A Firefly-inspired Self-organizing Communication Mechanism for Wireless Sensor Networks [1]

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Abstract

We have proposed a self-organizing communication mechanism for wireless sensor networks where a large number of sensor nodes are deployed. In this paper, we briefly introduce and overview our communication mechanism. In our mechanism, to accomplish application-oriented periodic communication without any centralized controls, we adopt traveling wave phenomena of a pulse-coupled oscillator model by regarding sensor nodes as oscillators and emission of radio signals as firing. Simulation results show that our mechanism delivers sensor information to a designated node in a more energy-efficient manner than other method, although it takes time to generate a traveling wave. In addition, we show implementation of our mechanism using MOTE MICAz and its practicality.

1 Introduction

In wireless sensor networks, due to several restrictions including limited battery capacity, random deployment, and a large number of fragile sensor nodes, a communication mechanism should be energy efficient, adaptive, robust, fully distributed, and self-organizing. Furthermore, it should be able to handle various types of communication, i.e., diffusion and gathering, involving the whole network in accordance with application requirements. For example, a sensor node detecting an emergency would distribute the notification over the whole network to alert the other nodes and make them cooperatively react to the emergency. On the contrary, a sensor node detecting an uncertain condition would collect and aggregate sensor information of the other nodes to have a more precise view of the environment from collected information.

To accomplish the above-mentioned goal, we have proposed a simple and energy-efficient communication mechanism which can organize a variety of communication, i.e., diffusion and gathering, depending on dynamically changing application requirements [1, 2]. The desired pattern of message propagation emerges through reactions of sensor nodes to surrounding conditions and local and mutual interactions among sensor nodes, that is, by self-organization. For this purpose, we adopt a pulse-coupled oscillator (PCO) model based on biological mutual synchronization such as that observed in flashing fireflies [3-5]. In a PCO model, synchronous behavior of a group of oscillators is considered. Each oscillator operates on a timer. When the phase of the timer reaches one, an oscillator fires. Oscillators coupled with the firing oscillator are stimulated and they shift the phase of timers by a small amount. Through mutual interactions by stimuli among oscillators, they eventually reach a synchronized behavior. There are several papers which employ a PCO model to make sensor nodes operate in synchrony, e.g., clock synchronization, through a distributed and self-organizing control mechanism [6-10].

In contrast to the other work, our mechanism focuses on another phenomenon observed in a PCO model. In a PCO model, it is shown that not only the global synchronization where all oscillators

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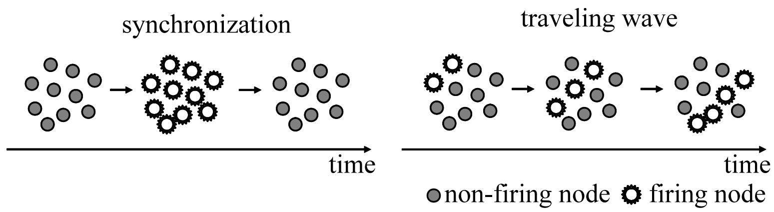


Figure 1: Global synchronization and traveling wave

fire synchronously, but a traveling wave, where oscillators behave synchronously but with fixed phase difference, appears (Fig. 1) [4, 5]. By adjusting parameters and functions of a PCO model, we can control the frequency, form, and direction of a wave. We have first investigated conditions of a phase response curve (PRC) with which a wireless sensor network reached a preferred phase-lock condition where the phase differences among sensor nodes are kept constant from arbitrary settings of the initial phase of sensor nodes. In addition, based on the investigation, we have proposed a self-organizing communication mechanism.

In this paper, we briefly introduce and overview our communication mechanism. In our mechanism, each sensor node broadcasts its sensor information in accordance with the phase of its own timer. When a sensor node receives a radio signal of others, it shifts the phase of its timer. Through mutual interactions among neighboring sensor nodes, they reach the phase-lock and emit sensor information alternately. The timings of message emissions are seen concentric traveling waves centered at a sensor node, which wanted to gather information from all sensor nodes or diffuse information to all sensor nodes. Simulation results show the effectiveness of our mechanism in comparison with other method. In addition, we show implementation of our mechanism using MOTE MICAz and verify its practicality. Details of our mechanism and further discusses can be found in [1, 2].

