Master's Thesis

Title

Frog Call-Inspired Self-Organizing Transmission Scheduling Scheme for Wireless Sensor Networks

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Abstract

Research on bio-inspired self-organized methods is being done in order to control complex networks where dynamic changes of topology and an increase of the nodes are expected. That kind of research targets at applying robustness and adaptability features of biological systems against environmental changes to computer networks. In the field of routing and time synchronization, research on biological systems such as the ants' feeding behavior and the synchronized firing behavior of fireflies has been performed. In this thesis, we focus on the Japanese tree frogs' calling behavior. They are known to make their calls alternatively among their neighbors in order to raise the probability of mating. This behavior can be applied to a phase control which realizes collision free transmission scheduling in wireless communication. Frogs also show a behavior called 'satellite', where a frog stops calling once it finds other neighboring frogs calling. This behavior can be applied to an energy efficient sleep control which provides adaptive access periods. We propose a self-organizing scheduling scheme inspired by the frogs' calling behavior for energy efficient and reliable data transmission in wireless sensor networks. Simulation results show that our proposed phase control is capable of reducing data transmission failures and improves the data collection ratio up to 24% compared to a random method. Furthermore, sleep control prolongs network life-time by 6.7 times over the method without sleep control for 80 % coverage ratio.

Keywords

sensor networks

alternate synchronization

pulse-coupled oscillator

self-organized control

scheduling

sleep control

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1 Introduction

It is expected that the number of the terminals which constitute a network will increase remarkably due to the diversity of applications and the increase in the number of terminals linked to the Internet. In addition, network topology changes frequently since a user may often join and leave in P2P (*Peer to Peer*) or ad hoc network. In a mobile environment realized by development of radio technology, reliable communication cannot always be guaranteed since communication is based on wireless connections. Systems for controlling these kinds of networks require high robustness, scalability, and adaptability. The self-organized control which is inspired by biological systems has been receiving more attention as a concept in order to realize these demands [1]. Biological systems always change and adapt themselves against continuous changes in the environment. Each component of a biological system makes decisions based on local interactions between neighbors without receiving directions from a specific leader, thus, the entire system can respond to changes in coordinated manner in spite of selfish behavior of individual components. Such simple mechanisms bring cognitive function to the whole system and self-organized control provides adaptability and robustness [2].

Methods have been proposed to adopt the advantages of biological systems to computer networks in such fields as routing [3] and clustering [4]. In the field of time synchronization, *pulse-coupled oscillators* (PCO) [5] are known to model the behavior of fireflies which flash in unison among neighbors. However, most research of the pulse-coupled oscillator model targeted the synchronization in a simultaneous fashion [6]. Alternate phase synchronization is necessary in the case where several terminals need to share the common resources. When several terminals process a task sharing one resource, the load can be balanced by a round-robin scheduling where each terminal is processed in turns. Similarly, in wireless communications, alternate phase synchronization of transmission scheduling reduces packet loss caused by collisions.

As a possible mechanism for realizing alternate phase synchronization, we consider the frogs' calling behavior, especially *advertisement calling* and *satellite*. It is assumed that one of the main reason of frogs' calling (advertisement calling) is to attract female frogs. If a male frog calls simultaneously with other frogs, it becomes difficult for the female frog to distinguish the caller, so they perform shifts in the timing of calling [7, 8]. We formulate this behavior of advertisement calling by the pulse-coupled oscillator model and apply it to phase control for alternate synchronization. Furthermore, it is applied to transmission scheduling in wireless communication aiming at avoiding of transmission failures. Conventional scheduling protocols have problems regarding the overhead for adjusting their schedule and lack in adaptability since the schedule is fixed and cannot be rescheduled according to environmental changes. However, the self-organizing scheduling based on the frogs' calling can solve these problems.

Additionally, there is a remarkable behavior called *satellite* as another feature of the frogs' calling behavior. When there are many competing frogs, certain frogs stop their calling based on the decision, comparing the merits of getting higher probability of mating over the demerits of losing energy by calling. We apply this behavior to the sleep control in wireless sensor networks. The decrease in cost of sensor nodes is expected to enable large deployments in the future. Under such situations, nodes will be deployed non-uniformly and redundantly, so that some nodes don't need to actively sense all the time. By performing the control equivalent to the satellite behavior, these redundant nodes turn off the transceiver power and are able to conserve energy. At this time, each node performs the sleep control considering the overlap of the sensing region between neighboring nodes and the number of active nodes can be adjusted without sacrificing coverage. In addition, efficient data gathering is achieved by adjusting the number of active nodes considering the traffic load.

In this thesis, we propose a self-organizing transmission scheduling scheme inspired by frogs' calling behavior. The outline of this thesis is as follows: Section 2 provides the motivation why we are interested in frogs and about alternate phase synchronization and sleep control in general by introducing some related work. Section 3 introduces the details of the mechanisms of two functions of proposal, the phase control method based on frogs' alternate calling behavior and the sleep control method based on frogs' satellite behavior. Section 4 shows the result from numerical simulations in single-hop networks. At first, we demonstrate that phase control can result in alternate phase synchronization in various environments and we perform a comparative evaluation of data collection ratio and synchronization error with other scheduling methods. Secondly, we evaluate the sleep control method and show the feasibility of our proposal to enable an energy efficient assignment of the access period and we provide a conclusion and present possible extensions in Section 5.

2 Background and Motivation

In this section, we explore the motivations behind self-organizing control in computer networks. We introduce some examples of biological systems with self-organizing control that are applied to the field of computer networks. Then, we explain why we paid attention to the behavior of frogs' calling behavior , and describe the way to apply this behavior in computer networks.

2.1 Self-Organization in Nature: Dynamics of the Tree-Frog

The information network will be complicated and diversified more in the future, due to the diversity of applications and increase of the terminals. In such networks, self-adaptability and self-organization capabilities are necessary for the terminals which constitute a network since unexpected various environmental changes are assumed as a result of the complexity and heterogeneity. The conventional network represented by the Internet has a hierarchical structure and is a centralized static network. The server exists in the center and manages all data with many routers attached the role of relaying data, and further a huge number of users connected via the routers. In such a centralized network, when a serious problem occurs at the server which takes the lead in a system, it will have a drastic influence on all the users and it may be very difficult to restore the network. Dynamic new networks, such as MANET (*Mobile Ad-hoc Network*) and P2P, have been proposed as a way to avoid and minimize such problems. In order to constitute such a dynamic network, the following three requirements are considered.

- Scalability
- Mobility
- Diversity

Each terminals needs to carry out adaptive operation according to the network condition for providing these requirements. Biological systems are suitable for establishing the dynamical network since it has the capability of high self-organization to realize the adaptability. The most important feature of the biological system is its self-organization. A group consisting of the autonomous individuals accomplishes the organized structure without specific rule. Self-organization is highly dependent on the behavior of each individuals and those interactions in biological system. Bonabeau defines the self-organization as follows [9].

Figure 1: Biological systems such as foraging activity of ants, pattern formation on the skin of mammals and simultaneous flashing of fireflies.

> Self-organization is a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components. The rules specifying the interactions among the system's constituent units are executed on the basis of purely local information, without reference to the global pattern which is an emergent property of the system rather than a property imposed upon the system by an external ordering influence.

Generally, there are four principles in self-organization of biological systems. *Positive feedback* to strengthen a good control, *negative feedback* to suppress over control and lead to a stable condition, *direct or indirect interactions* among each other, *randomness* to bring flexibility and escape from local solution.

Research on the application of these features of biological system into computer network has so far been done. Especially, the research on swarm intelligent and controlled behavior has been well studied. For instance, ants and bees divide complex task, such as making a nest or finding food, into simple work and perform one by one. In such emergent systems, the emergent property is a combination of individual contributions. Division of labor that specific individuals perform specific tasks in parallel improves efficiency. Each individual of swarm makes decision based on local information obtained from the exchanges with neighboring individuals without considering the condition of the whole system. And as a decision of one individual affects environment, other individuals adjust to this change. As a result, high order function as a group is self-organized.

Dorigo [10] introduced ACO (*Ant Colony Optimization*) as the probabilistic method to find the shortest path in the graph. ACO provides a sub-optimal solution to the *traveling salesman problem* (TSP) and can be adapted to changes of the graph. For this reason, ACO is suitable for routing in computer networks. The ant aims at looking for food, and leaves pheromone in the passage. It decides the route randomly based on left-behind pheromone and returns to the nest when it finds the resources. A pheromone disappears with time and the route unsuitable for finding resources is dismissed. Positive feedback works on an effective route and a pheromone becomes stronger by other ants choosing the route repeatedly. AntNet [11] is an application of ACO to routing and packet switching.

We can find various patterns on the skin of some animals such as the mammals and fish. Turing [12] modeled this pattern formation process on skin of animals with reaction diffusion equation. In a reaction diffusion model, the distribution of factor concentration changes due to interactions of form factors between adjoining cells, and various patterns, such as spots, meshes and stripes, are formed. The reaction diffusion model has been applied to several areas in the field of computer science and communication networks. Applying reaction diffusion to environmental observation with camera enables the adaptive assignment of encoding rate corresponding to the location and passing speed of the target. A reaction diffusion based MAC (Medium Access Control) protocol for ad hoc networks is also proposed [13]. A global communication pattern which avoids collision is generated based on local interactions.

Research on synchronization which is inspired by the phenomenon of firefly's simultaneous flashing or the pacemaker cell of the heart, etc. has also been done. A certain kind of firefly that lives in Southeast Asia flashes regularly according to an internal clock. It is known that when this kind of firefly forms a group, the timing of flash is adjusted by receiving a stimulus from flash of a surrounding firefly and eventually all the fireflies synchronize to flash. In this process, each individual makes decisions based on local information without receiving any directions from a special individual. This mechanism was modeled by Strogatz *et al.* as *pulse coupled oscillators* (PCO) [5], and is applied to the area of time synchronization and data gathering in a sensor network [14]. A sophisticated clock is not equipped to the sensor node and time information on the whole network may shift by node addition. PCO is able to synchronize the clocks of nodes in these situations. Wakamiya *et al.* [15] applied PCO to data gathering in sensor networks. PCO not only adjusts the time in unison but also can shift time according to a hop count. The application is in a sensor network with the base station located in the center of the network collecting data, which is transmitted subsequently by intermediate nodes like a traveling wave. In addition, the node irrelevant to data transmission can reduce energy consumption by turning power off.

