

## **Master's Thesis**

Title

**Proposal and evaluation of an inter-networking mechanism  
using stepwise synchronization for wireless sensor networks**

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## **Abstract**

To realize the ambient information society, where information devices embedded in the environment detect, reason, and satisfy demands of people unconsciously, a variety of network, interface, and platform technologies have been intensively developed in recent years. Regarding networking, one of fundamental technologies is to allow independent networks to cooperate with each other. For example, a wireless body network carried by a person should be connected with networks embedded in the environment immediately and smoothly to provide them with personal information necessary for ambient information services and to receive information services from the environment. However, it is not trivial to enable inter-networking among networks operating on different control policies. Especially in case of wireless sensor networks, which consist of small and powerless devices, they in general adopt a duty cycling mechanism to turn off unnecessary modules for energy conservation. Depending on applications, duty cycles are different among wireless sensor networks. Since it is waste of energy for a node in a frequently operating network to wait for a node in an infrequent network to wake up for message transmission, we need a mechanism for different wireless sensor networks to communicate with each other without sacrificing energy invaluable for network operation. In this thesis, we propose an smooth and moderate inter-networking mechanism for wireless sensor networks. With our inter-networking mechanism, nodes located near the border of networks adjust their operational frequencies in accordance with their distance to the border to bridge the gap between intrinsic operational frequencies of those networks, while other nodes keep their intrinsic operational frequency. To accomplish such stepwise control, we adopt a pulse-coupled oscillator model as a fundamental theory of synchronization. In the PCO model, a set of oscillators achieves the synchronization of timers emerges through mutual interaction among oscillators. Our inter-networking mechanism accomplishes the

stepwise synchronization in a fully distributed and autonomous way by adopting the PCO model. Through simulation experiments, we show that the delay in communication between border nodes was reduced, but at the sacrifice of energy at nodes near the border in the slower network.

### **Keywords**

Wireless Sensor Network

Synchronization

Pulse-Coupled Oscillator Model

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# 1 Introduction

The ambient information society or the post-ubiquitous society is the concept and framework where intelligent environment detects, reasons, and satisfies overt and potential demands of people unconsciously [1, 2, 3]. In so-called ubiquitous or pervasive environment, anyone can access a network anytime and anywhere to obtain helpful and useful information from the environment or through the Internet, control the environment or information devices locally and remotely, and communicate with others in the same or remote environment. However, it requires a user's intentional manipulation of devices to be connected to a network. That is, the ubiquitous information environment is a pull-type system. On the contrary, in the ambient information society, people do not need to be aware of existence of networked information devices embedded in the environment. They do not need to intentionally access a network to control the environment to make it comfortable and satisfy their demands. Instead, the embedded network controls the environment and provides even personalized information services to a person taking into account time, place, occasion, and person.

To realize the ambient information society, networks deployed and operating in the same environment must cooperate with each other in exchanging information, sharing information, and even controlling each other. For example, assume that a person comes into a room. He has a body area network which consists of vital sensors, accelerometers, PDA, and other devices. For the sake of easy handling, they might organize a network by wireless communication. On the other hand, a room has embedded wired and wireless networks which consist of sensors, e.g. temperature, humidity, and brightness, and actuators, e.g. air conditioner and lights for environmental control for example. Intelligent home appliances also constitute embedded networks. In general, those devices organize different and independent networks in accordance with their applications and characteristics of devices. Therefore, so that the room provides the person with a comfortable environment, those networks have to cooperate with each other. For this purpose, we need a mechanism for different networks to smoothly and dynamically connect and share their information. However, it is not a trivial task.

There are several proposals on dynamic composition of multiple networks [4, 5]. In [4], they consider a mechanism for overlay networks to dynamically compose a hierarchical structure by two types of composition schemes, i.e. absorption and gatewaying. In [5], cooperation between

wireless networks is accomplished by organizing an overlay network by connecting gateway nodes belonging to different wireless networks. Although they can be applied to ambient information networking to some extent, they have a major problem that they do not take into account the difference in operational policies, more specifically, operational frequencies of different wireless sensor networks.

In general, especially wireless sensor networks, but even devices with wired communication capability, adopt a sleep scheduling or duty cycling mechanism to save energy consumption. Under duty-cycling, all devices are not always at work. Operational frequencies, that is, frequencies that they wake up and resume operation, are different among networks depending on application's requirement and characteristics of devices. For example, it is not necessary for an air conditioner to adjust its thermostat on a per-second basis, and thus it intermittently obtains and uses the temperature information every ten minutes for example. On the other hand, devices to detect locations of people have to report their detection result very frequently at an order of seconds. When they want to exchange information among them for intelligent control of room temperature to intensively regulate the temperature around a person in the room, a node belonging to the location detection system has to keep active in order to wait for a node belonging to the thermal management system to wake up in transmitting a message. Even an energy-efficient MAC protocol such as S-MAC [6] and X-MAC [7] is used, such communication consumes the substantial energy at the former node and it would bring danger of energy depletion. It of course is possible to force a slower network to operate at the faster frequency, but it apparently is a mere waste of energy.

Our research group considers stepwise synchronization between wireless sensor networks for smooth and moderate inter-networking. In [8], the concept of stepwise synchronization is introduced, where sensor nodes located near the border of two networks operating in different intrinsic frequency adjust their operational frequencies to bridge the gap in operational frequencies. Since only nodes near the border change their operational frequency, the remaining nodes can keep their intrinsic frequency and thus energy consumption in inter-networking can be saved. The stepwise synchronization is based on a nonlinear mathematical model of synchronization of oscillators, called the pulse-coupled oscillator (PCO) model [9]. The PCO model describes synchronization which emerges in a group oscillators with different frequencies by a mean of mutual interactions through stimuli. By adopting the PCO model to scheduling, operational frequencies of nodes can be appropriately adjusted by exchanging messages as stimuli among nodes without any centralized

control in wireless sensor networks. However, in [8], only an idea of stepwise synchronization is shown and no detailed description on mechanisms is given.

Therefore, in this thesis, we propose a realistic mechanism of stepwise synchronization for inter-networking among wireless sensor networks with different operational frequencies. In our mechanism, we set the strength of entrainment in the PCO model at border nodes to intensively shift the operational frequency to that of the other network, and the degree of entrainment is weakened as the distance to the border increase. As a result, the operational frequencies of nodes at or near the border are adjusted to somewhere between the original operational frequencies of wireless sensor networks to cooperate. Through simulation experiments, we verify the practicality of our proposal in comparison with the cases where each of networks keeps its intrinsic operational frequency and either of them completely adjusts its operational frequency to the other.

The rest of this thesis is organized as follow. In section 2, we describe a background of this research, including general description on wireless sensor network, intra-network synchronization, and requirements on inter-networking. Then in section 3, we first explain the pulse-coupled oscillator model, and then we describe the details of our proposal. In section 4, we show and discuss results of our simulation experiments. Finally, we conclude the thesis in section 5.

## 2 Background

### 2.1 Wireless sensor network

By distributing a large number of sensor nodes with wireless communication capability and organizing a wireless sensor network, we can obtain detailed information about surroundings, remote region, and objects [10]. Each wireless sensor node can be equipped with a variety of sensors, e.g. thermometer, hygrometer, and illuminometer, as far as the space, cost, and energy allow. In wireless sensor networks, sensor nodes obtain observatory information about the environment and objects by using their sensors and report obtained sensor data to a base station or a sink node that has wireless or wired connection to the outer network, behind which an administrative user or monitoring center exists. In some cases, sensor data are directly sent to other sensor nodes to share information or to actuators to control other devices.

Generally, control mechanisms for wireless sensor networks must be scalable, adaptive, and robust, because of a large number of sensor nodes, random or unplanned deployment of sensor nodes, and dynamic topology changes due to addition, movement, and removal of sensor nodes. The instability and unreliability of wireless communication also is a reason for this requirement. In addition, due to difficulty in managing a large number of nodes in a centralized manner, mechanisms must be fully distributed and self-organizing. Specifically, communication overhead to collect and maintain up-to-date information about the condition of a wireless sensor network is very costly in regarding to the wireless bandwidth and energy. Furthermore, sensor nodes are limited in power and computation capacities because a sensor node has a poor processor and small memories, and runs on battery power to save cost and size. Therefore, mechanisms for wireless sensor networks must be simple and energy efficient.

Typically, in order to suppress energy consumption, sensor nodes adopt duty cycling or sleep scheduling. Duty cycling is a mechanism where a node switches off unused modules during operation. For example, it is only a waste of energy that a sensor node keeps activating a transceiver all the time for intermittent communication to report sensor data every one hour. However, when nodes adopt duty cycling, a problem arises that communication is not always possible. A sender node has to wait for a receiver node to wake up and turn its transceiver on to transmit a message. Such communication takes time and energy. Therefore, for energy-efficient and low-delay communication, it is necessary to coordinate duty cycling, that is, synchronization.

