Energy Efficient Sleep Scheduling in Wireless Sensor Networks Inspired by Satellite Behavior of Frogs

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

***Abstract*—One of the most challenging research tasks in the field of wireless sensor networks is controlling the power consumption of batteries and prolonging network lifetime. For sensor networks which consist of a large number of sensor nodes, self-organized control is more suitable than centralized control. In particular, research on bio-inspired self-organization methods attracts attention due to the potential applicability of such methods to wireless sensor networks. In this paper, we focus on the calling behavior of Japanese tree frogs. These frogs display a type of behavior known as "satellite behavior", where a frog stops calling once it detects the calls of other neighboring frogs. This behavior can be applied in the design of an energy-efficient sleep control mechanism which provides adaptive operation periods. We propose a self-organizing scheduling scheme inspired by the frogs' calling behavior for energy-efficient data transmission in wireless sensor networks. Simulation results show that our proposed sleep control method prolongs network lifetime by a factor of 6.7 as compared with the method without sleep control for a coverage ratio of 80%.**

***Keywords*-wireless sensor networks; self-organized control; bio-inspired control; sleep scheduling; satellite behavior**

I. INTRODUCTION

Self-organized control which is inspired by biological systems has been receiving considerable attention as a promising concept for the realization of robustness, scalability, and adaptability [1]. Biological systems always change and adapt themselves in response to 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 a coordinated manner in spite of the selfish behavior of individual components. Such simple mechanisms bring a cognitive function to the system as a whole, and self-organized control provides adaptability and robustness [2]. A number of methods have been proposed where the advantages of biological systems are applied to computer networks in fields such as routing [3] and clustering [4]. For example, in the field of time synchronization, pulse-coupled oscillators (PCO) [5] are known to mimic the behavior of fireflies, which flash in unison with their neighbors.

Although most of the existing research on the PCO model focuses on simultaneous synchronization, we consider that anti-phase synchronization of transmission scheduling can reduce packet loss caused by collisions on the wireless channel. As a possible mechanism for realizing anti-phase synchronization, we focus on the calling behavior of Japanese tree frogs [6], in particular *advertisement calling*. It is considered that one of the main reasons for the calling behavior of this species of frog is for the male to attract females. If a male calls simultaneously with other frogs, it becomes difficult for the female to distinguish between callers, and therefore they shift the timing of their calls [7]. Previously, we proposed a self-organizing scheduling scheme inspired by the calling behavior of this species of frog for reliable data transmission in wireless sensor networks [8]. We also showed that phase control reduces the occurrence of transmission failure by applying anti-phase synchronization. In addition, robustness against both packet loss and changes in topology was confirmed.

Energy conservation is a critical issue for sensor networks in addition to properties such as robustness or scalability since each node has access to limited amounts of energy provided by a battery and it is difficult to change or charge the battery in accordance with the deployment. Therefore, we focus on another interesting behavior called *satellite behavior*, which is characteristic to Japanese tree frogs. When there are many competing frogs, some frogs stop calling based on comparing the merits of obtaining a higher probability of mating over the demerits of losing energy by calling. We apply this behavior to sleep control in wireless sensor networks. The decrease in the per-unit cost of sensor nodes is expected to allow for massive deployments in the future. In such situations, nodes will be deployed non-uniformly and redundantly meaning that some nodes do not need to perform active sensing continuously. By performing control equivalent to the satellite behavior, redundant nodes turn off the transceiver power and are thus able to conserve energy. At this time, each redundant node is subjected to sleep control by considering the overlap of the sensing regions 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 by considering the traffic load.

In this paper, we propose a self-organizing transmission scheduling scheme inspired by the calling behavior of frogs. The outline of this paper is as follows: Section II provides the motivation behind our interest in frogs and sleep control in general by introducing related work. Section III introduces the details regarding the mechanism of the proposed sleep control method based on the satellite behavior of frogs. Section IV shows the results of numerical simulations on single-hop networks. In Section V, we evaluate the proposed sleep control method and show its feasibility with respect to energy-efficient assignment of access periods. In addition, we provide a conclusion as well as possible extensions of our research.