Figure 2: Japanese tree frog.

It has been shown that the bio-inspired method has robustness compared with the centralized method which a specific leader manages the system, since it controls the system in a self-organizing fashion based on local information. We paid our attention to Japanese tree frogs' calling behavior as new biological mechanism [7, 8, 16]. The Japanese tree frog (*Hyla japonica*) is a species of tree frog belonging to the genus *Hyla*. They are widely distributed in all parts of Japan also in Korean Peninsula and China. The size of the body is three to four centimeters and they live on the waterside or plants and hibernates under the ground in the winter. In mating season from spring to summer, male frogs make a loud chorus in the paddy field. This calling is called *advertisement call* which aims at telling a female frog about location of itself. The male attracts a female by an advertisement call and it catches the approached female to mate. Frog has another reason to make an advertisement call. When a male frog hears other frog's calling, by taking a constant distance (*spacing*), it reduces the interference of calling and avoids energy consumption caused by competing with male frogs and location estimation of female frog becomes easier. Thus, a territory of each male frog is formed. It is also known as frogs' behavior that it makes advertisement call alternately among other male frogs. This behavior avoids the interference of the calling and raises the probability to attract a female. When it hears the calling of other neighboring frog, sometimes it is suppressed to decelerate the calling timing, and sometimes it is promoted to accelerate the calling timing. This alternate calling has a meaning to reduce the possibility of position specification from enemy. As a result of recording and analyzing the calling of Japanese tree frogs which inhabit a paddy field, it is confirmed from the experiment that they make call alternation [17].

Some Japanese tree frogs take a behavior to hide intently near the other calling frog [18]. Insisting the territory and attracting the female frog by calling has strong impact, however, declaring the location with lots of energy makes it easy to be caught by enemy and expose itself to danger. In the environment where there are many other males, in spite of competing of calling becomes intense and the labor to call becomes large, possibility of catching the female falls down. At this time, the male frog stops calling and changes strategy spending all the labors in waiting to catch a female. In other words, this is the strategy that the frog uses near other calling frogs without calling and intercepts a female which is attracted to other frog's calling while other frogs compete with each other [19]. This strategy is called satellite behavior and even other animals such as fish or anurans are known to exhibit same behavior. The calling frog and the satellite frog change strategy alternately in some cases. It is supposed that it is based on body size, volume of calling and number of competing neighboring frogs as a factor of satellite behavior [20]. Frog is said to be able to distinguish the size of other frogs from the frequency of call. We apply the mechanism of frogs' alternate calling behavior to alternate phase synchronization and satellite behavior to sleep control in wireless sensor networks. The necessity of alternate phase synchronization and sleep control will be explained in detail in the next paragraph.

At last of this paragraph, we describe the policy when the biological system is applied to the computer network. Although research on biological system has been done, those targeted at optimizing performance. However, we emphasize on scalability, adaptability, robustness and self-organizing features as important capabilities of biological system. Biological systems have several important factors, especially, self-organization and robustness are crucial factors when applying the biological system to computer network. However, a self-organizing method is not always the best solution and there is a trade-off between self-organizing and centralized methods. In environment where there is no environmental changes such as node failure and excess traffic, the conventional centralized method is better in the point of performance. However, progress of network technology will guarantee such a small difference in near future.

The main purpose of self-organizing method is not to get optimal throughput but to retain adaptability with improvement of robustness against environmental changes. A similar concept, ESS (*Evolutionarily Stable Strategy*) , exists in the field of evolutionary biology [21]. This concept was suggested by Maynard and Price [22] in 1973, the basic idea is following.

> ESS is a strategy which, if adopted by a population of players, cannot be invaded by any alternative strategy that is initially rare.

The biology has changed the strategy according to surrounding environment in the process of evolution. For simplicity, consider about two strategies *fight* and *flight*.

In taking the fight option, there is the possibility of obtaining large profits, such as food and money, from winning and the risk of losing everything in defeat. Also, one can think of the great injuries after the fight. On the other hand, although the danger of losing a life disappears by taking the flight strategy, the possibility of survival decreases since there are little profits obtained. ESS determines a strategy based on the surrounding environment and past experiences. The essence of this concept is that ESS is not a cooperative strategy with a common global view, but the strategy that each individuals pursuing its profit and act selfishly. Furthermore, the strategy which maximizes profits is not necessarily evolutionarily stable. This has been applied to game theory and computer networks [23]. We interpret this concept that robustness leads to an evolutionary stable strategy which is based on self-organizing manner without a global view. We keep in mind such a concept of biology and apply biological system to computer network.

2.2 Alternate Phase Synchronization for Scheduling

Research on time synchronization using pulse-coupled oscillator model has been performed [24]. Those work target at adjusting oscillators' phase in unison, however the research on synchronization that shifts the phase of oscillators with certain intervals has not been previously considered in detail. We call conventional simultaneous synchronization as in-phase synchronization and call alternate synchronization of our target as anti-phase synchronization. For instance, in-phase synchronization is the phenomenon of simultaneous flashing of fireflies and anti-phase synchronization is seen in Christmas illuminations where the colorful bulbs flash alternately or alternate blinking of the crossing lamp.

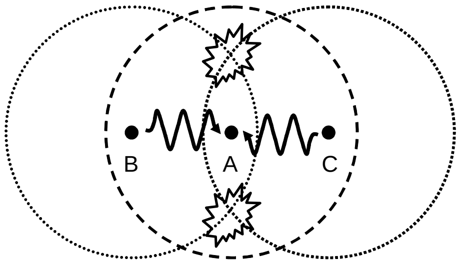


Figure 3: Hidden terminal problem. Terminals B and C may transmit simultaneously due to the lack of connection.

Anti-phase synchronization becomes effective for sharing the resource. Round-robin scheduling is known which assigns the same time slice to the process of a waiting state in order without priority. This method is supposed to be fair scheduling since resource is allocated to all the processes equally. In the field of wireless communication, TDMA (Time Division Multiple Access) is also a kind of anti-phase synchronization which divides the access period into fixed slots and assigns frequency used for communication. In TDMA, since it is not necessary to check a channel, delay is small and stable transmission speed is expectable. Furthermore, if anti-phase synchronization is applied to multi-hop network, a collision in the MAC layer in the wireless sensor network is avoidable. We explain the *hidden terminal problem* as a example of collision in MAC layer using Figure 3. When terminal B communicates to terminal A, collisions do not occur because terminal B checks the channel is free (*carrier sense*) before transmission. However, when terminal C is added here, terminal B and C can not check the channel properly since they are located out of communication range each other. In such case, when two terminals transmit simultaneously, interference takes place at the point of terminal A and the packet does not reach terminal A correctly. This is the hidden terminal problem which can be serious problems in wireless sensor networks. Interference can be reduced if the terminals in the relation of hidden terminal problem adjust transmission schedule by anti-phase synchronization.

There are some studies about anti-phase synchronization. DESYNC [25, 26] is a anti-phase synchronization method in distributed manner proposed by Nagpal *et al.*. Each node adjusts the firing time considering the last and next firing of itself so that the offsets of firings become equal. Even when there are many nodes, iteration of interactions leads whole network to anti-phase synchronized state. But, adjustment of timing in this method relies on information from only two nodes, this structure is not effective to multi-hop network. Stankovic [27] proposed another anti-phase synchronization method. This method adjusts the firing time for rare event detection considering the distribution of sensing region. However, this method needs a lot of calculation resources for building complex polynomial function and location information of the neighboring nodes is necessary for accurate anti-phase synchronization. PDTD (Phase Diffusion Time Division) [28] is a kind of anti-phase synchronization method that performs in a self-organizing manner. This method solves the hidden terminal problem by performing anti-phase synchronization between nodes within interaction range which is twice as large as communication range.

Exchange of information about all 1-hop nodes in communication range helps knowing the information about 2-hop nodes over interaction range, probabilistic control based on past collisions provides stability. Although research on anti-phase synchronization has been performed, it only considers phase control for synchronization. When performing anti-phase synchronization, all nodes cannot be allowed to transmit due to limitation of access period. Additionally, all nodes are not necessarily active for achieving the targeted performance. For these reasons, phase control becomes more adaptive to environment and energy efficient by combining it with sleep control.

2.3 Benefits of Sleep Scheduling

These days, the word ‘Green IT’ is attracting more attention. This is a familiar concept that the resources on the earth is limited, in order to reduce waste of energy, renewable materials are recommended for use and the consideration is paid to the earth. Sleep control lies under the same goal of Green IT. The main purpose of sleep control is to turn off the power of redundant nodes to reduce energy consumption and eventually, nodes can work for long period and network lifetime is extended. Energy efficiency is a more crucial issue in wireless sensor networks. Normally, a sensor node operates with limited battery and it is difficult to charge or exchange a battery due to its deployment. Moreover, the interference will occur if many nodes communicate simultaneously in the dense network, sleep control can solve this problem by limiting the number of active nodes. Sleep control is also effective for minimizing delay by adjusting the transmission schedule when performing data gathering.

Sleep control has been researched for such reasons. SMAC [29] is the most famous sleep control method. Packet collision, the reception of unrelated packet, the overhead of the control packet and redundant idling time are mentioned as reasons that waste energy. a sleep mechanism is proposed to reduce such problems. In this method, the collision of the packet are avoided by synchronizing the active time for reducing the idling time and virtual career sense with using RTS (Request to Send) and CTS (Clear to Send) packet. PEAS [30] is also a sleep method that nodes broadcast the probe packet regularly and transit to sleep state when there are many active nodes in the neighborhood. The delay is reduced by adaptively choosing the sleep time considering the number of active nodes. There is also sleep control method depending on the residual energy [31]. This technique becomes effective when nodes have dispersed residual energy. Changing the communication range adaptively is good for conserving the energy [32] since energy consumption is proportional to communication range. After clustering, the further node from a cluster head raises the probability to sleep due to earlier energy depletion. Greunen [33] proposed the sleep control method for minimizing the queuing delay in data transfer. DMAC [34] first builds a network tree and node transmits data in shifted timing based on the hop account from the sink. It runs down the delay from event detection to sink. There are coverage based sleep controls. CCP [35] guarantees the various degree of coverage depending on the application and reduces the energy consumption with satisfying the coverage and connectivity. Thus, function of sleep control changes according to the purpose. In this thesis, we perform the sleep control based on the satellite behavior of frogs for the purpose of energy conservation of redundant node and collision avoidance with keeping coverage.

