A Traveling Wave based Communication Mechanism for Wireless Sensor Networks

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***Abstract*— In this paper, we propose and evaluate a self-organizing communication mechanism for wireless sensor networks where a large number of sensor nodes are deployed. 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. We first investigate conditions of a phase-response curve to attain wave-formed firing patterns regardless of the initial phase of oscillators. We adopt the derived phase-response curve to accomplish the desired form of message propagation through local and mutual interactions among neighboring sensor nodes. Through simulation experiments, we confirm that our mechanism delivers sensor information to / from a designated node in a more energy-efficient manner than other method, although it takes time to generate a traveling wave.**

***Index Terms*— sensor network, traveling wave, pulse-coupled oscillator model, communication mechanism**

I. INTRODUCTION

The development of low-cost microsensor equipments having the capability of wireless communication has caused sensor network technology to attract the attention of many researchers and developers. It is possible to obtain information on behavior, condition, and position of elements in a local or remote region by deploying a network of battery-powered sensor nodes there. Each sensor node in such a sensor network has a general purpose processor with a limited computational capability, a small memory, and a radio transceiver.

A. Motivation

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 information over the whole sensor 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 by conjecturing from collected information.

Most of communication schemes cannot adopt to dynamically changing application requirements. For example, directed diffusion [2, 3] also considers both types of communication, i.e., pull and push. In the two-phase pull diffusion, sinks first emit an *interest* message to find sources. Interest messages are flooded across a network, and matching sources periodically send *exploratory data* to the sink along paths that interest messages traversed. After the initial exploratory data come, the sink chooses one and reinforces the corresponding paths to sources so that following data traverse them to the sink with the smallest latency. The pull-type communication is shown to be appropriate for a case with many sources and few sinks. On the contrary, in the push diffusion, sources first send exploratory data to notify possible sinks of the existence of data. The push-type communication is good for a case with many sinks and few sources. Although directed diffusion can support two different application requirements, these mechanisms cannot be used simultaneously and the mechanism to employ must be determined in advance taking into account expected conditions, including the number of sources and sinks and their communication frequency.

To answer dynamically changing application requirements, a communication mechanism should handle both types of communication, especially in an autonomous and self-organizing manner. In addition, taking into account the insufficient computational capability and memory capacity of inexpensive small sensor nodes, the mechanism must be as simple as possible. A simple mechanism can also avoid introducing programming and operational errors.

B. Overview of Our Mechanism

For this purpose, we adopt a pulse-coupled oscillator (PCO) model based on biological mutual synchronization such as that observed in flashing fireflies [4, 5]. In a

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This paper is based on “A Self-organizing Communication Mechanism using Traveling Wave Phenomena for Wireless Sensor Networks,” by Yoshiaki Taniguchi, Naoki Wakamiya, and Masayuki Murata, which appeared in the Proceedings of the 2nd International Workshop on Ad Hoc, Sensor, and P2P Networks (AHSP 2007), Sedona, USA, March 2007. [1]

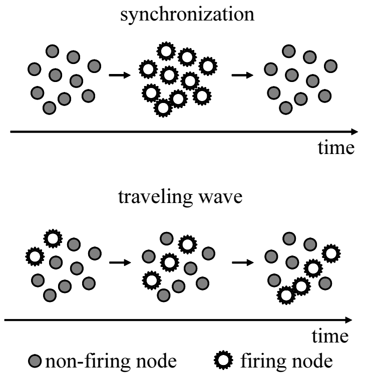
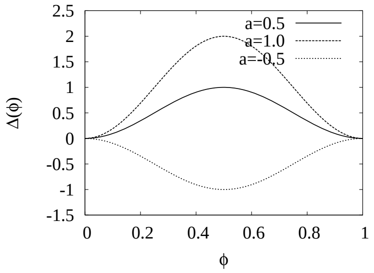


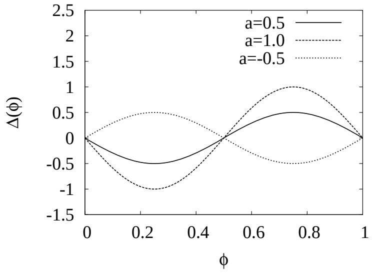
Figure 1. Global synchronization and traveling wave

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 [6-12]. In [11, 12], we proposed a data gathering scheme which employ synchronized behavior of a PCO model, and confirmed that it worked in a fully-distributed, self-organizing, robust, adaptive, scalable, and energy-efficient manner.