## 2.2 Intra-network synchronization

As stated above, duty cycling is indispensable for wireless sensor networks to save energy consumption and prolong the lifetime. However, it sometimes causes energy dissipation and the performance deteriorates such as communication delay due to inefficient communication. So that a wireless sensor network can pursue both of goals, energy efficiency and performance, it is necessary to coordinate and synchronize timings of sleep and wake up among nodes [11].

Synchronization in the context of wireless sensor network has two meanings [12]. One is to adjust a clock of wireless sensor node to a real world clock or the same timeline with other nodes. To identify the timing that sensor data is obtained and to derive information from a set of sensor data at the sink, it would be required for a node to put the timestamp, which is synchronized to a real world clock or keeps the same timeline as others, in a message.

The other type of synchronization is to make nodes wake up at the same time or following the coordinated schedule. Assume that nodes embedded in the room observe and report the room temperature to an intelligent air conditioner. In such an application, it is not necessary, although might be useful in for example history-based control, to know when sensor data are obtained. Instead, it is enough for an air conditioner to know the latest temperature information. Actually, it is a reasonable assumption that the last message received from a node is the latest temperature that it detected. More important than synchronization to a real world clock is to manage communication, more specifically timing that a node wakes up, obtains sensor data, receives a message, performs computation, transmits a message, and goes to sleep. If we can make a node wake up and turn on a receiver only when another node in its vicinity begins to send a message to the node, we can expect the minimum energy consumption and the maximum lifetime of a wireless sensor network. For such synchronization, it is not necessary to have and maintain a clock, but it is enough to keep a timer. In this thesis, we consider a timer-based duty cycling and synchronization among timers. We further assume that the interval of timer or the frequency of wake-up is determined in accordance with an application's requirement, e.g. hourly surveillance of a farm, and the operational frequency is the same among nodes belonging to a single wireless sensor network.

### **2.3 Requirement on moderate inter-network synchronization**

Although a wireless sensor network is useful for a variety of applications such as gathering information about surroundings and remote regions, they are developed and deployed in an application-oriented manner. There could be multiple wireless sensors deployed in the same region for different purposes. In the ambient information society, for the environment to conjecture user's demand more precisely, it must be helpful and effective for multiple wireless sensor networks to cooperate with each other. Cooperation of wireless sensor networks starts with exchanges of messages such as sensor data and control information among them. However, generally wireless sensor networks are independent from each other and operational policies are different among them. In order to exchange messages between two or more wireless sensor networks, they have to overcome differences in operational policies. Operational policies can be defined by various kinds of features of wireless sensor networks, e.g. operational frequency and communication protocol, based on application's requirements and characteristics of devices. In this thesis, we define the operational policy as the operational frequency.

As in the case of communication between nodes with duty cycling, communication between wireless sensor networks with different operational frequency is also difficult to achieve. In order to achieve smooth inter-networking between wireless sensor networks with different operational frequency, one possible approach is to force one network to operate at the other network's operational frequency. However, when all nodes in a slower network adjust its operational frequency to that of a faster network, it apparently consumes substantial energy of the slower network and shortens its lifetime. On the contrary, slowing down the operational frequency at all nodes in a faster network to keep the same pace as a slower network leads to degradation of observation resolution.

For smooth and moderate inter-networking, our research group considers stepwise synchronization between wireless sensor networks [8]. In our stepwise synchronization, wireless sensor nodes located near the border of two wireless sensor networks operating in different intrinsic frequency adjust their operational frequencies in accordance with their distance to the border to bridge the gap. Since only nodes near the border change their operational frequency, the remaining nodes can keep their intrinsic frequency and thus energy consumption in inter-networking can be saved. Furthermore, nodes can meet application's requirements because many of nodes operate in



near intrinsic frequency.

### 3 Stepwise synchronization-based inter-networking mechanism

#### 3.1 Pulse-coupled oscillator model and synchronization

A pulse-coupled oscillator model is a mathematical model which explains synchronized flashing of a group of fireflies [9]. It is considered that a firefly maintains a biological timer, based on which it intermittently flashes. When a firefly is alone, it flashes on timer expiration. Flashing frequency depends on its intrinsic timer frequency, which could be different among individuals. However, when fireflies form a group, they begin to flash in synchrony. A mechanism of biological synchronization is explained as follow. When a firefly observes a flash of other firefly, it is stimulated and advances its timer by a small amount. Because of nonlinearity in timer or stimulus, by repeatedly stimulating each other, their timers begin to expire synchronously. Among PCO models [9, 13, 14], in this thesis we use the model proposed in [9].

In the PCO model [9], a set of oscillators is considered. Oscillator  $i$  maintains phase  $\phi_i$  ( $0 \leq \phi_i \leq 1$ ) of a timer and state  $x_i$  ( $0 \leq x_i \leq 1$ ) given by a function of phase. The dynamics of phase  $\phi_i$  is determined by the following differential equation.

$$\frac{d\phi_i}{dt} = F_i \quad (1)$$

where  $F_i$  stands for the intrinsic frequency of oscillator  $i$ . State  $x_i$  is determined from phase  $\phi_i$  by the following monotonically increasing nonlinear function,

$$x_i = \frac{1}{b} \ln[1 + (e^b - 1)\phi_i] \quad (2)$$

where  $b$  ( $0 < b$ ) is a dissipation parameter that dominates the rate of synchronization. State  $x_i$  is 0 with phase  $\phi_i = 0$  and state  $x_i$  is 1 with phase  $\phi_i = 1$ .

When phase  $\phi_i$  and state  $x_i$  reach one, oscillator  $i$  fires and both phase  $\phi_i$  and state  $x_i$  go back to zero. When an oscillator fires, the oscillator stimulates oscillators that are coupled with the firing oscillator. If oscillator  $j$  is stimulated by oscillator  $i$  at time  $t$ , oscillator  $j$  increases its state  $x_j$  by a small amount  $\epsilon$  and phase  $\phi_j$  advances accordingly as

$$x_j(t^+) = B(x_j(t) + \epsilon), \quad (3)$$

where

$$B(x) = \begin{cases} x(0 \leq x \leq 1) \\ 0(x < 0) \\ 1(x > 1) \end{cases}$$

and

$$\phi_j(t^+) = \frac{e^{bx_j(t^+)} - 1}{e^b - 1} \quad (4)$$

When state  $x_j^+$  and phase  $\phi_j^+$  reach one by being stimulated, oscillator  $j$  also fires. At this time, oscillators  $i$  and  $j$  are considered synchronized. To avoid overshoot and instability, an oscillator is not stimulated by two or more oscillators at the same time, and an oscillator is not stimulated at the time when it fires.

Figure 1 shows how dissipation parameter  $b$  affects the relationship between state  $x$  and phase  $\phi$ , where  $b$  is changed from 1.0 to 7.0. As can be seen in Fig. 1, when  $b$  is set at a small value, e.g. 0.1, the amount of phase shift on receiving a stimulus is almost the same despite the timing that the stimulus is received. On the other hand, in the case that  $b$  is large, e.g. 7.0, a stimulated oscillator changes its phase by a large amount when its state is high. Then, as the value of  $b$  becomes larger, synchronization emerges more rapidly.

Now we show results of numerical analysis for four different scenarios. First, Fig. 2 illustrates how two oscillators become synchronized by the PCO model. The horizontal axis of Fig. 2 corresponds to elapsed time and the vertical axis corresponds to phase. The intrinsic frequency of oscillators is identical. Phase  $\phi_i$  of oscillator  $i$  reaches one at time  $t_1$  and oscillator  $i$  fires. Then, oscillator  $i$  stimulates coupled oscillator  $j$  and initializes its state  $x_i$  and phase  $\phi_i$  to 0. By being stimulated, oscillator  $j$  advances its phase  $\phi_j$ . Eventually, oscillator  $j$  fires at time  $t_2$  and stimulates oscillator  $i$ . The phase of oscillator  $i$  advances by a small amount at this time. At time  $t_3$ , oscillator  $i$  fires. As the amount of stimulus or the amount of phase shift is large when the phase is close to 1 as shown in Fig. 2, phase  $\phi_j$  of oscillator  $j$  reaches one by being stimulated by the fire. Now, timers of the two oscillators are synchronized.

Next, Fig. 3 shows phase transition of 100 oscillators arranged in a  $10 \times 10$  grid. Intrinsic frequency of each oscillator is randomly chosen within the range of [0.9, 1.1]. Initial phase  $\phi$  is also chosen at random. An oscillator is coupled with four neighbors located in up, right, down, and left of the oscillator and stimuli are never lost and always received by the four neighbors.