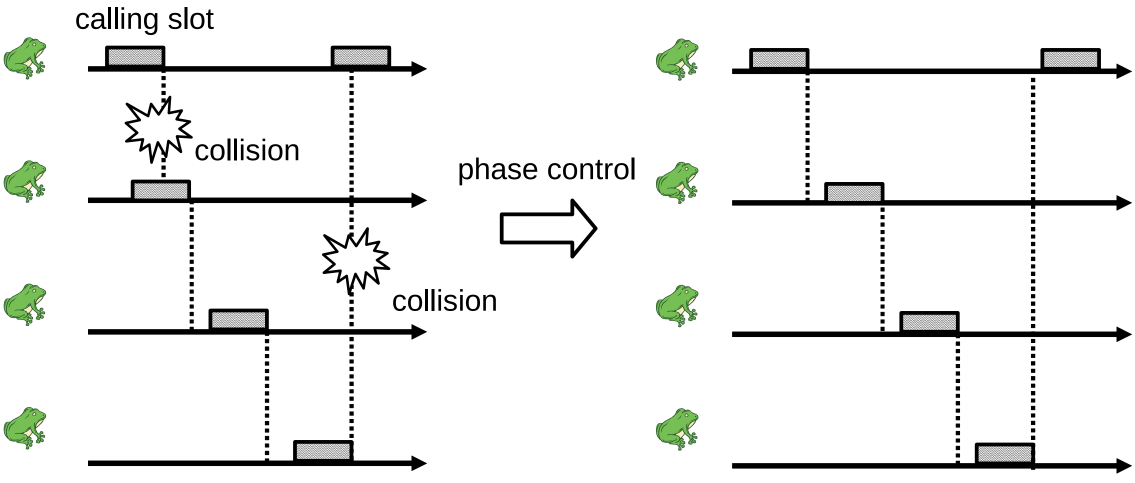


Figure 4: Outline of phase control which reduces the transmission failure by adjusting the transmission timing.

3 Frog Call-Inspired Transmission Scheduling Scheme

In this thesis, we propose a frogs' calling inspired scheduling scheme, in wireless sensor networks which uses self-organized control. In wireless sensor networks, a node has limited energy driven from the battery and it is difficult to change or charge the battery according to the deployment. Energy conservation is a critical issue for sensor networks. Robustness against changes of topology is required since it is considered that a node breaks down suddenly or that a node is added to replace a failed node in the process of operation. In addition, robustness against deterioration of communication environment is necessary since communication is based on wireless technology where the communication range is limited and communication may not be performed properly due to obstacles. Scalability over number of nodes is also important in order to achieve a network function. We show that these demands are satisfied by the self-organizing control. In this work, node is supposed to be able to communicate with all the other nodes in single hop network. A node has a sensing range smaller than communication range and brings coverage of whole network by nodes cooperating with each other. We describe the summary of each functions, phase control method based on call alternation, and sleep control method based on satellite behavior, as follows.

3.1 Proposed Phase Control Mechanism

The outline of phase control is shown in Figure 4. The frog repeats a calling after it keeps making sound for certain period and quiets down. If two or more male frogs call by random timing, a calling period may be overlapped. At this time, the interference of calling happens and the female frog, mating partner, cannot distinguish the caller. Therefore, the male frog shift the time of calling with listening other frogs' calling so that the calling period does not overlap. After all the frogs rotate these interactions, call alternation without interference is completed as whole group. Replacing this mechanism with sensor networks, the frog is the node, calling is packet transmission, interference is collision of packet. Wireless communication requires a certain amount of time for transmitting the packet. For transmitting P[bit] packet with connection of transmission speed K [bps], it takes $\frac{P}{K}$[sec] and transmitting node has sole possession of communication band during the transmission. If other node transmits a packet at same time, the collision of the packet occurs and both of those packets will be discarded. In order to prevent the collision of the packet, generally CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is used as the transmission protocol of MAC layer. In CSMA/CA, a node transmits a packet after carrier sense, confirming that the channel is free. If the channel is not free, after carrying out back-off for a random period carrier sense is performed again. However, if the node fails the carrier sense exceeding the maximum back-off time, transmission is aborted and the packet is discarded. By applying the phase control to the transmission scheduling in wireless sensor networks, the collision of the packet and transmission failure on a MAC layer is reduced.

Pulse-coupled oscillators is know as a model of synchronization mechanism in biology. We formulate the frogs' calling behavior with pulse-coupled oscillators. Each oscillator has a phase $\phi \in [0, 2\pi]$ which changes at firing frequency ω with time. When the phase reaches 2π, the oscillator fires and returns a phase to an initial value ($\phi = 0$). The oscillator j which is coupled with firing oscillator i receives a stimulus and changes firing frequency of next turn according to the phase offset $\Delta_{ji} \in [0, 2\pi]$ between coupled oscillators. The oscillator does not change the firing frequency immediately after receiving the stimulus, but memorizes the amount of stimulus and changes firing frequency after own firing.

$$\omega_j = \frac{d\phi_j}{dt} \tag{1}$$

$$\Delta_{ji} = \phi_j - \phi_i \tag{2}$$

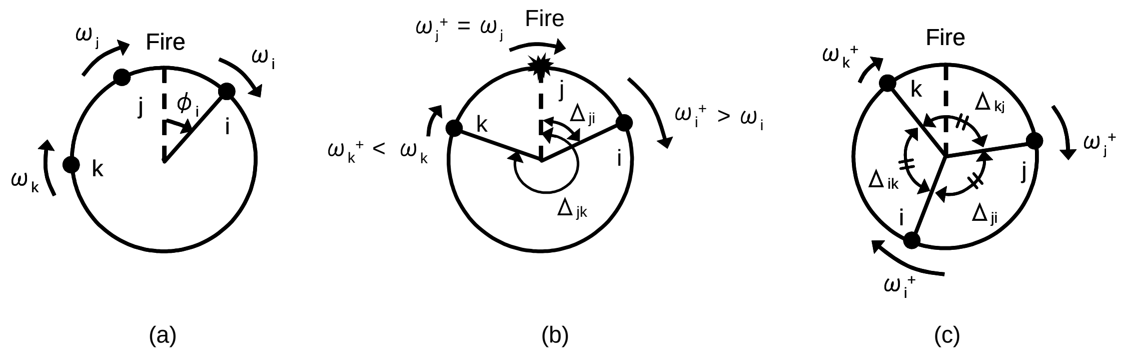


Figure 5: Phase control mechanism. (a) Each oscillator has its own phase and firing frequency. (b) Oscillator i receives positive stimulus and promote firing frequency, oscillator k receives negative stimulus and repress the firing frequency. (c) After iterations, the phase offset between each oscillator becomes equal and anti-phase synchronization is realized.

$$\omega_j^+ = \omega_j + g(\Delta_{ji}) \tag{3}$$

where g is phase shift function to give repulsive force which shifts the phase from other oscillators. Aihara *et al.* [36] suggested the phase shift function as follows:

$$g(\Delta) = \alpha \sin \Delta \tag{4}$$

where $\alpha > 0$ is the coupling coefficient of pulse-coupled oscillator model. When $\Delta_{ji} < \pi$, then $g(\Delta_{ji}) > 0$ and oscillator j advances the firing frequency to extend the phase offset with oscillator i. On the contrary, when $\Delta_{ji} > \pi$ then $g(\Delta_{ji}) < 0$, oscillator j slow down the firing frequency to spread the phase offset with oscillator i. After these interactions among coupled oscillators, oscillators are assumed to be in stable anti-phase synchronization state when the following conditions of (5) and (6) are finally fulfilled (Figure 5).

$$\Delta_{ij} = \Delta_{ji} \tag{5}$$

$$g(\Delta_{ij}) = g(\Delta_{ji}) = 0 \tag{6}$$

Then we think about the group N where n oscillators are coupled each other. When oscillator j fires at time t_j ($t_1 < t_2 < ... < t_n$), it changes the firing frequency ω_j as follows:

$$\Delta_{ji} = \phi_j(t_i) - \phi_j(t_i) \tag{7}$$

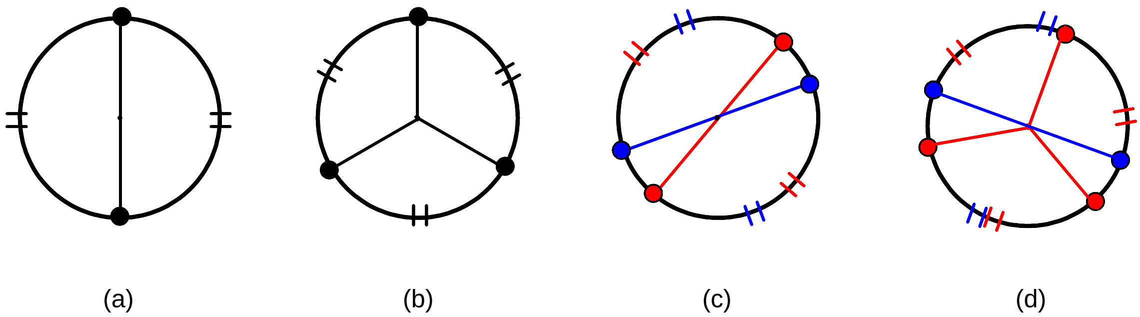


Figure 6: Difficulty on anti-phase synchronization. more than 4 oscillators are divided into the group of 2 oscillators and the group of 3 oscillators, they are anti-phase synchronized in each group.

$$\omega_j^+ = \omega_0 + \sum_{k \in N} g(\Delta_{jk}) \tag{8}$$

when the phase offsets between oscillators which fire consistently are all equal and the repulsive force of all oscillators is negated , this group N is assumed to be in stable anti-phase synchronized state. These conditions are described as well as the case of two oscillators.