In this paper, in contrast to the other works, we focus on another phenomenon observed in a PCO model. In a PCO model, it is shown that not only the global synchronization where all oscillators fire synchronously, but a traveling wave, where oscillators behave synchronously but with fixed phase difference, appears (Fig. 1) [5]. By adjusting parameters and functions of a PCO model, we can control the frequency, form, and direction of a wave. We first investigate 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. Next, we propose a self-organizing communication mechanism which generated concentric traveling waves centered at a sensor node, which wanted to gather information from all sensor nodes or diffuse information to all sensor nodes. 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. Through simulation experiments, we confirm the basic behavior of our mechanism. Furthermore, we evaluate effectiveness of our mechanism in comparison with other method.



(a) PRC of QIF model $\Delta_{\rm QIF}$



(b) PRC of RIC model $\Delta_{\rm RIC}$

Figure 2. PRC examples

The rest of this paper is organized as follows. First, in Section II, we briefly introduce the pulse-coupled oscillator model we adopted in this paper. Next, we investigate conditions of a PRC which leads to a desired form of a traveling wave from arbitrary settings of the initial phase in Section III. Then, we propose a distributed and self-organizing communication mechanism for wireless sensor networks in Section IV, and show simulation results in Section V. Finally, we conclude the paper and describe future research work in Section VI.

II. PULSE-COUPLED OSCILLATOR MODEL

A pulse-coupled oscillator model is developed to explain synchronous behaviors of biological oscillators such as pacemaker cells, fireflies, and neurons. In this section, mainly following the model described in [5], we give a brief explanation of the model.

Consider a set of N oscillators. Each oscillator i has phase $\phi_i \in [0, 1]$ $(d\phi_i/dt = 1)$. As time passes, ϕ_i shifts toward one and, after reaching it, the oscillator fires and the phase jumps back to zero. Oscillator j coupled with the firing oscillator i is stimulated and advances its phase by an amount $\Delta(\phi_j)$. Thus, we have

$$\phi_j \to \phi_j + \Delta(\phi_j), \tag{1}$$

where $\Delta(\phi)$ is called a phase-response curve (PRC). For example, for the quadratic integrate-and-fire (QIF) model, $\Delta_{\rm QIF}(\phi) = a(1 - \cos 2\pi\phi)$ (Fig. 2 (a)) and for the radial isochron clock (RIC) model, $\Delta_{\rm RIC}(\phi) = -a \sin 2\pi\phi$ (Fig. 2 (b)) [5]. Here, an oscillator ignores all stimuli at the moment of firing, and an oscillator identifies multiple stimuli received at the same time as one stimulus.

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

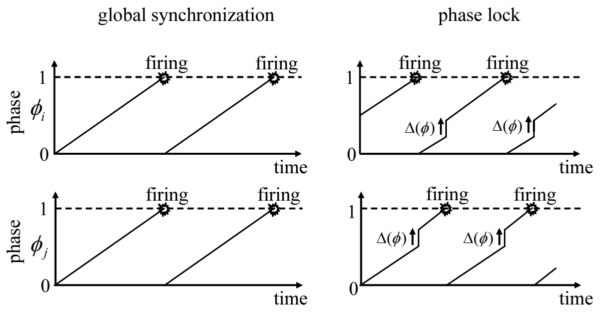
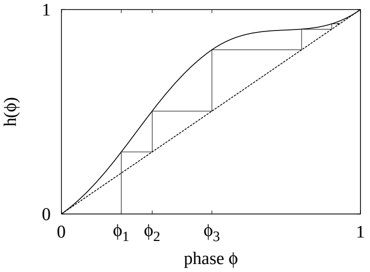
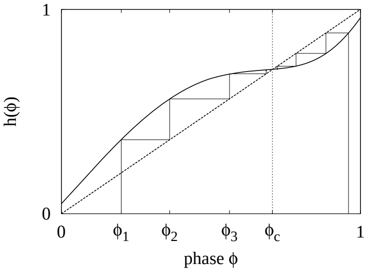


