Multi-channel Broadcast in Asymmetric Duty Cycling Wireless Body Area Networks

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***Abstract*—We formulate and study a broadcast problem arising in multi-channel duty cycling wireless body area networks (WBANs), where the sink needs to broadcast the control message to all sensor nodes. The objective is to design robust multi-channel wake-up schedule with minimum worst-case broadcast delay while guaranteeing the full broadcast diversity regardless of clock drifts and asymmetric duty cycles. To that end, we first derive the lower-bound of worst-case broadcast delay with full diversity of any broadcast protocol and then design a multi-channel broadcast protocol (MCB) that satisfies the performance requirement for the latency and diversity. Finally, the simulation results demonstrate the capability of MCB of ensuring successful broadcast delivery on every channel within the theoretical worst-case broadcast delay, even under asymmetric duty cycles and any amount of clock drifts.**

I. Introduction

Wireless Body Area Networks (WBANs) are the emerging networks designed and developed for human body to monitor and transmit the real-time physiological parameters [1]. Due to the extensive potential applications in the fields of health-care, entertainment and military, WBANs have been paid more attention [2]. A typical WBAN consists of one sink and several sensor nodes on, around or implanted in the human body [3].

Broadcast in WBANs that the sink disseminates the control message to all sensor nodes is an essential operation for network configuration and data collection [4]. However, the widely applied duty cycling technique in WBANs for energy conservation significantly challenges the broadcast protocol design. Specifically, under duty cycle, each node can switch between active and sleep states to save energy.

Moreover, the sink and sensor nodes can operate on multiple channels as specified in IEEE 802.15.6 standard [5] which is customized for WBANs. Such multi-channel characteristic introduces an additional dimension to broadcast problem in WBANs, since the sink not only needs to wake up in the same slot with the sensor nodes, but also should switch to a same channel in order to deliver the broadcast message. Furthermore, some wireless channels in WBANs may be unavailable due to the degradation of channel conditions resulted from the obstacle, noise and interference. Consequently, to achieve the maximum broadcast robustness, an effective multi-channel broadcast protocol needs to guarantee the delivery of broadcast message of the sink to all nodes on every channel.

Despite paramount importance, multi-channel broadcast problem in WBANs has not attracted much attention. A vast majority of existing work has focused on wireless sensor networks (WSNs) or ad hoc networks. The authors in [6] investigated the minimum latency broadcast scheduling problem in duty cycling ad hoc networks and presented a broadcast algorithm of small approximation ratios and low overhead in terms of the total number of transmissions. A novel broadcast scheme was presented in [7], in which the broadcast delivery happened on the overlapped band among multiple adjacent channels with a single transmission that significantly reduced the number of transmissions to multiple channels. Subsequently, with the knowledge of the schedules of the other nodes, the authors in [8] utilized the spatiotemporal locality of broadcast to reduce the total number of broadcast messages transmission. Recently, the authors in [9] constructed a broadcast backbone to minimize the number of transmission in duty cycling WSNs.

However, most of the existing work only considers the scenarios either with single channel or without duty cycle. Moreover, the local clock drift among nodes which can lead to the broadcast failure is overlooked. Besides, previous work cannot support the asymmetric duty cycles.

Motivated by the above observations, we argue that a robust multi-channel broadcast is called for duty cycling WBANs to guarantee the successful broadcast delivery regardless of any amount of clock drifts and any asymmetric duty cycles. To the best of our knowledge, no existing work can satisfy the requirements simultaneously. To fill this gap, we devote this paper to designing a Multi-Channel Broadcast protocol (MCB) for duty cycling WBANs.

The main contributions of this paper are articulated as follows. We first establish a theoretical framework on the multi-channel broadcast problem, under which we derive the performance bound of any multi-channel broadcast schedule achieving full broadcast diversity. Then, we propose MCB by designing channel hopping sequences with two odd numbers used to approximate the duty cycle with fine granularity and guarantee the successful broadcast delivery on every channel. Moreover, the simulation results demonstrate the capability of MCB of ensuring full broadcast diversity under arbitrary clock drift and asymmetric duty cycles.

Roadmap of this paper: Sec. II and III formulate the optimal multi-channel broadcast problem, and present its performance bound, respectively. We then design the multi-channel broadcast protocol and analyze its performance in Sec. IV. Subsequently, we evaluate the performance of MCB in Sec. V and finally conclude this paper in Sec. VI.