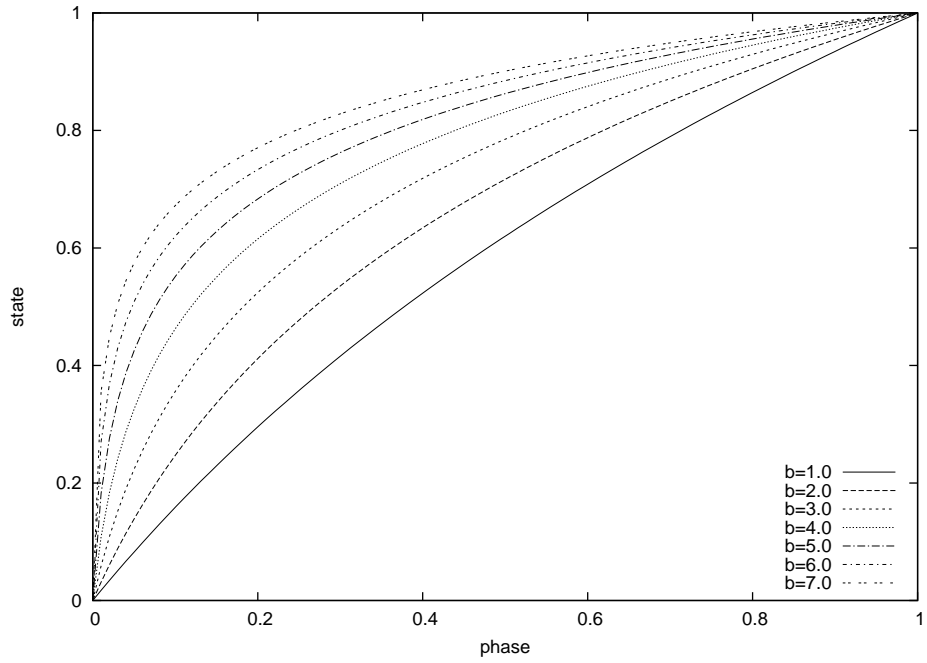


Figure 1: Effect of changing  $b$  on relationship between state and phase

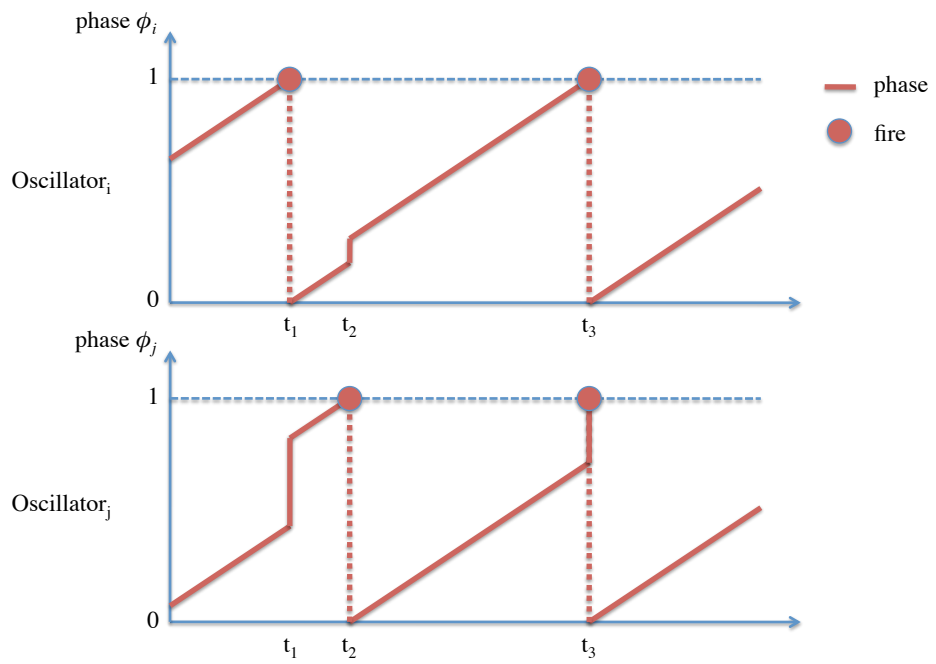


Figure 2: Mechanism of synchronization in pulse-coupled oscillator model

There is no delay in stimuli propagation and phase and state change.  $b$  and  $\epsilon$  are set at 3.0 and 0.1, respectively. At first, phases are different among oscillators. The increasing rates of phase are also different among oscillators due to the difference of intrinsic frequency. As time passes, timings of firing gradually get closer by stimulating each other. Finally, all oscillators become synchronized and fire at the same time.

Then, we show how two groups of oscillators whose intrinsic frequencies are different get synchronized to the same operational frequency. As in the above example, 100 oscillators are arranged in a  $10 \times 10$  grid. The initial phase is chosen at random, and  $b$  and  $\epsilon$  are set at 3.0 and 0.1, respectively. Half of oscillators in the left forming a  $5 \times 10$  grid set their intrinsic frequencies within the range of  $[0.9, 1.0]$  at random, and they belong to group 1. The other oscillators set their intrinsic frequency within the range of  $[1.0, 1.1]$  at random, and they belong to group 2, see Fig. 4. During the first three quarters of simulation time, oscillators are not stimulated by oscillators that belonged to the other group. That is, there is no coupling among oscillators of different groups. During the last quarter of simulation time, oscillators at the border are coupled with each other so that they can stimulate each other. As can be seen in Fig. 5, during the first three quarters, oscillators belonging to the same group identified by the same color get synchronized and oscillators belonging to different groups fire at different timings. As inter-group communication is allowed at time 80,000, two groups become integrated and oscillators fire all at the same time and same frequency. The operational frequency of the unified group is dominated by the highest frequency of intrinsic frequencies of all nodes, i.e. about 1.1.

Finally, we show a case that two groups of oscillators cannot accomplish synchronization for a big difference in operational frequencies. From the above setting, we change the ranges of operational frequency to  $[0.2, 0.3]$  and  $[1.0, 1.2]$ . An inter-group communication is allowed at time 50,000. An obtained result is shown in Fig. 6. As can be seen, the global synchronization cannot be attained and synchronization each group is even lost by being disturbed by stimuli from the other group. This result also supports a need for a stepwise synchronization mechanism to realize inter-networking between wireless sensor networks with largely different operational frequencies, such as hour and minute.

