A Distributed and Self-organizing Data Gathering Scheme in Wireless Sensor Networks

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Abstract

The development of low-cost microsensor equipment having the capability of wireless communications has caused sensor network technology to attract the attention of many researchers and developers. In this paper, we propose a fully-distributed and self-organizing data gathering scheme for a network where a large number of sensor nodes are deployed. To accomplish the periodic data gathering without centralized controls, we adopt the pulse-coupled oscillator model based on biological mutual synchronization such as that observed in flashing fireflies. By adjusting parameters and functions in the model according to application's requirements and conditions surrounding a sensor network, we can control the frequency, the form, and the direction of information propagation which is observed as a wave. In this paper, we show how to organize traveling waves in the model and how to adapt the model to data gathering in sensor networks.

1 Introduction

The development of low-cost microsensor equipment having the capability of wireless communications has caused sensor network technology to attract the attention of many researchers and developers [1]. One can obtain information on behavior, condition, and position of elements in a 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 capacity, a small amount of memory, and a radio transceiver. Data gathered by sensor nodes are transmitted directly or indirectly to a base station or a sink.

Since a sensor node is typically powered by a battery that can not be replaced often, a sensor network must use a data gathering scheme that is energy-efficient. In addition, because sensor nodes are often deployed and distributed in an uncontrolled way, a data gathering scheme can not be centralized one with a single node or a server maintaining all information and having all control functions.

In our previous research work [2], we proposed a fully-distributed, self-organizing, robust, adaptable, scalable, and energy-efficient data gathering scheme for a network with a large number of sensor nodes. We considered an application that periodically collected sensor information from sensor nodes to a base station. In the scheme, sensor information periodically propagates and aggregates from the edge of a sensor network to the base station as the propagation forms a wave on concentric circles. More specifically, sensor nodes on the same circumference periodically broadcast their sensor information at the same time with the same frequency, before the sensor nodes on the inner circumference broadcast their information, so that inner nodes can forward their sensor information.

To accomplish the periodic data gathering without centralized controls, each sensor node should independently determine the cycle and the timing at which it emits a message to advertise its sensor information based on locally available information. For this purpose, we adopted the pulse-coupled oscillator model based on biological mutual synchronization such as that observed in flashing fireflies [3]. Through simulation experiments and implementation, we verified that our scheme could accomplish concentric circle-shaped data gathering. However, according to application's requirements, there should occur different types of traveling waves. For example, we also need a traveling wave of the form of concentric circles where information propagates from the center to the edge to distribute information or control signal from a base station or a sensor node. When we consider a base station is located at the edge of a sensor network, we prefer a wedge-shaped traveling wave propagating from the opposite side of the network to the base station.

In this paper, we propose a fully-distributed and self-organizing data gathering scheme which can organize a variety of traveling waves on application's requirements. In our scheme, we adopt the pulse-coupled oscillator model described in [4]. In this model, it is shown that not only a global synchronization where all oscillators fire synchronously, but a traveling wave, where oscillators behave synchronously but

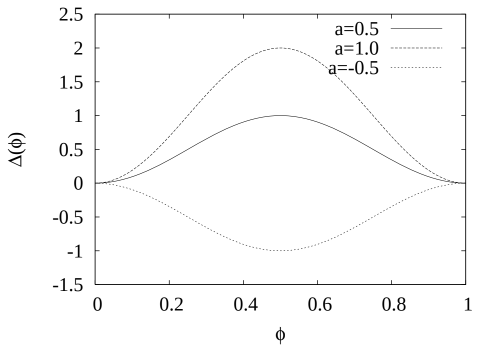

Figure 1: PRC of QIF model Δ_{QIF}

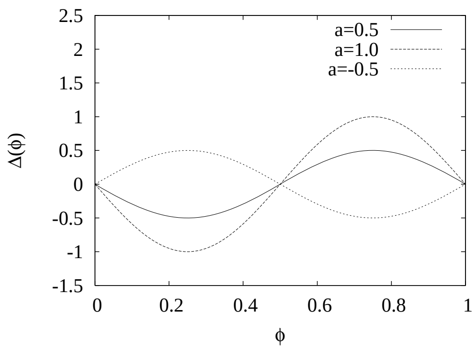

Figure 2: PRC of RIC model Δ_{RIC}

with fixed phase differences, appears depending on initial conditions of oscillators. By adjusting parameters and functions in the pulse-coupled oscillator model, we can control the frequency, the form, and the direction of a wave. In our scheme, each sensor node broadcast its sensor information in accordance with the phase of its own timer. When a sensor node receives a radio signal of other, it adjusts the phase of its timer. Through mutual interactions among neighboring sensor nodes, they reach the state, called a phase-lock, where differences among phases are kept constant, and they emit sensor information alternately.

