A Communication Mechanism using Traveling Wave Phenomena 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. 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. In addition, we implement our mechanism using MOTE MICAz and verify its practicality.

1 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.

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's 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's requirements. For example, directed diffusion [1] 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's 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's 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.

For this purpose, we adopt a pulse-coupled oscillator (PCO) model based on biological mutual synchronization such as that observed in flashing fireflies [2, 3]. In a PCO
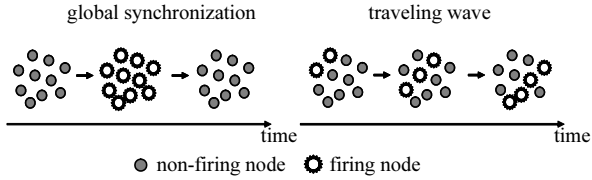
Figure 1. Global synchronization and traveling wave

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 [4–6]. In [6], 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 our previous research work [7], in contrast to the other works, we focused 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) [3]. By adjusting parameters and functions of a PCO model, we can control the frequency, form, and direction of a wave. We proposed a new simple communication mechanism which can organize a variety of communication, i.e., diffusion and gathering, depending on application's requirements. 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. We investigated conditions of a phase response curve (PRC) with which a wireless sensor network reached a preferred phase-lock condition from arbitrary settings of the initial phase of sensor nodes. In addition, we proposed 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. We further confirmed the basic behavior of our mechanism through simulation experiments. 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 state, called phase-lock, where the phase differences among sensor nodes are kept constant, and they emit sensor information alternately. In this paper, we evaluate our mechanism through additional simulation experiments. Furthermore, we implement our mechanism using MOTE MICAz [8], and verify that the mechanism can work on real wireless environment.

The rest of this paper is organized as follows. First, in Section 2, we briefly introduce how to generate traveling waves in a pulse-coupled oscillator model. Next, we introduce our communication mechanism for wireless sensor networks in Section 3, and show simulation results in Section 4. In Section 5, we implement our mechanism and confirm the feasibility and availability of the mechanism. Finally, we conclude the paper and describe future research works in Section 6.

2 Traveling waves in a 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 [3]. 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

$$\phi_j \rightarrow \phi_j + \Delta(\phi_j), \qquad (1)$$

where $\Delta(\phi)$ is called a phase-response curve (PRC). For example, for the quadratic integrate-and-fire (QIF) model, $\Delta_{\mathrm{QIF}}(\phi) = -a \sin 2\pi\phi$ and for the radial isochron clock (RIC) model, $\Delta_{\mathrm{RIC}}(\phi) = a(1 - \cos 2\pi\phi)$ [3]. 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 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 [9].

We have investigated conditions of PRC that led to desired phase-lock condition regardless of the initial phase [7]. We first consider a traveling wave in a PCO network where oscillators are arranged in a line. We assume a pacemaker,
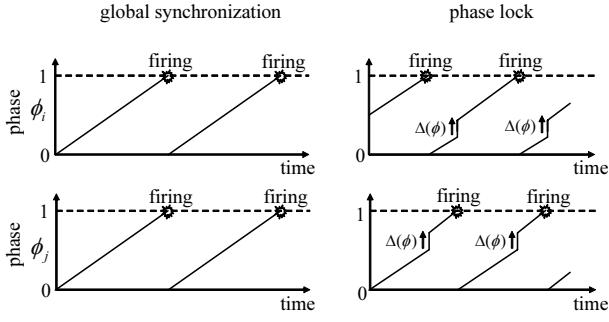
Figure 2. Global synchronization and phase-lock

Figure 3. PRC Δ_S of Eq. (3)

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. Therefore, there is no centralized control over a wireless sensor network and the model is self-organizing. Furthermore, we consider that an oscillator is stimulated only by its neighboring oscillators which are closer to the pacemaker.

In a 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 function must satisfy the following conditions.

$$
\begin{cases}
0 < \Delta(\phi) \leq 1-\tau-\phi & (0 \leq \phi < 1-\tau) \\
\Delta(\phi) = 0 & (\phi = 1-\tau) \\
1-\tau-\phi \leq \Delta(\phi) < 0 & (1-\tau < \phi < 1).
\end{cases}
\tag{2}
$$

For example, the following PRC function satisfies Eq. (2).

$$
\Delta_S(\phi) \quad = \quad a \sin \frac{\pi}{1-\tau}\phi + b(1-\tau-\phi)
\tag{3}
$$