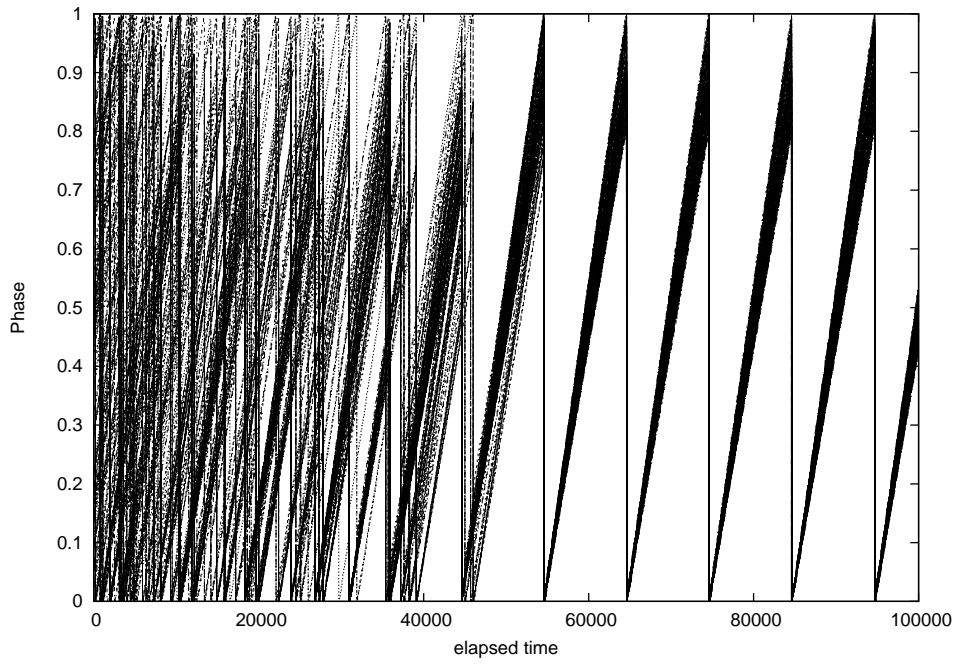


Figure 3: Phase transition: one group of oscillator case

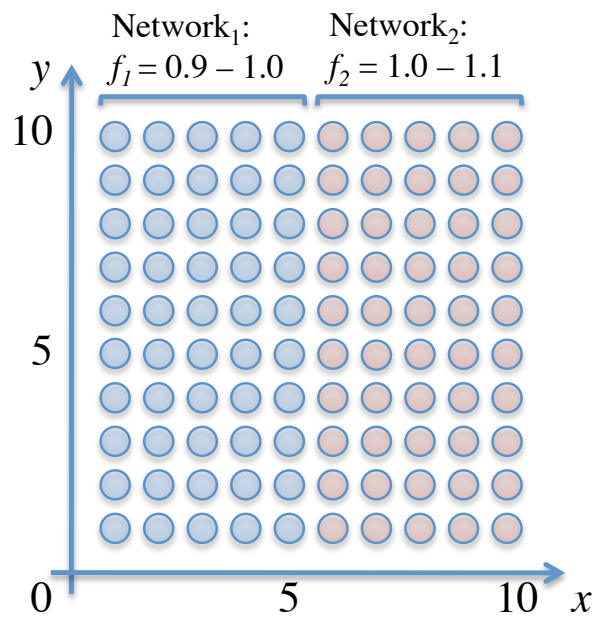


Figure 4: Node layout in numerical analysis

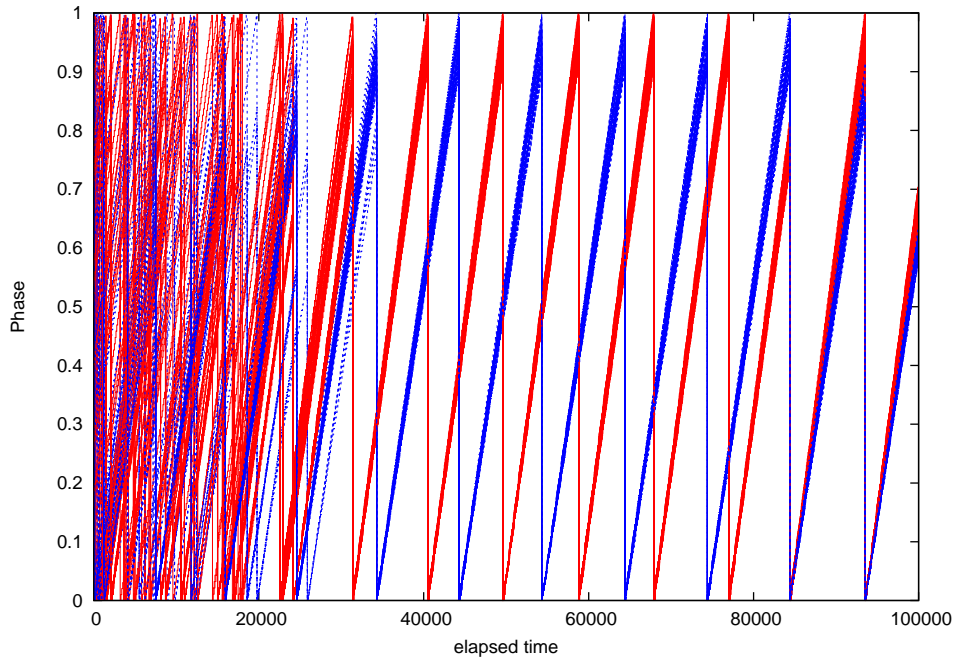


Figure 5: Phase transition: two groups of oscillator case

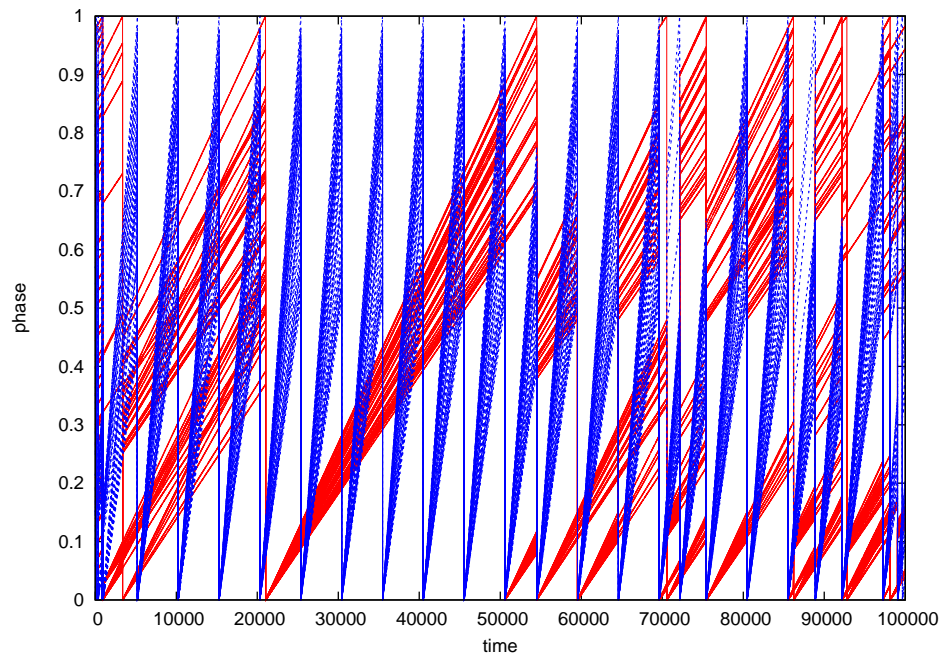


Figure 6: Phase transition: synchronization failure case

### 3.2 Inter-networking mechanism using stepwise synchronization

In this subsection, we describe how we apply the PCO model to synchronization in wireless sensor networks, and explain details of our stepwise synchronization-based inter-networking mechanism.

In applying the PCO model to wireless sensor networks, a wireless sensor node corresponds to an oscillator and it stimulates neighbor nodes in the range of radio signals by broadcasting a message. A message is used for both of synchronization and data communication with such a mechanism where control messages for synchronization are embedded in messages for sensor data [15]. Node  $i$  maintains state  $x_i$  and phase  $\phi_i$  as variables of a timer of frequency  $F_i$  and calculates its new state and phase at regular intervals, that is, the timer advances. When state  $x_i$  and phase  $\phi_i$  reach one, node  $i$  sets both state  $x_i$  and phase  $\phi_i$  at zero and tries to broadcast a message which informs neighbor nodes that the node fires. Message broadcasting is performed by the underlayer MAC protocol. Since a wireless channel is the shared medium, there is possibility that broadcasting is delayed to wait for the channel to become available. However, from our preliminary experiments, the influence of delay on synchronization is negligible. When a node receives a broadcast message, it is stimulated. The stimulated node, say node  $j$ , increments its state  $x_j$  by a small amount  $\epsilon$  by Eq. (3) and calculates new phase  $\phi_j^+$  based on the new state  $x_j^+$  by using Eq. (4). If the new state  $x_j^+$  and new phase  $\phi_j^+$  reach one, node  $j$  also fires and broadcasts a message. Since duty cycling is adopted on a node, it is not always ready to receive stimuli. Details of integration of duty cycling and the PCO model will be given later.

Now we propose a stepwise synchronization-based inter-networking mechanism. In our mechanism, we assume that two or more wireless sensor networks operating in different operational frequencies co-exist and nodes belonging to the same network are synchronized to the same frequency by a PCO-based synchronization mechanism. A node can communicate with any awake nodes in its communication range independently of whether they belong to the same network or not. A node can know the distance, i.e. the number of hops, from the border of networks by using a mechanism which will be given later. As an example, in Fig. 7, two wireless sensor networks with different operational frequencies are adjacent, and they attempt to cooperate. When we only couple border nodes to let them stimulate each other, two wireless sensor networks will be unified to a single network with the operational frequency identical to the faster one or they will remain independent in accordance with difference in operational frequencies. To accomplish stepwise



synchronization where nodes at or near the border change their operational frequency to the frequency between the two original frequencies, we adjust the degree of entrainment. We focus on the fact that the dissipation  $b$  and the stimulus  $\epsilon$  influence the degree of entrainment and the speed of synchronization. As shown in Fig. 1, a larger  $b$  fastens synchronization for a larger shift in phase against a stimulus. Apparently, as the amount of shift in state increases with a larger  $\epsilon$ , a group of oscillators or a wireless sensor network reaches synchronization faster and more aggressively. In Fig. 8, we show how the cumulative number of flashing oscillators changes with different parameters  $b$  and  $\epsilon$  against time. The fact that the number increases the most with “ $b=3.0, \epsilon=0.1$ ” means that oscillators flash more often than their intrinsic frequency. This is because flashes of oscillators are not synchronized and oscillators are stimulated by other oscillators very often. The height of stepwise increase in the number corresponds to the number of oscillators simultaneously flashing. From the figure, we can see that the time when a group of oscillators reach synchronization is 30,000 with “ $b=0.1, \epsilon=3.0$ ”, 20,000 with “ $b=3.0, \epsilon=3.0$ ”, 13,000 with “ $b=1.0, \epsilon=5.0$ ”, and 4,000 with “ $b=0.3, \epsilon=5.0$ ”. When we adopt larger  $b$  and  $\epsilon$ , the speed of synchronization apparently decreases.

Therefore, in our proposal, we set larger values of  $b$  and  $\epsilon$ , e.g.  $b = 4.0$  and  $\epsilon = 0.3$ , at nodes located at the border of wireless sensor networks as indicated by blue in Fig. 7 to strengthen entrainment at the border and shift the operational frequency much. Then smaller values are applied to nodes as the distance to the border becomes larger, e.g.  $b = 3.5$  and  $\epsilon = 0.1$  at purple nodes. By receiving stimuli from the other network, blue nodes actively changes their operational frequencies for larger parameters while keeping being stimulated by nodes of the same network. We should note here that nodes belonging to a faster network do not change their frequencies that much even with larger parameters. Purple nodes are also entrained by blue nodes, but the impact is smaller for smaller parameters and thus their operational frequencies stay rather closer to the original frequency. Consequently, we observe a stepwise change in operational frequencies around the border of two networks. Furthermore, such stepwise synchronization can bridge the large gap in operational frequencies which cannot be overcome by the PCO model alone.