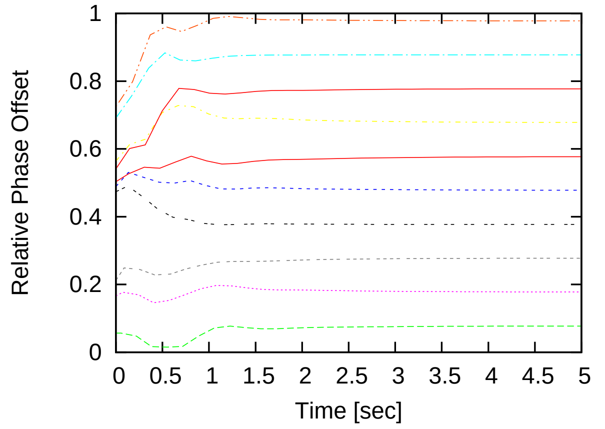
$$\Delta_{12} = \Delta_{23} = ... = \Delta n1 \tag{9}$$

$$\sum_{k \in N} g(\Delta_{1k}) = \sum_{k \in N} g(\Delta_{2k}) = ... = \sum_{k \in N} g(\Delta_{nk}) \tag{10}$$

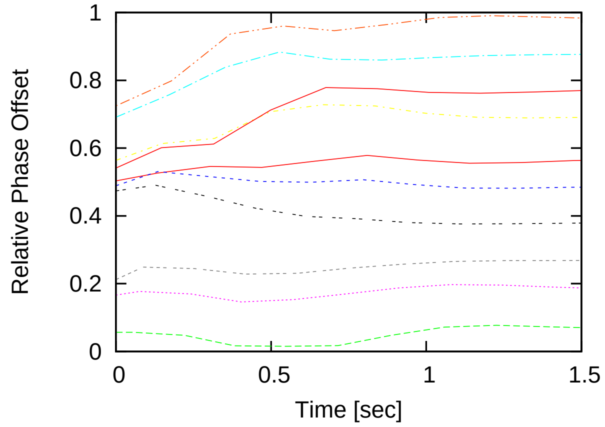
It is confirmed that the 2 or 3 oscillators are anti-phase synchronized with phase shift function 3.1 (Figure 6(a), (b)). However, this function cannot make more than 4 oscillators anti-phase synchronized since they are divided into the group of 2 oscillators and the group of 3 oscillators (Figure 6(c), (d)). This is caused by the phase shift function which is a symmetric function and the repulsive force is negated in the situation which does not satisfy condition (9) despite the condition (10) is satisfied and oscillators converge to a stable state. The stimulus needs to be weighted depending on phase distance δ for this problem. The smaller the phase distance δ with the coupled oscillator, the stronger the oscillator should be in order to receive the stimulus. For this reason, we adopt the following equation.

$$\delta(\Delta) = \min(\Delta, 2\pi - \Delta) \tag{11}$$

$$g(\Delta) = \alpha \sin(\Delta) \exp(-\delta(\Delta)) \tag{12}$$



(a) Convergence to stable state.



(b) Detail of process.

Figure 7: Relative phase offset vs. time.

By this phase shift function 3.1, the conditions, (9) and (10), are always satisfied not depending on the number of oscillators. Figure 7 shows the process of anti-phase synchronization among 10 oscillators. The phase of oscillators which is discrete in initial state, is shifted to anti-phase synchronized state with interactions between coupled oscillators. The phase offset between consecutive oscillators becomes approximately the same at the point of 1.0 second. After this point, although the oscillator receives stimulus, a positive and negative stimulus are negated and the group keeps in stable state.

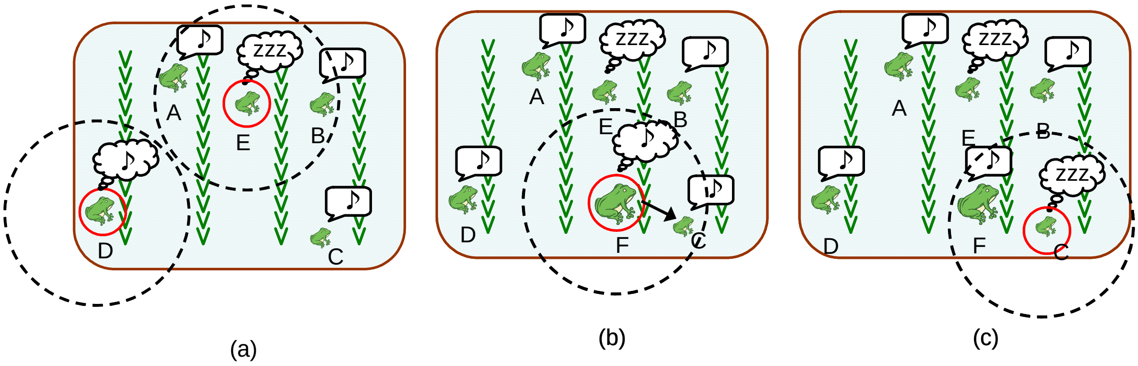


Figure 8: The outline of sleep control. A dotted line indicates the territory and the red circle represents the confirming frog. The size of frog shows the body size.

3.2 Sleep Control Mechanism based on Frogs' Satellite Behavior

The other function of proposal is sleep control inspired by frogs' satellite behavior. As mentioned in Section 2.1, details of satellite behavior was discussed, however the following three elements are taken up in this thesis.

- territory
- the number of competing frogs in neighbor
- body size

Considering these three elements, the frog judges whether to use satellite behavior or not. We explain each condition of judgment using Figure 8. The dotted line indicates the territory and the red circle represents the confirming frog which is thinking of its behavior. The frog is located in one paddy field and is able to hear all other frogs' calling.

(a) Three frogs A, B and C have already been calling and two frogs are confirming the environment. The frog D of left side first confirms that there is no calling frog in its territory, and next checks that there are not many calling frogs in the paddy field, and then begins to call. On the other hand, the frog E of right side takes satellite behavior as it finds other frog A and B calling in its territory.

(b) A new big frog F appears and monitors its surroundings. It finds another frog C calling in its territory but comparing the size of body, it judges that the probability of winning the competition is large and begins to call. We call this behavior as '*intercept*'.

(c) Then, the small frog C realizes the presence of stronger frog in its territory and choose the satellite behavior in order to avoid competing.

Replacing this mechanism with sensor networks, the frog is the sensor node, satellite behavior is sleep, territory is sensing region, the number of surrounding competing frogs is the number of access nodes and body size is residual energy. The following target is achieved with such a sleep control.

- energy conservation of redundant node.
- distribution of coverage.
- assignment of access period for reducing the collisions.

In sensor networks, a large number of nodes are supposed to be deployed and several nodes may be arranged closely and within range of each other. It is not necessary for neighboring nodes to sense the same region and either is enough in this situation. Energy consumption is reduced when the redundant node considers satellite behavior to sleep. Additionally, the proposed method that the node sleeps not randomly but considering the condition of neighboring nodes is energy efficient whilst satisfying the coverage. Although anti-phase synchronization is performed accurately, there is limitation in the number of nodes being able to transmit in turns depending on the frequency of data transmission and data packet size. By performing sleep control and considering these factors, the collisions of the packet caused by over traffic can be prevented.

The sensor node maintains two states of *active* and *satellite*. It confirms the situation of network regularly and changes the state. In active state, the node executes the confirming process periodically just before the data transmission ($\phi = 2\pi$), in satellite state, it confirms after sleep period T_s. We call the node which performs the confirming process as a *confirming node* (CN) and sensing region as a *territory* and a node in territory as a *territory competing node* (TCN). It is possible to take the place of a node which has small residual energy even if many nodes have already been in active state. We call a node with the smallest residual energy in the active state as a *phase competing node* (PCN). The flow of confirming process is shown in Figure 9. (1) At first, CN checks whether there is a territory competing node. (2) When CN finds a TCN, it compares the residual energy with TCN for considering the probability of intercept. If the residual

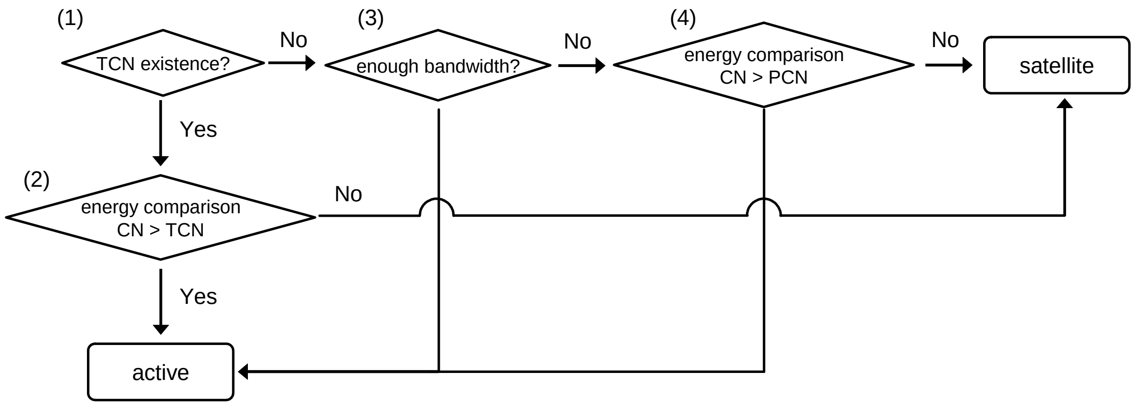


Figure 9: Flow chart of confirming process.

energy of CN is larger, CN judges that it will not lose the competition and turns to active state for transmission, otherwise it turns to satellite state for saving energy. (3) When there is no TCN, CN investigates the margin of access period. If there is enough access period, CN consider that it is possible for transmission and shifts to active state. (4) When the access period is full with active nodes, the confirming node compares the residual energy with PCN for the intercept. If CN has larger residual energy, it changes to active state and otherwise changes to satellite state. The active node performs periodical data transmission and the satellite node sleeps to conserve energy. In order for satellite node to be in active state, the residual energy must be larger than PCN at least. In addition, the higher the node's residual energy, the more often it performs the confirming process to raise the probability of being in active state. For these reasons, the satellite node decides the sleep period T_s based on standard sleep time T_{std} considering the residual energy of own E_{CN} and the residual energy of PCN E_{PCN}.

$$T_s = T_{std} \cdot \exp(1 - \frac{E_{CN}}{E_{PCN}}) \tag{13}$$

The proposal performs such sleep control on the concept of conserving the energy consumption by sleep execution of redundant nodes, reducing the collisions by adaptive assignment of access period, prolonging the network life-time by performing the sleep control considering the residual energy of nodes.