Figure 3. Global synchronization and phase-lock



(a) $h(\phi)$ generating the global synchronization



(b) $h(\phi)$ generating the phase-lock

Figure 4. Phase transition

condition where phases are different among oscillators with a constant offset as shown in Fig. 3. 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 [13]. In Fig. 4, $h(\phi)$ indicates the phase at which an oscillator is stimulated again by a neighboring oscillator, after the oscillator is stimulated from a neighboring oscillator at the phase of ϕ. For example, in the case of a pair of oscillators, it is defined as $h(\phi) = 1 - F(1 - F(\phi))$ where $F(\phi) = \phi + \Delta(\phi)$. A dotted diagonal line stands for $h(\phi) = \phi$, and a stepwise line stands for phase transition of an oscillator whose initial phase is ϕ_1. When an oscillator is stimulated at ϕ_1, the oscillator changes its phase by using Eq. (1), and it will observe the next fire and be stimulated at ϕ_2.

In Fig. 4 (a), through being stimulated several times, the phase $h(\phi)$ becomes one from arbitrary initial phase. $h(\phi) = 1$ means that an oscillator receives a stimulus from another firing oscillator when the oscillator itself is firing. Therefore, they fire at the same time. On the contrary, if oscillators have a PRC corresponding to Fig. 4 (b), $h(\phi)$ converges at ϕ_c independently of the initial phase. It means that all oscillators reach the condition where the phase is always ϕ_c when being stimulated. Therefore, oscillators fire with the time difference of ϕ_c at the stable condition.

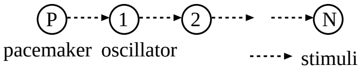


Figure 5. Oscillators in tandem

III. CONDITION OF PRC TO GENERATE TRAVELING WAVES

In this section, we investigate conditions of PRC that lead to desired phase-lock condition regardless of the initial phase to generate preferred traveling waves. We call an oscillator which dominates and controls a PCO network as a pacemaker. To keep the timing and frequency of communication, a pacemaker will not be stimulated and will fire at regular intervals, which corresponds to the data gathering or diffusion cycle in a wireless sensor network.

A. *Oscillators in Tandem*

First, we consider a traveling wave in a PCO network where oscillators are arranged in a line as shown in Fig. 5. Each circle stands for an oscillator, each arrow shows the direction of stimuli, and oscillators are numbered by the number of hops from the pacemaker. An oscillator is stimulated only by its neighboring oscillator which is closer to the pacemaker. A pacemaker fires periodically at regular intervals of one time unit. Oscillators fire in order of the pacemaker, oscillator 1, oscillator 2, $\cdots$, oscillator N at constant phase-difference τ. Therefore, if a pacemaker fires at time 0, oscillator 1 fires at time τ, and oscillator N fires at time $N\tau$. Here, we consider $0 < \tau < 1$.

Now, consider phase transitions of oscillators at the phase-lock condition. Assume that after t time unit since oscillator i $(1 \leq i \leq N)$ fired, an oscillator i is stimulated by oscillator $i-1$. Oscillator 0 corresponds to the pacemaker. Since oscillators fire at constant phase-difference τ, the phase of an oscillator becomes $1-\tau$ when it is stimulated by a neighboring oscillator, i.e., $F(t) = 1 - \tau$. Then, oscillator i fires at $\tau + t$. Since an oscillator fires at regular intervals of one at the phase-lock condition, we have $t + \tau = 1$. Hence, we have

$$\Delta(1-\tau) = 0. \tag{2}$$

To generate a desired traveling wave regardless of the initial phase, an oscillator should advance its phase towards $1-\tau$ when it is stimulated during $0 \leq \phi < 1-\tau$, and push back its phase towards $1-\tau$ when it is stimulated during $1 - \tau < \phi < 1$. Finally, we have following

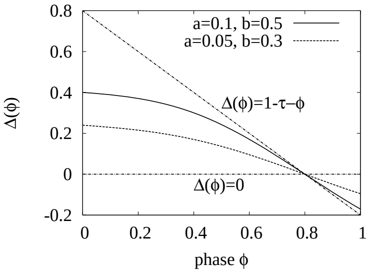


Figure 6. PRC Δ_s from Eq. (4)

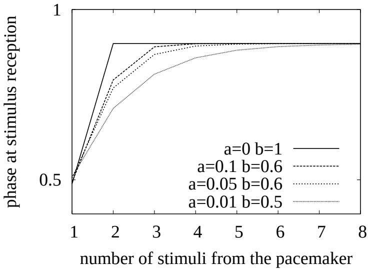


Figure 7. Phase transition of oscillator 1

conditions of PRC to generate a traveling wave regardless of the initial phase.