2 Generating Traveling Waves in a Pulse Coupled Oscillator Model

A pulse-coupled oscillator (PCO) model is developed to explain synchronous behaviors of biological oscillators such as pacemaker cells, fireflies, and neurons [4]. In a PCO model, oscillator i has a timer, whose phase is denoted as $\phi_i \in [0, 1]$. When the phase reaches one, oscillator i fires. Oscillators coupled with the firing oscillator are stimulated and they shift their phase by small amount $\Delta(\phi_j)$, where j is an identifier of stimulated oscillator. The function $\Delta(\phi)$ is called Phase Response Curve (PRC).

Through mutual interactions, a set of oscillators reach either of the global synchronization where they have the same phase and fire all at once, or the phase-lock condition where phases are different among oscillators with a constant offset as shown in Fig. 2. In the case of the phase lock, the geographic propagation of firings seems like a traveling wave as shown in Fig. 1. Whether a network reaches the global synchronization or the phase-lock depends on the initial phase of timers or properties of the PRC [11].

In [2], we have investigated conditions of PRC that led to desired phase-lock condition regardless of the initial phase. We assume a pacemaker, that is an oscillator which dominates and controls a firing pattern on a PCO network. A pacemaker is different from other oscillators only in a point that it will not be stimulated by other oscillators and thus fires at its own periodic timing, which corresponds to the data gathering or diffusion cycle in a wireless sensor network. Furthermore, we consider that an oscillator is stimulated only by its neighboring oscillators which are closer to the pacemaker.

In above PCO network, to generate a desired traveling wave where oscillators fire from a pacemaker toward the edge at constant phase-difference τ regardless of the initial phase of oscillators, a PRC

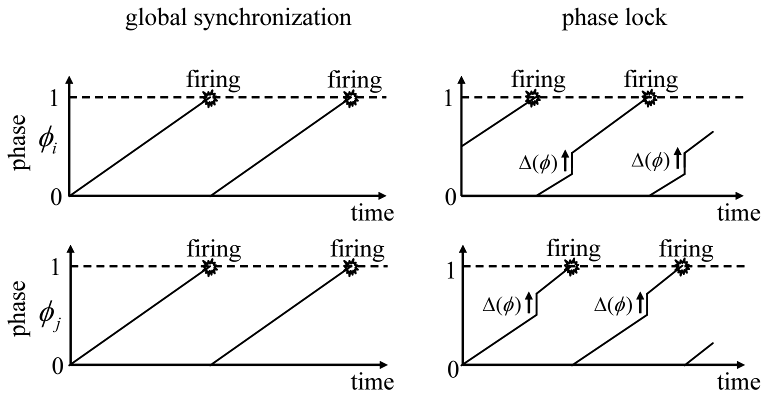


Figure 2: Global synchronization and phase-lock

function must satisfy the following conditions.

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

For example, the following PRC function satisfies Eq. (1).

$$\Delta_S(\phi) \quad = \quad a \sin \frac{\pi}{1-\tau}\phi + b(1 - \tau - \phi) \tag{2}$$

Here, a and b are parameters which determine characteristics of the PRC. As parameters a and b increase, a traveling wave emerges more rapidly.

PRC Δ_S can generate two types of traveling wave. By setting τ as $\tau < 0.5$, a traveling wave from the peacemaker toward the edge of a PCO network with constant phase-difference can be organized. On the contrary, with $\tau > 0.5$, a traveling wave moves from the edge of a PCO network toward the peacemaker.

3 A Traveling Wave-based Communication Mechanism

We now briefly introduce our communication mechanism for wireless sensor networks. In our mechanism, any of sensor nodes can become a point, called a core node, from which messages are disseminated or to which messages are gathered. When there is no session, sensor nodes emit messages at their own timing and independently from the others.