II. Problem Formulation

A. System Model

We consider a time-slotted (but not synchronized) duty cycling WBAN with one sink and R sensor nodes operating on N frequency channels in a channel set $\mathcal{N}$, i.e., $N{=}|\mathcal{N}|$. In multi-channel environment, each node wakes up periodically and switches across different channels. Note that each node can only hop to one channel each time. Thus, the main design challenges we need to address are summarized as follows:

1. *Lack of clock synchronization*: due to the energy constraint, it is extremely difficult to maintain tight synchronization, and thus the clock between the sink and the nodes may drift away from each other by an arbitrary amount of time, which may lead to the broadcast failure.

2. *Asymmetric duty cycles*: the duty cycles of the sink and the nodes are typically asymmetric, depending on their individual energy constraint and independent applications. Multi-channel broadcast protocol for duty cycling WBANs should ensure that the sink and each node can wake up in the same slot regardless of their duty cycles.

3. *Broadcast via channel hopping*: to implement the multi-channel broadcast, the sink and each node can hop across multiple channels to deliver or receive the broadcast message. The message can be delivered successfully from the sink to nodes if they hop to the same channel in the same slot. Therefore, we need to design the channel hopping sequence to define the order with which the sink and the node visit the set of the broadcast channels regardless of the clock drifts.

Definition 1 (Multi-channel Wake-up Schedule)**.** *The multi-channel wake-up schedule of an arbitrary node z is defined as a sequence $\mathrm{x}_z \triangleq \{x_z^t\}_{1\leq t\leq T_z}$, where T_z is the period of the sequence, and*

$$x_z^t = \begin{cases} 0, & z \text{ sleeps in slot } t \\ h \in \mathcal{N}, & z \text{ wakes up, operating on channel } h \end{cases}$$

Definition 2 (Duty Cycle)**.** *The duty cycle of an arbitrary node z, denoted by δ_z, is defined as the percentage of slots per period of the multi-channel wake-up schedule x_z where z is active. Formally, δ_z is defined as*

$$\delta_z \triangleq \frac{|t \in [1, T_z] : x_z^t \neq 0|}{T_z}$$

The reciprocal of δ_z is denoted by d_z.

Clock drift. We use *cyclic rotation* to describe the situation where the clocks of different nodes are not synchronized. Specifically, given a multi-channel wake-up schedule x_z, we denote $\mathrm{x}_z(k)$ a cyclic rotation of x_z by k slots, thus

$$\mathrm{x}_z(k) = \{r_z^t\}_{1\leq t\leq T_z}, \text{ where } r_z^t = x_z^{(t+k) \bmod T_z}.$$

In a WBAN, consider the sink s and a node a with their multi-channel wake-up schedules being x_s and x_a whose periods are T_s and T_a, respectively. Given the periodicity of x_s and x_a, it suffices to consider consecutive $\mathrm{lcm}(T_s, T_a)$ slots, i.e. $1{\leq}t{\leq}\mathrm{lcm}(T_s, T_a)$, where $\mathrm{lcm}(\cdot,\cdot)$ defines the least common multiple. If $\exists t{\in}[1, \mathrm{lcm}(T_s, T_a)]$ and $h{\in}\mathcal{N}$ such that $x_s^t{=}x_a^t{=}h$, we say that s can deliver the broadcast message to node a in slot t on channel h. Slot t is called the broadcast slot and channel h is called broadcast channel between the sink s and node a. Example 1 illustrates the above definition.

Slot index	1	2	3	4	5	6	7	8	9	10	11	12	…
Sink s:	0	1	0	2	0	1	0	2	0	1	0	2	…
Node a:	0	2	0	1	0	0	0	2	0	1	0	0	…

(a) Without clock drift

Slot index	1	2	3	4	5	6	7	8	9	10	11	12	…
Sink s:	0	1	0	2	0	1	0	2	0	1	0	2	…
Node a:	2	0	1	0	0	0	2	0	1	0	0	0	…