$$\begin{cases} 0 < \Delta(\phi) \leq 1 - \tau - \phi & (0 \leq \phi < 1 - \tau) \\ \Delta(\phi) = 0 & (\phi = 1 - \tau) \\ 1 - \tau - \phi \leq \Delta(\phi) < 0 & (1 - \tau < \phi < 1). \end{cases} \quad (3)$$

For example, following PRC function satisfies Eq. (3).

$$\Delta_s(\phi) \quad = \quad a \sin \frac{\pi}{1-\tau}\phi + b(1 - \tau - \phi) \quad (4)$$

Here, a $(-\frac{b(1-\tau)}{\pi} < a \leq \frac{(1-b)(1-\tau)}{\pi})$ and b $(0 < b \leq 1)$ are parameters which determine characteristics of PRC. Figure 6 illustrates PRC $\Delta_s(\phi)$ for two different settings of a and b when $\tau = 0.2$. Two dot-and-dash lines stand for $\Delta(\phi) = 0$ and $\Delta(\phi) = 1 - \tau - \phi$, respectively. The curve of PRC satisfying Eq. (3) must lie between these two lines.

With a PRC satisfying the above conditions, oscillators fire in order of the pacemaker, oscillator 1, oscillator 2, $\cdots$, oscillator N at constant phase-difference of τ at the phase-lock condition. This can also be regarded as a traveling wave propagating from oscillator N toward the pacemaker, with constant phase-difference $1 - \tau$. Therefore, to have a diffusion type of communication, where information propagates from the peacemaker to oscillator N with constant phase-difference τ, τ should be set as $\tau < 0.5$. On the contrary, to have a gathering type of communication, τ should be set as $\tau > 0.5$.

Figure 7 shows a phase of oscillator 1 when it receives a stimulus from the pacemaker where $\tau = 0.1$ and $N = 1$. The initial phase of oscillator 1 is randomly chosen, and results are averaged over 1000 simulations. At $a \neq 0$, as parameters a and b increase, a traveling wave emerges more rapidly. Especially, a traveling wave emerges by only one interaction, i.e., stimulus, among oscillators with $a = 0$ and $b = 1$. However, such aggressive setting spoils the resilience of the mechanism against a failure of node and unexpected influence from the environment, since a single firing emitted at a wrong time will drastically change the state of the whole system. Therefore, a PRC function and its parameters should be appropriately determined taking into account the trade-off between the speed that a traveling wave emerges and the resilience against failures.

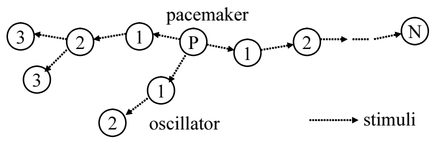


Figure 8. Two-dimensional arrangement of oscillators

B. Oscillators in Two-Dimensional Arrangement

A PRC satisfying Eq. (3) can also be applied to the case of two dimensional arrangement of oscillators. By making a tree whose root is the pacemaker and setting the direction of stimuli as shown in Fig. 8, we can adopt the same PRC and generate a traveling wave propagating from or to the pacemaker in a two-dimensional area. Although any routing protocol for wireless sensor networks is viable to organize such tree-type topology, a simple way of setting such relationship among oscillators will be given in the next section.

IV. A DISTRIBUTED AND SELF-ORGANIZING COMMUNICATION MECHANISM

In this section, we propose a fully-distributed and self-organizing communication mechanism for wireless sensor networks. In our mechanism, any of sensor nodes can become a point, called core node, from which messages are disseminated or to which messages are gathered in accordance with application requirements. Core node plays a role of a pacemaker in the PCO model.

