Firefly and Glowworm Algorithms

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- Algorithmic approaches gleaned from the way in which fireflies and glow worms use light

Fireflies versus Glowworms

- Fireflies and glowworms are neither flies nor worms but they are beetles that can emit light (bioluminescence) and are (mostly) of the family of Lampyridae

- The difference between glowworms and fireflies (from our perspective) :
  - Glow worms: flightless species of the Lampyridae
  - Fireflies: flighted species of the Lampyridae

- For a complete picture, consult:
  - http://www.firefliesandglow-worms.co.uk

Why Flash? Two good reasons

Finding mating partners:

- Fireflies (both males and females) use the flashing light to attract each other

Attracting prey:

- Glowworms build sticky snares and emit light to attract insects and trap them in their snares

Firefly Synchronization Algorithms

- Inspired by the synchronized flashing behavior of fireflies in South-East Asia
- Autonomous entities interacting directly with each other in a peer-to-peer fashion show a highly organized emerging behavior
- A powerful alternative for master-slave synchronization

Mysterious Mass Synchrony

- In Thailand there are fantastic firefly shows; enormous congregations of fireflies blinking on and off in unison, in displays that supposedly stretched for miles along the riverbanks (Also occurring in Africa, and some more places)

- Accounts on this phenomenon by Western travelers to South East Asia go back as far as 300 years.

- Mysterious form of mass synchrony

Early theories

- In 1917 Philip Laurent wrote up an explanation in Science: “the apparent phenomenon was caused by the twisting or sudden lowering and raising of my eyelids the insects had nothing to do with it”

- Some force called “Einfuehlung” (being on someone’s wavelength in humans) is the cause

- The fireflies have a coordinator or orchestra conductor

- Buck and Buck took fireflies into their room at night and they spontaneously synchronized when they were put to the ceiling, without external force.

Pulse-Coupled Oscillators (1)

- Fireflies can be abstracted as oscillators that emit a pulse of light periodically

- A colony of fireflies can be abstracted as a network of connected pulse-coupled oscillators

- Pulse-coupled oscillator oscillate periodically in time and interact each time they complete an oscillation

Pulse-Coupled Oscillators (2)

- A pulse-coupled oscillator is completely described by its phase function $\Phi(t)$
- This function evolves linearly over time until it reaches the threshold value Φth
- When this happens, the oscillator fires, meaning that it will transmit a pulse and reset its phase

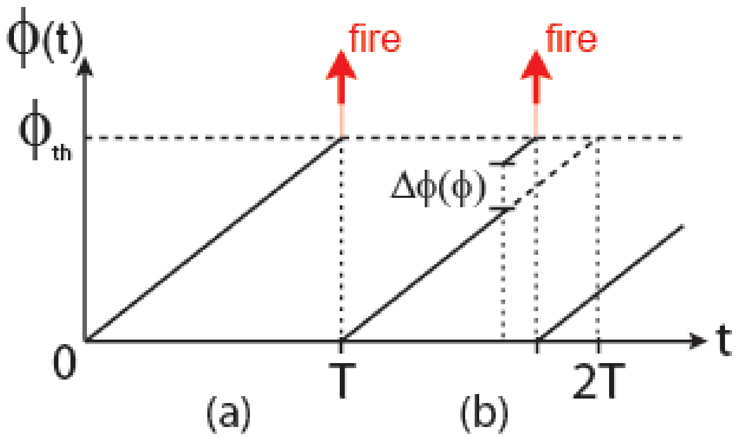


Fig. 1. Time evolution of the phase function

Pulse-Coupled Oscillators (3)

- When coupled to others, an oscillator is receptive to the pulses of its neighbors
- When receiving such a pulse, it directly increments its phase by an amount that depends on the current value:

