Frog Call-Inspired Self-Organizing Anti-Phase Synchronization for Wireless Sensor Networks

Akira Mutazono
Graduate School of Information
Science and Technology
Osaka University
1-5, Yamadaoka, Suita-shi,
Osaka 565-0871, Japan
Email: a-mutazono@ist.osaka-u.ac.jp

Masashi Sugano
School of Comprehensive Rehabilitation
Osaka Prefecture University
3-7-30, Habikino, Habikino-shi,
Osaka, 583-8555, Japan
Email: sugano@rehab.osakafu-u.ac.jp

Masayuki Murata
Graduate School of Information
Science and Technology
Osaka University
1-5, Yamadaoka, Suita-shi,
Osaka 565-0871, Japan
Email: murata@ist.osaka-u.ac.jp

***Abstract*—In this paper, we focus on the calling behavior of Japanese tree frogs, which make calls alternately with their neighbors in order to increase the probability of mating. This behavior can be applied in phase control which realizes collision-free transmission scheduling in wireless communication. We propose a self-organizing scheduling scheme inspired by this frog calling behavior for reliable data transmission in wireless sensor networks. Simulation results show that our proposed method for phase control is capable of reducing data transmission failures and improves the data collection ratio up to 24 % compared to a random transmission method.**

I. Introduction

Self-organized control inspired by biological systems has been receiving more attention as a concept for the realization of high robustness, scalability, and adaptability [1]. Each component of a biological system makes decisions based on local interactions with its neighbors, without receiving directions from a specific leader. Thus, the entire system can respond to changes in a coordinated manner in spite of the self-oriented behavior of the individual components. Such simple mechanisms bring cognitive functionality to the whole system, and self-organized control provides adaptability and robustness [2].

There has been methods 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 with their neighbors. However, most research on the pulse-coupled oscillator model has focused on simultaneous synchronization [6]. Anti-phase synchronization [7] (alternate phase synchronization) is necessary in the case where several terminals need to share common resources. When several terminals process a task by sharing common resources, the load can be balanced by applying round-robin scheduling, where each terminal is processed in turns. Similarly, in wireless communication, anti-phase synchronization of transmission scheduling reduces packet loss caused by collisions.

As a possible mechanism for realizing anti-phase synchronization, we consider the calling behavior of Japanese tree frogs [8], especially *advertisement calling*. It is considered that one of the main reasons for the calling behavior of this type of frog is to attract females. If a male calls simultaneously with other frogs, it becomes difficult for the female to distinguish the caller, and therefore they shift the timing of their calls [9, 10]. We formulate this behavior of advertisement calling by using the pulse-coupled oscillator model, and it is applied in phase control for anti-phase synchronization as well as in transmission scheduling in wireless communication with the aim of avoiding 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 in accordance with environmental changes. However, self-organizing scheduling based on frog calling is expected to solve these problems.

Fig. 1. Japanese tree frog (*Hyla japonica*).

In this paper, we propose a self-organizing transmission scheduling scheme inspired by frog calling behavior. We demonstrate that phase control can result in anti-phase synchronization in various environments, and we perform a comparative evaluation with DESYNC [11, 12], which is another distributed anti-phase synchronization technique.

The outline of this paper is as follows: Section II provides the motivation and some related work about anti-phase synchronization. Section III introduces details of the mechanisms of the phase control method based on frogs' alternate calling behavior. Section IV shows the result from numerical simu-

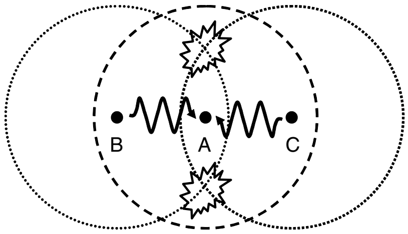


Fig. 2. Hidden terminal problem. Terminal B and C may transmit simultaneously in order not to know a mutual existence.