A. Basic Behavior

Sensor node i $(1 \leq i \leq N)$ has a timer with phase $\phi_i \in [0, 1]$. It maintains PRC function $\Delta(\phi)$, level value l_i, session identifier s_i, direction δ_i, and offset τ $(0 < \tau < 0.5)$. Initially a level value, a session identifier, and a direction are set to zero. A level value indicates the number of hops from the 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 PRC function and offset are determined at the deployment phase, but the offset can be dynamically adjusted as explained later. In this paper, based on Eq. (4), we use the following PRC function for all sensor nodes.

$$\Delta(\phi) \quad = \quad a \sin \frac{\pi}{g}\phi + b(g-\phi), \tag{5}$$

Here, g 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. To avoid unintended termination of communication by other sensor nodes, a core node might advertise its desired communication period in a message it emits. However, it requires an additional mechanism such as clock synchronization, and it is left as one of future research issues. 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. We should note here that a sensor node only emits a message in accordance with the phase of its timer. No additional message is required to organize a traveling wave. The algorithm is illustrated in Fig. 9.

B. Power-Saving Mode

Through mutual interactions among neighboring sensor nodes, they reach the phase-lock, and a sensor node moves to a power-saving mode. In power-saving mode, a sensor node 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 by turning off its radio transceiver and other needless modules.

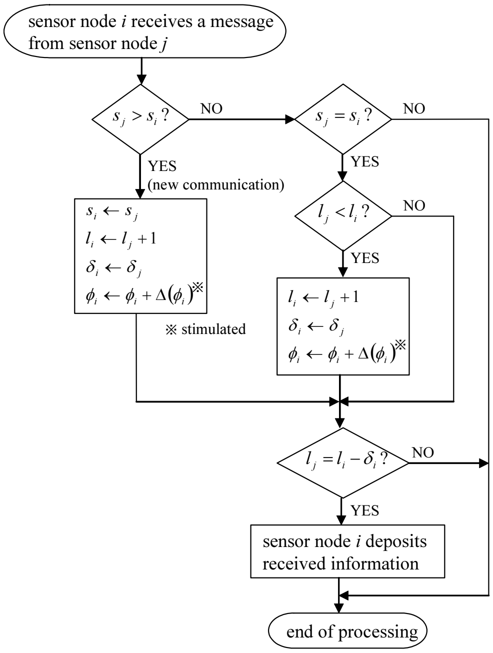


Figure 9. Node behavior on message reception

Here, τ should be appropriately determined considering trade-off between the rate of successful message reception and the lifetime of sensor network. The smaller τ is, the smaller probability of successful message reception by missing messages delayed by collisions in radio signals. At the same time, a smaller τ leads to longer lifetime of sensor network, since a node is awake for the duration of 2τ in one communication cycle.

To judge whether the phase-lock condition is globally accomplished or not, we consider T_{max} as the worst-case time required for a sensor node to establish the phase-lock condition with a neighboring node closer to the core node. We can expect that a sensor node can move to a power-saving mode after $(l_i + (1-\delta_i)/2) \times T_{max}$ since the level value is updated.

If the phase-lock condition is lost for some reasons after a power-saving mode is activated, a sensor node does not receive any valid message when it is awake. In such a case, a sensor node stops a power-saving mode to reorganize the phase-lock condition.

C. Addition and Removal of Sensor Nodes

Next, we consider the case where a new sensor node is introduced in a sensor network in operation. Initially, the session identifier of a new sensor node is set at zero. Therefore, it does node affect other sensor nodes. Being stimulated several times, its level value, session identifier, and direction are correctly identified, and its timer synchronizes at constant phase-difference with that of a neighboring sensor node whose level is smaller by one.

On the contrary, when a sensor node disappears due to battery depletion or removal, a sensor node that is synchronized with the vanished node will be stimulated by another of the same level as the vanishing node. If there is no other node with a smaller level value in its vicinity, the sensor node becomes isolated. Since it does not receive stimuli any more, it can recognize the isolation and then it initializes its session identifier so that it can synchronize with other neighboring sensor nodes.

D. *Multiple Core Nodes*

In addition, we consider the case that there are two or more core nodes with the same session identifier in a sensor network. Since it takes time for information to propagate between the edge of a wireless sensor network and a core node, it is a good idea to have multiple core nodes for one communication to solve the scalability problem. In such case, the sensor network is divided into clusters each of which has one core node. Each core node can gather or diffuse information in its cluster.

A sensor node which is at the same hop count from more than one core node, which we call a border node, receives messages from different clusters. Since session initiation is not necessarily synchronized among core nodes and time required for stimulus propagation would differ among paths from core nodes, such multiple stimuli prevent a border node from establishing the phase-lock condition with neighboring nodes.