$$\phi \longrightarrow \phi + \Delta\phi$$

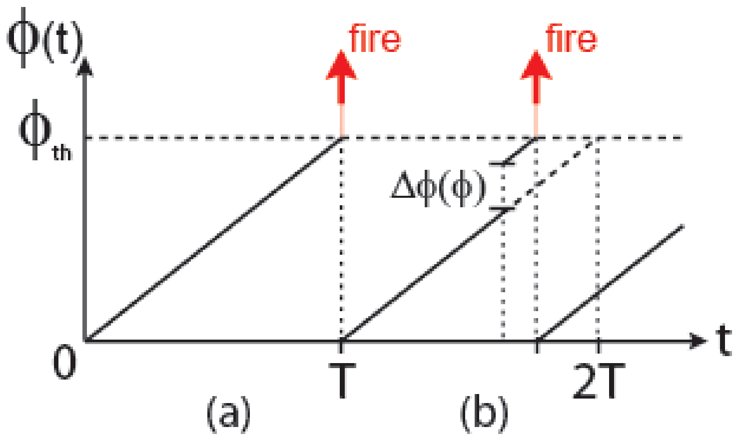
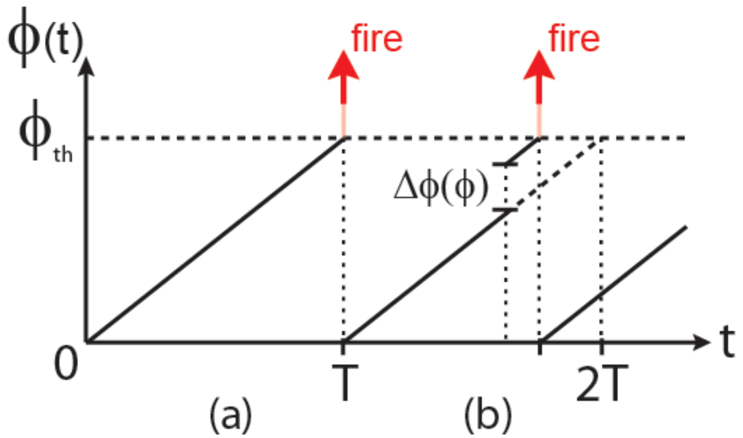


Fig. 1. Time evolution of the phase function

Pulse-Coupled Oscillators (4)

- The phase increment depends on the current phase, and it is determined by the Phase Response Curve (PRC):

$$\phi + \Delta\phi = \min\left(\alpha \cdot \phi + \beta, 1\right) \quad \text{with} \quad \begin{cases} \alpha = \exp(b \cdot \epsilon) \\ \beta = \frac{\exp(b \cdot \epsilon) - 1}{\exp(b) - 1} \end{cases}$$



b is the dissipation factor
ε is the amplitude increment

The threshold ϕ_{th} is set to a normalized value of 1

R. Mirollo and S. Strogatz, “Synchronization of pulse-coupled Biological oscillators,” *SIAM J. APPL. MATH*, vol. 50, no. 6, pp. 1645–1662, Dec. 1990.

Convergence and Time to Synchronicity

- If the network of pulse-coupled oscillators is “fully meshed” and $\varepsilon > 0$ and $b > 0$, the system always converges (i.e., synchronizes)

- All oscillators will fire as one independently of initial conditions.

- the time to synchrony is inversely proportional to the product $\beta \cdot \varepsilon$ in

$$\phi + \Delta\phi = \min(\alpha \cdot \phi + \beta, 1) \quad \text{with} \quad \begin{cases} \alpha = \exp(b \cdot \epsilon) \\ \beta = \frac{\exp(b \cdot \epsilon) - 1}{\exp(b) - 1} \end{cases}$$