4 Evaluation

In this section, we present the discussion obtained from computer simulations.

4.1 Simulation Setup

Through the simulations, sensor nodes are deployed randomly in the monitoring region of 10 m radius and decide the data transmission timing based on the phase assigned randomly in the initial state. The communication range of node is assumed to be 20 m and the nodes can communicate with all other nodes in the network. The node carries out sensing of monitoring region of 5 m radius every 0.16 seconds, and transmits the sensed data to the base station, called a sink, at 50 kbps transmission speed. CSMA/CA is used for transmission protocol of MAC layer. A data packet includes the sensing information and the time-stamp which represents the delay caused by the back-off of CSMA/CA and size of packet is set to 400 bits. Therefore, it takes 8 ms for transmitting one data packet, and the transmission node takes sole possession of communication band during that period. The standard sleep time T_{std} in sleep control is set to 3.2 seconds. We use the following evaluation metrics.

- Average Error

  This value shows the average value of phase offset between nodes. The smaller average error is, the higher the accuracy of synchronization becomes.

- Transmission Failure Probability

  Probability of transmission failure by over-failure of back-off in CSMA/CA over communication trial of node.

- Data Collection Ratio

  Ratio of the data reached to the sink to all the data sent to the sink from the node.

- Coverage Ratio

  Ratio of the region with 1-coverage to the monitoring region.

- Energy Utilization Ratio

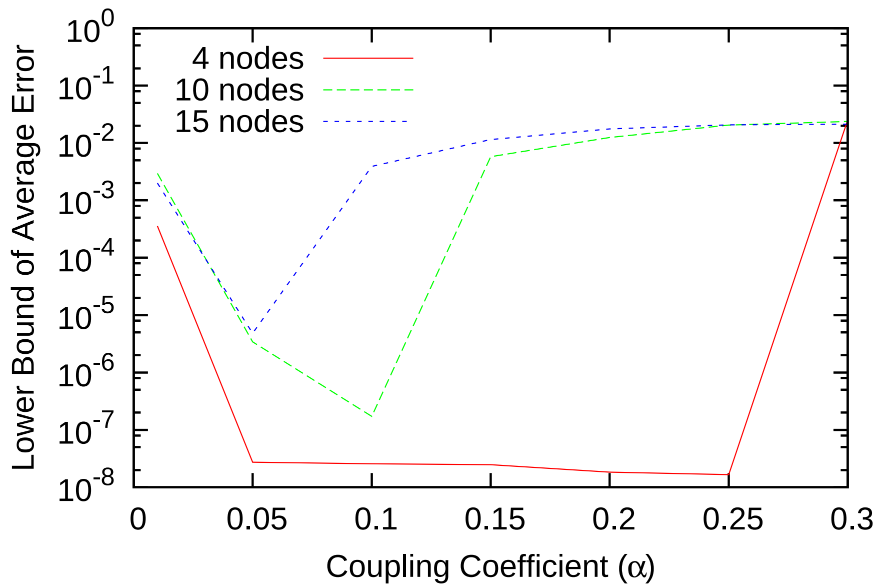
Ratio of the mean residual energy of all nodes to the mean residual energy of all active nodes. When this value is close to 1, we regard that the task is divided fairly and the energy is consumed evenly among nodes.

4.2 Performance of the Phase Control Mechanism

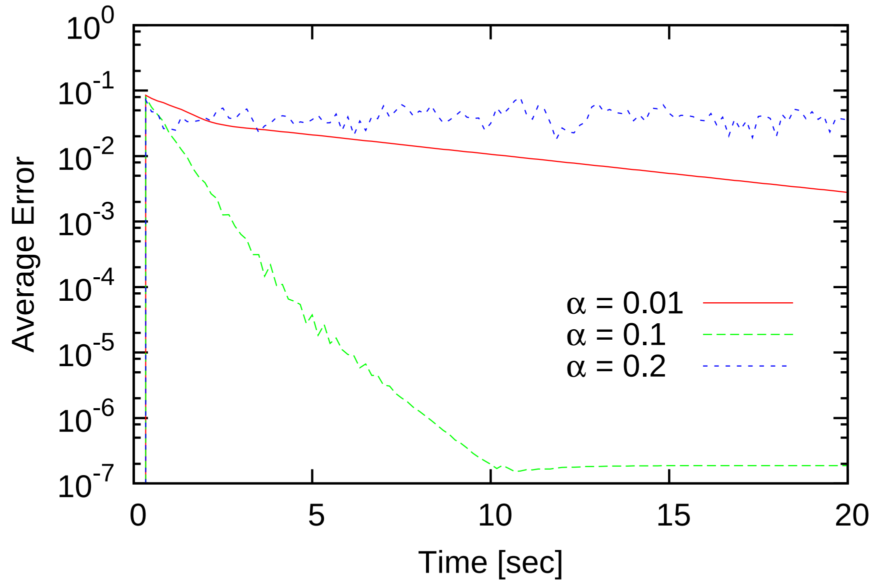
4.2.1 Dynamics of Synchronization

We evaluate the coupling coefficient α which is an important parameter of pulse-coupled oscillator model. In order to learn the suitable parameter setting according to the number of node, we estimate the average error after certain period (20 seconds). Figure 10(a) shows that the average error of 10^{-2} becomes the boundary value of synchronization, if better than the boundary value, accuracy of synchronization gets higher as time goes by, otherwise the phase keeps fluctuation and not converge to stable state. Additionally, the large width of setting enables the network to meet the stable state in the environment of small number of nodes and it becomes difficult to converge stable state with too large value of coupling coefficient. This is caused by the number of coupled nodes, in other words, the more the node is coupled with other node and the larger coupling coefficient is, the stronger the stimulus becomes. Hence, it is drawn from simulation that over stimulation disturbs the convergence to stable state. On the contrary, although the small value of coupling coefficient requires long duration to be synchronized, the condition approaches a stable state steadily (Figure 10(b)). These result tells us that adaptive setting of coupling coefficient is necessary for anti-phase synchronization. The setting also depends on the requirement of application such as small coupling coefficient for delay tolerant application and large coupling coefficient for accuracy tolerant application. The number of nodes and data transmission interval also affect the setting. Various factors should be considered for the setting of coupling coefficient and it is supposed that those factors changes every moment. Therefore, static setting is not sufficient and it is required for each node to set the parameter dynamically according to the number of nodes and the amount of traffic in self-organizing manner. But, this is beyond the scope of this work and we leave it to future work.

The phase control method requires the scalability over the number of nodes. We perform the evaluation in the network where 4, 10, 20 nodes are deployed and use the coupling coefficient as 0.06 in any case. The result of average error with the progress of time is shown in Figure 11(a).

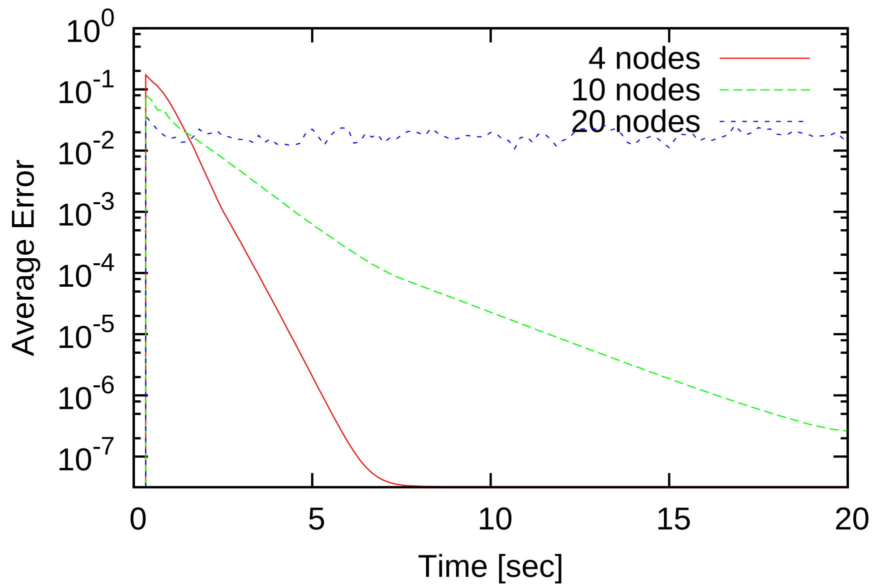


(a) Average error.

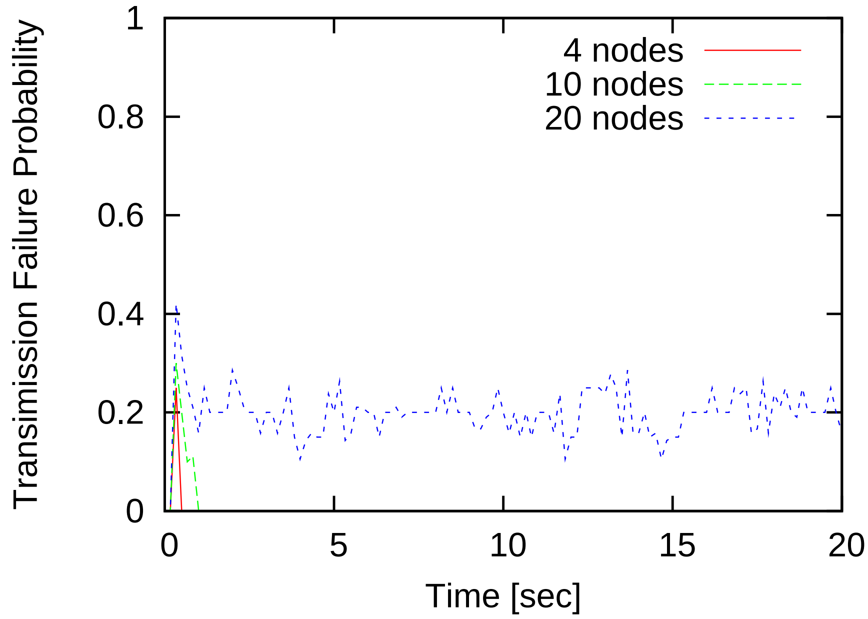


(b) Average error with 10 nodes vs. time.