II. BACKGROUND AND MOTIVATION

A. *Dynamics of the Tree-Frog Satellite Behavior*

Certain species of Japanese tree frogs display a behavior where they hide in waiting near other calling frogs. Claiming territory and attracting female frogs by calling is important, however, a frog announcing its location by expending large amounts of energy for producing calls makes it an easy target for predators. The possibility of attracting the attention of females decreases in an environment where there are many other males, for there is intense calling competition and large amounts of energy are needed to produce the calls. At this time, some male frogs stop calling and change their strategy, instead spending most of their energy in attempts to catch a female. In other words, in this strategy the frog approaches other calling frogs without calling and intercepts a female which is attracted to the calls of other frogs while they compete with each other [9]. This “satellite behavior” is also known among other animals, such as fish or anurans. The calling frog and the satellite frog change strategy alternately in some cases. It is assumed that some of the factors governing the satellite behavior are body size, the loudness of the calls and the number of competing neighboring frogs [10]. Frogs are considered to be able to estimate the size of other frogs on the basis of the frequency of their calls. We apply the mechanism of satellite behavior to sleep control in wireless sensor networks. The need for sleep control will be explained in detail in the next subsection.

B. *Benefits of Sleep Scheduling*

The main purpose of sleep control is to turn off the power of redundant nodes in order to reduce energy consumption. As a result, nodes can operate for longer periods of time and the network lifetime is extended. Energy efficiency is a more crucial issue in wireless sensor networks. Normally, a sensor node operates with a battery which has limited capacity, and it is difficult to charge or replace batteries due to the deployment of the nodes. Moreover, interference occurs if many nodes communicate simultaneously in a dense network, and sleep control can solve this problem by limiting the number of active nodes. Sleep control is also effective for minimizing delays by adjusting the transmission schedule when performing data gathering.

For the above reasons, sleep control has been the subject of extensive research. Packet collision, the reception of unrelated packets, the overhead of control packets and redundant idling time are often regarded as causes of energy waste, and a sleep mechanism is proposed to reduce such problems. S-MAC [11] is the most well-known sleep control method. In this method, packet collision is avoided by synchronizing the active time for reducing the idling time, and virtual carrier sense using RTS (Request to Send) and CTS (Clear to Send) packets. PEAS [12] is another sleep method, where nodes broadcast probe packets regularly and enter a sleep state whenever the number of active nodes in the neighborhood becomes larger than a certain level. The delay is reduced by adaptively choosing the sleep time by considering the number of active nodes. There is also another sleep control method, which depends on the residual energy [13]. This technique becomes effective when nodes are dispersed with respect to their residual energy. Greunen [14] proposed a sleep control method for minimizing the queuing delay in data transfer. In addition, the DMAC protocol [15] first builds a network tree and nodes transmit data following shifted timing based on the hop account from the sink, thus reducing the delay between event detection and the transmission of detected data to the sink. There are also coverage-based sleep control methods. For example, CCP [16] guarantees various degrees of coverage depending on the application and reduces the energy consumption while satisfying the requirements for coverage and connectivity. Thus, the function of sleep control changes according to the requirements. In this paper, we propose sleep control based on the satellite behavior of frogs for the purpose of energy conservation of redundant nodes and the prevention of packet collision while maintaining high coverage.

III. FROG CALL-INSPIRED TRANSMISSION SCHEDULING

In this paper, nodes are assumed to be able to communicate with all other nodes in a single-hop network. A node has a sensing range which is smaller than its communication range, and coverage of the entire network is ensured by cooperation between nodes. First, we outline a phase control method based on call alternation, and then describe the proposed sleep control method based on the abovementioned satellite behavior.

A. *Outline of Phase Control Mechanism*

The outline of phase control is shown in Figure 1. A frog produces a call by making sound for a certain period of time, after which it quiets down. If two or more male frogs produce calls at random times, their calling periods might overlap. In this case, interference occurs between their

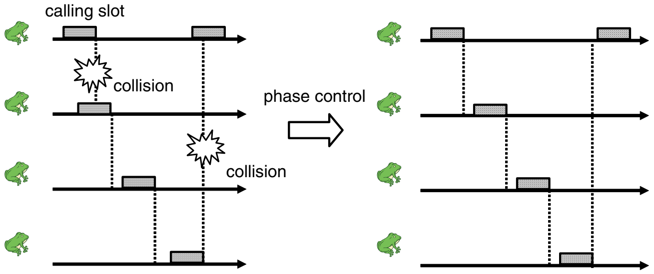


Figure 1. Outline of phase control which reduces the occurrence of transmission failure by adjusting the transmission timing.