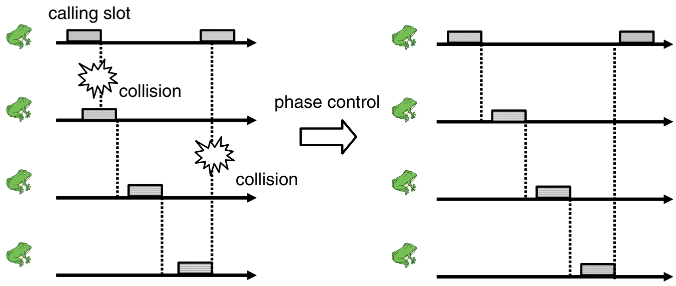


Fig. 3. Outline of phase control which reduces the transmission failure by adjusting the transmission timing.

lations in single-hop networks. We provide a conclusion and present possible extensions in Section V.

II. Alternate Phase Synchronization for Scheduling

Research on time synchronization using pulse-coupled oscillator model has been performed [13]. 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.

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 2. 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 [11, 12] 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 [14] 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) [15] 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.

III. Transmission Scheduling Inspired by Frog Calling

The outline of phase control is shown in Figure 3. The frog calls by making a sound for a certain period of time and then quiets down before repeating the call. If two or more male frogs call at random, the timing of their calls might overlap. In such a case, the calls interfere with each other and the female frog (the mating partner) cannot distinguish between the callers. Therefore, each male frog shifts the timing of its calls by listening to the calls of other frogs so as to avoid such overlap. After all frogs establish this interaction pattern, call alternation without interference is achieved within the group.

Pulse-coupled oscillators are used as models of various synchronization mechanisms in biology. Here, we formulate frog calling behavior with pulse-coupled oscillators. Each oscillator has a phase $\phi \in [0, 2\pi]$ which changes with time with a firing frequency ω. When the phase reaches 2π, the oscillator fires and returns the phase to the initial value ($\phi = 0$). Oscillator j which is coupled with firing oscillator i receives a stimulus and changes the firing frequency of the next turn in accordance

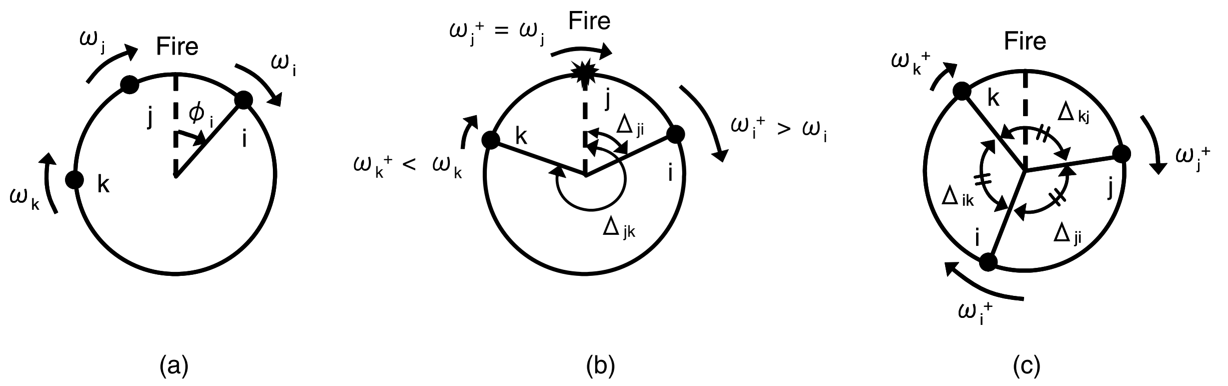


Fig. 4. Phase control mechanism. (a) Each oscillator has its own phase and firing frequency. (b) Oscillator i receives positive stimulus and promote firing frequency, oscillator k receives negative stimulus and repress the firing frequency. (c) After iterations, the phase offset between each oscillator becomes equal and anti-phase synchronization is realized.

with the phase offset $\Delta_{ji} \in [0, 2\pi]$ between the coupled oscillators. The oscillator does not change the firing frequency immediately after receiving the stimulus; instead, it memorizes the size of the stimulus and changes the firing frequency after firing its own stimulus.

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

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

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

where $g()$ is the phase shift function which generates repulsive force which shifts the phase away from that of other oscillators. Aihara *et al.* [16] suggested the following phase shift function:

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

where $\alpha > 0$ is the coupling coefficient of a 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 respect to oscillator i. On the contrary, when $\Delta_{ji} > \pi$, then $g(\Delta_{ji}) < 0$ and oscillator j slows down the firing frequency in order to spread the phase offset with respect to oscillator i. After these interactions, the oscillators are assumed to be in a stable anti-phase synchronized state when the following conditions of Eqs. (5) and (6) are fulfilled (Figure 4).

