OR-based Block Combination for Asynchronous Asymmetric Neighbor Discovery Protocol

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Abstract

The neighbor discovery protocol (NDP) is one of the critical research subjects in wireless sensor networks (WSNs) for efficient energy management of sensor nodes. A block design concept can be applied to find a neighbor discovery schedule that guarantees at least one common active slot between any pair of sensor nodes. However, the block design-based solutions in literature are not flexible enough because block design cannot support asymmetric asynchronous operations. In this paper, we introduce a new approach for asymmetric asynchronous neighbor discovery protocol that combines two optimal block designs using the OR operation. OR-based block combination solves the problem of original block design, which cannot support asymmetric scenarios. We evaluate the performance of OR-based block combinations using a simulation study. According to our simulation results, OR-based block combination performs up to 71% better than other asymmetric algorithms, such as U-Connect and Disco with 10% and 1% duty cycles.

Keywords: *Wireless sensor network, Neighbor discovery protocol, Block design, block construction, Asymmetric*

1. Introduction

In most wireless sensor networks (WSNs) applications, tiny sensor devices are deployed randomly in remote and inaccessible areas. These sensor devices have a limited energy supply, and their functionality continues until their energy drains. They continually not only collect sensing information but also send and receive data packets. Therefore, an ultimate goal of WSN applications is to increase the lifetime of sensor devices by minimizing energy waste [1-2].

A neighbor discovery protocol (NDP) is one of representative techniques to increase the lifetime of sensor devices. NDP is used for sensor nodes to find their neighbors during the network initial setup. Two important criteria during this initial discovery process are the latency and energy consumption, since these two criteria are directly related to the initial set-up delay and lifetime of sensor networks [2-3].

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There have been a number of studies for developing energy-efficient NDPs for WSNs [1-2]. In particular, according to the studies in the literature, the block design-based approach delivers the best solution for symmetric asynchronous NDPs. However, due to the lack of various supporting WSN applications, which require asymmetric scenarios, the block design-based NDPs cannot be adapted widely and can be used only in some WSN applications with asynchronous symmetric scenarios.

In this paper, we introduce a new approach for asymmetric asynchronous NDPs. The proposed algorithm combines two block designs, which have short and long parts. Then, one sensor has the short block design and another sensor has the combined block design. Therefore, they always have at least one common active slot.

2. Related Works

In Combinatorial design theory, the concept of Balanced Incomplete Block Design (BIBD) has been widely applied for the scheduling technique in various WSNs. Moreover, the scheduling algorithms using the BIBD concept and similar techniques are proposed for NDPs [3-8].

The Disco NDP in [3] uses two different prime numbers to generate a schedule for neighbor discovery. Disco guarantees that any pair of two sensor nodes always has a common active slot within the length of one scheduling cycle by using the properties of the Chinese remainder theorem. However, the energy consumption of Disco is not optimal because it requires more frequent active slots than other protocols proposed later. In [5], another NDP called U-Connect, was proposed by using a single prime number. In general, a single prime number-based scheduling scheme cannot guarantee the existence of a common active slot between randomly selected two sensor nodes since they may choose the same prime number p. Therefore, in U-connect, the sensor always wakes up the first $(p+1)/2$ slots at the beginning of its discovery cycle to ensure the discovery of all neighboring sensors. Although U-Connect performs better than the Disco protocol, the worst-case discovery latency of U-Connect is still too high when two sensors choose the same prime number for their discovery schedule.

Zheng *et al.* [8] propose an NDP based on the solution of a block design problem in combinatory. If NDP uses the same combinatorial block design, the sensors always have at least one common active slot with neighbors while maintaining the length of the discovery schedule much shorter than that of other NDPs. It was proved that the NDP based on combinatorial block designs is the theoretically optimal solution for neighbor discovery problems. However, the NDP based on combinatorial block designs has a critical weakness: the combinatorial block design-based NDP is applicable only for symmetric WSN applications where all the sensors have same duty cycles.