Sensor node i has a timer with phase $\phi_i \in [0, 1]$, $d\phi_i/dt = 1/T$, where T is a cycle of data diffusion or gathering. It maintains PRC function $\Delta(\phi_i)$, level value l_i, session identifier s_i, direction δ_i, and offset τ. A level value indicates the number of hops from a core node and it is used to define the relationship among sensor nodes. Direction δ_i is a parameter which controls the direction of information propagation, and it is set at 1 for diffusion and -1 for gathering. The offset defines the interval of message emission between a node of level $l - 1$ and that of level l. The offset τ is determined taking into account the density of sensor nodes in the whole network. In this paper, based on Eq. (2), we use the following PRC function for all sensor nodes.

$$\Delta(\phi_i) = a \sin \frac{\pi}{g_i}\phi_i + b(g_i - \phi_i), \tag{3}$$

Here, g_i is defined as $(1 + \delta_i \tau) \bmod 1$.

As time passes, phase ϕ_i shifts toward one and, after reaching it, sensor node i broadcasts a message and the phase jumps back to zero. A message that sensor node i emits contains level value l_i, session identifier s_i, direction δ_i, and its information aggregated with other sensor's information kept in its buffer. To initiate a new communication, a core node broadcasts a message containing a new session identifier set at the current value plus one, a level value of zero, the direction, and information to disseminate or gather.

Now, sensor node i receives a message from sensor node j. If session identifier s_j is larger than s_i, sensor node i considers that a new communication begins. Therefore, it sets its level value l_i at $l_j + 1$, session identifier s_i at s_j, and direction δ_i at δ_j. Then, it is stimulated to join a new traveling wave. This mechanism means that the current communication is terminated by a newly initiated communication. If session identifiers are the same but the level value l_j is smaller than l_i, sensor node i sets its level value l_i at $l_j + 1$, direction δ_i at δ_j, and it is stimulated. Stimulated sensor node i shifts its phase based on the PRC function. As in the PCO model, a sensor node is not stimulated by messages from sensor nodes with a smaller level value during the following duration of τ when it has already been stimulated, to avoid being stimulated by deferred messages. If the session identifier is the same and level value l_j is $l_i - \delta_i$, sensor node j is an upstream node of sensor node i. Therefore, to relay information of sensor node j to the next downstream node, sensor node i deposits the received information in its local buffer. If a message does not satisfy any of the above conditions, sensor node i ignores it.

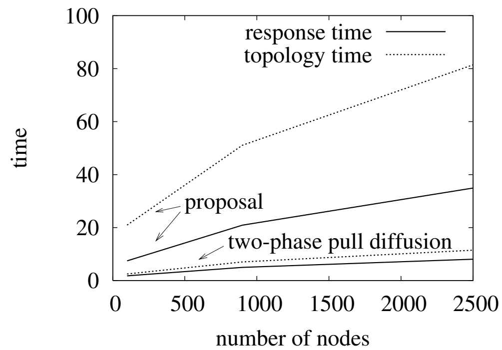
Through mutual interactions among neighboring sensor nodes, they reach the state, called phase-lock, where the phase differences among sensor nodes are kept constant, and they emit sensor information alternately. After reaching the phase-lock, a sensor node starts a sleep schedule. It wakes up when its phase is at $1 - \tau$ to receive messages from upstream nodes. Upstream nodes are scheduled to emit their messages from $1 - \tau$ to 1. When its phase reaches one, a sensor node broadcasts a message. After that, it keeps awake for τ to receive messages from downstream nodes, and then goes to sleep. Therefore, a node is awake for the duration of 2τ in one communication cycle.

Although further details are not shown in the paper, our mechanism can adapt to additional deployment and removal of sensor nodes, multiple core nodes, and node failures [2].