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

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

We then consider the group N, in which n oscillators are coupled with each other. When oscillator j fires at time t_j ($t_1 < t_2 < \cdots < t_n$), it changes the firing frequency ω_j as follows:

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

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

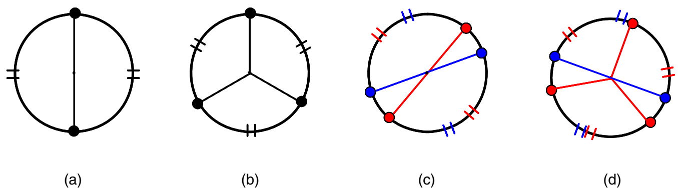


Fig. 5. Difficulty on anti-phase synchronization. More than four oscillators are divided into the group of two oscillators and the group of three oscillators, they are anti-phase synchronized in each group.

When the phase offsets between oscillators which fire consistently are all equal and the repulsive force of all oscillators is negated, the group is assumed to be in a stable anti-phase synchronized state. These conditions are described below together with 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 two or three oscillators can be anti-phase synchronized with phase shift function Eq. (4) (Figure 5(a), (b)). However, this function cannot anti-phase synchronize more than four oscillators since they are divided into groups of two and three oscillators (Figure 5(c), (d)). This is caused by the phase shift function, which is a symmetric function, and the repulsive force is negated in situations in which condition Eq. (9) is not satisfied, despite the fact that condition Eq. (10) is satisfied and the oscillators converge to a stable state. The stimulus needs to be weighted depending on the phase distance δ in order to resolve this problem. The smaller the phase distance δ between the coupled oscillators, the stronger the oscillators should be in order to receive the stimulus. For this reason, we adopt the following equation.

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

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

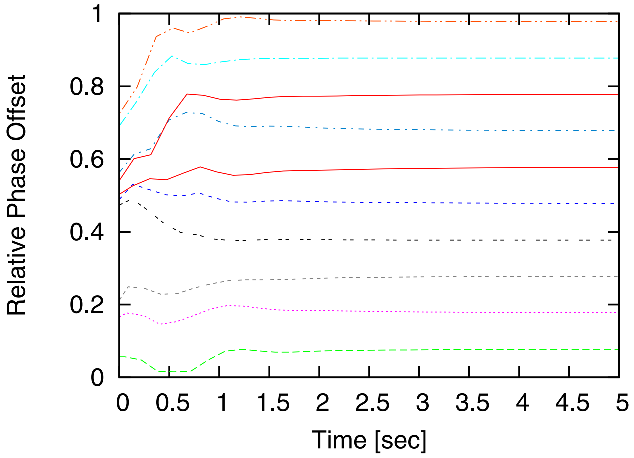
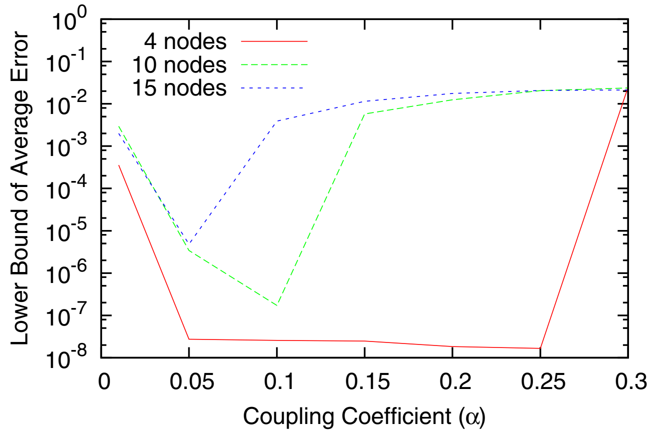
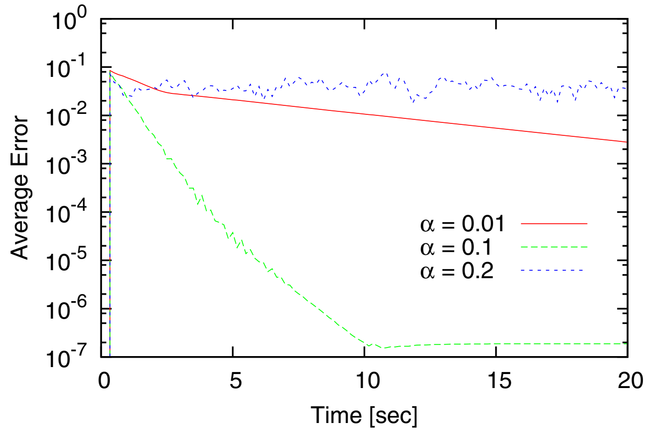