calls and the female frog (mating partner) cannot distinguish individual callers. Therefore, by listening to the calls of other frogs, male frogs shift the time of calling in such manner that the calling periods do not overlap. After each frog adjusts the call timing, call alternation without interference is realized in the group. In our proposal, this mechanism is applied in sensor networks, where frogs are replaced by nodes, calling corresponds to packet transmission and interference is packet collision. Wireless communication requires a certain amount of time for transmitting a packet, and transmitting nodes have exclusive control of the communication band during the transmission. If another node transmits a packet at the same time, packet collision occurs and both transmitted packets are discarded. In order to prevent packet collision, generally CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is used as the transmission protocol for the MAC layer. In CSMA/CA, a node transmits a packet after performing carrier sensing, thus confirming that the channel is free. If the channel is not free, after carrying out backoff for a random period or time, carrier sensing is performed again. However, if the node fails to perform carrier sensing by exceeding the maximum backoff time, transmission is aborted and the packet is discarded. By applying phase control to transmission scheduling in wireless sensor networks, both packet collision and transmission failure in the MAC layer can be reduced.

We modeled the operation of each node by PCO and introduced a mathematical model for realizing anti-phase synchronization, which is described in detail in [8].

B. Sleep Control based on Frog Satellite Behavior

Next, we explain our proposed sleep control method, which is inspired by frog satellite behavior. As mentioned in Section II-A, where the details of the satellite behavior were discussed, we consider the following three factors:

- Territory
- Number of competing frogs in the neighborhood
- Body size

Considering these three factors, the frog decides whether or not to adopt satellite behavior. We explain each condition for the decision in Figure 2. The red circles represent the target frogs which are considering their behavior, and the dotted lines indicate their respective territories. The frogs are located in a paddy field, and it is assumed that each frog is able to hear all other frogs calling.

(a) Three frogs (denoted A, B and C) are already calling, and two other frogs are evaluating the environment. Frog D on the left first confirms that there is no calling frog in its territory, next confirms that the number of calling frogs in the paddy field is not exceedingly large, and then begins to produce calls. On the other hand, frog E on the right assumes satellite behavior as it finds two other frogs (A and B) calling in its territory.

(b) A new large frog F appears and evaluates its surroundings. It finds frog C calling in its territory. However, after comparing the size of their bodies, it concludes that the probability of winning the competition is large and begins to call. We refer to this behavior as *interception*.

(c) The small frog C detects the presence of a stronger frog in its territory and chooses the satellite behavior in order to avoid competing.

Applying this mechanism to sensor networks, the territory of a frog corresponds to the sensing region, the number of competing frogs in the neighborhood is the number of access nodes, and body size is the remaining energy. The following targets are achieved with such a sleep control mechanism.

- Energy conservation for redundant nodes
- Distribution of coverage
- Assignment of bandwidth (i.e., access period) for reducing packet collisions

In sensor networks, a large number of nodes are assumed to be deployed randomly, in which case several nodes might be arranged closely within each other's range. It is not necessary for all such neighboring nodes to perform sensing in the same region since a single node is sufficient in this situation. Energy consumption is reduced when redundant nodes adopt satellite behavior in order to enter sleep mode. Additionally, the proposed method, in which nodes enter sleep mode not randomly but after considering the state of its neighboring nodes, is energy efficient while satisfying the requirements for network coverage. Although anti-phase synchronization is performed accurately, there is a limit to the number of nodes which can transmit in turns depending on the frequency of data transmission and the data packet size. By performing sleep control and considering these factors, packet collision caused by excessive traffic can be prevented.

Each sensor node maintains two states, *active* and *satellite*. It confirms the state of the network regularly and changes its own state accordingly. In the active state, the node executes the confirmation process periodically immediately before data transmission, while in the satellite state it performs confirmation after a sleep period T_s. We refer to the node which executes the confirmation process as a *confirming node* (CN), the sensing region as a *territory* and other nodes in the territory as *territory competing nodes* (TCN). It is possible to take the place of a node which

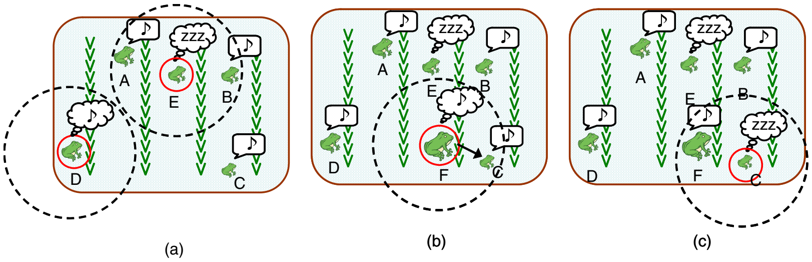


Figure 2. Outline of sleep control. Red circles denote the target frogs and dotted lines indicate their respective territories. Each frog in the figure is drawn to scale to show body size.