Now, we describe details of our proposal. A node wakes up slightly earlier than expiration of a timer to receive messages from neighbor nodes as shown in Fig. 9. When the ratio of active period, i.e. duty ratio, is  $T_{active}$  in the interval  $\frac{1}{F_i}$ , node  $i$  wakes up at phase  $\phi_i = 1 - T_{active}$ . However, when a node receives a stimulus and advances its phase, the actual duration of active period be-

comes shorter to  $T_{active}^t$  for the  $t$ -th active period. After a certain period of time for broadcasting, a node goes to sleep independently whether it could successfully broadcast a message or fall in broadcasting for channel busy. Therefore, the duration of the  $t$ -th cycle is given as  $T_{sleep}^t + T_{active}^t$ . When a node receives a message from one of neighbor nodes, it performs PCO-based adjustment of a timer. When the phase and state of a timer reach one as time passes or on reception of a message, a node tries to broadcast a message. So that other nodes in the network can recognize their relative distance to the border, a node at the border sets the distance field in the header of message it broadcasts as 1, meaning that the message is from a node at the border. On receiving a message, a node can set its distance as the number indicated in the distance field plus one, if it has not decided its distance or its distance identified by the previous message is larger than the number in the header. The distance information is also embedded in messages that it broadcasts, so that the distance information propagates through a network. A node at the border begins to use value 0 for the distance field, if it has not received any messages from the other network for a certain period of time to notify other nodes of the end of cooperation. Receiving this message, distance information is initialized to 0 on other nodes. Once a node recognizes its distance to the border, it adjusts  $b$  and  $\epsilon$  in accordance with the distance. In this thesis, the adjustment of  $b$  and  $\epsilon$  is determined from preliminary experiments. Initially, all nodes set their  $b$  and  $\epsilon$  at 3.0 and 0.1, respectively. For stepwise synchronization, nodes at the border set  $b$  and  $\epsilon$  at 4.0 and 0.3, respectively. Nodes next to the border set  $b$  and  $\epsilon$  at 3.5 and 0.05, respectively. The other nodes also set their parameters as summarized in Fig. 10. Nodes that is more distant from the border of networks set their parameters at the same values of green nodes in Fig. 10.