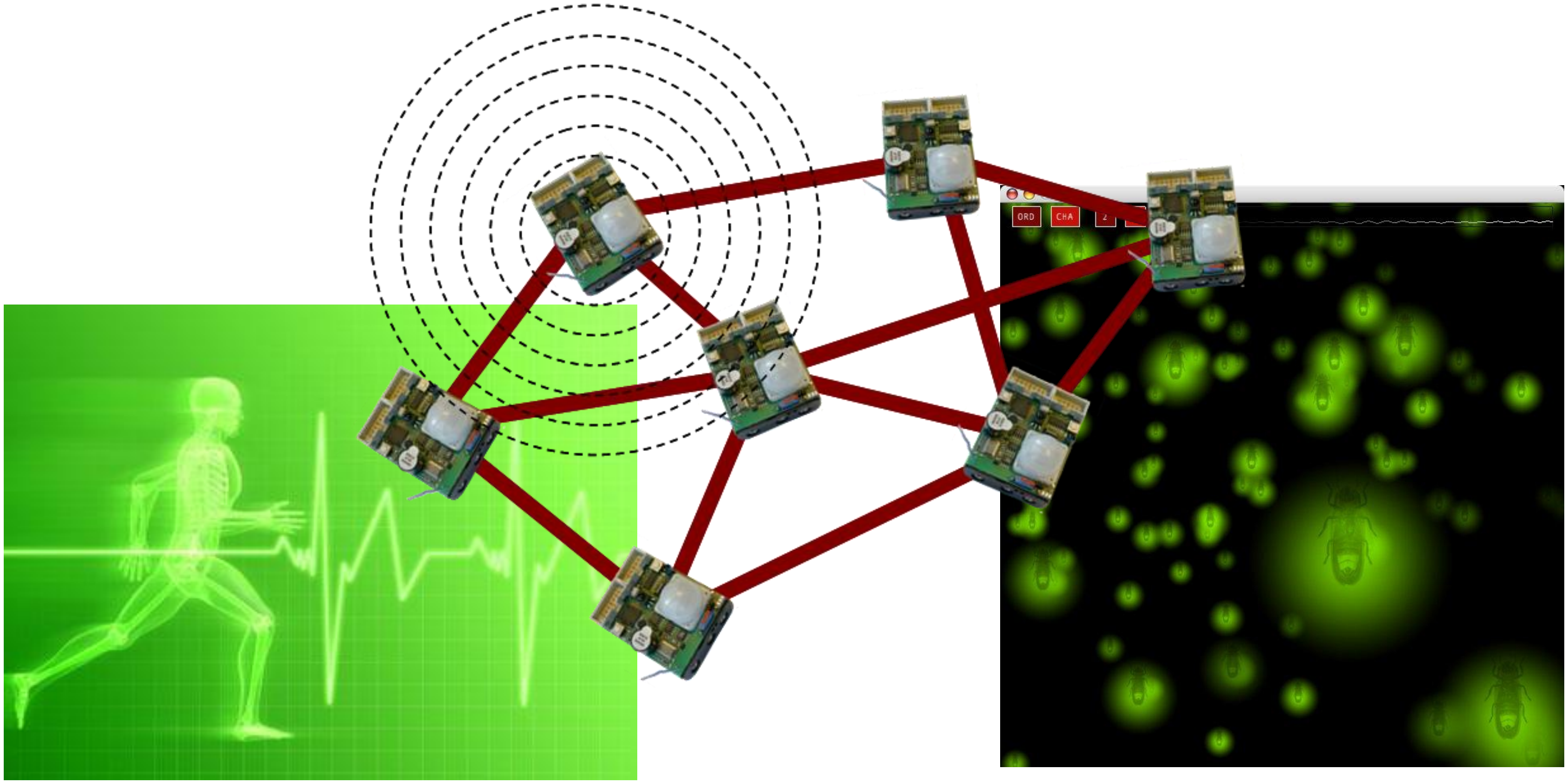
R. Mirollo and S. Strogatz, “Synchronization of pulse-coupled Biological oscillators,” *SIAM J. APPL. MATH*, vol. 50, no. 6, pp. 1645–1662, Dec. 1990.

Some Remarks on Synchronization and Pulse-Coupled Oscillators

- The synchronization scheme relies on
  - Pulses arrive instantaneously
  - Receivers adjusting their phases when detecting this pulse
  - Two pulses emitted simultaneously can superimpose constructively (no interference problem as in wave systems)

- The same model can be used for modeling heartbeat (10000 oscillators), brain cell systems, earthquakes

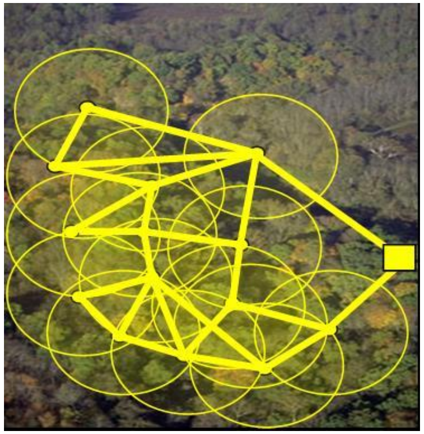
Synchronizing using Pulse-Coupled Oscillators: Fireflies, Heart, and Wireless Networks

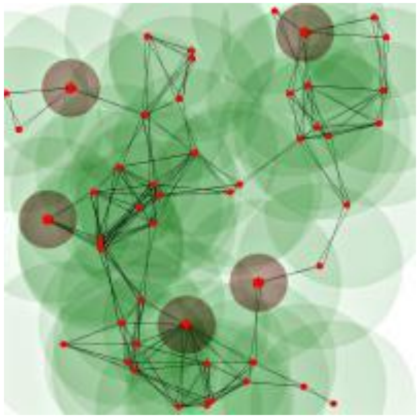


A. Tyrrell, G. Auer, C. Bettstetter. Firefly Synchronization in Ad Hoc Networks. 3rd MiNEMA Workshop, Leuven, Belgium, 2006.