Fig. 6. Transision of relative phase offset.



(a) Relation between coupling coefficient α and lower bound of average error.



(b) Transition of average error with 10 nodes.

Fig. 7. Setting of coupling coefficient α.

By using this phase shift function Eq. (12), conditions (9) and (10) are always satisfied, regardless of the number of oscillators. Figure 6 shows the process of anti-phase synchronization between 10 oscillators. The phase of the oscillators, which is discrete in the initial state, is shifted to an anti-phase synchronized state with interactions between coupled oscillators. The phase offset between consecutive oscillators becomes approximately the same at time = 1.0 second. After this point, although the oscillator receives stimuli, positive and negative stimuli cancel each other out, and the group maintains a stable state.

IV. Evaluation

A. Simulation setup

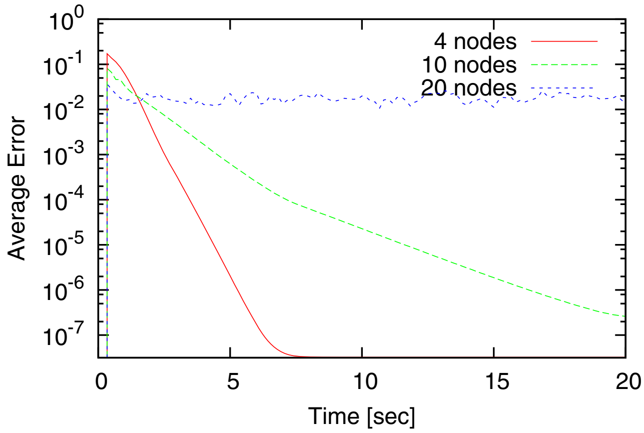
Through simulations, sensor nodes are deployed randomly in a monitoring region with a radius of 10 m and the timing of data transmission is determined on the basis of a phase which is assigned randomly in the initial state. The communication range of the node is assumed to be 20 m, and the nodes can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

- Average Error
  This value shows the average value of the phase offset between nodes. The smaller the average error, the higher the accuracy of the synchronization.
- Transmission Failure Probability
  The probability of transmission failure caused by over-failure of the back-off in CSMA/CA during the communication attempt of the node.
- Data Collection Ratio
  Ratio of the number of data packets reaching the sink to the overall number of data packets sent to the sink from the node.

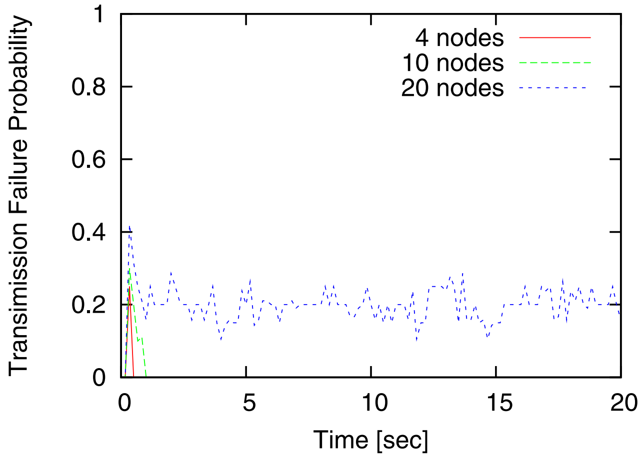
B. Performance of the proposed phase control mechanism