3. OR-based Block Combination

3.1. Block Design Scheme in Scheduling

In a combinatorial block design concept [9], there is a well-studied experimental design called a Balanced Incomplete Block Design (BIBD). A BIBD has been used for various sensor network applications. The design and definitions of BIBD are defined as follows:

Definition 1. A *design* is a (X, A) pair, which satisfies two properties as follows:
  1) X is a set of elements called points
  2) A is a collection of X's subset blocks.

Definition 2. A ***(v, k, λ)-Balanced Incomplete Block Design*** (which we abbreviate to (v, k, λ)-BIBD) is a design (X, A) where v, k, and λ are positive integers such that v > k ≥ 2. It satisfies following properties:

1) |X| = v,
2) Each block contains exactly k points, and
3) Every pair of distinct points is contained in exactly λ blocks.

In wireless sensor network scheduling, there are many researches which use (v, k, λ)-BIBD to make symmetric schedules and utilize various sensor environments. In this paper, we use BIBD properties to make a new block construction. The schedule and duty cycle are defined as follows:

Definition 3. A ***schedule*** S has **active and sleep modes (slots)** representing a sequence of '1' and '0', respectively. In an active mode, sensor nodes turn on a radio module to send and receive data packets. In a sleep mode, sensor nodes turn off the radio module to save the battery.

Definition 4. A ***duty cycle*** is the ratio of active slots over the total number of slots. Then, a duty cycle D is defined as follows:

$$D = \frac{A}{T} \times 100\%$$

If the properties of BIBD are introduced into a schedule, we know that different schedules have at least one common slot at the same time as follows:

Property 1. Let (X, A) be given as in the definition 2. If a schedule S_i consists of (v, k, λ)-BIBD, then there is for some schedule S_j with the (v, k, λ)-BIBD such that S_i and S_j have common active slots.

Proof. Since (X, A) is (v, k, λ)-BIBD in the definition 2, we can write the X and A as follows:

$$X = \{a_1, a_2, \dots, a_v\}$$
$$A = \{B_i \mid B_i \subset X, |B_i| = k\}$$

We know that, by the second property in the definition 2, each B_i contains k points. Hence we can write $B_i = \{a_{i_1}, a_{i_2}, \dots, a_{i_k}\}$. Assume that the pair of distinct points (a_{i_l}, a_{j_m}) such that $a_{i_l} \in B_i$ and $a_{j_m} \notin B_i$ and a_{i_l} in S_i, a_{j_m} in S_j. By the third property in the definition 2, there is the block which must contain the pair of points (a_{i_l}, a_{j_m}). Therefore, there is a block $B_j \neq B_i$ that contains (a_{i_l}, a_{j_m}). Hence we know that there is the common active point in the $B_i = \{a_{i_1}, a_{i_2}, \dots, a_{i_k}\}$ and $B_j = \{a_{j_1}, a_{j_2}, \dots, a_{j_k}\}$ that is for some a_{j_l} in B_j such that $a_{j_l} = a_{i_l}$. Thus S_i and S_j have at least one common active slot.

However, if sensor nodes have different duty cycles, they cannot ensure at least one common active slot. The next section shows the solution to solve this problem.

3.2. OR-based Block Combination Construction

In this section, we introduce a new approach to solve (v, k, λ)-BIBD problem, which cannot support asymmetric scenarios. In order to define new OR-based block combinations, we use a (v, k, λ)-NDD for neighbor discovery design, which has some properties. In the (v, k, λ)-NDD, the number of X is v, and each block contains exactly k active slots, and every pair of distinct blocks contains at least λ common active slots. In order to support an asymmetric situation, OR-based block combination can be constructed as follows:

Definition 5. Let *N* be a $(v_1, k_1, λ_1)$-NDD and *M* be a $(v_2, k_2, λ_2)$-NDD. Then, small v value of *N* and *T* is a **short block design**, and a block design which has a long v value

is **a long block design**. A $N \otimes M$ indicates that the total length of a short block design is increased until it equals the total length of the long block design. Increased slots are filled with all 0. Then, N and M block designs are combined using an OR operation as Figure 1. Then, a **short part** of $N \otimes M$ is a short block design and a **long part** is the long block design.