Here, a and b are parameters which determine characteristics of the PRC. Figure 3 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. (2) must lie between these two lines. As parameters a and b increase, a traveling wave emerges more rapidly. Especially, a traveling wave emerges by only one interaction, i.e., stimulus, with $a = 0$ and $b = 1$. However, such aggressive setting spoils the resilience of the mechanism against a failure of node, skewness of a timer, and unexpected influence from the environment, since a single firing emitted at a wrong timing will drastically change the state of the whole system. Therefore, a PRC function and its parameters should
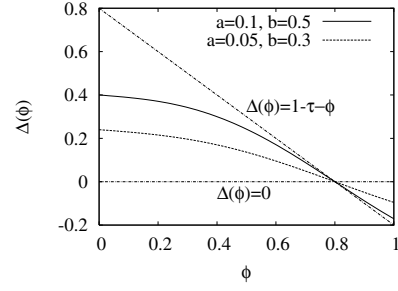
be appropriately determined taking into account the trade-off between the speed that a traveling wave emerges and the resilience against failures.

PRC Δ_S can generate both 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. The same PRC can also be applied to the case of two dimensional arrangement of oscillators by making a tree whose root is the pacemaker. In a tree, an oscillator is stimulated by its parent, i.e., an oscillator closer to the pacemaker. Although any routing protocol for wireless sensor networks is viable to organize such tree-type topology and it can be combined with our mechanism, a simple way of setting such relationship among oscillators will be given in the next section.

3 A distributed and self-organizing communication mechanism

In this section, we briefly introduce our fully-distributed and self-organizing communication mechanism for wireless sensor networks [7]. In our mechanism, any sensor node can gather or diffuse information in accordance with an application's requirements. In our mechanism, a node from which messages are disseminated or to which messages are gathered is called a core node and plays a role of a pacemaker in the PCO model.

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 corresponds to the number of hops from the core node and it is used to define the relationship among sensor nodes in stimulation. 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. (3), we use the following PRC function

for all sensor nodes.

$$\Delta(\phi) = a \sin \frac{\pi}{g} \phi + b(g - \phi), \qquad (4)$$

Here, g is defined as $(1 - \delta_i \tau) \bmod 1$. δ_i is a parameter which controls the direction of information propagation. It is set at 1 for diffusion and -1 for gathering.

Basic behavior of a sensor node is as follows. A sensor node wakes up when its phase is at $1 - \tau$, and then it receives and processes messages as needed. When its phase reaches one, a sensor node broadcasts a message. 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 which it kept in its buffer. After that, it keeps awake for τ to receive and process messages as needed, and then goes to sleep. 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 the 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 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 among sensor nodes i and j 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 $l_i - \delta$, 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. Information aggregation can be done at this time or just before next message emission. If a message does not satisfy 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.

Although we do not describe details due to limitation of the space, our mechanism also considers additional deployment and removal of sensor nodes, multiple core nodes, and node failures [7].

4 Simulation experiments

We first evaluate our communication mechanism through simulation experiments. 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 [8]. Initial energy is 50 J for all nodes. We use Eq. (4) 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. All results are averaged over 100 simulation experiments.

Figure 4 shows comparison with the directed diffusion where per-hop delay is set at 0.1 time units. 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. In Fig. 4 (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. 4 (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.

Figure 4 (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
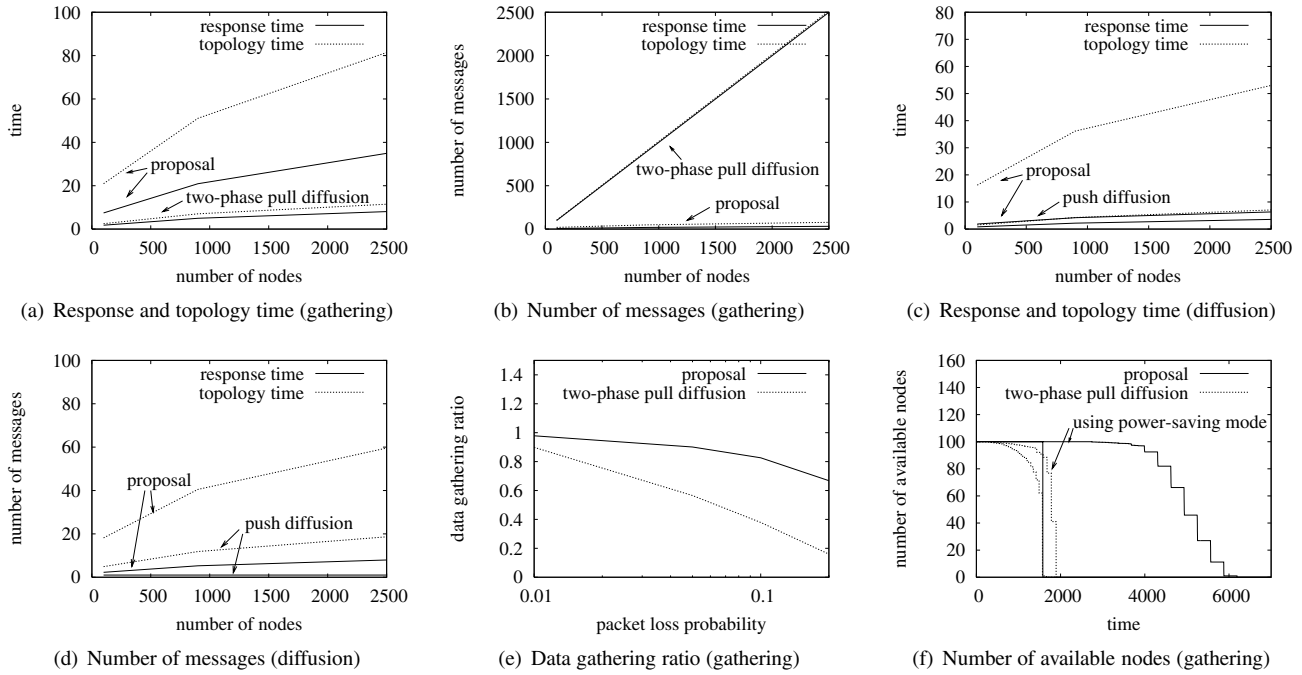
(a) Response and topology time (gathering)