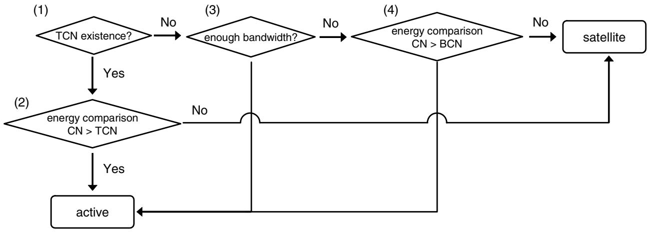


Figure 3. Flow chart of confirmation process.

has little remaining energy even if many nodes are already in active state. We refer to a node with the lowest residual energy in active state as a *bandwidth competing node* (BCN). That is, if the remaining energy of CN is larger than the remaining energy of BCN, CN becomes active instead of BCN. The flow of the confirmation process is shown in Figure 3:

(1) At first, CN checks whether there is a territory competing node.

(2) If CN finds a TCN, it compares the remaining energy with that of TCN in order to evaluate the probability of interception. If the residual energy of CN is higher, CN concludes that it will not lose the competition and enters active state for transmission, otherwise it enters satellite state in order to save energy.

(3) If there is no TCN, CN evaluates the bandwidth. If there is enough bandwidth, CN considers that it is possible to perform transmission and enters active state.

(4) If the bandwidth is occupied by active nodes, the confirming node compares the remaining energy with PCN for interception. If CN has higher residual energy, it enters active state, otherwise it enters satellite state.

Active nodes perform periodical data transmission and satellite nodes sleep to conserve energy. In order for satellite nodes to be in active state, the remaining energy must be higher than at least that of PCN. In addition, the higher the remaining energy of the node, the more often it performs the confirmation process in order to increase the probability of entering active state. For these reasons, the satellite node decides the sleep period T_s on the basis of a standard sleep time T_{std} by considering its own residual energy E_{CN} and the residual energy E_{BCN} of BCN.

$$T_s = T_{std} \cdot \exp\left(1 - \frac{E_{CN}}{E_{BCN}}\right) \tag{1}$$

In this manner, the proposed mechanism performs sleep control which conserves energy by ensuring that redundant nodes enter sleep state, reduces collisions by adaptive assignment of access periods and prolongs the network lifetime by performing sleep control considering the remaining energy of nodes.

IV. EVALUATION

A. Simulation Setup

In these simulations, sensor nodes are deployed randomly in a monitoring region with a radius of 10 m, and the nodes decide the data transmission timing on the basis of the phase, which is assigned randomly at the initial state. The communication range of a 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 a monitoring region with a radius of 5 m every 0.16 seconds and transmits the sensing data to the base station, referred to as a sink, at a transmission speed of 50 Kbps. CSMA/CA is used for the transmission protocol of the MAC layer. A data packet includes the sensing information and a time stamp which represents the delay caused by the backoff of CSMA/CA, and the size of a packet is set to 400 bits. Therefore, it takes 8 ms for transmitting one data packet, and the transmission node takes exclusive control over the communication band during that period. The standard sleep time T_{std} in the sleep control is set to 3.2 seconds. We use the following evaluation metrics:

- Transmission Failure Probability
  Probability of transmission failure induced by timeout due to backoff in CSMA/CA during a communication attempt of a node.
- Data Collection Ratio
  Ratio of the amount of data reaching the sink to all data sent to the sink from a node.
- Coverage Ratio
  Ratio of the region with 1-coverage to the entire 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, it is considered that the task is divided fairly and the energy consumption is distributed evenly between nodes.

B. Performance of the Proposed Sleep Control Mechanism

The objectives of the proposed sleep control mechanism are 1) energy conservation for redundant nodes, 2) even distribution of coverage and 3) assignment of access periods which reduces packet collisions. Perfect anti-phase synchronization cannot ensure alternate data transmission for all nodes when the number of nodes is large and the access period is narrow. In this case, if there are many active nodes, the overlap of access periods is prevented by making redundant nodes enter sleep mode, and data transmission becomes free from transmission failure. In other words, sleep control brings adaptability to phase control for reliable transmission. After this section, we describe the results for 20 nodes which were deployed in the monitoring region in order to evaluate the efficiency of the proposed sleep control mechanism.