Figure 10: Setting of coupling coefficient α.



(a) Average error vs. time.



(b) Transmission failure probability vs. time.

Figure 11: Influence of number of nodes on anti-phase synchronization.

It is easier for small number of nodes to be synchronized within short period. When the number of nodes increases to 10, the equal phase offset is formed and nodes are synchronized by the interaction among nodes although it takes longer time compared to 4 nodes. The process of phase shift are already shown in Section3.1. However, 20 nodes cannot be synchronized with insufficient average error and the average error keeps fluctuation and they cannot converge to stable state. The reason of this failure is described as follows. In this simulation, the node transmits the 400 bits data to the sink by 50 kbps transmission speed every 160 ms. One data transmission needs 400 [bits] / 50 [kbps] = 8 [ms]. Since the transmission width is 160 ms and time slot is 8 ms, the perfect anti-phase synchronization provides alternate transmission of 20 nodes. However, such a situation is difficult to realize and the transmission failure is certainly generated in the process of the synchronization (Figure 11(b)). The transmission failure interrupts the node from broadcasting the firing information, the phase control is not performed properly and the average error falls. The iteration of this operation leads the failure of anti-phase synchronization of 20 nodes. Thus, the number of transmission node by anti-phase synchronization is constrained due to the limitation of access period. We fix the number of nodes to 20 and coupling coefficient to 0.1 after this section. The control of number of nodes for collision avoidance will be presented in Section 4.3.

4.2.2 Robustness against Perturbations

The target of adopting biological system is robustness against the perturbation. Wireless communication in sensor networks brings the shadowing where a radio wave is shadowed by an obstacle and fading which is caused by the interference of a radio wave. The energy of node may be depleted and the function of node stops due to the unexpected failure. Furthermore, a node may be added to the network in order to take place a failure node. In this section, we regard the packet loss and the change of topology by an addition and failure of node as perturbations, and show that self-organized anti-phase synchronization method is robust to these perturbations. The influence that the packet loss brings to average error and transmission failure is shown in Figure 12. A packet is dropped randomly based on packet loss rate and a packet does not reach to the destination. In the environment where packet loss hardly happens, node adjusts the phase with suitable interval to other nodes and a precise anti-phase synchronization is performed. Although several times of transmission failure appear, it shall be allowed since the node has random phase in the initial condition. Even the synchronous accuracy falls as the packet loss rate increases, the phase offset among

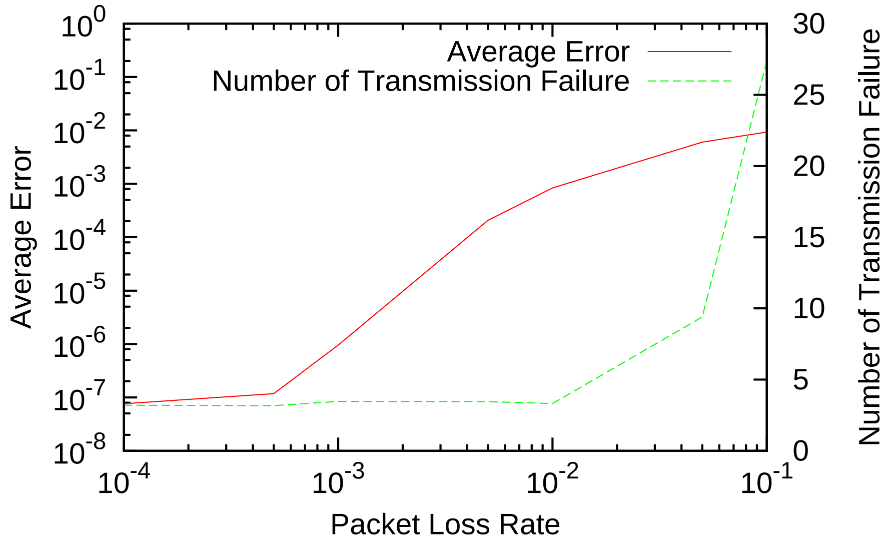
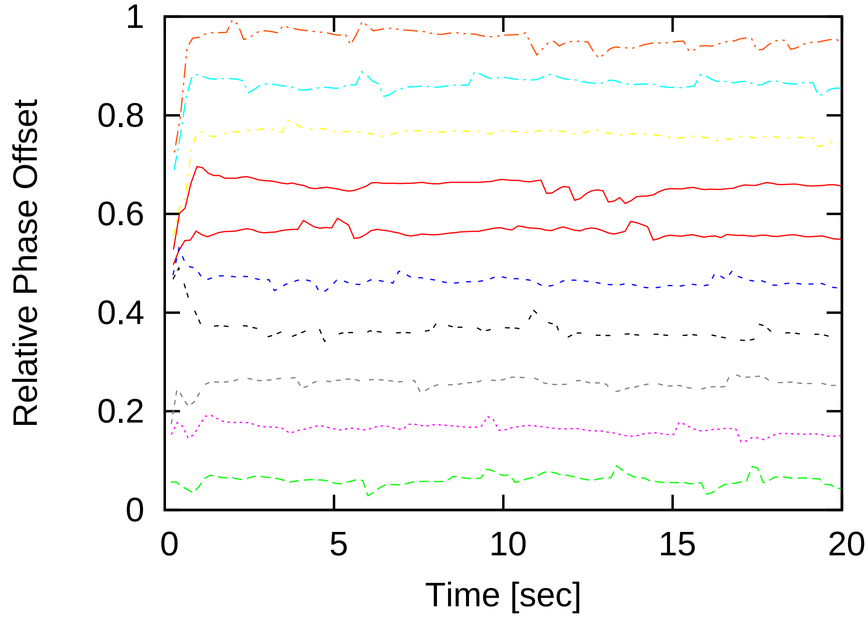
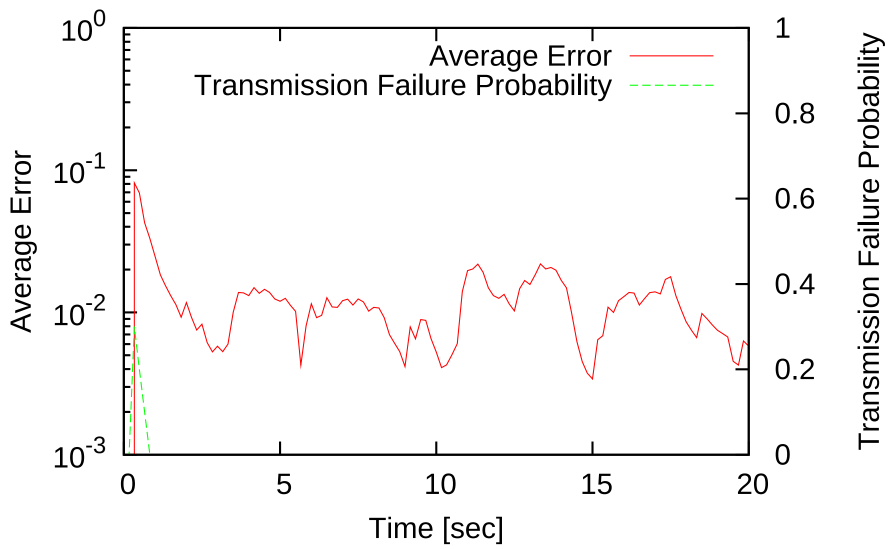


Figure 12: Influence of a packet loss.

nodes in the environment of packet loss rate 10^{-2} is maintained at an acceptable level and data transmission is carried out without failure. Figure 13 shows the result in this condition. The phase moves with fluctuation due to the failure of phase control caused by the packet loss (Figure 13(a)). Eventually, node shifts the phase and keeps the synchronized state with receiving the influence of packet loss. In the environment where the packet loss happens frequently (packet loss rate = 10^{-1}), as the node cannot achieve enough interactions between neighboring nodes for stable anti-phase synchronization, the overlap of phase leads the transmission failure. Yet it is not perfect in the environment where the packet loss occurs very often, the proposal shows robustness against packet loss. The uniform dependence on the information brings robustness of self-organizing method against a packet loss. For instance, the influence of packet loss becomes large in centralized control since the node located on the lower layer of hierarchy decides its operation depending on the information from the node of the higher layer. Several methods are known as a solution of packet loss such as ACK (ACKnowledgement) where a receiving node replies a reception confirmation to a transmitting node, and FEC (Forward Error Collection) which carries out an error collection, there are also demerits on those methods such as an increase of control packet and an extension of delay. Not hierarchical but the local exchange of information on self-organizing control yields robustness against packet loss without executing those measures.

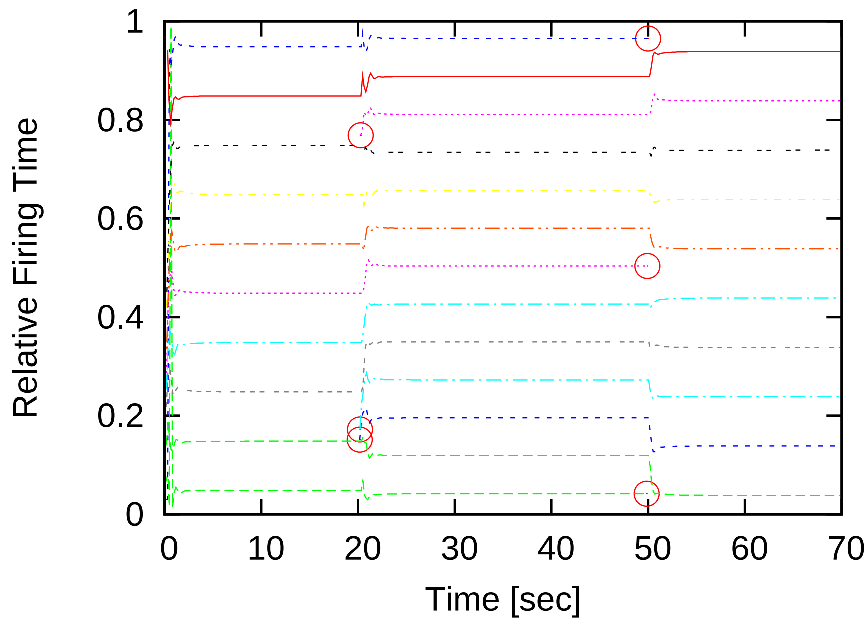


(a) Relative phase offset vs. time.