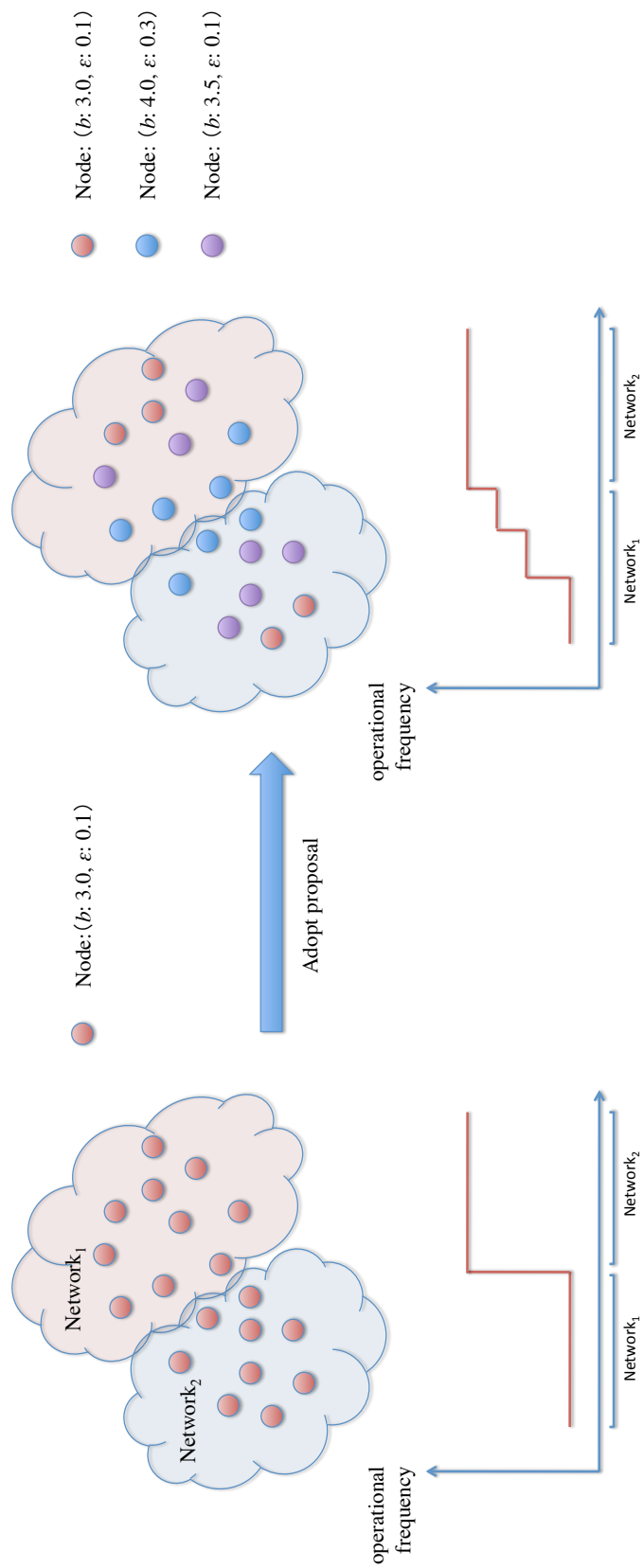


Figure 7: Idea of proposal

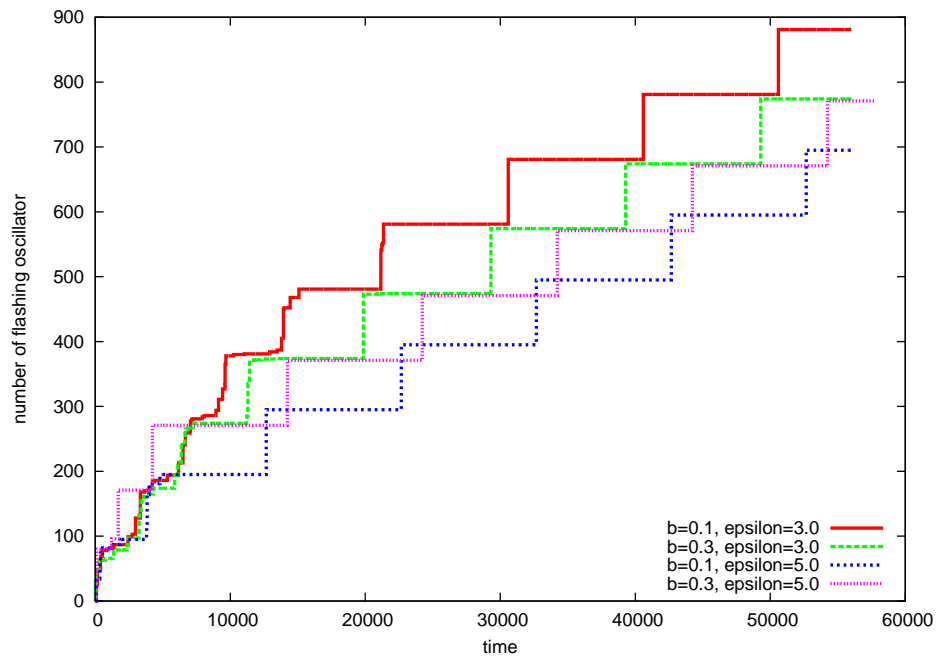


Figure 8: Cumulative number of flashing oscillators

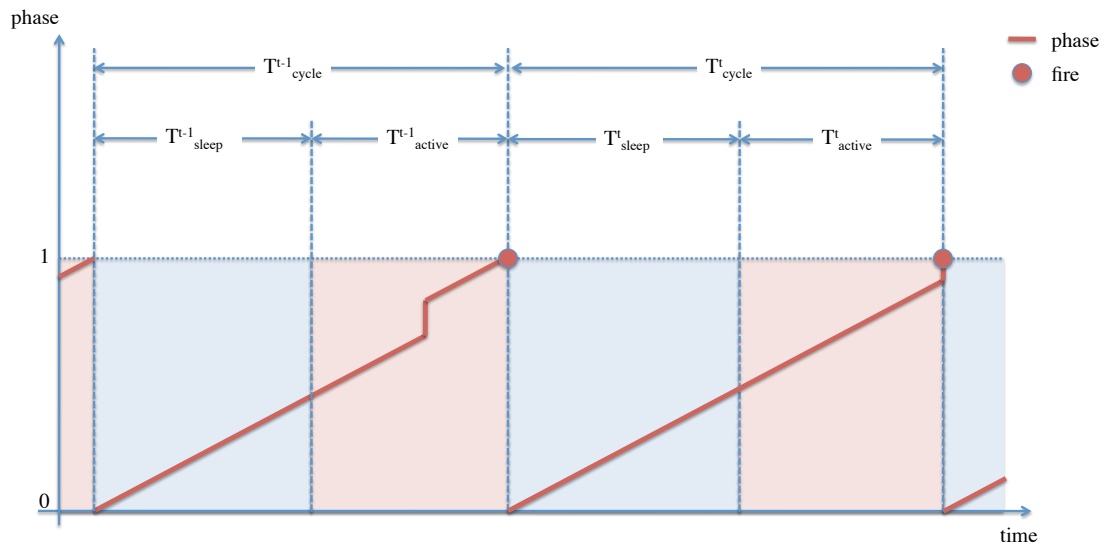


Figure 9: Duty cycling in PCO model

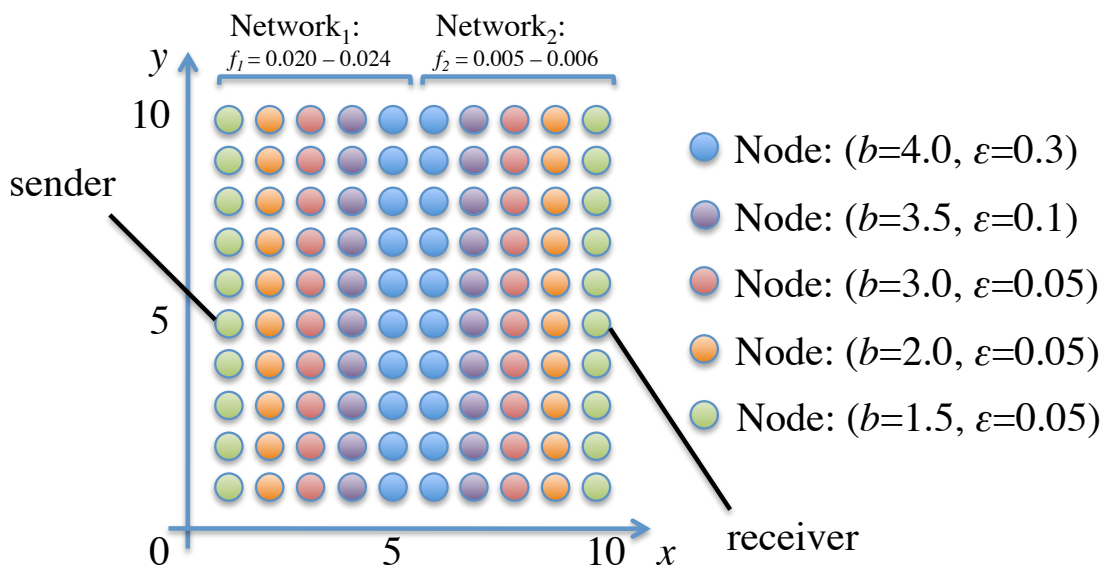


Figure 10: Node layout in simulation

## 4 Performance evaluation

### 4.1 Simulation settings

In addition to duty cycling based on the PCO-model, we further adapt duty cycling on the MAC layer. Low power listening (LPL) is an approach widely used in energy-efficient MAC protocols such as X-MAC [7]. Figure 11 illustrates the behavior of X-MAC in unicast communication. With X-MAC, a node periodically wakes up by turning on a transceiver to see whether there is any message destined to itself. The duration that a node is ready for reception is denoted as  $R_l$  and the interval between successive active periods is denoted as  $R_s$  when the transceiver is off. A sender node that intends to send a message first transmits small messages, called Short Preamble, to notify a receiver of the existence of message. It keeps sending preambles until it receives an ACK for the preambles from an intended receiver. There is a short interval between preambles to receive an ACK from a receiver. When a receiver, that is, a node that the sender wants to send the message to, wakes up, it would receive one of preambles during its active period. Then, the receiver sends back an ACK message to the sender and extends its active period accordingly. On receiving the ACK, the sender begins to send the message. After receiving the whole message, the receiver sends an ACK again to the sender. Finally, unicast communication is completed and both nodes go back to the sleep state. In a case of broadcasting, where a message is not intended for any specific node but all nodes in the vicinity, a sender begins to send a message itself repeatedly for the duration of slightly longer than  $R_s$  without communication initialization by Short Preamble as shown in Fig. 12. There is no acknowledgement either for broadcasting. In stimulation experiments in the thesis, we assume X-MAC as a MAC protocol.

We arranged 100 nodes in a  $10 \times 10$  grid. Nodes in the left-hand area belong to Network 1 and the others does Network 2 as shown in Fig. 4. Each node can communicate with nodes in its up, right, down, and left. Parameters are set as summarized in Tables 1 and 2. Therefore, the duration  $T_{cycle}$  of each cycle is about 42 to 50 seconds in Network 1 and 167 to 200 seconds in Network 2. At the fastest frequency of 0.024, the PCO-based active period  $T_{active}$  is as long as 4 seconds and enough for a message to travel from the sender to the receiver. A tick of a timer is set at 100 ms. Initial states are set at random. Parameters  $b$  and  $\epsilon$  used in cooperation are shown in Fig. 10. We change the duty ratio from 0.1 to 0.9 at intervals of 0.1. The duty ratio is identical among two networks. Therefore, with duty ratio of 0.1, nodes in Network 1 has the PCO-based active period

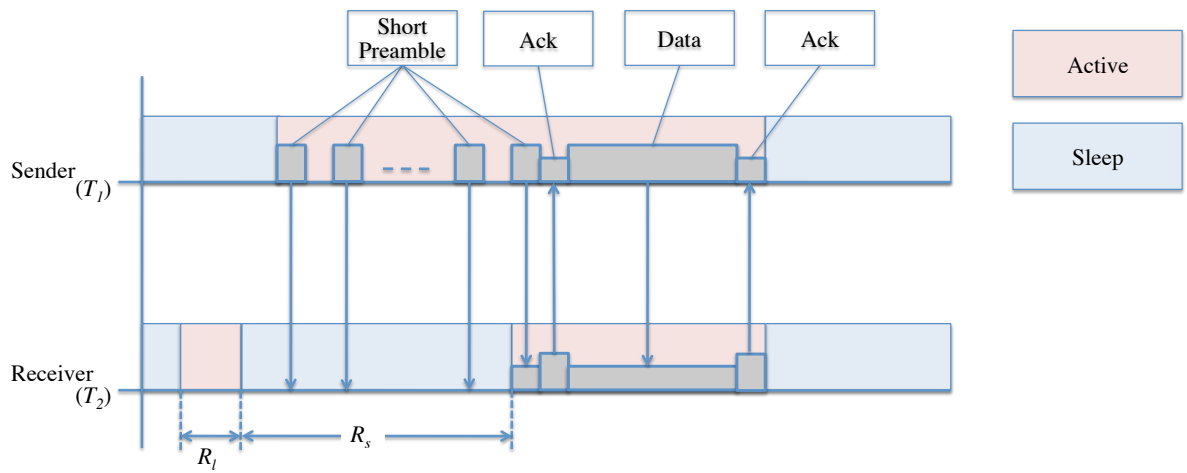


Figure 11: Mechanism of unicast communication between two nodes in X-MAC

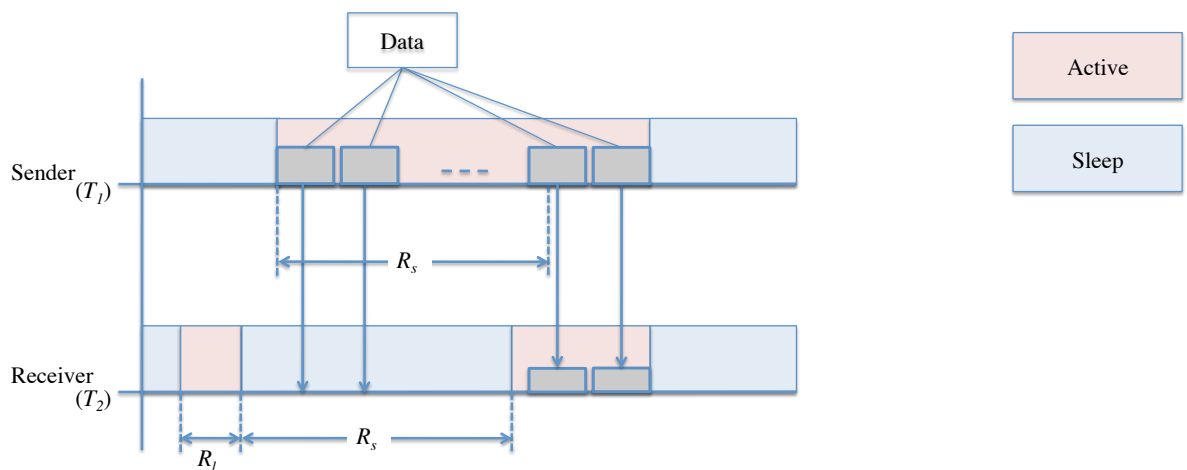


Figure 12: Mechanism of broadcast communication in X-MAC

of 4 to 5 seconds and those in Network 2 has that of 17 to 20 seconds.