The rest of this paper is organized as follows. First, in Section 2, we briefly introduce the pulse-coupled oscillator model we adopted in this paper. Next, we investigate initial conditions that lead to desired form of a traveling wave in Section 3. Then, in Section 4, we present a scenario to apply the pulse-coupled oscillator model to data gathering in sensor networks. Finally, we conclude the paper and describe future research works in Section 5.

2 Pulse-Coupled Oscillator Model

The 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 oscillators. Each oscillator i has phase ϕ_i ($d\phi_i/dt = 1$). As time passes, ϕ_i shifts toward one and, after reaching it, an oscillator fires and the phase jumps back to zero. Oscillators coupled with the firing oscillator are stimulated and advance its phase by an amount $\Delta(\phi)$. Then, we have

$$\phi_i^{'} = 1 + \Delta(\phi_i)\delta(\phi_j), \qquad (1)$$

where $\delta(\phi)$ is the Dirac impulse function. $\Delta(\phi)$ is called a phase-resetting curve (PRC). For example, for the quadratic integrate-and-fire (QIF) model, $\Delta_{\mathrm{QIF}}(\phi) = -a \sin 2\pi\phi$ (Fig. 1) and for the radial isochron clock (RIC) model, $\Delta_{\mathrm{RIC}}(\phi) = a(1-\cos 2\pi\phi)$ (Fig. 2). Here, let $F(\phi) = \phi + \Delta(\phi)$ where $F^{'} > 0$, $F(0) = 0$, and $F(1) = 1$.

Through mutual interactions, depending on initial conditions of oscillators, 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 kept constant and different among oscillators and the propagation of fires seems like a traveling wave.

3 Generation of Traveling Waves

In this section, we investigate initial conditions that lead to desired phase-lock conditions, i.e., traveling waves. We start from the simplest case, two alternately firing oscillators, then move to a ring, a line, two types of concentric circles, a wedge, and a radar-shaped traveling wave.

3.1 Two Oscillators

First, we consider phase-lock condition in a pair of oscillators [5]. Suppose that when oscillator 1 fires at time 0, oscillator 2 is at ϕ_2 so that the new phase for oscillator 2 becomes $F(\phi_2)$. At $t_1 = 1 - F(\phi_2)$ oscillator 2 fires, then oscillator 1 at $\phi_1 = t_1 = 1 - F(\phi_2)$ moves to the new phase $F(t_1) = F(1 - F(\phi_2))$. At $t_2 = 1 - F(t_1)$ oscillator 1 fires once again, and the phase of oscillator 2 is $1-F(t_1) = 1-F(1-F(\phi_2))$. To have the phase-lock condition, $\phi_2 = 1 - F(1 - F(\phi_2))$. Consequently, when initial conditions are comply with $\phi_f = 1 - F(1 - F(\phi_f))$, oscillators fire alternately. In the case of $\phi^{'} = 1$, the occurrence condition is $|\phi_1 - \phi_2| = 1 - \phi_f$.

3.2 Ring

Next we consider the case of a ring of N oscillators [4]. Since an oscillator is stimulated by two neighboring oscillators, Eq. (1) becomes as

$$\phi_i^{'} = 1 + \Delta(\phi_i)[\delta(\phi_{i-1}) + \delta(\phi_{i+1}) - \delta(\phi_{i-1})\delta(\phi_{i+1})], \quad (2)$$

where we identify 0 with N and $N+1$ with 1. Consider oscillators fire in order of $1 \to 2 \to \cdots \to N$ at constant phase-difference τ. When oscillator N fires, oscillator $N-1$ and 1 are stimulated. At this time, the phase of oscillator $N-1$ is τ and its new phase becomes $F(\tau)$. Oscillator 1 is at $(N-2)\tau + F(\tau)$ and