Wireless Sensor Networks (WSN)

- Spatially distributed networks of small low-cost autonomous devices containing micro-sensors and low-power wireless communication units
- Usable for a wide range of environmental monitoring tasks, e.g., marine, soil, and atmospheric contexts
- Requirement: scalability, robustness, reliability, self-reconfiguration
- Challenges: discovering neighbors autonomously, efficient autonomous routing, and **autonomous synchronization**





A. Cerpa, J. Elson, D. Estrin, L. Girod, M. Hamilton, and J. Zhao. Habitat monitoring: application driver for wireless communications technology. *SIGCOMM* 31 2, 20-41, 2001.

Application to Ad-Hoc Networks

- The synchronization scheme described previously can be applied to wireless systems

- Real-world wireless systems come with delays:
  - Pulses are not instantly received and decoded by other oscillators
  - Solitary pulses are hardly recognized; realistically a sequence of pulses (a burst) is to be considered
  - During transmission of pulses a node is not able to receive

A. Tyrrell, G. Auer, C. Bettstetter. Firefly Synchronization in Ad Hoc Networks. 3rd MiNEMA Workshop, Leuven, Belgium, 2006.

Multiple Delays

T_0: Propagation delay

- Time to propagate from an emitting node to a receiving node; proportional to the distance between two nodes

T_{Tx}: Transmitting delay

- Length of the burst; while transmitting, a node is in a transmit state and cannot listen to other synchronization messages

T_{dec}: Decoding delay

- Time required by the receiver to decode a synchronization message

Note: see here that our simple PCO model gets more complex again

Propagation delays

- If a propagation delay T_0 occurs between two pulse coupled oscillators, the system can become unstable
- The pulse of one oscillator could cause the other oscillator to transmit after T_0, and this transmitted pulse causes the first oscillator to fire again after T_0, and so on
- To avoid this avalanche effect a **refractory period** of duration T_{refr} needs to be added after transmission, during which the phase function of a node stays equal to 0 and is not modified if receiving a pulse
- Stability is maintained if echoes are not received, which translates to a condition on T_{refr}: $T_{refr} > 2 \cdot T_0$

U. Ernst, K. Pawelzik, and T. Geisel, "Synchronization induced by temporal delays in pulse-coupled oscillators," *Physical Review Letters*, vol. 74, no. 9, pp. 1570–1573, Feb. 1995.

Total Delay and Blind Spots

- The total delay (the total time between transmission and reception) within real-world wireless systems is

$$T_{del} = T_0 + T_{Tx} + T_{dec}$$

- The delays can cause "blind spots" of duration T_{del}, during which synchronization is not possible

- The synchronization accuracy is lower bounded by T_{del}

Including Waiting Times

- To combat the loss of accuracy the transmitter is delayed in its transmission for a certain time equal to:

  $$T_{wait} = T - (T_x + T_{dec})$$

  where T denotes the synchronization period

- This scheme modifies the natural oscillatory period of an oscillator, which is now equal to 2 ·T