We evaluate the coupling coefficient α, which is an important parameter of the pulse-coupled oscillator model. In order to obtain the suitable parameter settings in accordance with the number of nodes, we estimate the average error after a certain period (20 seconds). Figure 7(a) shows that the average error of 10^{-2} becomes the boundary value for synchronization, where the accuracy of synchronization becomes higher with time if it is lower than the boundary value, otherwise the phase keeps fluctuating and does not converge to a stable state. Additionally, the large width of the coupling coefficient enables the network to reach a stable state in environments consisting of a small number of nodes, and it becomes difficult to converge to the stable state if the value of the coupling coefficient is too large. This is a result of the number of coupled nodes, in other words, the stimulus becomes stronger as the node becomes coupled with more nodes and the coupling coefficient becomes larger. Hence, it is concluded from the simulation that overstimulation disturbs the convergence to a stable state. On the contrary, although small values of the coupling coefficient require longer synchronization times, the condition approaches a stable state in a steady manner (Figure 7(b)). These results indicate that anti-phase synchronization requires the coupling coefficient to be set adaptively. The choice of coupling coefficient also depends on the requirements of the particular application; for example, a small coupling coefficient for delay-tolerant applications and large coupling coefficient for accuracy-tolerant application. The number of nodes and the data transmission interval also affects the choice. Various factors should be considered when setting the coupling coefficient, and it is assumed that those factors constantly change. Therefore, setting a static coupling coefficient is not sufficient, and it is required that the parameter is set dynamically for each node in accordance with the number of nodes and the amount of traffic in a self-organizing manner. However, as this problem is beyond the scope of this work, it will be left for future study.

The phase control method requires scalability over the number of nodes. We perform an evaluation of a network where 4, 10 or 20 nodes are deployed, and use a coupling coefficient of 0.06 in all three cases. The result of the average error with the progress of time is shown in Figure 8. It is easier for a small number of nodes to be synchronized within a short period or time. When the number of nodes increases to 10, an equal phase offset is formed, and the nodes are synchronized as a result of the interaction between the nodes, although the time until the synchronized state is reached is longer as compared to the case of 4 nodes. However, 20 nodes cannot be synchronized due to the insufficient control of average error, and as a result, the average error keeps fluctuating and the oscillation cannot converge to a stable state. The reason for this failure can be described as follows. In this simulation, the node transmits 400 bits of data to the sink with a transmission speed of 50 kbps every 160 ms. The transmission of one data packet requires 400 [bits] / 50 [kbps] = 8 [ms]. Since the transmission width is 160 ms and the time slot is 8 ms, perfect anti-phase synchronization provides alternate transmission for up to 20 nodes. However, such a situation is difficult to realize in practice, and transmission failures inevitably occur in the process of synchronization (Figure 8(b)). The transmission failure interrupts the node from broadcasting the firing information, and consequently phase control is not performed properly and the average error increases. The iteration of this operation leads to the failure of anti-phase synchronization in the case of 20 nodes. Thus, the number of transmission nodes which can be synchronized by anti-phase synchronization is constrained by the access period.



(a) Transition of average error.



(b) Transition of transmission failure probability.

Fig. 8. Influence of number of nodes on anti-phase synchronization.

C. *Robustness against Perturbations*

The reason for adopting a biological system in this method is its robustness against perturbations. In wireless communication in sensor networks, radio waves are shadowed by obstacles and fade as a result of the interference of radio waves. The energy of the nodes can thus be depleted and the node might cease to function in the case of such an unexpected failure. Furthermore, a node can be added to the network in order to replace a failed node. In this section, we regard the packet loss and the changes in topology induced by the addition and the failure of nodes as perturbations, and show that the self-organized anti-phase synchronization method is robust against such perturbations.

The influence that the packet loss brings to average error and transmission failure is shown in Figure 9. In this simulation, a packet is dropped randomly based on packet loss rate and does