(b) Node a drifts by 1 time slot to the left

Fig. 1. An example of multi-channel wake-up broadcast schedule

Example 1. *Consider a WBAN with the sink s and one node a operating on two channels, the wake-up schedules of s and a are $\mathrm{x}_s = \{0, 1, 0, 2\}$ and $\mathrm{x}_a = \{0, 2, 0, 1, 0, 0\}$ that have the period lengths of $T_s = 4$ and $T_a = 6$, respectively. The duty cycles of s and a are $\delta_s = \frac{1}{2}$ and $\delta_a = \frac{1}{3}$ or $d_s = 2$ and $d_a = 3$. The multi-channel broadcast schedules of s and a are repeated each 12 (lcm(T_s, T_a)=12) slots. As illustrated in Fig.1 (a), the broadcast delivery can occur in slot 8 on channel 2 and in slot 10 on channel 1 between the sink s and node a. However, when one-clock drift happens in node a, we have $\mathrm{x}_a(1) = \{2, 0, 1, 0, 0, 0\}$, and the sink s cannot deliver the broadcast message to node a in any slot on any channel any more, as shown in Fig.1 (b).*

B. Multi-Channel Broadcast Problem

Let $\{a, a_1, a_2, ..., a_{R-1}\}$ be the set of R sensor nodes. For clarity, in the rest of the paper, we assume node a to be the one with maximum period of schedule sequence, i.e., $T_a \geq T_{a_j}$ for all $j \in [1, R-1]$.

Performance Metric 1: Maximum Broadcast Delay (MBD). In multi-channel broadcast, MBD is the primary performance, which can be interpreted as the latency (in number of slots) before successful broadcast for all possible clock drifts between the sink and all nodes in the worst case. Since the node a with the maximum period of schedule sequence suffers from the worst-case delay, the MBD occurs between the sink s and the node a. Recall Example 1, we can observe that the MBD is infinity, because the broadcast delivery will not occur between $\mathrm{x}_s(0)$ and $\mathrm{x}_a(1)$ as shown in Fig.1 (b).

Performance Metric 2: Maximum Broadcast Delay with Full Diversity (MBD-FD). Full diversity implies the robustness of a multi-channel broadcast protocol. A protocol achieves *full* broadcast diversity if the broadcast delivery can be guaranteed on *every* channel. Thus, MBD-FD is defined as the broadcast time to accomplish full diversity in the worst-case. For example, the multi-channel schedule in Fig.1 (a) fulfills full broadcast diversity in the 10th slot.

Problem 1. *In a WBAN, the multi-channel broadcast problem is defined as follows:*

$$\begin{aligned} &\textit{minimize} \quad T, \\ &\textit{subject to} \quad \forall t_s^0 \in [1, T_s], t_a^0 \in [1, T_a], \forall \delta_s, \delta_a, \exists t \leq T \\ &\qquad\qquad \textit{such that } x_s^t(t_s^0) = x_a^t(t_a^0) = h, \forall h \in \mathcal{N}. \end{aligned}$$

That is, devising multi-channel broadcast schedules to minimize the worst-case broadcast delay T while achieving full diversity between the sink s and node a for any duty cycle pair (δ_s, δ_a), any initial time offset t_s^0 and t_a^0, and any channel set $\mathcal{N}$.

To streamline the paper, in what follows, we first establish a theoretical performance bound of any multi-channel broadcast schedule and then design the multi-channel broadcast schedule to satisfy the requirements.

III. Multi-channel Broadcast Delay Lower-bound

Here, we derive the performance bound of any multi-channel broadcast schedule achieving full broadcast diversity which established the lower-bound of Problem 1.

Theorem 1. *For any multi-channel broadcast protocol solving Problem 1, the MBD-FD between the sink s and the node a, denoted by L, is lower-bounded by $N^2 d_s d_a$, where d_s and d_a denote the reciprocals of the duty cycles of s and a, i.e., $d_s = \frac{1}{\delta_s}$ and $d_a = \frac{1}{\delta_a}$.*

Proof: Denote by T_s and T_a the period of x_s and x_a, i.e. the mutli-channel wake-up schedules of s and a. It can be noted that regardless of the clock drift, the wake-up schedules of s and a repeats every T_sT_a time slots. Hence, if they can map with each other with full diversity regardless of the clock drift, the worst-case broadcast delay until full diversity L is upper-bounded by T_sT_a following from CRT [10].