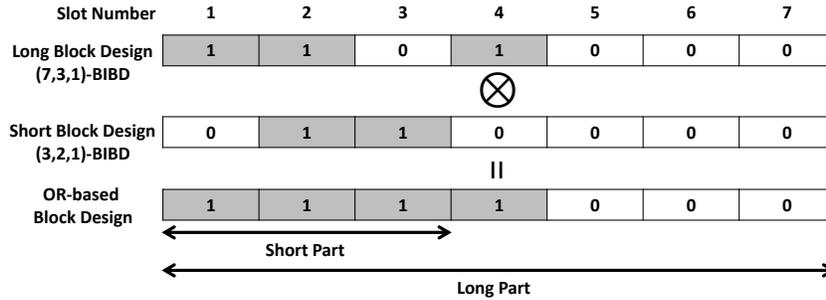Figure 1 shows the OR-based block combination of (7,3,1)-BIBD and (3,2,1)-BIBD.

Figure 1. An Example of OR-based Block Combination

If a block $N \otimes M$ is constructed by using the operation $\otimes$ given in *Definiton 5*, any two different schedules randomly selected from N, M or $N \otimes M$ have at least one common slot.

Property 2. Let N be a (v_1, k_1, λ_1)-NDD and M be a (v_2, k_2, λ_2)-NDD. Then an OR-based block combination Q made by $N \otimes M$ has at least one common active slot with N and M.

Proof. According to Property 1, the every pair of B_i extracted by N and M contains at least λ common active slot(s). Then, the every pair of Q block design, which is made by *Definition 5*, also contains at least λ common active slot(s) because the short and long block designs of Q block design are also a (v, k, λ)-BIBD. Moreover, in this situation, if v_2 is higher than v_1, N is short block design and M is long block design. They have at least one common active slot with Q block design which includes short and long block designs. Therefore, an OR-based block combination Q made by $N \otimes M$ has at least one common active slot with N and M.

4. Simulation Experiments

To evaluate the effectiveness of the proposed block combination selection scheme, we built a TOSSIM simulator using nesC in TinyOS [10]. In order to calculate energy consumption, our simulator uses the PowerTOSSIM module [11] which provides various elements related to the energy expenditure elements such as the CPU, sensing modules, EEPROM, ADC, LED, and a radio module. For radio communications, sensor nodes use the CC2420 radio module [12]. The channel access scheme is based on CSMA/CA, and a link model proposed by ANRG group at USC [13] is applied to our simulation study. Then, we consider football field parameters for the log-normal path loss model. The path loss (PL) is calculated using the length of path, denoted by d, the reference distance, denoted by d_0, the pass loss exponent, denoted by α, and a normal random variable, denoted by X, as follows:

$$PL(d)dB = \overline{PL(d_0)} + 10\alpha \log_{10}\left(\frac{d}{d_0}\right) + X \tag{1}$$

For the simulation network topology, we assume 50 sensor nodes are randomly deployed within 100×100 m football field. All the sensor nodes turn on or off a radio module depending on their scheduling algorithm, and the duration of a time slot is 15ms. Scheduling algorithm consists of active and sleep slots. In the active slot, sensor nodes turn on the radio module to send or receive data packets. In the sleep slot, sensor nodes turn off the radio module to reduce energy consumption. In this paper, we consider an asymmetric ratio R for asymmetric simulation, which is used in U-connect protocol [5], as follows:

$$R = \frac{duty \; cycle \; of \; higher \; duty \; cycle \; node}{duty \; cycle \; of \; lower \; duty \; cycle \; node} \qquad (2)$$

For example, if sensor nodes have 10% and 2% duty cycles, R value is 5. Similarly, if sensor nodes have 10% and 1% duty cycles, R value is 10. For evaluating the performance of an OR-based block design, we focus on the following two criteria: discovery latency and energy consumption. These metrics are:

- **Latency:** The elapsed time that a particular sensor node spends until it finally discovers its neighbors.
- **Energy Consumption:** the total energy consumption that a certain sensor node uses for neighbor discovery.