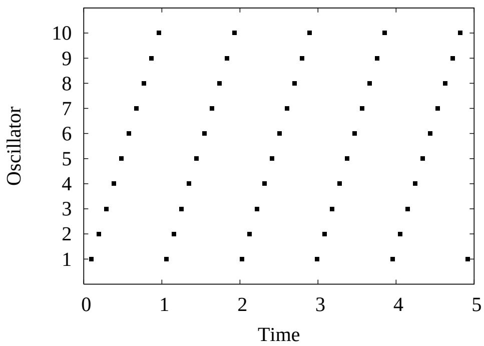

Figure 3: Timing of Firing in a Ring

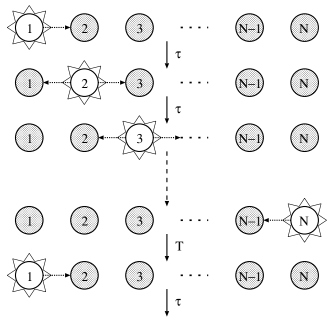

Figure 4: Firing Pattern in a Line

its new phase ϕ_1 becomes $F((N-2)\tau + F(\tau))$. Here, $\phi_1 = 1 - \tau$ holds because oscillator 1 will fire after τ. Therefore, the phase of each oscillators in a traveling ring wave should satisfy the following conditions.

$$
\begin{aligned}
\phi_{N-1} &= F(\tau) \\
\phi_{N-2} &= \tau + F(\tau) \\
\vdots &= \vdots \\
\phi_i &= (N-i-1)\tau + F(\tau) \\
\vdots &= \vdots \\
\phi_2 &= (N-3)\tau + F(\tau) \\
\phi_1 &= F((N-2)\tau + F(\tau)) = 1 - \tau.
\end{aligned}
$$

From this, we have the following formula.

$$F((N-2)\tau + F(\tau)) + \tau = 1. \quad (3)$$

Waves with multiple cycle replace the 1 with m.

Figure 3 shows the timing of firing in a ring of oscillators, where $N = 10$. We used the RIC PRC with $a = 0.1$. τ was set at 0.0964 derived from Eq. (3). In Fig. 3, we can see that a fire travels along a ring. X-axis corresponds to time and y-axis corresponds to identifiers of oscillators. Each dot stands for the timing that an oscillator fires.

3.3 Line

In this subsection, we consider a line of N oscillators. Consider oscillators fire in order of $1 \to 2 \to \cdots \to N$ at constant phase-difference τ, and oscillator 1 fires

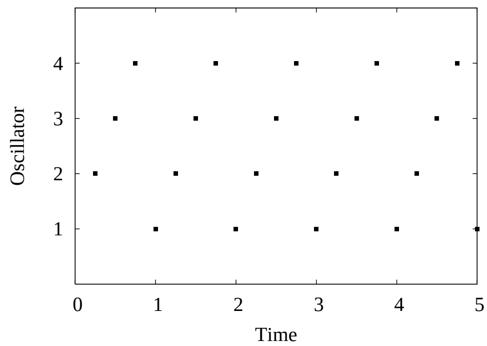

Figure 5: Timing of Firing in a Line

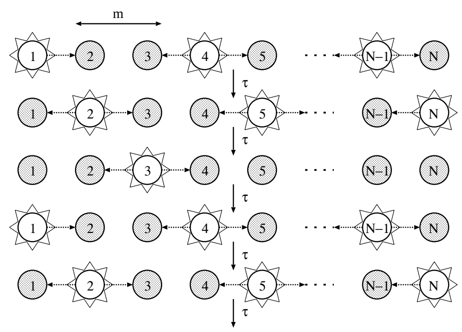

Figure 6: Multiple-Firing Pattern in a Line

after T unit of time from a fire of oscillator N as illustrated in Fig. 4 where dashed arrows stand for stimuli given by a firing oscillator to neighboring oscillators.

When oscillator i $(1 \le i < N-1)$ fires, the new phase of oscillator $i+1$ becomes

$$F((N-3)\tau + T + F(\tau)) = 1 - \tau. \quad (4)$$

Similarly, when oscillator $N-1$ fires, the new phase of oscillator N becomes

$$F((N-2)\tau + T) = 1 - \tau. \quad (5)$$

Finally, when oscillator N fires, the new phase of oscillator 1 becomes

$$(N-2)\tau + F(\tau) = 1 - T. \quad (6)$$

Equations (4) through (6) describe the condition for the existence of traveling waves on a line of oscillators. Figure 5 shows the timing of firing in a line, where $N = 4$, $T = 0.25$, and $\tau = 0.25$. We used $\Delta(\phi) = -a \sin 4\pi\phi$ as PRC, where $a = 0.05$.

