# Experiments and Considerations on Reaction-Diffusion based Pattern Generation in a Wireless Sensor Network

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## Requirements of WSNs

- Difficulty of centralized control in WSN
  - A large number of sensor nodes
  - Random or unplanned deployment
  - Dynamic topology changes
- Requirements of WSNs
  - Scalable to the size of a network
  - Robust to failures of sensor nodes
  - Adaptive to changing topology and changes in wireless communication environment

➡Fully-distributed and self-organizing control
➡These features can be found in biological systems



## Approach and Main Contribution

Focusing on Reaction-Diffusion Equation
- Model of a biological system
- Autonomous pattern generation mechanism

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Pattern generation on a sensor network

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Autonomous control based on patterns
- Clustering, routing, scheduling, and topology control

- There have been some proposals



## Approach and Main Contribution

Focusing on React...

Autono...
- ... routing, s...ng, and topology control

But, is it really possible or efficient to generate a pattern on a WSN?

Main contribution

We show the applicability of reaction-diffusion equation to wireless sensor networks



## Reaction-Diffusion based Mechanism

## Reaction-Diffusion Equation

- Mathematical model of pattern generation on the surface of body of fishes and mammals
- Pattern emerges through local interactions using local information among neighboring cells


Zebra

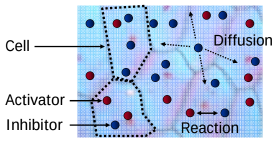

Emperor Angelfish


Leopard



## Pattern Generation with Reaction-Diffusion

- Each cell has two morphogens (chemicals): activator and inhibitor
- Two interacting parts:
  - Diffusion: Long-ranged, slowly propagating diffusion of morphogens
  - Reaction: Local reaction to morphogen concentrations

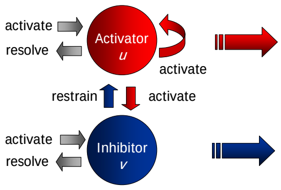



- Color of each cell is decided based on the concentration of activator



## Condition for Pattern Generation

- Behavior of morphogens
  - Morphogens move only among neighboring cells
  - Inhibitor diffuses faster than activator
  - Positive feedback and negative feedback among morphogens




Reaction-diffusion equation

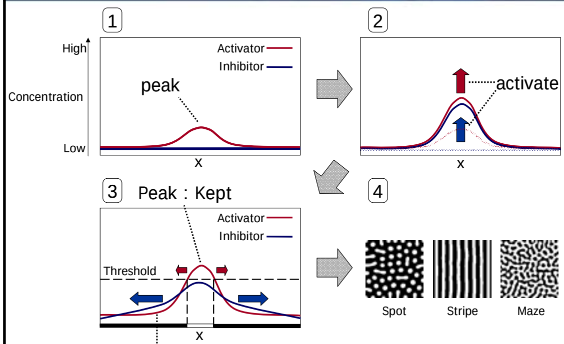
$$\frac{\partial u}{\partial t} = F(u,v) + D_u \nabla^2 u$$

$$\frac{\partial v}{\partial t} = G(u,v) + D_v \nabla^2 v$$

Reaction term | Diffusion term



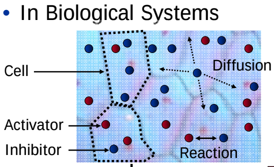
## Pattern Generation Mechanism






## Applying Biological System to WSN

- In Biological Systems

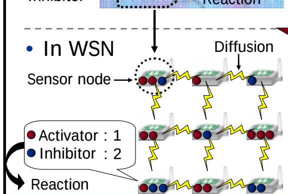



Continuous reaction-diffusion equation

$$\frac{\partial u}{\partial t} = F(u,v) + D_u \nabla^2 u$$

$$\frac{\partial v}{\partial t} = G(u,v) + D_v \nabla^2 v$$

- In WSN




Discrete reaction-diffusion equation

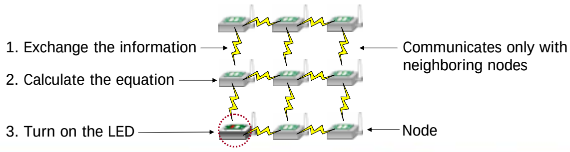
$$u_{t+1} = u_t - \Delta t\{F(u_t, v_t) + D_u \frac{u_t^n + u_t^e + u_t^s + u_t^w - 4u_t}{\Delta h^2}\}$$

$$v_{t+1} = v_t - \Delta t\{G(u_t, v_t) + D_v \frac{v_t^n + v_t^e + v_t^s + v_t^w - 4v_t}{\Delta h^2}\}$$



## Pattern Generation in WSN

- Procedure for each node
  1. Exchange concentrations of two morphogens
  2. Calculate discrete reaction-diffusion equation
  3. Perform an action based on morphogens



## Methods for Faster Pattern Generation

- Normal method
  - Large energy consumption
    - A large number of communication
    - A large number of calculation