In our simulations, the sender node sends a data message to the receiver node by using multi-hop unicast communication once per 10 operational cycles. Data messages take the shortest path to the receiver node, that is, on the horizontal line connecting sender and receiver. The resultant number of hops is 9. A node receives a data message in its PCO-based active period. Then, it immediately tries sending the message to a next-hop node unless it is the destination node. It transmits preambles until it receives an ACK from the next-hop node, even after the end of the PCO-based active period, i.e. expiration of timer. When the transmission of the data message is completed, the node moves to the sleep state if the phase of timer is in the range of the PCO-based sleep period. Otherwise, it keeps awake in the PCO-based active period. In case that the timing of completion of message transmission is in the broadcasting period, which is after timer expiration and for the duration slightly longer than  $R_s$ , it starts to broadcast a stimulus message.

## 4.2 Results and discussion

We compare three scenarios, where both networks keep their intrinsic frequencies in communication denoted as "independent", Network 2 (slower network) changes its operational frequency to  $f_1$  denoted as "synchronized", and our proposal is adopted denoted as "proposal". We conducted 200 simulation runs for each of duty ratio setting. As performance measures, we use communication delay which is defined as the duration between the time when a node begins to send preambles for data message transmission and the time when a node receives an ACK for message reception, and energy consumption which is defined as the total time when a transceiver is active on all nodes. Communication delay between the sender and the receiver is defined as the duration from emission of preambles at the sender node and reception of an ACK from the receiver node at the previous node of the receiver. In the following results, we first obtain the maximum communication delay in each simulation run. Regarding energy consumption, we first obtain the total duration that transceivers are active from the time when cooperation starts to the end of a simulation run. Then, a median of 200 simulation runs is used for each of duty ratio setting in figures.

First, we confirm that the stepwise-based synchronization is achieved. Figure 13 shows how nodes adapt their operational frequencies with our proposal, where the y-axis corresponds to the actual length  $T_{cycle}^t$  of cycles. At first two networks are independent and nodes are synchronized with each other in each network. At 350 s, inter-networking is allowed. Nodes at the border



begins to receive broadcast messages from nodes of the other network. As can be seen in Fig. 13, nodes at the border of the slower network, i.e. Node(6, 5) in Fig. 13, drastically shorten its length of cycle, because its operational frequency is entrained to the faster frequency of the faster network by being stimulated by Node(4, 5). Node(7, 5) next to Node(6, 5) moderately changes its operational frequency towards that of Node(6, 5). Being affected by broadcast messages which are emitted at the shifted frequency, the operational frequencies of Node(8, 5) and Node(9, 5) are also changed in this case. Finally, we observe the stepwise shift in operational frequencies to bridge the gap in the intrinsic operational frequencies of Network 1 and 2. We should note here that the operational frequency of nodes in Network 2, i.e. the faster network, dose not change much for cooperation.

Next, we evaluate communication delay between the sender node and the receiver node as well as delay of each hop. Figure 14 shows the communication delay between the sender node and the receiver node. When all nodes are synchronized to the fastest operational frequency, the communication delay becomes minimum. A reason that we see the small increase of delay in "synchronized" with duty ratio of 0.1 is that there are some cases that synchronization cannot be accomplished for the small duty ratio. When the PCO-based active period is rather small for the small duty ratio, broadcast messages that a border node of one network cannot be received by a border node of the other network. In the figure, we see that the communication delay of our proposal is the worst whereas the stepwise synchronization is accomplished. Figures 15 through 17 explain a reason. Within the faster network, i.e. Network 1, a message travels fast without much communication delay as shown in Fig. 15, where communication delay between Node(4, 5) and Node(5, 5) is depicted. On the other hand, in the slower network, i.e. Network 2, shown in Fig. 17, communication delay between Node(6, 5) and Node(7, 5) drastically increases only with our proposal. It is because they operate in different operational frequencies as shown in Fig. 13. Therefore, Node(6, 5) has to wait for Node(7, 5) to wake up to send a message. Similarly, we observe waiting time in communication between Node(5, 5) and Node(6, 5) in Fig. 16. As it is intuitively apparent, communication delay with "independent" is larger than "proposal" between Node(5, 5) and Node(6, 5), for the major gap in operational frequencies. It means that Node(5, 5) can save energy by our stepwise synchronization in cooperative communication, but at the sacrifice of longer end-to-end delay and energy of nodes in the slower network.

Finally, we evaluate energy consumption in Fig. 18 where we show the total length of time

when a transceiver is switched on at all nodes and Fig. 18 where the number of broadcasting is shown, after 350 seconds, i.e. the beginning of cooperation. In the region where the duty ratio is small, i.e. from 0.1 to 0.5, the duration of communication with “synchronized” becomes the highest. A reason for this is that nodes in Network 2 (slower network) operate on the faster frequency and thus broadcast messages more often. As a result, the total number of successful broadcast communication becomes as many as 2,500,000 times in the case of “synchronized”. Since the number of data transmission is small in our experiments, the duration of communication, where transceivers are active, is mostly dominated by frequent broadcasting. We should note here that, in a data gathering application where data are collected from all nodes, broadcast messages play a role of data transmission as well. Thus, the broadcasting in such case is not overhead. In the case of “independent”, the duration of communication and the number of broadcasting are the minimum among all scenarios. Synchronization helps in reduction of the number of broadcasting. When a node finds the wireless channel is used by other node, it stops broadcasting a message until the channel becomes available or the broadcasting period ends. Therefore, in our proposal, the number of broadcasting increases for different operational frequencies where a node has more chance to find the available channel, and as a consequence the duration of communication increases. A reason for the increase of the duration of communication and the number of broadcasting against the increase of the duty ratio is that a node is stimulated more often during a longer PCO-based active period. Then, the amount of shift in operational frequency becomes large and more diverse among nodes for mutual interaction. However, as we compare “proposal” with “synchronized”, it is more energy efficient with a smaller duty ratio, which wireless sensor networks usually adopt for energy saving.

Table 1: Parameter settings: pulse-coupled oscillator model

PCO	
parameter	value
$b$	3.0
$f_1$	0.020 - 0.024
$f_2$	0.005 - 0.006
$\epsilon$	0.1

Table 2: Parameter settings: X-MAC

X-MAC					
parameter	value [ms]	parameter	value [ms]	parameter	value [ms]
$S_{pre}$	2.0	$R_{pre}$	2.0	$R_{sleep}$	200
$S_{ack}$	2.0	$R_{ack}$	2.0	$R_{listen}$	20
$S_{data}$	4.0	$R_{data}$	4.0		

