergence speed by introducing **an external controller** to the self-organizing system
  - An external controller
    - collects system information via a part of nodes
    - estimates future states of the system using collected information
    - provides optimal feedback inputs for faster convergence



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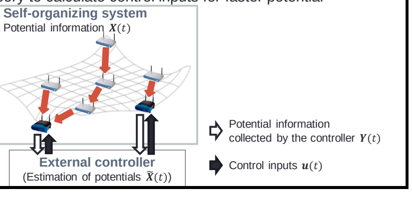
Overview of our proposal

- We take potential-based routing and enhance potential convergence speed with **an external controller**
  - Route toward sink nodes are represented by a potential field
    - A potential field constructed only by local information and iterative calculation
  - A controller maximizes the convergence speed of potential field
    1. collects potential information of nodes via sink nodes
    2. estimates future states of all nodes using collected information
    3. uses optimal control theory to calculate control inputs for faster potential convergence



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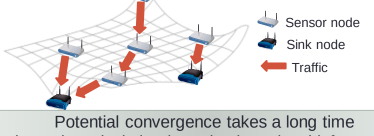
Potential-based routing [1] (PBR)

- Self-organizing routing mechanism for wireless sensor networks
  - Each node has a scalar value called **potential** which is updated every step based on local interactions of nodes
    - The smaller the number of hops from sink nodes is, the lower potential value assigned to the node is
  - Data packet collection toward sink nodes can be carried out by forwarding data to its neighbor node with lower potential



Potential convergence takes a long time due to its calculation based only on local information

[1] D. Kominami, M. Sugano, M. Murata, and T. Hatauchi, "Controlled and self-organized routing for large-scale wireless sensor networks," ACM Transactions on Sensor Networks, vol.10, no.1, pp.13:1-13:27, Nov. 2013.

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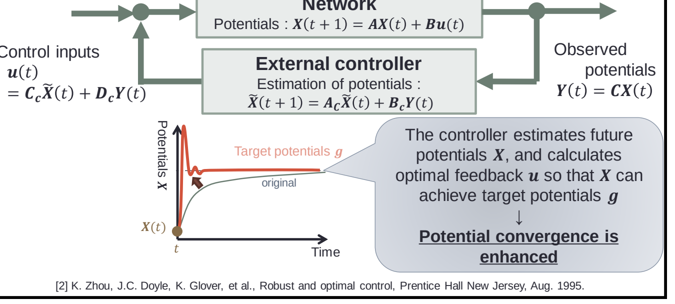
Optimal feedback [2] for PBR

- The external controller estimates future potentials based on the model that describes the network dynamics, and then provides an optimal feedback to the network



[2] K. Zhou, J.C. Doyle, K. Glover, et al., Robust and optimal control, Prentice Hall New Jersey, Aug. 1995.

Potential dynamics

- Node n updates its potential $\emptyset_n(t)$ every step by

$$\emptyset_n(t+1) = (\alpha+1)\emptyset_n(t) - \alpha\emptyset_n(t-1) + \beta\sigma \sum_{k \in Nb(n)} \{\emptyset_k(t) - \emptyset_n(t)\} + f_n(t) + \eta_n(t)$$

Potential of node n | Potentials of node n's neighbors | Control term

- Control term $\eta_n(t)$ is the control input that is provided by the controller to node n at time t

$Nb(n)$: The set of neighbors of node n
α, β, σ : Parameters that determine the weight of potentials
$f_n(t)$: Flow-injection rate of node n at time t

- The dynamics of all nodes
  - The external controller estimates future potentials by

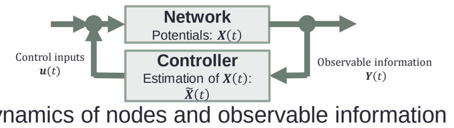
$$\boldsymbol{X}(t+1) = \boldsymbol{AX}(t) + \boldsymbol{Bu}(t)$$

where $\boldsymbol{X}(t) = \boldsymbol{\Theta}(t) - \widetilde{\boldsymbol{\Theta}}$

Current potentials | Target potentials

$\boldsymbol{\Theta}(t)$: Current potentials of nodes ($= [\boldsymbol{\theta}_1(t) \dots \boldsymbol{\theta}_N(t)]^T$ where $\boldsymbol{\theta}_n(t) = [\theta_n(t)\ \theta_n(t+1)]$)
$\widetilde{\boldsymbol{\Theta}}$: Target potential values

Optimal feedback inputs



- The dynamics of nodes and observable information

$$\boldsymbol{X}(t+1) = \boldsymbol{AX}(t) + \boldsymbol{Bu}(t)$$
$$\boldsymbol{Y}(t) = \boldsymbol{CX}(t)$$

$\boldsymbol{X}(t)$: Potential information
$\boldsymbol{u}(t)$: Control inputs
$\boldsymbol{Y}(t)$: Observable information

- The controller calculates control inputs $\boldsymbol{u}(t)$ by

$$\widetilde{\boldsymbol{X}}(t+1) = \boldsymbol{A_c}\widetilde{\boldsymbol{X}}(t) + \boldsymbol{B_c}\boldsymbol{Y}(t)$$
$$\boldsymbol{u}(t) = \boldsymbol{C_c}\widetilde{\boldsymbol{X}}(t) + \boldsymbol{D_c}\boldsymbol{u}(t)$$