Figure 2 shows the maximum and average latency of each duty cycle based on the (v, k, λ)-BIBD in a symmetric asynchronous scenario. Then, an OR-based block combination also has the same result as the original block design because short and long parts of an OR-based block design (X,A) means one original block respectively. In this graph, a low duty cycle has a large standard deviation and a high latency. In contrast, a high duty cycle has a small standard deviation and a low latency.
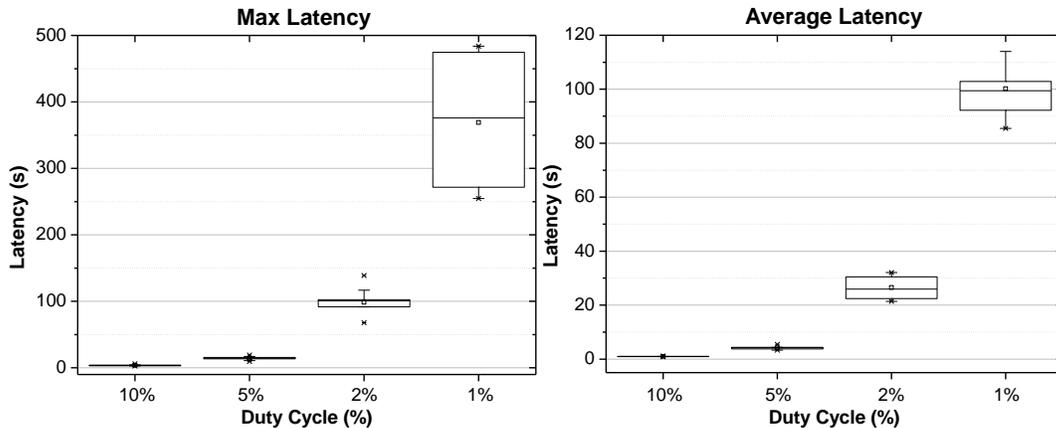

Figure 2. Average Latency each Duty Cycle based on Block Designs in Symmetric Scenarios

Figure 3 the shows maximum and average latency of each scheduling algorithm, which supports asymmetric asynchronous scenario. Then, we consider four R values of 1, 2, 5 and 10. Then, randomly placed sensor nodes are divided into two groups with equal numbers, and each group selects its duty cycles based on the R values such as (10%, 10%), (10%, 5%), (10%, -2%) or (10%, 1%). In Fig. 4, the NDP using the OR-based block combination surpasses the U-connect and Disco NDPs. On the contrary, the max latencies of the U-connect NDP are up to 71% higher than that of the OR-based