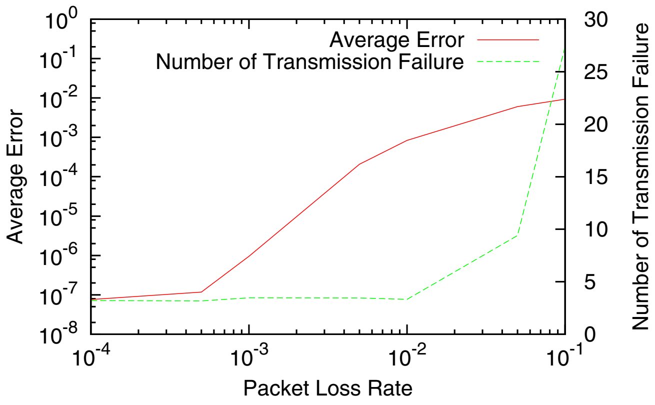
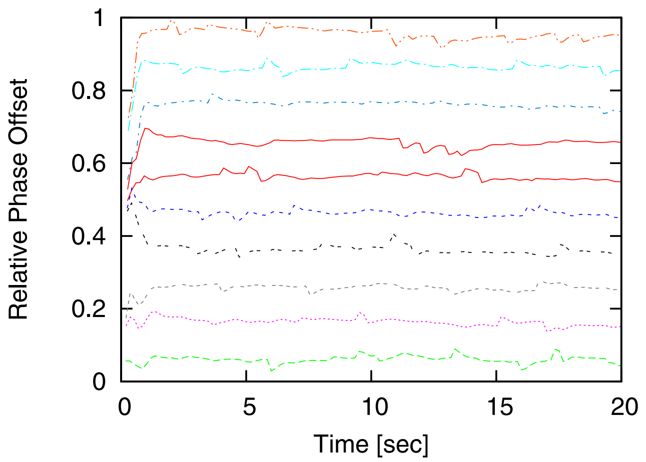
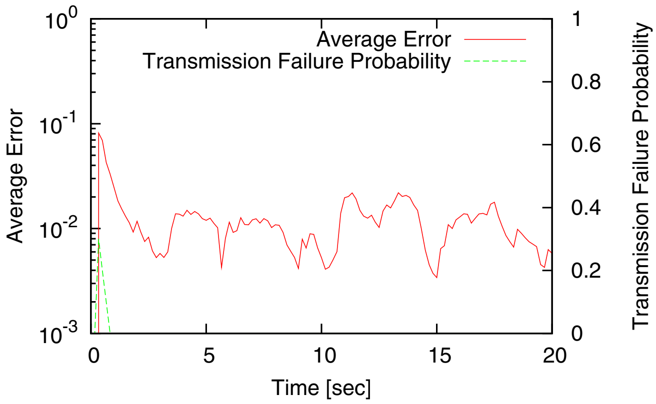


Fig. 9. Influence of a packet loss.

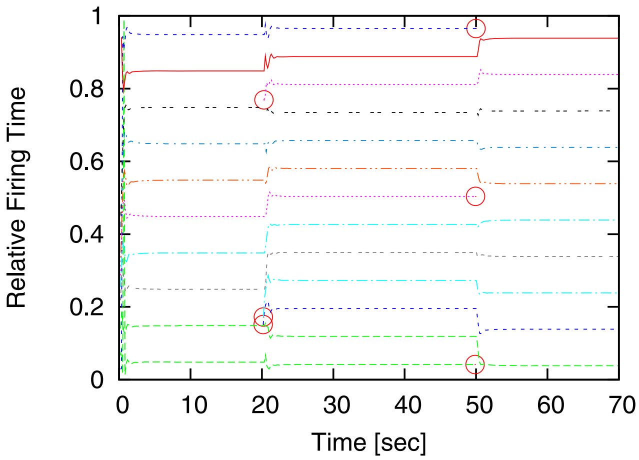


(a) Transision of relative phase offset.

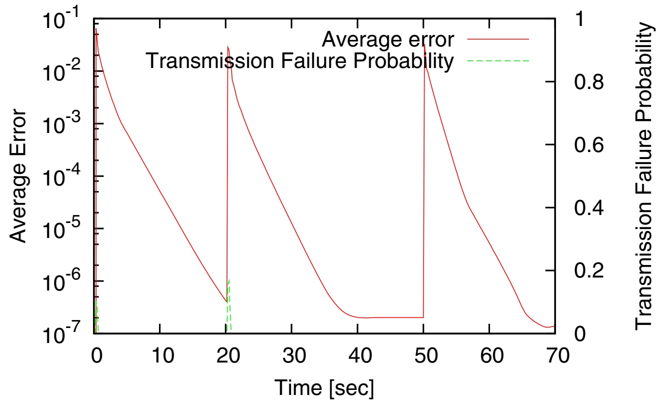


(b) Transision of average error and transmission failure probability.