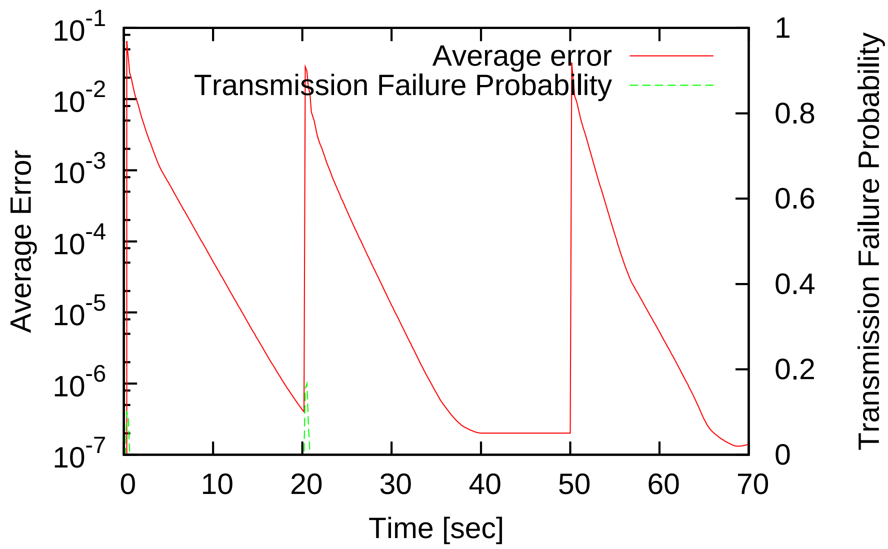


(b) Average error and transmission failure vs. time.

Figure 13: Performance in the network with packet loss rate 10^{-2}.



(a) Relative phase offset vs. time.



(b) Average error vs. time.

Figure 14: Influence caused by the change of topology: Addition and failure of the node.

As a addition and failure of node are expected in sensor networks, robustness against changes of topology is necessary. Therefore, we confirm that the proposal recovers anti-phase synchronized state by performing the phase control after a addition and failure of node. Three nodes with random phase are added to the network at the time of 20 seconds, and three nodes break down at the time of 50 seconds. Figure 14 shows that 10 nodes with random phase in the initial state converge to stable anti-phase synchronization immediately. At the time of 20 seconds, the average error decreases and a synchronized state is impaired due to the node addition. As a result of transmission almost simultaneous at this time, the transmission failure arises because the carrier sense is performed over maximum back-off time on CSMA/CA (Figure 14(b)). However, the node adjusts the phase in self-organizing manner against the addition of node, and anti-phase synchronization state is recovered in a short period. The same performance can be confirmed to the failure of nodes. Self-organized control is able to hold such robustness against a change of topology due to its function of local interactions. In centralized control, if the node which plays an important role like a cluster head crashes, a normal node miss a direction without receiving the order from that crucial node. On the other hand, a task is equally assigned to nodes in self-organizing control and the system does not contain the risk as centralized control.

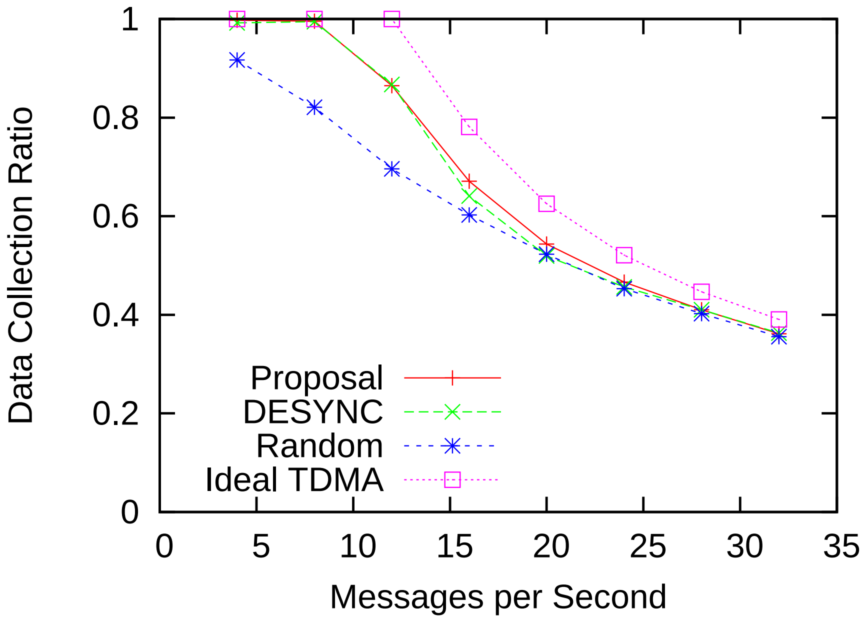
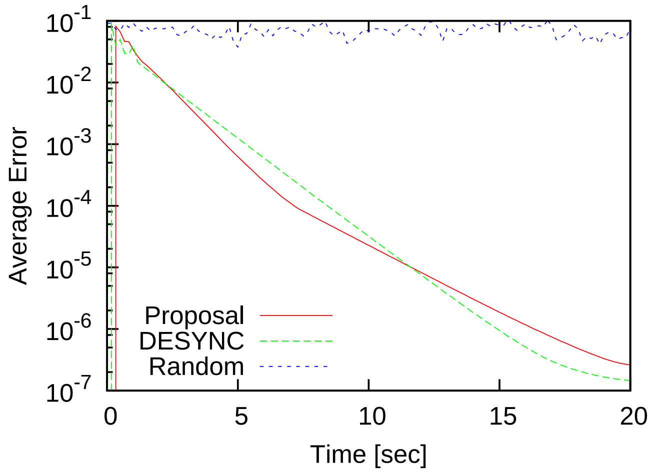


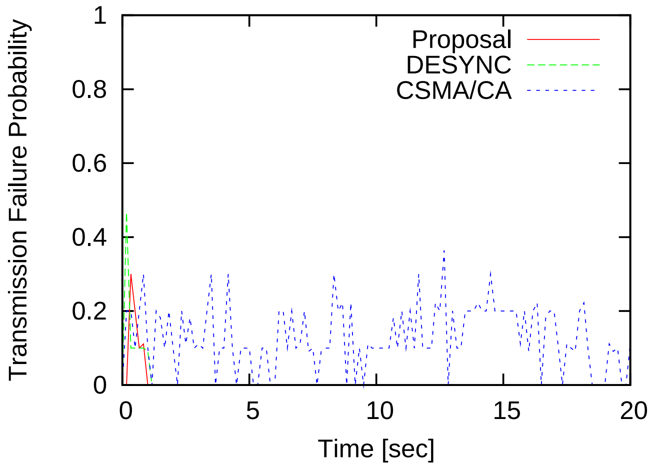
Figure 15: Comparison of data collection ratio.

4.2.3 Comparison to Other Schemes

In order to know the features of proposal we perform the comparative evaluation with three other schemes. *DESYNC* [25] is a distributed anti-phase synchronization scheme which achieves a synchronized state by adjusting the phase based on the information from two coupled nodes. *Random* gives the random transmission timing to the nodes. *Ideal TDMA* uses a ideal value which provides optimal scheduling. MAC layer of both methods, DESYNC and Random, is based on CSMA/CA and same topology is given through the simulation. Figure 15 shows the influence of the traffic, the number of data generated by a node, on each schemes. The proposal realizes the high data collection ratio over small traffic by reducing the data transmission failure. As the traffic increases, the data collection ratio goes down due to failure of data transmission caused by too much traffic over the width of access period. Although the proposal does not reach an ideal value to such excessive load traffic, it keeps a higher data collection ratio than the random control. A transmission failure occurs in random control when several nodes try the transmission at same time (Figure 16(b)). On the comparison to distributed control, the obvious difference is not found in the point of data collection ratio and average error, shown in Figure 16(a), over 6 messages per second. The difference



(a) Average error vs. time.



(b) Transmission failure vs. time.

Figure 16: Comparison in the case of 6 messages per second.

is mainly caused by the setting of coupling coefficient. The advantage of proposal is the feasibility of extension to multi-hop network since the stimulus is brought from all nodes in proposal, while only from two in DESYNC. The comparison between self-organizing and distributed control is a crucial issue in the point of synchronous stability, extendibility, robustness, *etc.* and these are left for future work.

4.3 Performance of the Sleep Control Mechanism

The objectives of the proposed sleep control are 1) energy conservation of redundant nodes, 2) a distribution of coverage, 3) an assignment of access period which reduces packet collisions. As mentioned in Section 4.2.3, the perfect anti-phase synchronization cannot carry out the alternate data transmission of all the nodes for large number of nodes and small width of access period. So, if there are many active nodes, the congestion of access period is prevented by making a redundant node sleep, and a data transmission becomes free from failure. In other words, the sleep control brings adaptability for reliable transmission to phase control. After this section, we deployed 20 nodes in the monitoring region in order to perceive the efficiency of sleep control.

As a principle of sleep control, a node with large residual energy tries to replace a node with small residual energy and performs sensing. This principle brings the fair energy consumption among nodes. Figure 17 shows the number of active nodes and energy utilization ratio. At the beginning, seven nodes become active for sensing and other nodes go to sleep mode since it is impossible for all 20 nodes to transmit during the same transmission period. The value of energy utilization ratio decreases as the seven active nodes consume energy. Then at the time of 50 seconds, the intercept is performed by the satellite node, the nodes change state, the energy utilization ratio rises because of participation of fresh node. After 50 seconds, nodes keep changing the state depending on the residual energy so that the value of energy utilization ratio is maintained at 1.0.