Therefore, a border node chooses one cluster which it belongs to. First, after a level value is updated, a border node waits for the duration of $(l_i - 1) \times T_{max} + \tau$ until the phase-lock condition is established in each of clusters. Then, it begins to stick on the timing of the first message it receives. To avoid being stimulated by deferred messages or message originated from another core node, it ignores received stimuli during the following duration of $1 - \tau$ when it has already been stimulated.

E. *Node Failures*

Finally, we consider cases of node failures. First, the failure of a radio transmitter has no influence on other communication, since a failed sensor node can not emit any message and never stimulate neighboring nodes. On the other hand, a sensor node with a failed receiver keeps sending messages based on its timer. The timer of a failed node keeps its own pace independently of the others. Therefore, when the phase-lock condition is not established yet, the failed node disturbs establishment of the phase-lock condition by stimulating neighboring nodes at inappropriate timings. However, a failed node eventually considers it is isolated for not receiving any message from neighboring nodes. Then, it initializes its state and it does not affect others anymore.

In some cases, a timer gains or loses, being affected by, for example, geomagnetism. Basically, a wrong timer will be correctly adjusted from stimulations. A sensor node with a timer which gains, stimulates neighboring nodes at a wrong timing, since sensor nodes take the first message it receives and ignores the following delayed messages. If a wrong timer keeps an advanced phase, the problem is that the interval between message emission of the failed node and its upstream node becomes smaller than τ and it does not bring any serious influence on message propagation.

On the other hand, a sensor node with a timer which loses does not affect the phase-lock condition very much. If a sensor node which is stimulated by a failed node has another normal node with a smaller level value, it is always stimulated by the normal sensor node and ignores delayed messages from the failed node. Otherwise, the interval of message emission of the failed sensor node and the affected sensor node becomes longer than τ.

In addition, we consider wrong setting of parameters such as δ_i, l_i, and s_i of sensor node i by temporal error of memory or CPU. Direction δ_i is updated periodically when a sensor node receives a message from a sensor node with a smaller level value.

When level value l_i is incorrectly larger than the actual hop count from a core node, messages emitted by sensor node i do not affect neighboring sensor nodes with a smaller level value. On the contrary, if the level value is too small, neighboring nodes would wrongly identify their distance from the core node. It first disturbs establishing the phase-lock condition. However, since the level value of the failed sensor node is the smallest in its range of radio signals, it does not receive any stimulus, i.e., a message with a further larger level value. Therefore, it considers it is isolated and initializes its session identifier so that its level value will be adjusted correctly.

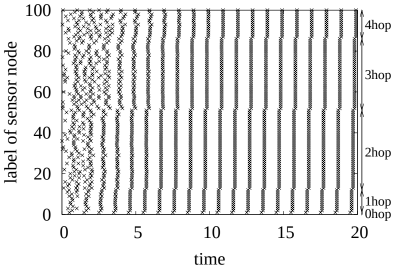
When the session identifier s_i is incorrectly smaller than the current session identifier used in a wireless sensor network, the failed sensor node does not affect the others at all. Its session identifier will be corrected on receiving a message from a neighboring sensor node. On the contrary, a larger session identifier s_i means that a new communication is initiated by the failed sensor node. Since the other nodes cannot judge whether a new communication is actually initiated or not, it is handled as normal. When another sensor node initiates a new communication, a new session identifier is used and the failed node does not affect the others any more.

V. SIMULATION EXPERIMENTS

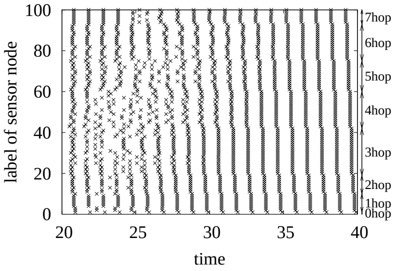
In this section, we show results of simulation experiments. In the simulation, the range of the radio signal is fixed at 2 units of length. The initial phase of sensor node is randomly chosen. A sensor node consumes 81 mW for transmission, 30 mW for receiving and idle, and 0.003 mW for sleep [14]. Initial energy is 50 J for all nodes. We use Eq. (5) with $a = 0.01$ and $b = 0.5$ as the PRC function and τ is set at 0.1.