As one of the principles of sleep control, a node with high residual energy attempts to replace a node with low residual energy and subsequently performs sensing. This principle ensures a fair distribution of energy consumption between nodes. Figure 4 shows the number of active nodes and the energy utilization ratio. At the beginning, seven nodes become active for sensing and other nodes enter sleep mode since it is impossible for all 20 nodes to transmit during the same transmission period. The value of the energy utilization ratio decreases as the seven active nodes consume energy. Then, after 50 s, interception is performed by the satellite nodes, the nodes change state, and the energy utilization ratio rises due to the participation of fresh nodes. After another 50 s, the nodes keep changing their state depending on the residual energy, and thus the value of the energy utilization ratio is maintained at 1.0.

We observe the kinds of changes caused by sleep control through a comparison of the phase control method with and without sleep control. Figure 5 shows the results for the number of nodes and the coverage ratio as a function of time. The method with sleep control provides a large sensing region over a long period of time with a small number of active nodes. On the contrary, the method without sleep control can achieve a rather high coverage ratio as a result of the fact that sensing is performed by all nodes, however, the energy of the nodes is depleted within a short period of time. The sleep control mechanism prolongs the network lifetime by a factor of about 6.7 for a coverage ratio of 80%.

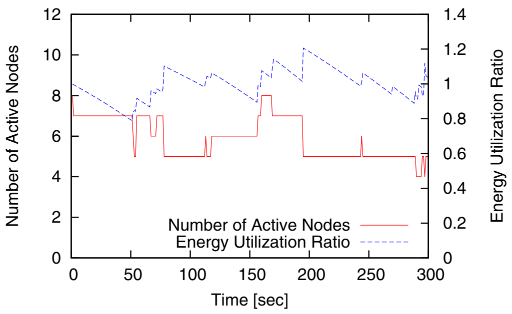
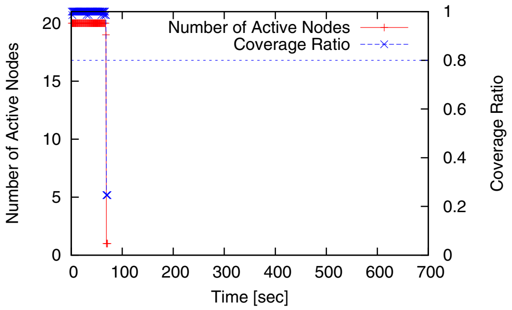
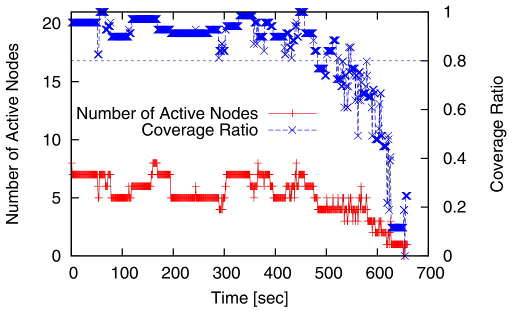


Figure 4. Number of active nodes with respect to the energy utilization ratio.



(a) The case where phase control is implemented without sleep control



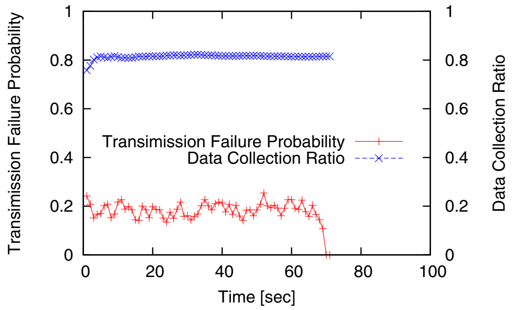
(b) The case where both phase control and sleep control are implemented

Figure 5. Comparison of coverage ratio.

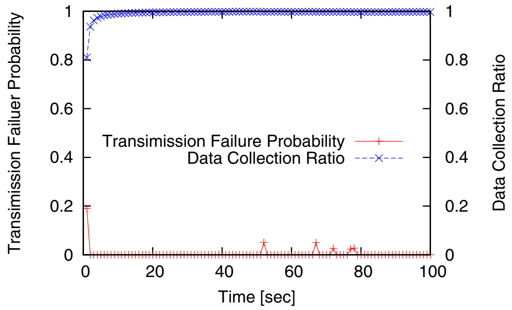
We evaluate the data collection ratio for the two methods. In the method without sleep control, data transmission failure occurs without the assignment of access periods to the nodes. As a result, the sink cannot collect all data. On the other hand, the method with sleep control assigns access periods only to the active nodes and realizes reliable data transmission. Although transmission failure occurs after the cycle of node alternation is completed, the amount of failure is sufficiently small not to affect the data collection ratio. The combination of phase control and sleep control reduces the occurrence of transmission failure by adaptive assignment of access periods, prolongs the network lifetime and satisfies the requirement of high coverage.