Fig. 10. Performance of the network under the situation where a packet loss rate is 10^{-2}.



(a) Transition of relative phase offset.



(b) Transition of average error and transmission failure probability.

Fig. 11. Influence caused by the change of topology: Addition and failure of the node.

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 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 10 shows the result in this condition. The phase moves with fluctuation due to the failure of phase control caused by the packet loss (Figure 10(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.

Subsequently, we confirm that the proposed method restores the anti-phase synchronized state by performing phase control after the addition or the failure of a node. Three nodes with random phases are added to the network at 20 seconds, and three nodes fail at 50 seconds from initiation. Figure 11 shows that 10 nodes with random phases in the initial state immediately converge to a stable anti-phase synchronization state. At 20 seconds, the average error decreases and the synchronized state is destroyed due to the addition of nodes. As the transmission has been almost simultaneous up until that time, transmission failure arises as carrier sensing is performed over the maximum back-off time on CSMA/CA (Figure 11(b)). However, the node adjusts the phase in a self-organizing manner against the addition of nodes, and the anti-phase synchronization state is restored within a short period of time. The same performance can be confirmed in the case of failure of nodes. Self-organized control is characterized by such robustness against changes in topology due to its intrinsic function of local interactions. In centralized control, if the node which plays an important role (such as a cluster head) fails, ordinary nodes stop functioning properly without receiving orders from that central node. On the other hand, a task is equally distributed to nodes in self-organized control, and the system is not influenced by the risks associated with centralized control.

D. Comparison with other schemes

In order to understand the features of the proposed method, we perform a comparative evaluation with three other schemes. *DESYNC* [11] is a distributed anti-phase synchronization scheme which achieves a synchronized state by adjusting the phase on the basis of information from two coupled nodes. *Random* gives random transmission timing to the nodes, while *Ideal TDMA* uses an ideal value which provides optimal scheduling. The MAC layer of the first two methods (DESYNC and Random) is based on CSMA/CA, and the same topology is used in the simulation. Figure 12 shows the influence of the traffic, namely the number of data generated by a node, on each scheme. The proposed method achieves a high

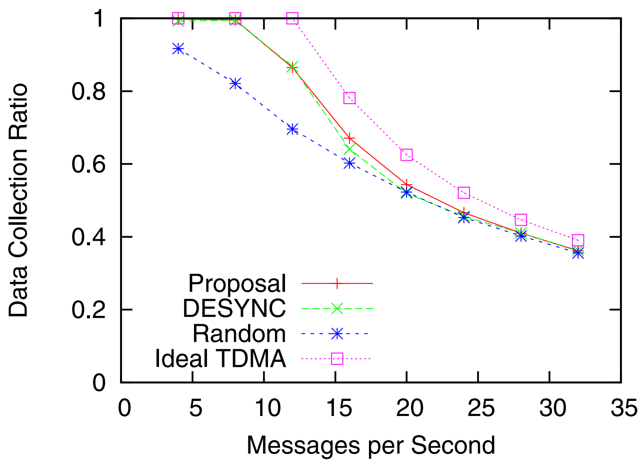


Fig. 12. Comparison of data collection ratio.

data collection ratio in the case of low traffic by reducing the number of data transmission failures. As the traffic increases, the data collection ratio decreases due to failures of data transmission caused by too much traffic over the width of the access period. Although the proposed method does not reach an ideal value in such excessive traffic, it maintains a higher data collection ratio than the random control method. The difference is mainly due to the choice of coupling coefficient. The advantage of the proposed method is the feasibility of extension to multi-hop networks since the stimulus in the proposed method arrives from all nodes, while in DESYNC it arrives from only two nodes. The comparison between self-organizing and distributed control is a crucial point in terms of synchronous stability, extendibility, robustness, and so forth, which will be examined in future work.