block combination NDP. Similarly, the max latencies of the Disco NDP are up to 70% higher than that of the OR-based block combination NDP.
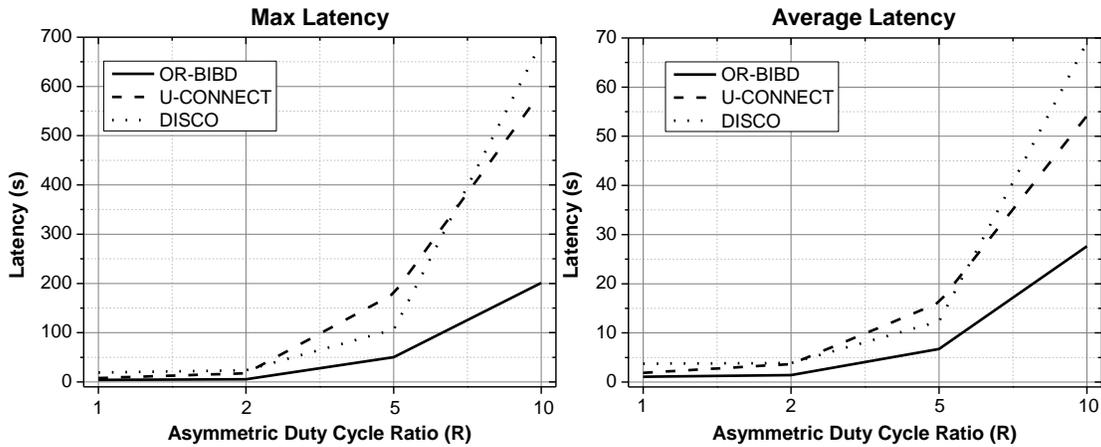

Figure 3. Max and Average Latency each Duty Cycle in Asymmetric Scenarios

Figure 4 shows the maximum and average energy consumptions of three different NDPs at R=1, R=2, R=5 and R=10. The graphs in Figure 4 also show that the OR-based block combination NDP consumes less energy than U-connect and Disco NDPs. Through these experimental results, we conclude that the proposed OR-based block combination NDP is flexible and efficient for asymmetric asynchronous scenarios.
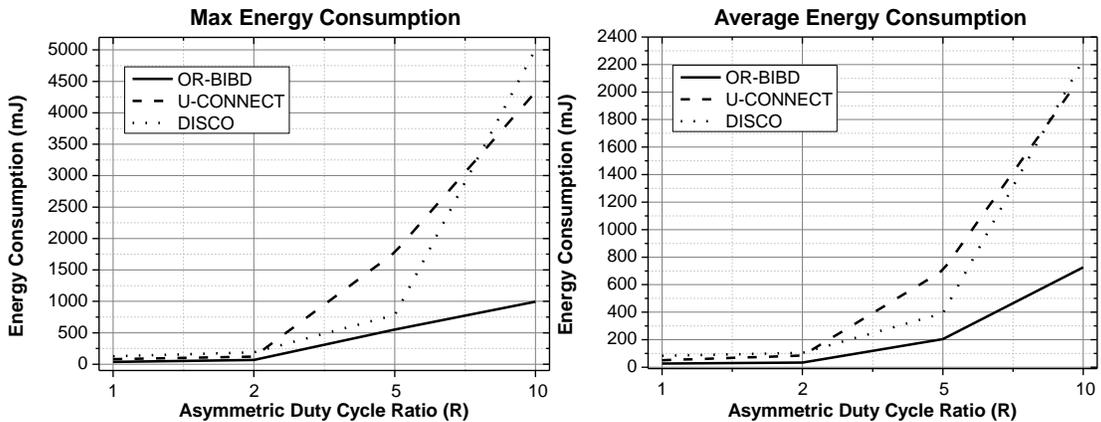

Figure 4. Max and Average Energy Consumption each Duty Cycle in Asymmetric Scenarios

5. Conclusion

Neighbor discovery protocols are one of the critical issues in WSNs. Its ultimate goal is to reduce latency and energy consumption during the discovery phase. In this paper, we introduced a new approach using an OR operation for constructing a block schedule for NDPs. Through the simulation study, we proved that the OR-based block combination NDP outperforms other NDPs, such as U-Connect and Disco, in terms of the latency and energy efficiency. Based on the results of our experimental study, we also conclude that the delay

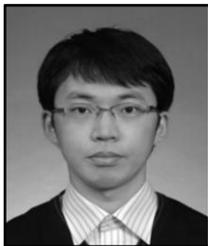guarantee of the proposed OR-based block NDP is very close to that of the NDP based on optimal block designs.

Acknowledgments

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