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Advanced Network Architecture Research Group

A Firefly-inspired Self-organizing Communication Mechanism for Wireless Sensor Networks

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Traveling Waves in Nature

- Synchronous flashing of fireflies



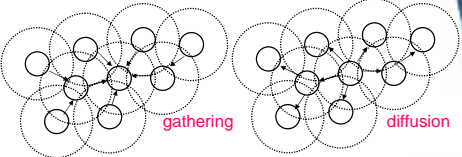
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Goal of this Research

- Generate traveling waves inspired by biology for periodic communication in WSN:
 - Information gathering (e.g. temperature data) sensor nodes → base station
 - Information diffusion (e.g. control signals) base station → sensor nodes



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Why use Traveling Waves?

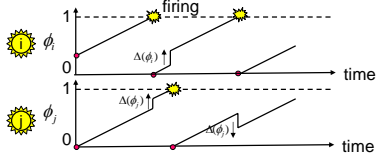
- Synchronization of message emission
 - Efficient sleep scheduling possible → Energy efficient operation
- Only local interactions between nodes
 - Scalable with number of nodes
 - Fully distributed operation
 - Robust to topology changes
- However: Several iterations necessary for adaptation!

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Pulse-Coupled Oscillator Model

- Oscillator i has phase $\phi_i \in [0, 1]$
- When the phase reaches 1, the oscillator i fires and the phase jumps back to 0
- Other oscillators coupled with the firing oscillator are stimulated and advance their phase by an amount $\Delta(\phi)$ (PRC: Phase Response Curve)



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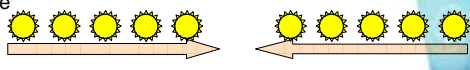
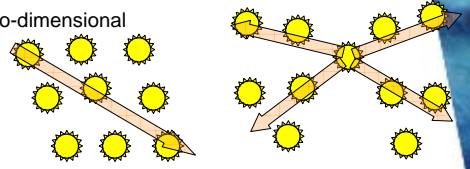
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Two Types of Synchronization

- Depending on the initial phase and PRC $\Delta(\phi)$, a set of oscillators reach either:
 - Global synchronization**: They keep the same phases and fire simultaneously. (Graph shows parallel phase lines that eventually align at 1.)
 - Phase-lock condition**: Phases are offset at constant difference. (Graph shows phase lines that are parallel but offset, with phase jumps that maintain the offset.)

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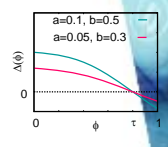
Types of Traveling Wave

- By adjusting parameters and PRC in the PCO model, we can control the traveling wave
 - Line
 
 - Two-dimensional
 

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PRC for Generating Traveling Waves

- Conditions of PRC $\Delta(\phi)$ to generate a traveling wave regardless of the initial phases

$$\begin{cases} 0 < \Delta(\phi) \leq 1 - \tau - \phi & (0 \leq \phi < 1 - \tau) \\ \Delta(\phi) = 0 & (\phi = 1 - \tau) \\ 1 - \tau - \phi \leq \Delta(\phi) < 0 & (1 - \tau < \phi < 1) \end{cases}$$

- An example of PRC

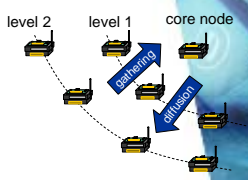
$$\Delta(\phi) = a \sin \frac{\pi}{1 - \tau} \phi + b(1 - \tau - \phi)$$

a, b: parameters which determine characteristics of PRC
 $0 < \tau < 0.5$: diffusion type with phase-difference τ
 $0.5 < \tau < 1$: gathering type with phase-difference $1 - \tau$

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Communication Mechanism

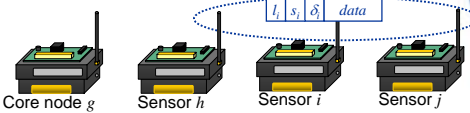
- Core node
 - Sensor node that gathers / diffuses information
- Sensor node i has:
 - Timer phase $\phi_i \in [0, 1]$
 - PRC function $\Delta(\phi)$
 - Offset τ
 - Interval of message emission
 - Session identifier s_i
 - Level value l_i
 - Number of hops from the core node
 - Direction of propagation δ_i
 - 1: gathering, 1: diffusion