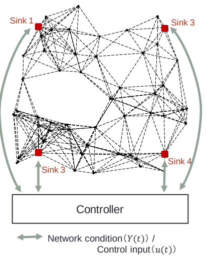
$\widetilde{\boldsymbol{X}}(t+1)$: Estimation of $\boldsymbol{X}$
$\boldsymbol{A_c}, \boldsymbol{B_c}, \boldsymbol{C_c}, \boldsymbol{D_c}$: Design parameters

  - The controller determines control inputs $\boldsymbol{u}(t)$ to minimize the difference between potentials and their target values, and control inputs

$$\text{minimize: } \sum_{t=0}^{\infty} \left(\boldsymbol{X}^T(t)\boldsymbol{X}(t) + r\boldsymbol{u}(t)^T\boldsymbol{u}(t)\right)$$

r : A parameter that specifies the trade-off between the convergence speed and input energy

Simulation settings



- Network topology
  - 54 nodes (including 4 sink nodes)
    - The controller collects potential information via sink nodes, and provides feedback inputs to them
    - The controller broadcasts potential request packets via sink nodes every step for collecting potential information
      - Potential request packets are broadcasted within 2 hops from the sink node, and then, return to the sink node collecting potential values
    - All nodes and the controller are completely asynchronous
- Parameter settings
  - Parameter r : 10
    - specifies the tradeoff between convergence speed and input energy

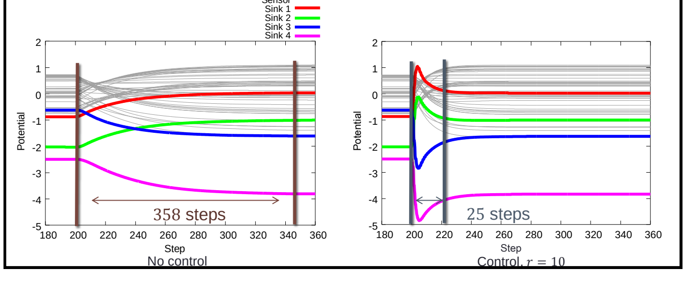
Simulation scenario

1. Data packet generation rates change at 200 step
2. The potential field is reconstructed so that sink nodes receive data packets equally
   - We evaluate the potential convergence speed and traffic changes
   - We consider potential convergence is achieved if $\boldsymbol{X}(t) (= \boldsymbol{\Theta}(t) - \widetilde{\boldsymbol{\Theta}})$ becomes lower than the threshold.

- We assume two situations
  1. An ideal situation
     - where the controller collects potential information any time without error and cost
  2. Realistic situation in WSNs
     - where the controller collects potential information via sink nodes with packet losses and communication delay

Potential convergence

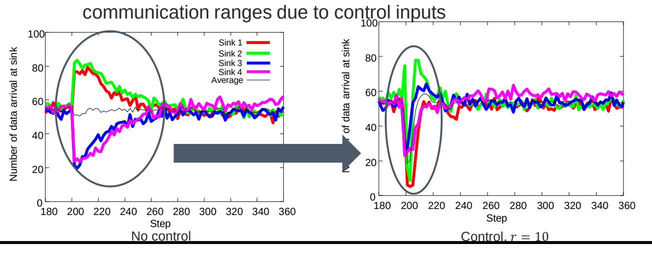
- In an ideal situation
- By introducing optimal feedback, the potential convergence speed is improved by about 7.3 times
  - This is the upper limit of convergence speed with an optimal feedback



No control | Control, r = 10

Traffic changes

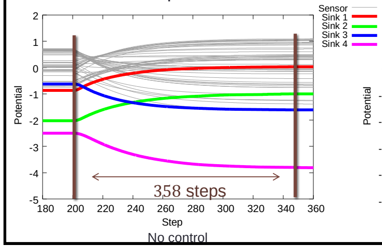
- In an ideal situation
- The time until the number of data packet arrivals at each sink node becomes equal is reduced by an optimal feedback
  - The number of data packet arrivals in sink nodes is decreased just after data packet generation rates change
    - Sink nodes temporarily get highest potentials within their communication ranges due to control inputs



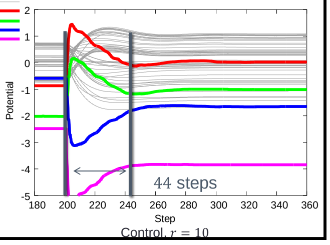
No control | Control, r = 10

Convergence with restrictions in WSNs

- <u>In realistic situation in WSNs</u>
- The potential convergence speed is improved by about 4.1 times
  - The controller dose not always collect latest potential information
    - Congestion occurs around sink nodes because the controller collects potentials via sink nodes



No control



Control, $r = 10$

Conclusion and future work

- Conclusion
  - We introduce an optimal feedback to potential-based routing
    - We show that an optimal feedback enhance potential convergence speed even with some constraints in WSNs
- Future work
  - We will reduce computational cost by introducing **<u>model reduction</u>**
    - Computational cost for estimating the potential dynamics increases exponentially as the number of nodes becomes larger
  - We now trying **<u>a distributed control</u>** for large-scale networks
    - Several controllers provide optimal feedback in a distributed manner
    - We consider that a distributed control can enhance convergence with lower computational cost and communication overhead