Next, we consider another pattern of traveling wave in a line illustrated in Fig. 6. In this case, oscillators which are distant by m (m is a natural number) fire at the same time. Suppose that oscillator i $(1 < i < N)$ fires at time 0. At time τ, oscillator $i+1$ fires and the new phase of oscillator i becomes $F(\tau)$. After $(m-1)\tau$ unit of time, oscillator $i-1$ fires, and the new phase of oscillator i becomes,

$$F((m-1)\tau + F(\tau)) \quad = \quad 1 - \tau. \quad (7)$$

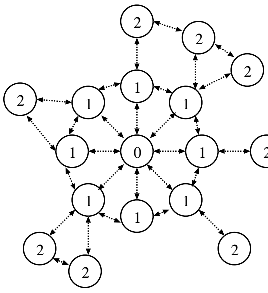

Figure 7: Firing Pattern in a Concentric Circle

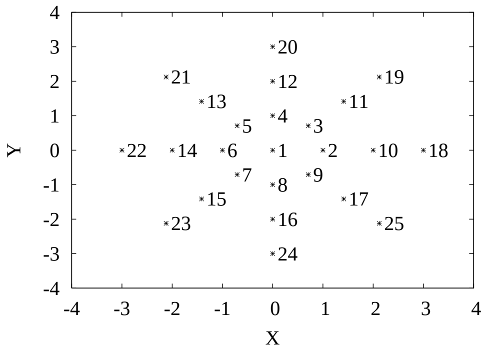

Figure 8: Location of Oscillators in a Concentric Circle

Similarly, let us consider oscillator 1. Oscillator 1 fires at time 0. At time τ, oscillator 2 fires and the new phase of oscillator 1 becomes $F(\tau)$. After $m\tau$, oscillator 1 will fire again. Therefore,

$$(m-1)\tau + F(\tau) \quad = \quad 1-\tau. \tag{8}$$

Finally, we consider oscillator N. Oscillator $N-1$ fires after $m\tau$ from oscillator N fires.

$$F(m\tau) \quad = \quad 1-\tau. \tag{9}$$

Equations (7) through (9) describe the condition for the existence of traveling waves. We should note that Eqs. (7) through (9) are identical to Eqs. (4) through (6) when m is equal to $N-1$ and T is equal to τ.

3.4 Concentric Circle

In this subsection, we consider a traveling wave drawing a concentric circle as in [2]. Figure 7 illustrates interactions among firing oscillators in concentric circles. The number in each circle, i.e., an oscillator, indicates the number of hops from the center of circles called level in [2]. Oscillators fires in order of levels. We assume an oscillator ignores all stimuli at the moment of firing [5], and an oscillator identifies multiple stimuli received at the same time as one stimulus. Following this assumption, we can regard oscillators on the same level as one oscillator. Therefore, we can apply the same condition derived in subsection 3.3 by defining the same initial condition for oscillators on the same level.

We confirmed the existence of phase-lock condition to generate a concentric circle-shaped traveling wave.

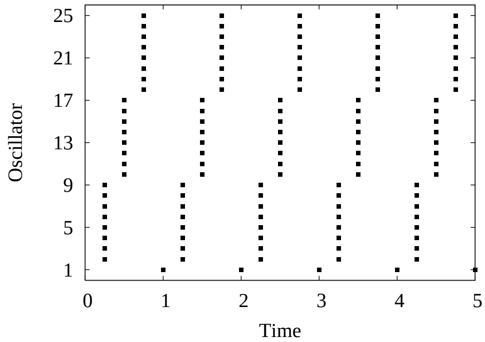

Figure 9: Timing of Firing in a Concentric Circle

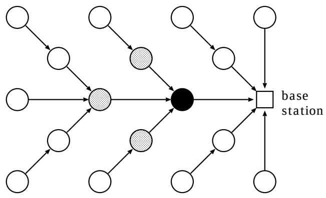

Figure 10: Firing in a Wedge

Figure 8 illustrates the simulated network of 25 oscillators. For easier understanding, oscillators are placed to form concentric circles. However, we can generate a traveling wave of the form of a concentric circle on a sensor network with arbitrary node distribution. Oscillators are numbered from the center to the edge. Each oscillator interacts with all other oscillators that are within distance of 1.5. We used $T = 0.25$ and $\tau = 0.25$ on Eqs. (4) through (6). In Fig. 9, we can observe a traveling wave propagating from the center toward the edge where all oscillators on the same circumference fire synchronously. When we give the initial conditions of oscillators in reverse, a wave propagates from the edge toward the center.