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Sensor Node Behavior

- Sensor node i broadcasts a message within its radio signal range when timer reaches 1
- A message contains:
 - Level l_i , session id s_i , direction δ_i , sensor data
 - Core node: $l_i < 0$, $s_i \leftarrow s_i + 1$ for new session

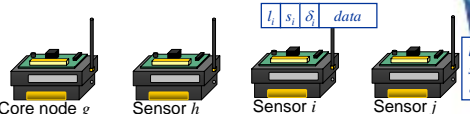


Phase ϕ_g	0.2	Phase ϕ_h	0.3	Phase ϕ_i	1.0	Phase ϕ_j	0.9
Level l_g	0	Level l_h	1	Level l_i	2	Level l_j	5
Session id s_g	3	Session id s_h	3	Session id s_i	3	Session id s_j	2
Direction δ_g	1	Direction δ_h	1	Direction δ_i	1	Direction δ_j	-1

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Message Reception (1)

- If session identifier $s_j < s_i$
 - New communication session begins
 - Sensor node j sets level l_j , session id s_j , direction δ_j
 - React to stimulation

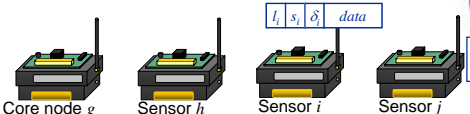


Phase ϕ_g	0.2	Phase ϕ_h	0.3	Phase ϕ_i	0	Phase ϕ_j	0.92
Level l_g	0	Level l_h	1	Level l_i	2	Level l_j	3
Session id s_g	3	Session id s_h	3	Session id s_i	3	Session id s_j	3
Direction δ_g	1	Direction δ_h	1	Direction δ_i	1	Direction δ_j	1

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Message Reception (2)

- If session identifier $s_j = s_i$ but level value $l_j > l_i$
 - Sensor node j sets level l_j , direction δ_j
 - React to stimulation
- If message comes from upstream node ($l_i = l_j - \delta_j$)
 - Process received information



Phase ϕ_g	0.2	Phase ϕ_h	0.3	Phase ϕ_i	0	Phase ϕ_j	0.92
Level l_g	0	Level l_h	1	Level l_i	2	Level l_j	3
Session id s_g	3	Session id s_h	3	Session id s_i	3	Session id s_j	3
Direction δ_g	1	Direction δ_h	1	Direction δ_i	1	Direction δ_j	1

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Power-saving Mode

- After traveling wave is generated, sensor node sleeps when $\tau < \phi_i < 1 - \tau$
- Energy consumption is reduced during power-saving mode

Core node g Sensor h Sensor i Sensor j

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Simulation Experiments

- Simulation settings
 - 100, 900, 2500 nodes are randomly distributed in 10x10, 30x30, 50x50 region
 - Range of radio signal is fixed at 2
 - Offset $\tau = 0.1$
 - A core node gathers information from all nodes
 - Energy consumption model is based on MOTE MICA2
- Evaluation metrics
 - Response time / number of messages
 - Number of available nodes (lifetime)
- Compared method
 - Two-phase pull diffusion (information gathering)

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Response Time / Number of Messages

- Response time:** duration until reception of data from all nodes
- Proposal has **larger delay**, but **less overhead**

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Number of Available Nodes

- Proposal is more energy efficient
- Lifetime of sensor network is extended

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Implementation of the Mechanism

- MOTE MICAz
 - Omni-directional antenna
 - IEEE 802.15.4 MAC protocol
- Packet format (48 bits long)

0	Level	δ	Reserved	8
Session identifier				
Node ID				
Data				48

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Demonstration Video

- Settings:
 - Cycle time: 3 s, offset $\tau = 0.3$ s
- Scenario:
 - No core node exists
 - Node #6 becomes core node for information diffusion
 - Node #11 becomes core node for information gathering

Experimental topology Video

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Conclusion and Outlook

- Proposal of a bio-inspired communication mechanism for gathering / diffusion in sensor networks
 - Fully distributed and self-organizing
 - Evaluation through simulation and practical implementation
- Future work
 - Improvement of the mechanism
 - Additional experiments
 - > More nodes, obstructions, interferences, collisions