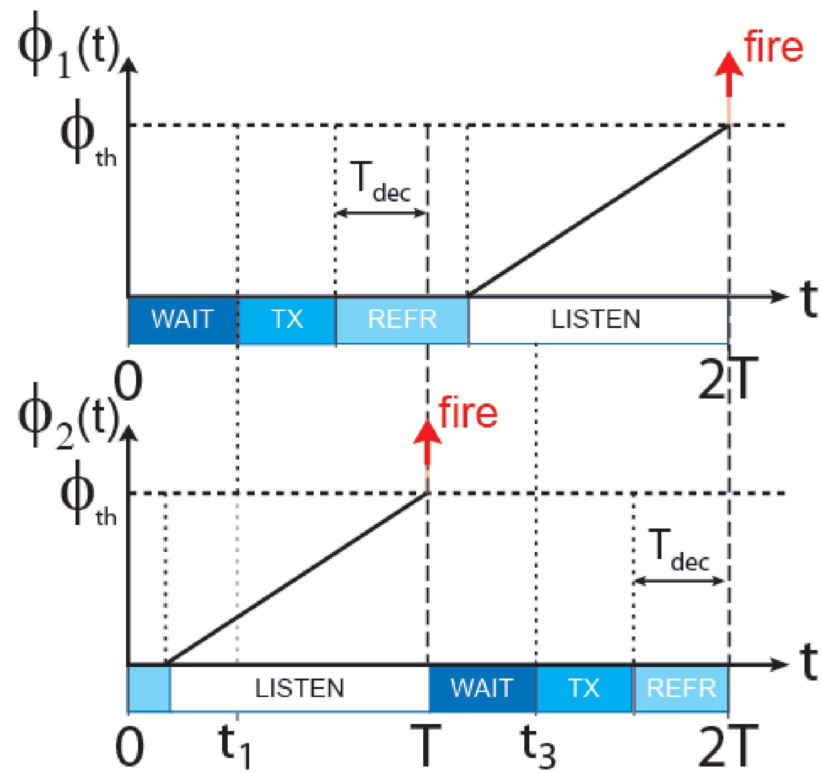


Fig. 2. Description of the timing advance transmit strategy for two periods

Synchronization with multiple delays (2)

- The time during which the phase function will increment is reduced by the waiting, transmitting, and refractory delays

- It is now equal to:

$$T_{\mathrm{Rx}} = 2 \cdot T - (T_{\mathrm{wait}} + T_{\mathrm{Tx}} + T_{\mathrm{refr}})$$