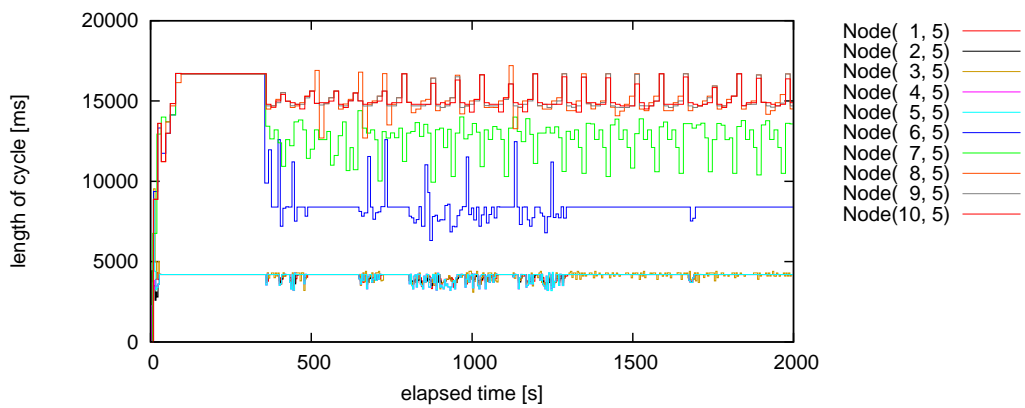


Figure 13: Results: adapted duty cycles by stepwise synchronization

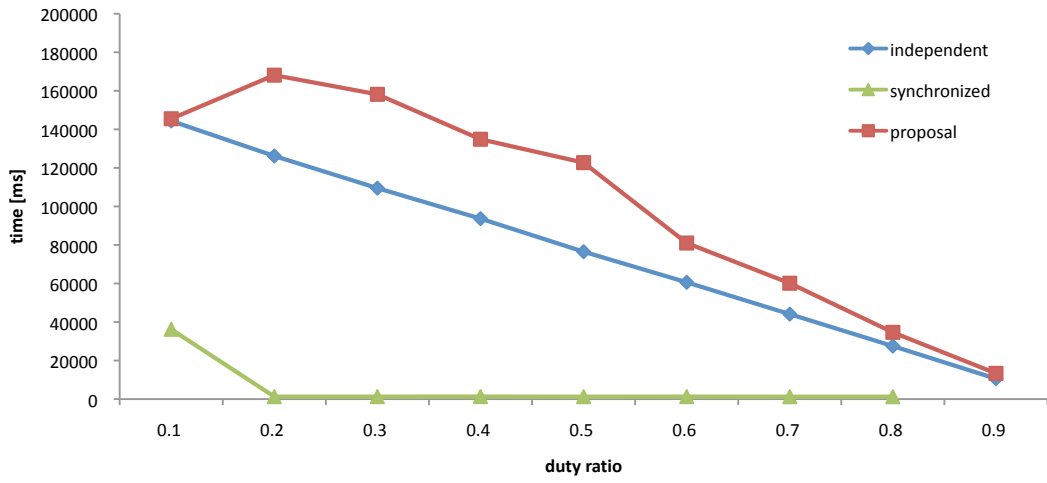


Figure 14: Results: communication delay between sender and receiver

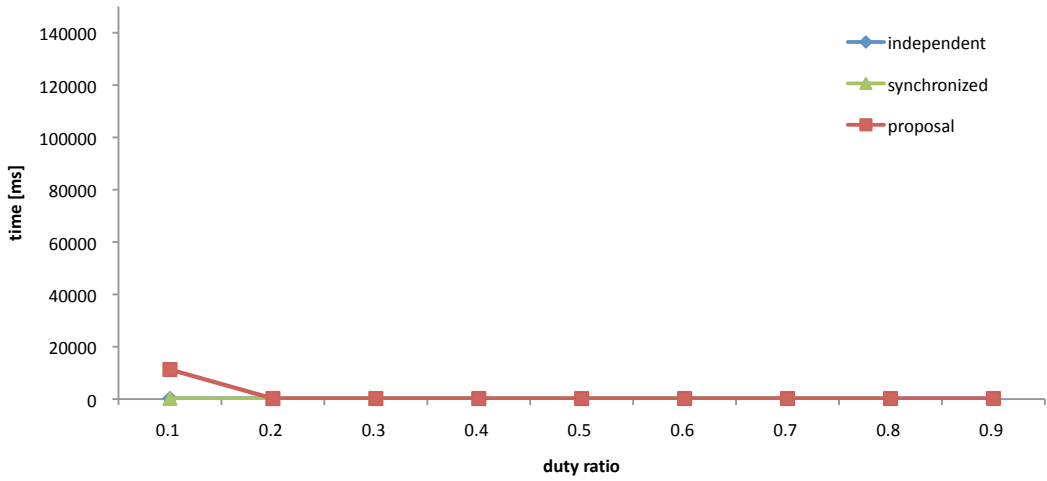


Figure 15: Results: communication delay between Node(4, 5) and Node(5, 5)

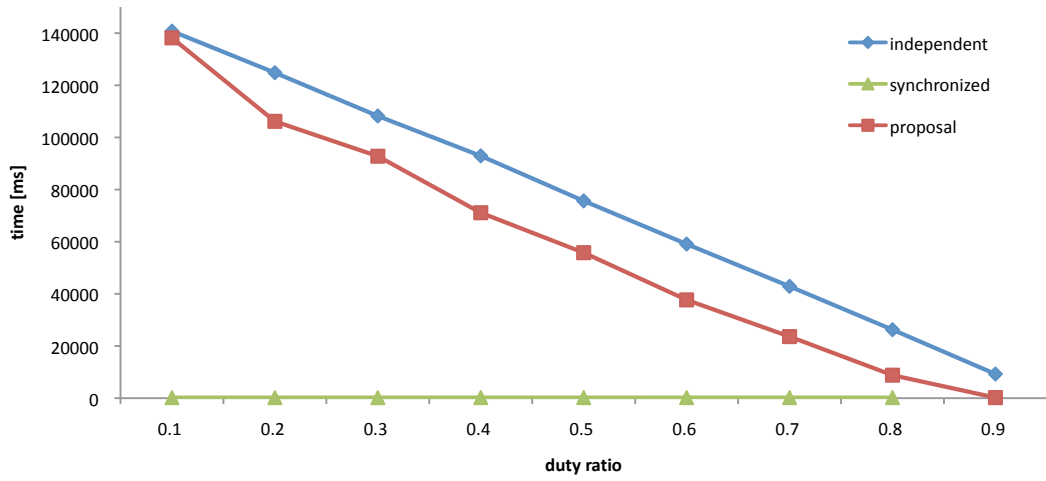


Figure 16: Results: communication delay between Node(5, 5) and Node(6, 5)

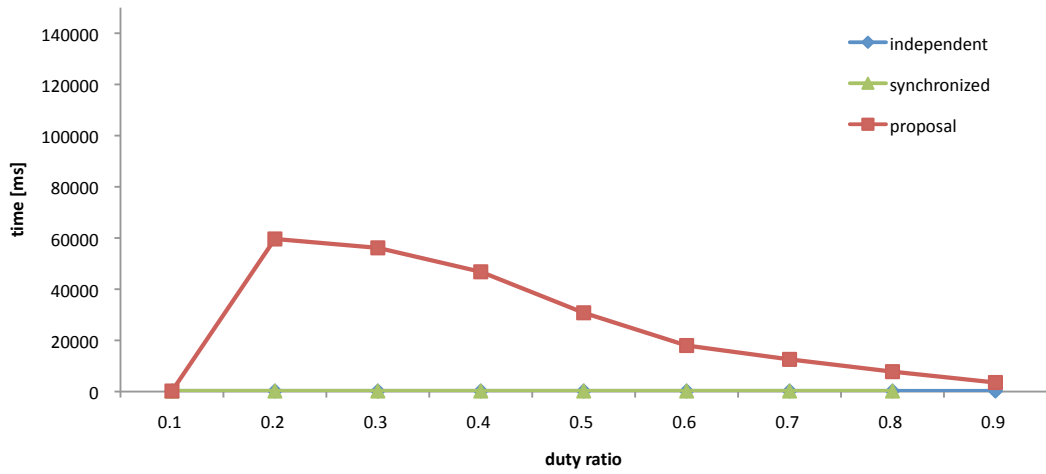


Figure 17: Results: communication delay between Node(6, 5) and Node(7, 5)

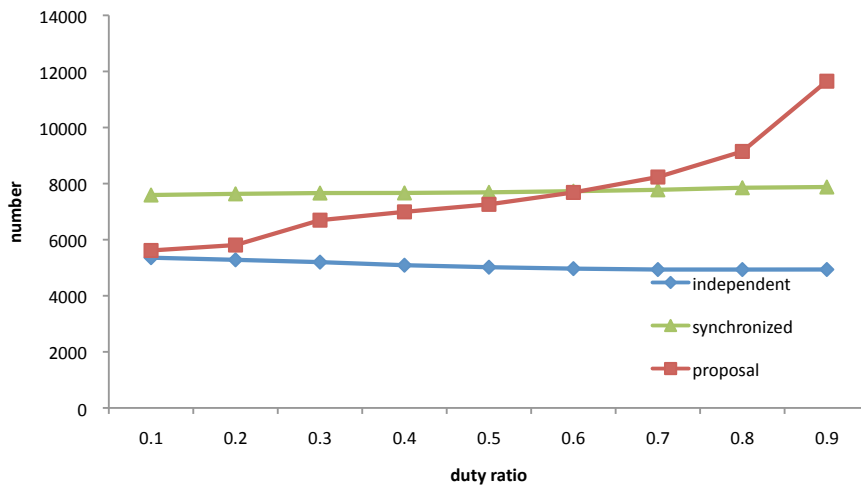


Figure 18: Results: total duration of communication

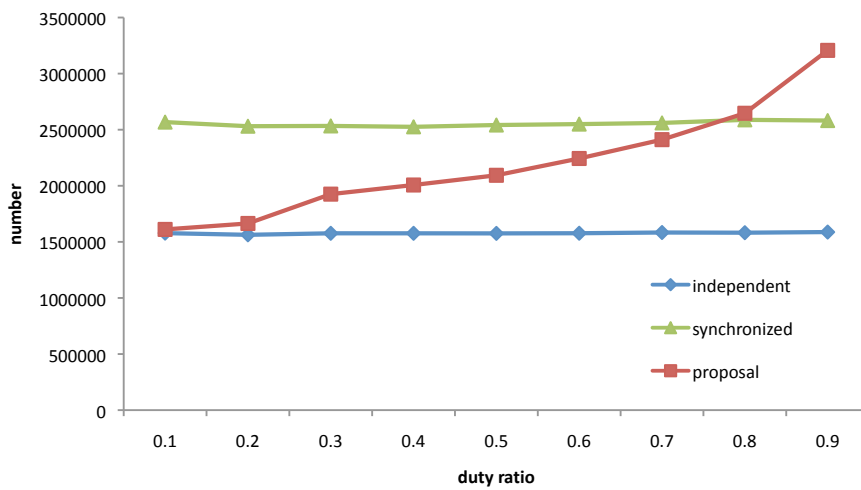


Figure 19: Results: number of broadcast communication

## 5 Conclusion

In this thesis, to achieve smooth and moderate inter-networking between wireless sensor networks with different operational frequencies, we propose a stepwise synchronization-based inter-networking mechanism. In this mechanism, we adopt the pulse-coupled oscillator model to autonomously accomplish stepwise synchronization. Through simulation experiments, it was shown that the delay in communication between border nodes was reduced, but at the sacrifice of energy at nodes near the border in the slower network.

As future work, we plan to improve our proposal to achieve more energy-efficient inter-networking by careful arrangement of parameters  $b$  and  $\epsilon$ . We also need to show the strategy of parameter setting under different conditions, such as in the number of nodes, the difference in operational frequencies, and the duty ratio.

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