V. CONCLUSION AND POSSIBLE EXTENSIONS

In this paper, we introduced a self-organizing scheduling scheme inspired by the calling behavior of Japanese tree frogs as a method for reducing energy consumption as well



(a) The case where phase control is implemented without sleep control



(b) The case where both phase control and sleep control are implemented

Figure 6. Comparison of data collection ratio.

as packet collision while satisfying the requirements of high coverage. We performed an evaluation through computer simulations in a single-hop network for the proposed functions by implementing a sleep control method inspired by the frogs' satellite behavior. The simulation results indicated that sleep control realizes adaptive assignment of access periods, fair distribution of coverage and extension of the network lifetime.

Although this paper presents the application of the proposed technique to a single-hop network, the possibility for expanding this to the multi-hop case and applying it to larger networks should be explored. For that purpose, we aim at establishing a mathematical model of satellite behavior. From the complex structure of the satellite behavior, we applied only the operation of stopping calling in accordance with the strength of the individuals present in the surroundings to the sleep control of sensor networks. However, actual frogs intercept females attracted to stronger males or move to another location where stronger individuals are not present. We consider that such behavior will also be applicable in various situations for wireless sensor networks.

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REFERENCES

[1] H. Kitano, "Biological robustness," *Nature Reviews Genetics*, vol. 5, no. 11, 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 4th International Workshop on Ant Colony Optimization and Swarm Intelligence*, Jul. 2004, pp. 154–165.

[4] H. Chan and A. Perrig, "ACE: an emergent algorithm for highly uniform cluster formation," in *Proceedings of the 1st European Workshop on Wireless Sensor Networks*, Jan. 2004, pp. 154–171.

[5] R. E. Mirollo and S. H. Strogatz, "Synchronization of pulse-coupled biological oscillators," *Journal on Applied Mathematics*, vol. 50, no. 6, pp. 1645–1662, Dec. 1990.

[6] 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.

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

[8] A. Mutazono, M. Sugano, and M. Murata, "Frog call-inspired self-organizing anti-phase synchronization for wireless sensor networks," in *Proceedings of the 2nd International Workshop on Nonlinear Dynamics and Synchronization*, Jul. 2009.

[9] J. R. Lucas, R. D. Howard, and J. G. Palmer, "Callers and satellites: chorus behaviour in anurans as a stochastic dynamic game," *Animal Behaviour*, vol. 51, no. 3, pp. 501–518, 1996.

[10] C. J. Leary, D. J. Fox, D. B. Shepard, and A. M. Garcia, "Body size, age, growth and alternative mating tactics in toads: satellite males are smaller but not younger than calling males," *Animal Behaviour*, vol. 70, no. 3, pp. 663–671, 2005.

[11] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on networking*, vol. 12, no. 3, pp. 493–506, Jun. 2004.

[12] F. Ye, G. Zhong, J. Cheng, S. Lu, and L. Zhang, "PEAS: a robust energy conserving protocol for long-lived sensor networks," in *Proceedings of the 23rd International Conference on Distributed Computing Systems*, 2003, pp. 28–37.

[13] M. Pearlman, J. Deng, B. Liang, and Z. Haas, "Elective participation in ad hoc networks based on energy consumption," in *Proceedings of IEEE GLOBECOM 2002*, vol. 1, 2002.

[14] J. van Greunen, D. Petrovic, A. Bonivento, J. Rabaey, K. Ramchandran, and A. Vincentelli, "Adaptive sleep discipline for energy conservation and robustness in dense sensor networks," in *Proceedings of IEEE ICC 2004*, Jun. 2004, pp. 3657–3662.

[15] G. Lu, B. Krishnamachari, and C. Raghavendra, "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," in *Proceedings of International Parallel and Distributed Processing Symposium*, 2004.

[16] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill, "Integrated coverage and connectivity configuration in wireless sensor networks," in *Proceedings of ACM SenSys 2003*, Nov. 2003, pp. 28–39.