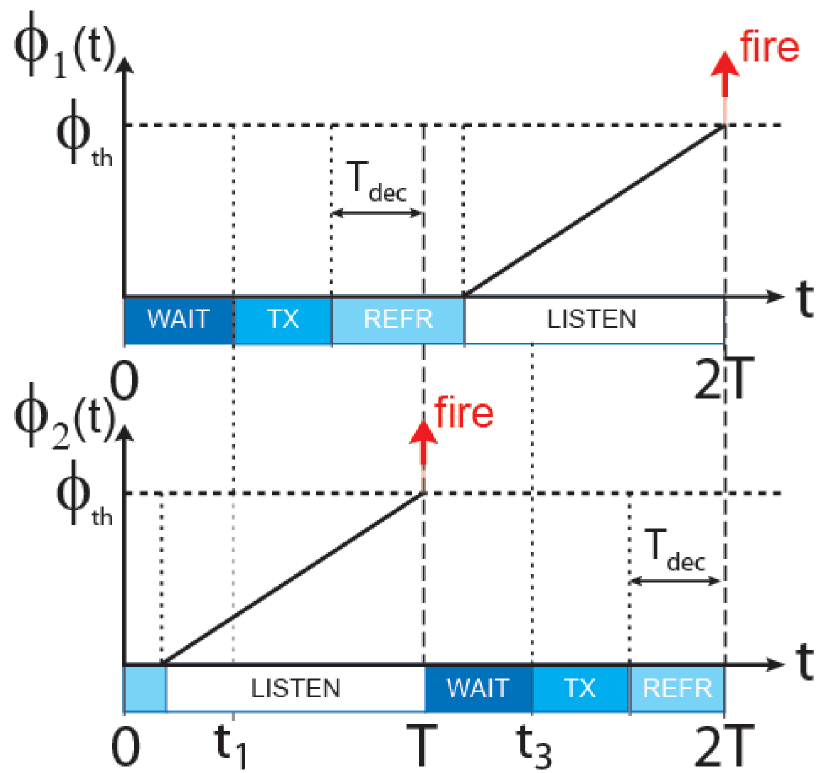


Fig. 2. Description of the timing advance transmit strategy for two periods

Example Scenario

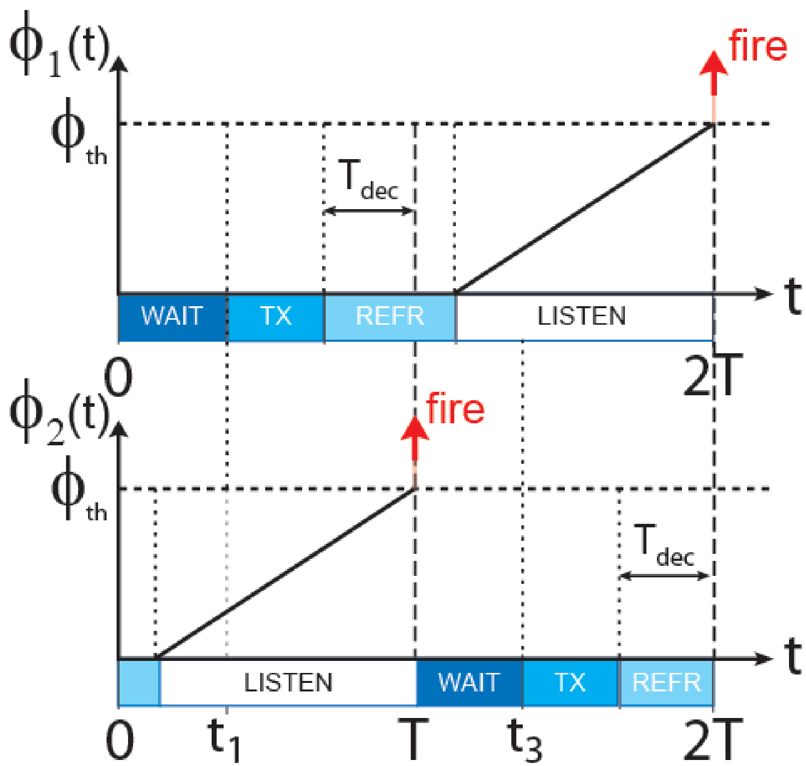
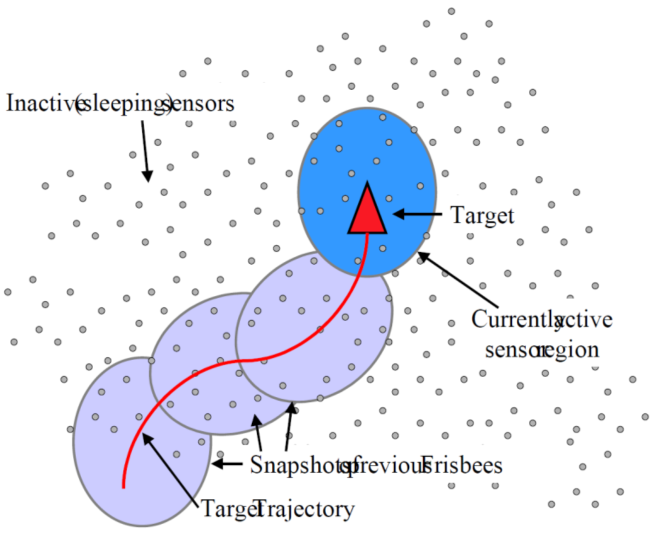


Fig. 2. Description of the timing advance transmit strategy for two periods

- At instant 0, oscillator 1 reaches ϕ_{th}. It waits until $t_1 = T_{wait}$ before starting to transmit a synchronization burst.
- At $t_2 = T_{wait} + T_x + T_{dec} = T$, oscillator 2 has successfully received and decoded the burst.
- As the two oscillators are already synchronized, it will follow the same scheme as oscillator 1 and wait until $t_3 = T + T_{wait}$ before transmitting

Information propagation

- Once the sensor network is synchronized, the protocol can also be used to propagate information
- If a node wants to transmit data, it will spontaneously shift the established reference instant, thus breaking the equilibrium and also forcing surrounding nodes to shift their reference instant
- This global shift can be used to convey information to an observer that will detect the offset in the reference instant



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Summary

- Coupled Oscillators can explain spontaneous synchronization of fireflies
- The same model can be used for modeling heartbeat (10000 oscillators), brain cell systems, earthquakes
- Computer science application to wireless sensor network synchronization
- Delays (no instantaneous transmission) demand for adaptations such as refractory times

Pacemaker of the Heart

- C.S. Peskin also proposed a schematic model for how the pacemaker cells of the heart synchronize themselves

- The pacemaker of the heart
  - A very impressive oscillator
  - A cluster of 10,000 cells called sinoatrial node
  - Generates electrical rhythm that commands the rest of the heart to beat
  - Should be reliable and robust (fit for approx. three billion beats in a lifetime)
  - Unlike most cells in heart, pacemaker cells oscillate automatically: isolated in petri dish, their voltage rises and falls in a regular rhythm