A. *Basic Behavior*

We first confirm the basic behavior of our communication mechanism. We consider sensor networks of 100 sensor nodes randomly distributed in a 10×10 region. From 0 to 20 time units, we randomly chose a sensor node A as a core node for information diffusion. Then,



(a) Diffusion



(b) Gathering

Figure 10. Timing of message emissions

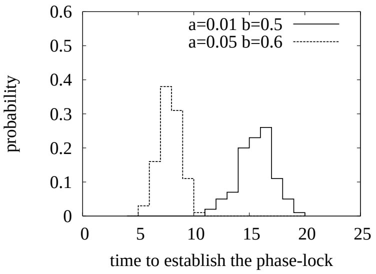


Figure 11. Distribution of the time to establish the phase-lock condition

from 20 to 40 time units, we randomly chose another sensor node B as a core node for information gathering.

Figure 10 shows how the sensor network reached the phase-lock condition in a certain simulation experiment. 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. In the upper figure, at first, all sensor nodes randomly and independently emit messages. However, by exchanging stimuli several times, the phase-lock condition is eventually accomplished and a regular pattern appears. It is clearly shown that message emission is in order of the hop count of sensor nodes, from the core node to nodes with larger numbers. In the lower figure, it is shown that the phase-lock condition for information diffusion is first broken for information gathering initiated by sensor node B. Then, although it takes longer time than for diffusion, the new phase-lock condition appears, where information propagates from the edge of the sensor network towards the core node B.

Over 100 experiments, the average time to establish the phase-lock condition is 15.5 time units. The time ranges from 11.6 to 19.6 depending on the distribution of sensor nodes, location of the core node, and phase of sensor nodes. The histogram is shown in Fig. 11. The time to reach the stable phase-lock condition can be reduced by using a set of larger a and b satisfying Eq. (3). For example, with $a = 0.05$ and $b = 0.6$, the minimum, average, and maximum are 5.96, 8.10, and 10.7, respectively.

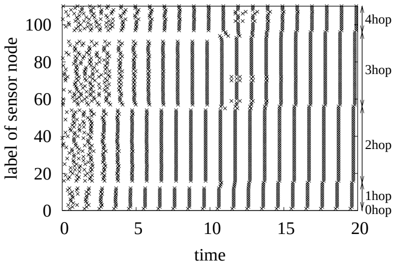


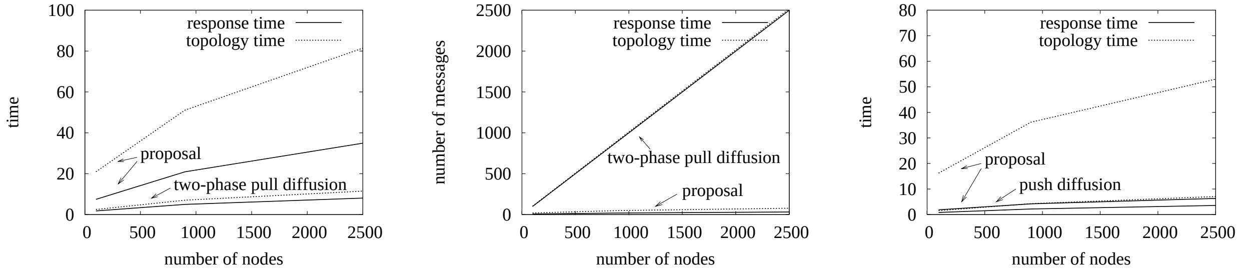
Figure 12. Timing of message emission with dynamic deployment

We confirmed that traveling waves can be formed in a wireless network with addition, movement, and removal of sensor nodes, and failed nodes. In Fig. 12, an example of the case of node addition is illustrated. At 10 time units, after the phase-lock condition is established for information diffusion, ten sensor nodes are deployed at random locations in the wireless sensor network. As can be seen in the figure, newly added sensor nodes initially emit messages independently of their location. When a new sensor node receives a message from an existing sensor node, it sets the level value as the received value plus one. However, its timer has not been adjusted well yet. Therefore, the phase-lock condition of neighboring sensor nodes is lost as in the case of timer errors. However, as time passes, they begin to behave in synchrony with sensor nodes at the same distance from the core node and the phase-lock condition is re-established in the whole sensor network.