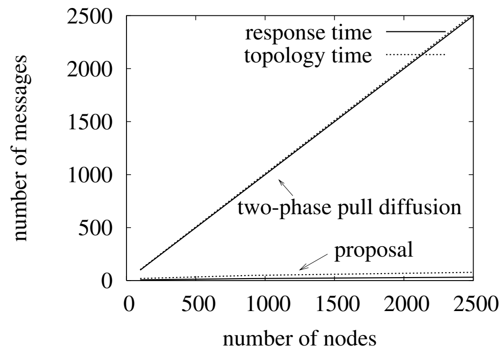
4 Simulation Experiments

In this section, we show some simulation results. We consider wireless sensor networks of 100, 900, and 2500 sensor nodes randomly distributed in 10×10, 30×30, and 50×50 region, respectively. The range of radio signal is fixed at 2 units of length. Initial phase of sensor nodes is set at random. A core node is randomly chosen for data gathering. A sensor node consumes 81 mW for transmission, 30 mW for receiving and idle, and 0.003 mW for sleep [12]. Initial energy is 50 J for all nodes. We use Eq. (3) with $a = 0.01$ and $b = 0.5$ as the PRC function and τ is set at 0.1. For comparison purposes, we also conduct simulation experiments for the directed diffusion [13, 14] where per-hop delay is set at 0.1 time units. The directed diffusion also considers two types of communication, i.e., pull and push. All results are averaged over 100 simulation experiments.

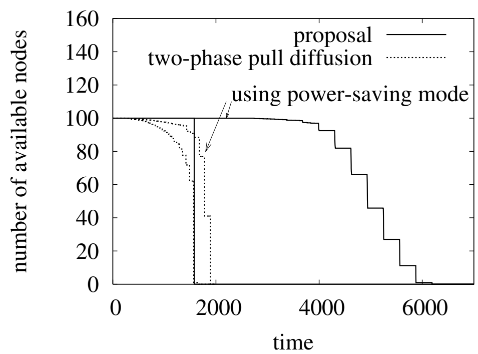
The response time indicates the duration from emission of an interest or a message with a new session identifier to reception of sensor information from all nodes. The topology time indicates the duration from emission of an interest or a message with a new session identifier to reception of reinforcement messages at all nodes or to establish the phase-lock condition. The number of messages indicates the average number of messages that a node sends and receives during the response time or the topology time. The lifetime is defined as the duration from emission of an interest or a message with a new session identifier to death of any sensor node due to depletion of energy.



(a) Response and topology time



(b) Number of messages



(c) Number of available nodes

Figure 3: Comparison among proposal and directed diffusion in information gathering

In Fig. 3 (a), both of the response time and topology time with our mechanism are longer than those with the directed diffusion. A traveling wave is generated thorough local and mutual interactions, whereas the directed diffusion relies on message flooding. However, the overhead in terms of the number of messages is much smaller with our mechanism. It is only 1 to 6 % of the directed diffusion in the response time and 4 to 26 % in the topology time as shown in Fig. 3 (b). Since a sensor node emits a message per cycle in our mechanism, the number of message increases in proportional to the response and topology time. As described in Section 2, the response time and topology time can be reduced by adjusting a PRC function and its parameters.

Finally, we verify energy efficiency of our mechanism from a viewpoint of a lifetime of a sensor network of 100 nodes. As shown in Fig. 3 (c), the lifetime with our mechanism is 1577 time units whereas that with the directed diffusion is 265 time units in the case of information gathering. Furthermore, by using a power-saving mode, the lifetime with our mechanism becomes as long as 2733 time units wheres that with the directed diffusion is 304 time units.

Although results are not shown in the paper, we also conducted simulation experiments for information diffusion, where a randomly chosen node diffuses information to the whole sensor network. Details of simulation results are shown in [2].