3.5 Wedge

In this subsection, we consider another type of a traveling wave. Taking into account spatial correlation of sensor information, we can expect efficient and effective aggregation of data by relaying sensor information as illustrated in Fig. 10. To save battery power in activating a transceiver, it is desirable for sensor nodes (shaded circles in Fig. 10) whose next hop is the same (filled circle) to emit their information simultaneously. Such information propagation can be attained by setting level value as shown in Fig. 11 and applying the same condition in subsection 3.3.

Figure 12 illustrates the simulated network of 48 oscillators. Each oscillator interacts with all other oscillators that are within distance of 1.5. We used $m = 3$ and $\tau = 0.25$ in Eqs. (7) through (9). Figure 13 shows that a traveling wave appeared as expected.

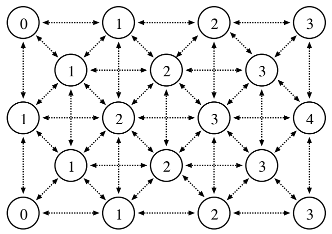

Figure 11: Firing Pattern in a Wedge

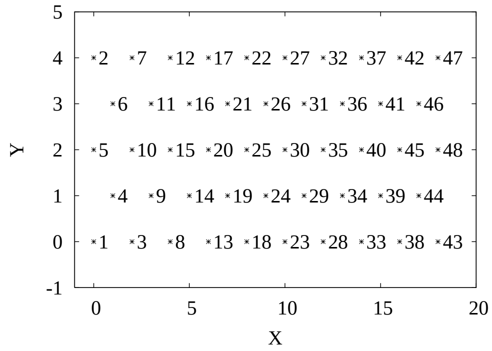

Figure 12: Location of Oscillators in a Wedge

3.6 Radar

In this subsection, we consider a radar-shaped traveling wave as illustrated in Fig. 14. The number in each circle indicates the order of firing on a circumference, and we call it as level. Oscillators with the same level value on different circumferences do not necessarily fire simultaneously. On the contrary, oscillators with different level values on different circumferences fire simultaneously if they are on the same radius. For example, at time 0, oscillators 0, $0'$, and $0''$ on the same radius fire simultaneously. When we consider a cycle of T, $T/8$ unit of time later, oscillator 1, $2'$, and $3''$ fire at the same time. Between them, oscillator $1'$ fires at $T/16$, and oscillators $1''$ and $2''$ fires at $T/24$ and $T/12$, respectively.

A radar-shaped traveling wave can be generated by first organizing oscillators into concentric circles. Next, on each of a circumference, a ring-shaped traveling wave is generated while making oscillators on a radius fire simultaneously. For this purpose, we assume that an oscillator receives stimuli only from neighboring oscillators on the same circumference and those in the same radius as shown by dashed arrows in the figure. In addition, we assume that the center node does not fire, or oscillators on the most inner circle ignore firing of the center node.

Figure 15 illustrates the simulated network of 60 oscillators. Oscillators from 1 to 10 are on the most inner circle which has a radius of one unit of distance. Oscillators from 11 to 30 are on the middle circle, and ones from 31 to 60 are on the third. Each oscillator interacts with all other oscillators that are within distance of 1. Derived from Eq. (3), τ was set at 0.0964, 0.0482, and 0.0323 for the most inner, the middle, and the third circle, respectively. Figure 16 shows the timing of firing. A solid line indicates the time that oscillator 1 fired. In Fig. 16, we can observe a radar-shaped traveling wave where oscillators on the same circumference fire in order the same time and those on the same radius fire at.