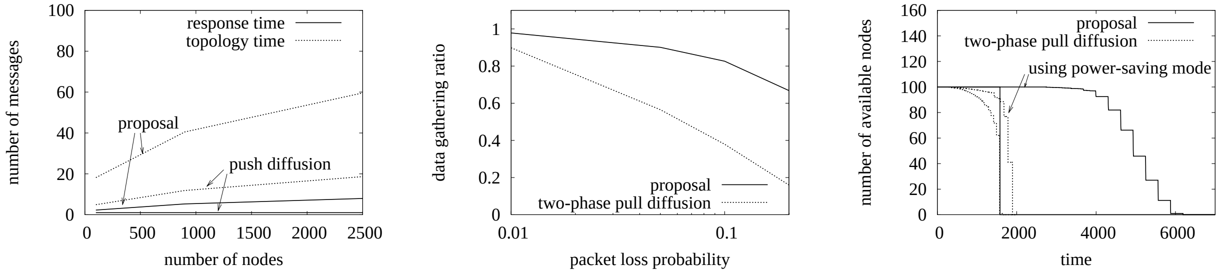
B. *Effectiveness of the Mechanism*

We next evaluate effectiveness of our communication mechanism. We consider wireless sensor networks of 100, 900, and 2500 sensor nodes randomly distributed in 10×10, 30×30, and 50×50 region, respectively. A core node is randomly chosen for data gathering or information diffusion. For comparison purposes, we also conduct simulation experiments for the directed diffusion [2, 3] where per-hop delay is set at 0.1 time units. 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) Response and topology time in gathering (b) Number of messages in gathering (c) Response and topology time in diffusion



(d) Number of messages in diffusion (e) Data gathering ratio (f) Number of available nodes in gathering

Figure 13. Comparison among proposal and directed diffusion

a node sends and receives during the response time or the topology time. The data gathering ratio is defined as the ratio of data reached to a core node or a sink node to the number of nodes. 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.

In Fig. 13 (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. 13 (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 III, the response time and topology time can be reduced by adjusting a PRC function and its parameters.

Figure 13 (c) shows results for the case of information diffusion, where a randomly chosen node diffuses information to the whole sensor network. When comparing to the push diffusion of the directed diffusion, our proposal takes longer to diffuse information to all nodes. Differently from the data gathering scenario, the overhead is larger with our mechanism. It is 220 to 790 % of the directed diffusion in response time and 718 to 877 % in topology time as shown in Fig. 13 (d). In the case of diffusion, only one source node floods exploratory data to all other nodes in the push diffusion, but our mechanism takes time to generate a traveling wave and thus requires much message exchanges.

Figure 13 (e) shows the data gathering ratio against the packet loss probability in a 10×10 network. A sensor node randomly fails in transmitting a message at the packet loss probability shown on the x-axis. In Fig. 13 (e), our mechanism always achieves higher data gathering ratio than the directed diffusion with the same packet loss probability. In our mechanism, broadcasting contributes to achieving multi-path effect and this leads to the higher gathering ratio.

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. 13 (f), 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. On the contrary, although the figure is not shown, the lifetime with our mechanism is 1577 time units whereas that with the directed diffusion is 251 time units in the case of information diffusion. Furthermore, by using a power-saving mode, the lifetime with our mechanism becomes as long as 3680 time units whereas that with the directed diffusion is 286 time units.

VI. Conclusion and Future Work

In this paper, we first investigated initial conditions that lead to a desired form of traveling wave regardless of the initial phase of oscillators in a pulse-coupled oscillator model. Next, we proposed a fully-distributed and self-organizing communication mechanism in wireless sensor networks. Through simulation experiments, we confirmed that our scheme can gather or diffuse information in accordance with application requirements in a dynamic wireless sensor network. In addition, we confirmed that our mechanism delivers sensor information to / from designated nodes in a more energy-efficient manner than other method, although it takes time to generate a traveling wave.

As future research work, we plan to implement our mechanism using off-the-shelf sensor to verify the practicality of our mechanism. In an actual environment, radio signals are unstable and unreliable. Due to collisions among synchronized transmission of messages from sensor nodes at the same distance from a core node, i.e, with the same level value, messages will be lost or delayed. In [12], we implemented another PCO-based data gathering scheme where all sensor nodes of the same level value behave in synchrony and confirmed that it worked as expected with some additional mechanisms to solve the instability and unreliability of radio communication. We consider the mechanism proposed in this paper can also work well with a similar approach.

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