We observe the kind of change sleep control causes by comparing the phase control method with sleep control and the phase control method without sleep control. Figure 18 shows the result of the number of nodes and coverage ratio through the progress of time. The method with sleep control provides large sensing region over long period with small number of active nodes. On the contrary, the method without sleep control can achieve a quite high coverage ratio by the sensing of all nodes, however, the energy of the node is depleted in short term. The sleep control maintains the network life-time about 6.7 times longer in the point of 80 % of coverage ratio.

We evaluate the data collection ratio between two methods. In the method without sleep control, a data transmission is failed without assignment of access period to all nodes. Eventually, the sink cannot collect all data. On the other hand, the method with sleep control assigns access period only to the active nodes, and realizes the reliable data transmission. Although the transmission failure occurs after the rotation of node, the amount of failure is small enough not to affect the

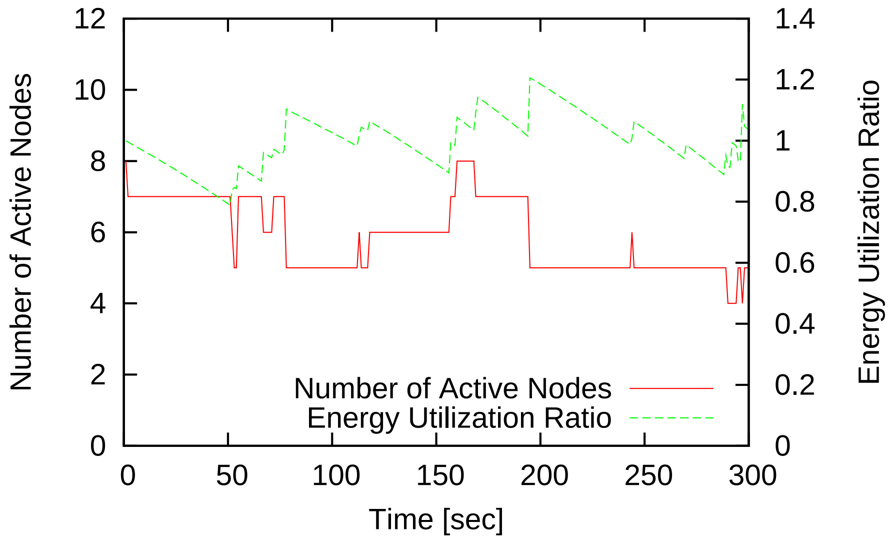
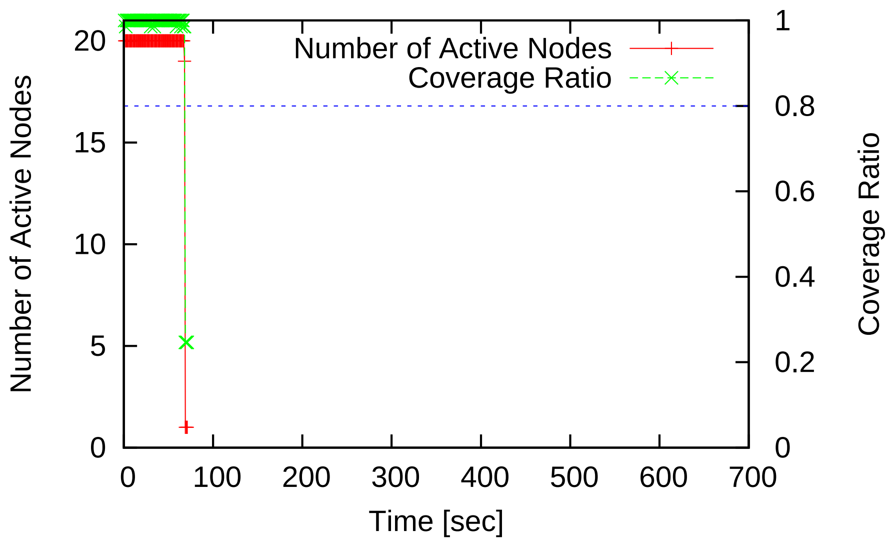
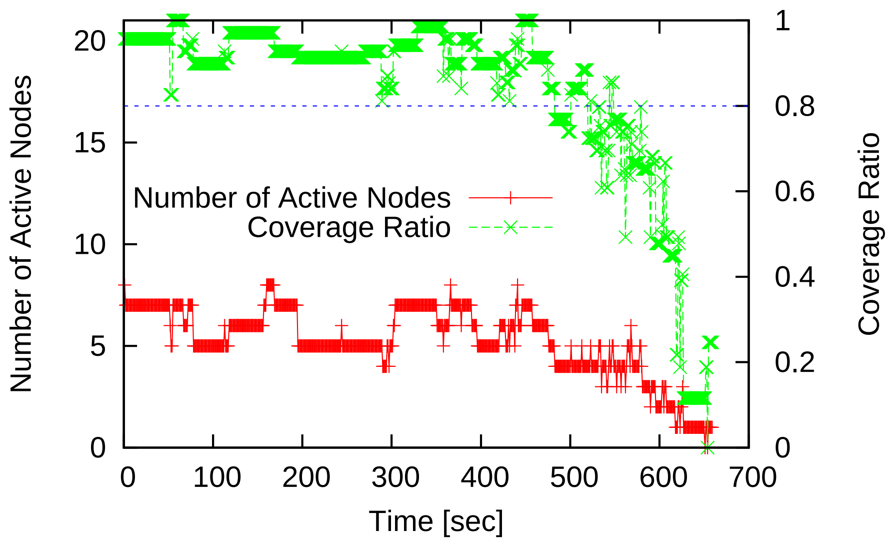


Figure 17: Transition of the number of nodes depending on the energy utilization ratio.

data collection ratio. The combination of phase control and sleep control enables the reduction of transmission failure by adaptive assignment of access period and prolonging the network life-time and satisfying the high coverage.

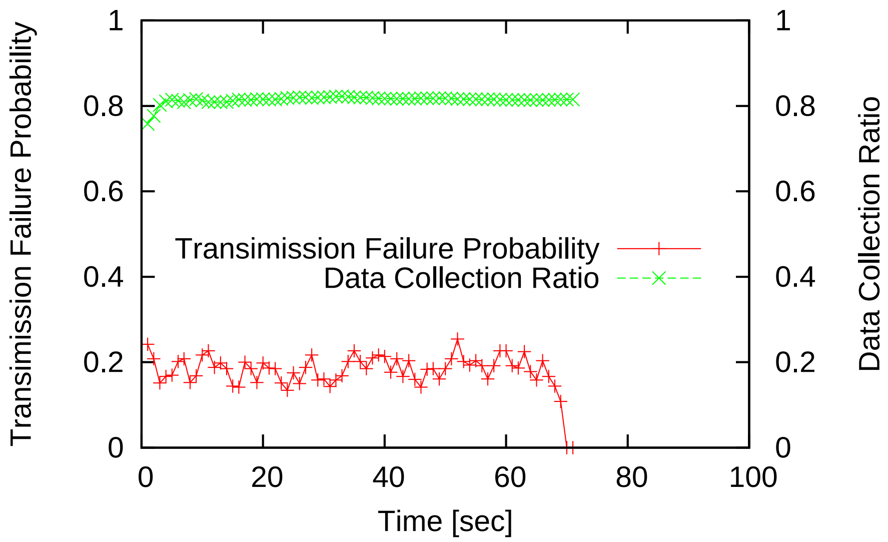


(a) Phase control method without sleep control.

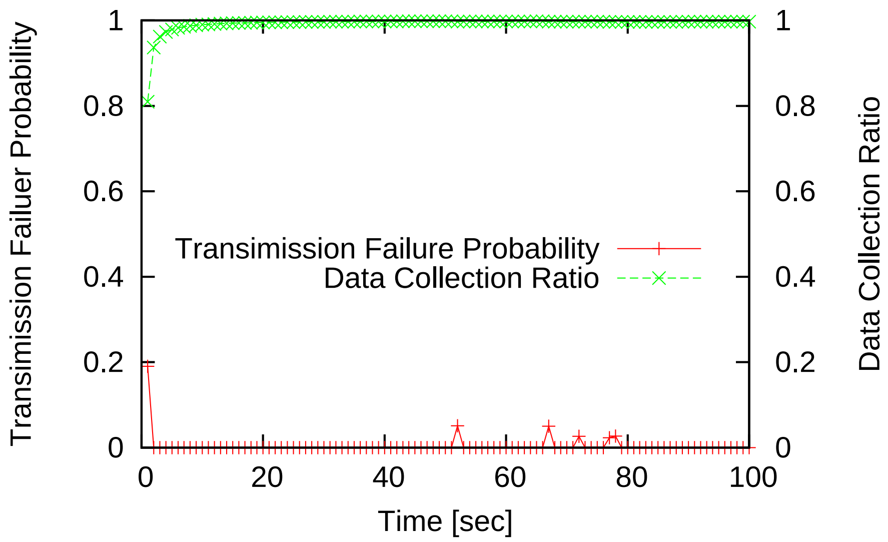


(b) Phase control method with sleep control.

Figure 18: Comparison on a coverage ratio.



(a) Phase control method without sleep control.



(b) Phase control method with sleep control.

Figure 19: Comparison on a data collection ratio.

5 Conclusion and Possible Extensions

Robustness, adaptability and scalability are essential features for managing complex and diverse networks. In this thesis, we introduced a self-organizing scheduling scheme inspired by the frogs' calling behavior as a method in order to provide such requirements. We performed the evaluations through computer simulations in a single-hop network for two proposed functions, namely a phase control method inspired by frogs' alternate calling behavior, and a sleep control method inspired by frogs' satellite behavior. Simulation results explored that a phase control reduces the transmission failures by anti-phase synchronization independent of the number of nodes. In addition, robustness against packet loss and changes of topology was confirmed, and a stable anti-phase synchronization was maintained by an adaptive response to the perturbations. Furthermore, it was confirmed that sleep control provides the adaptive assignment of access periods, the distribution of coverage, and the extension of network life-time.

Research on anti-phase synchronization is a relatively new field and several factors are yet to be explored. In order to prove the feasibility of convergence to a stable anti-phase synchronized state, the mathematical analysis of synchronous stability of phase shift function is still required. The phase control mechanism should be improved for the extension to multi-hop networks that also considers the hidden terminal problem. The comparative evaluation of a distributed method and the proposed method from the viewpoint of information would reflect the benefits of both methods.

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