V. Conclusion and Possible Extensions

Robustness, adaptability and scalability are essential features for managing complex and diverse networks. In this paper, we introduced a self-organizing scheduling scheme inspired by frog calling behavior as a method for fulfilling such requirements. We performed evaluations through computer simulations in a single-hop network for a phase control method inspired by the alternate calling behavior of Japanese tree frogs. The simulation results showed that phase control reduces the transmission failures by applying anti-phase synchronization, regardless of the number of nodes. In addition, robustness against packet loss and changes in topology was confirmed, and stable anti-phase synchronization was maintained by realizing adaptive response to perturbations.

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 the convergence to a stable anti-phase synchronized state, it is necessary to perform mathematical analysis of the synchronous stability of the phase shift function. The phase control mechanism should be improved in order to achieve extendibility to multi-hop networks, which also considers the hidden terminal problem. The comparative evaluation of the proposed method with distributed methods from the viewpoint of the transmission of information would reflect the benefits of both methods.

ACKNOWLEDGEMENT

This research was supported in part by the "Global COE (Centers of Excellence) Program" of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

REFERENCES

[1] H. Kitano, "Biological robustness," *Nature Reviews Genetics*, vol. 5, pp. 826–837, Nov. 2004.

[2] F. Dressler, *Self-organization in sensor and actor networks*. Wiley, Jan. 2007.

[3] Y. Zhang, L. Kuhn, and M. Fromherz, "Improvements on ant routing for sensor networks," in *Proceedings of the Fourth International Workshop on Ant Colony Optimization and Swarm Intelligence*, pp. 154–165, July 2004.

[4] H. Chan and A. Perrig, "ACE: an emergent algorithm for highly uniform cluster formation," in *Proceedings of the First European Workshop on Wireless Sensor Networks (EWSN 2004)*, pp. 154–171, Jan. 2004.

[5] R. E. Mirollo and S. H. Strogatz, "Synchronization of pulse-coupled biological oscillators," *Journal on Applied Mathematics*, vol. 50, pp. 1645–1662, Dec. 1990.

[6] A. Mutazono, M. Sugano, and M. Murata, "Evaluation of robustness in time synchronization for sensor networks," in *Proceedings of the 2nd International Conferenece on Bio-Inspired Models of Network, Information, and Computing Systems (BIONETICS 2007)*, pp. 89–92, Dec. 2007.

[7] L.-Y. Cao and Y.-C. Lai, "Antiphase synchronism in chaotic systems," *Physical Review E*, vol. 58, pp. 382–386, July 1998.

[8] I. Aihara, S. Horai, H. Kitahata, K. Aihara, and K. Yoshikawa, "Dynamical calling behaviors experimentally observed in Japanese tree frogs (Hyla japonica)," *IEICE Trans Fundamentals*, vol. E90-A, pp. 2154–2161, 2007.

[9] W. E. Duellman and L. Trueb, *Biology of amphibians*. Johns Hopkins University Press, Mar. 1994.

[10] H. C. Gerhardt and F. Huber, *Acoustic communication in insects and anurans: common problems and diverse solutions*. University of Chicago Press, July 2002.

[11] J. Degesys, I. Rose, A. Patel, and R. Nagpal, "DESYNC: Self-organizing desynchronization and TDMA on wireless sensor networks," in *Proceedings of the 6th International Conference on Information Processing in Sensor Networks (IPSN 2007)*, pp. 11–20, Apr. 2007.

[12] J. Degesys and R. Nagpal, "Towards desynchronization of multi-hop topologies," in *Proceedings of the Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO 2008)*, pp. 129–138, Oct. 2008.

[13] M. B. H. Rhouma and H. Frigui, "Self-organization of pulse-coupled oscillators with application to clustering," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 23, pp. 180–195, Feb. 2001.

[14] Q. Cao, T. Abdelzaher, T. He, and J. Stankovic, "Towards optimal sleep scheduling in sensor networks for rare-event detection," in *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN 2005)*, Apr. 2005.

[15] K. Sekiyama, Y. Kubo, S. Fukunaga, and M. Date, "Phase diffusion time division method for wireless communication network," in *Industrial Electronics Society, 2004. IECON 2004. 30th Annual Conference of IEEE*, vol. 3, Nov. 2004.

[16] I. Aihara, H. Kitahata, K. Yoshikawa, and K. Aihara, "Mathematical modeling of frogs' calling behavior and its possible application to artificial life and robotics," *Artificial Life and Robotics*, vol. 12, pp. 29–32, Mar. 2008.