5 Implementation of the Mechanism

We implemented our mechanism using a commercial sensor unit MOTE MICAz [12]. It has an omnidirectional antenna and employs IEEE 802.15.4 [15] and B-MAC [16] protocol on 2.4 GHz bandwidth

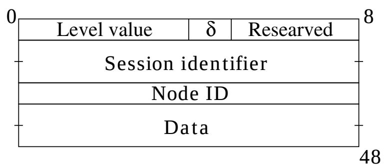


Figure 4: Packet format

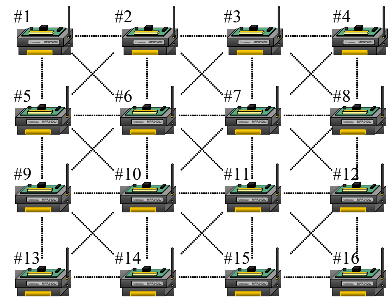
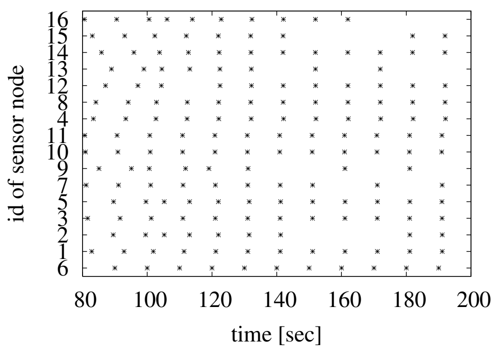
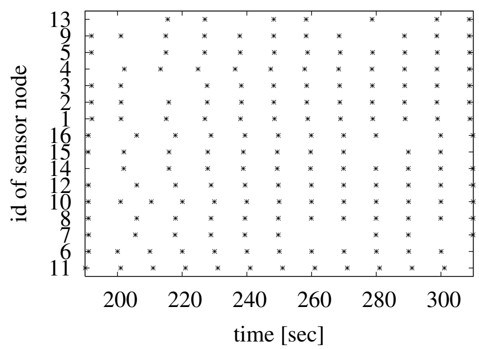


Figure 5: Experimental topology



(a) Diffusion



(b) Gathering

Figure 6: Timing of message emissions

for radio communication.

A 10-seconds timer is implemented by shifting phase ϕ_i by 0.01 at every 100 milliseconds. As shown Fig. 4, a message is 48 bits long where the first 4 bits are for level value, 1 bit for δ, 3 bits reserved, 8 bits for node ID for filtering, 16 bits for session identifier, and the last 16 bits for data.

We confirmed basic behavior of our mechanism on a sensor network consisting of 16 nodes arranged in a grid as shown in Fig. 5. To maintain the stable network topology, we introduce a filter with which a node ignores messages from non-neighboring nodes. A pair of nodes connected by a solid line in Fig. 5 exchange messages. Since the filter is implemented on the application layer, collisions of radio signals among non-neighboring nodes occur. A cycle of data gathering or dissemination is set at 10 seconds. Other parameters and settings are the same as those used for the simulation experiments in the previous section. First, all sensor nodes periodically broadcast messages independently from each other. At time 100 seconds, sensor node 6 becomes a core node and initiates a data diffusion session. Then, at time 200 seconds, sensor node 11 initiates a new data session for data gathering.

Figures 6 (a) and 6 (b) show how the sensor network reached the phase-lock condition. Each mark stands for an instant when a sensor node emitted a message. For easier understanding, sensor nodes are sorted in order of the hop count from the core node. At first, all sensor nodes independently emit messages. However, by exchanging messages, the phase-lock condition for information diffusion eventually appears at about 130 seconds. Figure 6 (a) shows that sensor nodes emit messages in order of the hop count from the core node, and thus information propagates from sensor node 6 to the edge of sensor network. From time 200, the phase-lock condition for information diffusion is first broken by initiating a new session. Then, the new phase-lock condition for information gathering appears at about 250 seconds, where information propagates from the edge of sensor network towards the sensor node 11. After reaching phase-lock condition, data delivery ratio of about 87 % is accomplished.

6 Conclusion and Future Work

In this paper, we briefly introduced our fully-distributed and self-organizing communication mechanism. We showed some simulation and practical experiment results, and verified the effectiveness and practicality of the proposal. As future research work, we consider additional experiments to improve our mechanism under a larger network environment with more randomly deployed sensor nodes, more obstructions, more interference, and more collisions.

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