Energy-efficiency is important for WSNs

- Methods to accelerate pattern generation
  - Method (a)
    - Enlarge discrete step $\Delta t$

$$u_{t+1} = u_t + \Delta t\{F(u_t, v_t) + D_u \frac{u_t^n + u_t^e + u_t^s + u_t^w - 4u_t}{\Delta h^2}\}$$

$$v_{t+1} = v_t + \Delta t\{G(u_t, v_t) + D_v \frac{v_t^n + v_t^e + v_t^s + v_t^w - 4v_t}{\Delta h^2}\}$$

  - Method (b)
    - Calculate $K$ iterations of reaction-diffusion equation at each step



## Experiments





## Simulation Experiments

Simulation Settings

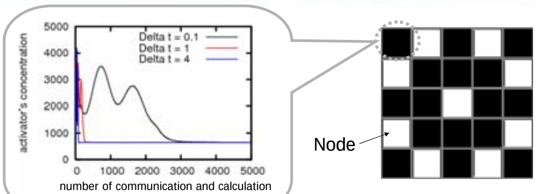
- 5 × 5 = 25 nodes
- Synchronized nodes
  - Exchange the information about morphogens concentrations at the same time
    - No information loss / Random information loss
  - Calculate the reaction-diffusion equation at the same time

Evaluation Metrics

- Communication and calculation time until concentrations of morphogens converge
- Probability of successful pattern generation against information loss



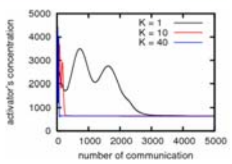
## Simulation Experiment: Result of Method (a)

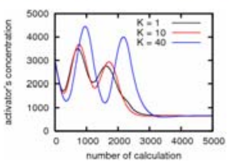



- Method (a) : Enlarge discrete step $\Delta t$
- Decrease in number of communication and calculation
- Mathematical upper limit of $\Delta t$ = 4.35
  - If $\Delta t$ > 4.35, the patterns do not converge

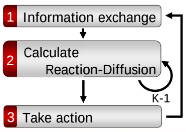


## Simulation Experiment: Result of Method (b)



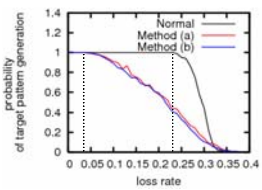




- Method (b) :
  Calculate equation $K$ times per information exchange
- Decrease in number of communication
- No decrease in number of calculation
- Upper limit of $K$ : 130
  - If $K$ > 130, the patterns do not converge






## Simulation Results with Information Loss



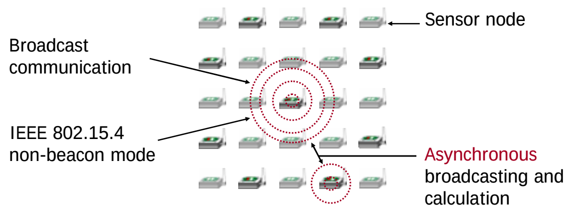

Normal : $\Delta t$ = 0.1, $K$ = 1
Method (a) : $\Delta t$ = 1, $K$ = 1
Method (b) : $\Delta t$ = 0.1, $K$ =10

Probability of successful pattern generation: The rate of simulation runs which reach the same stable pattern as without loss of information

Probability of information loss: The rate of information which is not received.

- Without acceleration method
  - Tolerate up to 23% information loss
- With acceleration method
  - Tolerate up to 4% information loss

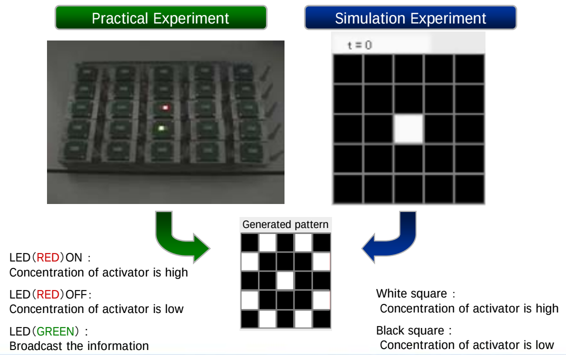
## Practical Experiments




- Broadcast interval $T$ = 1.4 [sec]
- Using Method (a) : Discrete step $\Delta t$ = 1



## Practical Experiment Result






## Conclusion and Future Work

1. Motivation
2. Reaction-Diffusion based Mechanism
3. Experiments
4. Conclusion and Future Work



## Conclusion and Future Work

- Conclusion
  - We show the applicability of reaction-diffusion equation to a wireless sensor network
    - We can accelerate the pattern generation to achieve energy-efficiency
    - The nodes can make the pattern in actual environment with some loss of information
- Future Work
  - Evaluate scalability for a large number of nodes
  - Random node layout, dynamic changes in topology
  - Mobile nodes
  - Much faster pattern generation
  - Target application using patterns



Thank you.