- Using a single leader-cell to do the “pacemaking” is not so robust, the heart needs mass synchronization

The Millennium Bridge

- The Millennium Bridge started to sway uncontrollably due to pedestrians unintentionally walking in step
- The small sway of the bridge caused the pedestrians to correct their balance (unconsciously)
- However, instead the synchronized steps of the people reinforced the oscillations

Optimization with Fireflies and Glowworms

Firefly Algorithm (FA)

- Proposed very recently by X.-S. Yang in 2008
- An optimization algorithm based on a model of the attraction of fireflies selecting mating partners based on differences in **light intensities**
- Can be used for solving real-valued multi-modal optimization problems
- Very similar to PSO, and under certain special conditions corresponds to a standard PSO algorithm

X. S. Yang, Firefly algorithms for multimodal optimization, in: Stochastic Algorithms: Foundations and Applications, SAGA 2009, Lecture Notes in Computer Sciences, Vol. 5792, pp. 169-178 (2009).

The Three Rules of a Firefly Algorithm

- All fireflies are unisex, so that one firefly will be attracted to all other fireflies

- Attractiveness is proportional to their brightness, and for any two fireflies, the less brighter one will attract (and thus move) to the brighter one; however, the brightness can decrease as their distance increases

- If there are no fireflies brighter than a given firefly, it will move randomly

The Firefly Algorithm Algorithmically

Firefly Algorithm

Objective function $f(\mathbf{x}), \qquad \mathbf{x} = (x_1, ..., x_d)^T$

Generate initial population of fireflies $\mathbf{x}_i$ $(i = 1, 2, ..., n)$

Light intensity I_i *at* $\mathbf{x}_i$ *is determined by* $f(\mathbf{x}_i)$

Define light absorption coefficient γ

while $(t <$ *MaxGeneration*$)$

for $i = 1 : n$ *all* n *fireflies*

    for $j = 1 : i$ *all* n *fireflies*

        if $(I_j > I_i)$, *Move firefly* i *towards* j *in d-dimension*; **end if**

        Attractiveness varies with distance r *via* $\exp[-\gamma r]$

        Evaluate new solutions and update light intensity

    end for j

end for i

Rank the fireflies and find the current best

end while

Postprocess results and visualization

Requires:
- Formulation of attractiveness
- Movement method

Attractiveness (1)

- The attractiveness β of a firefly is determined by its light intensity *I* which is proportional to the objective function value of the position of the firefly

- Attractiveness should be seen in the eyes of the beholder; light intensity decreases over distance, hence, so does attractiveness

Attractiveness (2)

- The attractiveness of a firefly i to firefly j is determined as:

$$\beta(r) = \beta_0 e^{-\gamma r^2}$$

where:

  - r is the distance between firefly i and j
  - β_0 is the objective function value of I
  - γ is an absorption coefficient

Movement

- The movement of a firefly i that is attracted to another more attractive firefly j is determined by

$$\mathbf{x}_i = \mathbf{x}_i + \beta_0 e^{-\gamma r_{ij}^2} (\mathbf{x}_j - \mathbf{x}_i) + \alpha \left(\text{rand} - \frac{1}{2}\right)$$

where:

- A is a randomization (scaling) parameter
- rand is a random number uniformly drawn from the interval [0,1]

Firefly Algorithm Conclusion

- Shows another way in which fireflies served as inspiration for algorithmic schemes
- MALTAB code is available here: http://www.mathworks.com/matlabcentral/fileexchange/29693-firefly-algorithm
- Presented as competitive with PSO and GA

Glowworm Swam Optimization (GSO)

- Again an optimization algorithm based on a model of the attraction of glowworm selecting mating partners based on differences in **light intensities**
- Can be used for solving real-valued multi-modal optimization problems
- Very similar to the FA algorithm, but intends to allow the swarm of glowworms to split into sub-groups
- Proposed very recently by K.N. Krishnanand and D. Ghose in 2006

K.N. Krishnanand and D. Ghose. (2006). Glowworm swarm based optimization algorithm for multimodal functions with collective robotics applications. Multi-agent and Grid Systems, 2(3): 209–222.

Concluding Remarks

- The behavior of fireflies and glowworms has served as inspiration for computing paradigms
- The algorithmic methods inspired by fireflies and glow worms are very new
- It is too early to say whether these methods are really competitive with current methods