(b) Number of messages (gathering)

(c) Response and topology time (diffusion)

(d) Number of messages (diffusion)

(e) Data gathering ratio (gathering)

(f) Number of available nodes (gathering)

Figure 4. Comparison among proposal and directed diffusion through simulation experiments

mechanism. It is 220 to 790 % of the directed diffusion in response time and 718 to 877 % in topology time as shown in Fig. 4 (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 4 (e) shows the data gathering ratio against the packet loss probability in a 10×10 network. 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. A sensor node randomly fails in transmitting a message at the packet loss probability shown on the x-axis. In Fig. 4 (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. 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. As shown in Fig. 4 (f), the lifetime with our mechanism is 1577 time units whereas that with the directed diffusion is 265 time units. Furthermore, by using a power-saving mode [7], the lifetime with our mechanism becomes as long as 2733 time units wheres that with the directed diffusion is 304 time units.

5 Implementation and evaluation

We implement our mechanism using a commercial sensor unit MOTE MICAz [8]. It has an omni-directional antenna and employs IEEE 802.15.4 MAC protocol on 2.4 GHz bandwidth for radio communication. A 10-seconds timer is implemented by shifting phase ϕ_i by 0.01 at every 100 milliseconds. A message is 40 bits long where the first 4 bits are for level value, 1 bit for δ, 3 bits reserved, 16 bits for session identifier, and the last 16 bits for data.

We confirm basic behavior of our mechanism on a sensor network consisting of 16 nodes arranged in a grid as shown in Fig. 5 (a). 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 (a) 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.

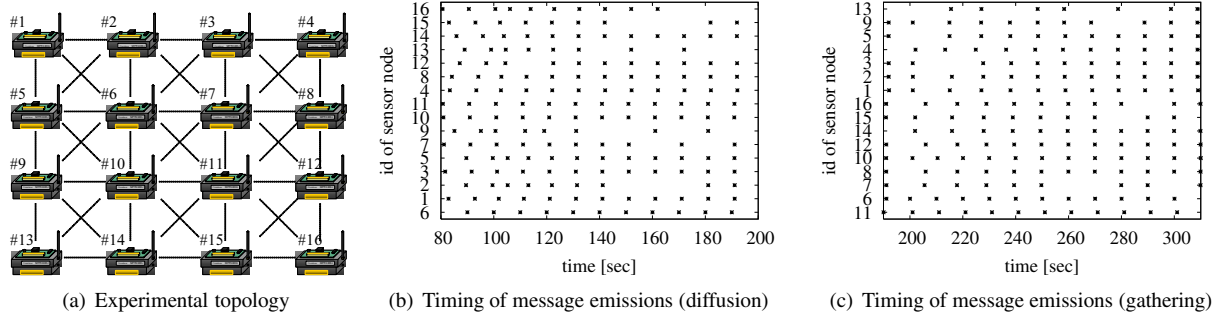Figures 5 (b) and 5 (c) show how the sensor network

(a) Experimental topology　　(b) Timing of message emissions (diffusion)　　(c) Timing of message emissions (gathering)

Figure 5. Experimental evaluation

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 5 (b) 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.

6 Conclusion and future work

In this paper, we first briefly introduced our fully-distributed and self-organizing communication mechanism. We conducted simulation and practical experiments to verify the effectiveness and practicality of the proposal. As future research works, 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.

Acknowledgment

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