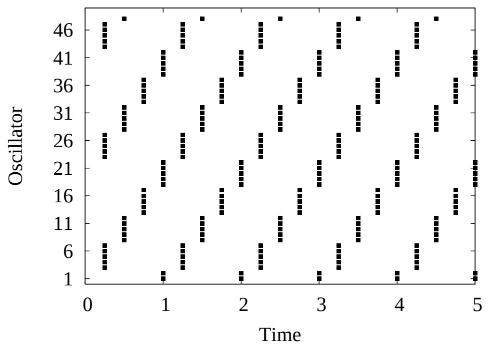

Figure 13: Timing of Firing in a Wedge

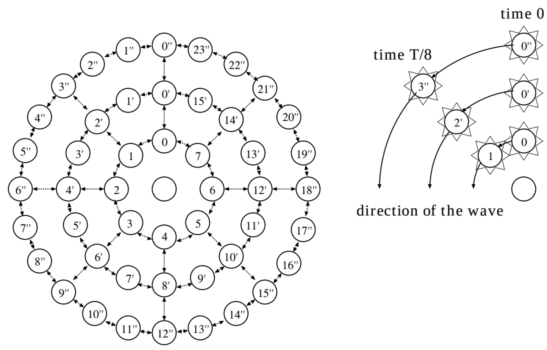

Figure 14: Firing Pattern in a Radar

4 A Distributed and Self-organizing Data Gathering Scheme

In this section, we present a scenario to apply the pulse-coupled oscillator model to data gathering in sensor networks. Here, we make some assumptions. First, we consider a static and stable sensor network where there is no addition, removal, and movement of sensor nodes. Second, the communication delay is negligible in comparison with temporal granularity of control. A sensor node has a timer which shifts from zero to one at the frequency of data gathering and jumps back to zero when it expires.

We denote a set of n sensor nodes as $\mathcal{S} = \{S_1, \cdots, S_n\}$. Initial setting of a sensor network for data gathering is performed as follows. First, a sensor node or a base station that gathers or disseminates information determines PRC function $\Delta(\phi)$ and the phase-difference τ to generate a desired traveling wave. The node is called a core node. A core node broadcasts a message within its range of radio signals. The message contains $\Delta(\phi)$, τ, an identifier of a type of a traveling wave, the direction of information propagation, i.e., fusion or diffusion, and a level value zero

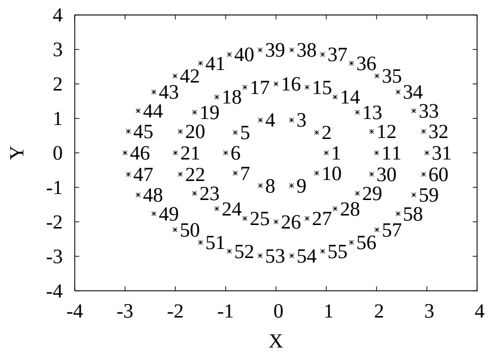

Figure 15: Location of Oscillators in a Radar

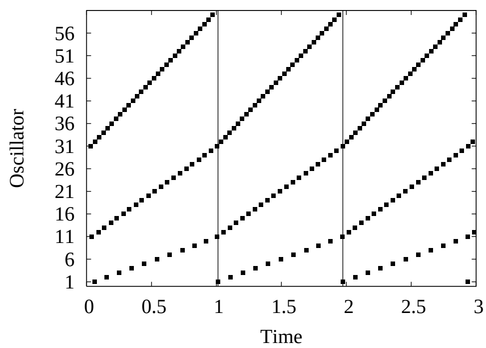

Figure 16: Timing of Firing in a Radar

(diffusion) or N (fusion). Then, on receiving a message from node S_j, node S_i adjusts its level and phase in accordance with a type of a traveling wave. For example, in a case of a concentric circle wave (fusion), level l_i is determined as the maximum level value among all messages it receives minus one. When its level is changed, a sensor node also adjusts the phase as $1-\tau$. In a case of a radar wave, we assume that each sensor node knows its geographical or relative location. Based on messages it received from sensor nodes which are on the same circumference and in the opposite direction of a wave, node S_i initializes its level l_i as the minimum level plus one and phase ϕ_i as $1-\tau$.

Once the initial phase is set, a sensor node begins to shift a timer and periodically emits messages additionally including sensor information and its level value. On receiving a message, a sensor node examines the message to decide whether it has to be stimulated or not. In a case of a concentric circle wave, node S_i is stimulated by a message with level l_i-1 and one with level l_i+1. If a message is from a sensor node with l_i-1, node S_i deposits sensor information into its local memory and emits them together with its own sensor information at the timing of message emission. Otherwise, the message is ignored. In a case of a radar wave, node S_i is stimulated by a message emitted by a sensor node with level l_i+1 or l_i-1 or on the same radius. The latter can be identified by their location information.

5 Conclusion and Future Work

In this paper, we considered to adopt the pulse-coupled oscillator model for a fully distributed and self-organizing data gathering scheme in sensor networks. We first investigated initial conditions that lead to desired phase-lock conditions, i.e., traveling waves in the pulse-coupled oscillator model. Next, we presented a brief sketch of a scenario to apply the pulse-coupled oscillator model to data gathering in sensor networks.

As the next step of this research work, we first consider a data gathering scheme in more details taking into account changes in network topology and radio conditions. We also consider several application scenarios which benefit much from our scheme.

Acknowledgment

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