Without loss of generality, we fix x_s and cyclically rotate x_a by k slots, denoted as $\mathrm{x}_a(k)$, where $k = 0, 1, \ldots, T_sT_a-1$. Since the MBD-FD is the worst-cast broadcast delay until full diversity among all initial clock phases of s and a, there must exist at least N broadcast slots among L slots where both s and a wake up, resulting a minimal number of broadcast slots $\frac{NT_sT_a}{L}$ within consecutive T_sT_a slots. Let S denote the total number of accumulated broadcast slots within consecutive T_sT_a slots between x_s and $\mathrm{x}_a(k)$ as k is incremented from 0 to $T_sT_a - 1$, we have

$$S \geq \frac{N(T_sT_a)^2}{L} \tag{1}$$

On the other hand, let n_s^h (n_a^h, respectively) denote the number of time slots in x_s (x_a, respectively) in which s (a) wakes up on channel h within consecutive T_sT_a slots. We can express the reciprocals of the duty cycles of s and a as

$$d_s = \frac{T_sT_a}{\sum_{h\in\mathcal{N}} n_s^h}, \quad d_a = \frac{T_sT_a}{\sum_{h\in\mathcal{N}} n_a^h}.$$

After some algebraic operations, we obtain

$$T_sT_a = \sum_{h\in\mathcal{N}} d_s n_s^h = \sum_{h\in\mathcal{N}} d_a n_a^h = \sum_{h\in\mathcal{N}} \frac{d_s n_s^h + d_a n_a^h}{2}. \tag{2}$$

Since x_s and $\mathrm{x}_a(k)$ achieve full diversity, for any channel h, the total accumulated number of broadcast between x_s and $\mathrm{x}_a(k)$, as k is incremented from 0 to $T_sT_a - 1$, in which the broadcast channel is h, is $S = \sum_{h\in\mathcal{N}} n_s^h n_a^h$.

For $d_s n_s^h d_a n_a^h \leq (\frac{d_s n_s^h + d_a n_a^h}{2})^2$, it follows from Eq.(2) that

$$S = \sum_{h\in\mathcal{N}} n_s^h n_a^h = \frac{\sum_{h\in\mathcal{N}} d_s n_s^h \cdot d_a n_a^h}{d_s d_a} \leq \frac{(T_sT_a)^2}{d_s d_a N}.$$

It then follows from Eq.(1) that $\frac{N(T_sT_a)^2}{L} \leq \frac{(T_sT_a)^2}{d_s d_a N}$, which leads to $L \geq N^2 d_s d_a$. ■

IV. Multi-channel Broadcast Protocol Design

In this section, we first introduce the co-prime pair property which is the methodology of this paper and then design MCB protocol and analyze its performance.

A. Preliminary

In a WBAN, the wake-up schedules of the sink s and node a are determined by their duty cycles. Specifically, we consider s and a with sets of integers (not necessarily distinct) $D_s = \{d_1^s, d_2^s, ..., d_{|D_s|}^s\}$ and $D_a = \{d_1^a, d_2^a, ..., d_{|D_a|}^a\}$, respectively. If the integer sets of D_s and D_a satisfy the following *co-prime pair property*, the sink s and node a will wake up simultaneously in the same slot.

Property 1 (Co-prime Pair Property)**.** *For the sink s and the node a under a co-primality, there exits an integer in D_s that is co-prime to an integer in D_a, i.e., $\exists d_{i_0}^s \in D_s$ and $\exists d_{j_0}^a \in D_a$ such that $d_{i_0}^s$ and $d_{j_0}^a$ are co-prime. The wake-up sequence $\mathrm{x}_a \triangleq \{x_a^t\}_{1\leq t\leq T_a}$ under this co-primality is*

$$x_a^t = \begin{cases} 1 & t \text{ is divisible by some } d_j^a \in D_a, \\ 0 & \text{otherwise}. \end{cases}$$

The period length is $T_a = lcm(d_1^a, d_2^a, ..., d_{|D_a|}^a)$ and its duty cycle δ_a is

$$\delta_a = \sum_{1\leq j_1\leq|D_a|} \frac{1}{d_{j_1}^a} - \sum_{1\leq j_1<j_2\leq|D_a|} \frac{1}{lcm(d_{j_1}^a, d_{j_2}^a)} \cdots + (-1)^{|D_a|+1} \frac{1}{lcm(d_1^a, d_2^a, ..., d_{|D_a|}^a)}.$$

Following from the Chinese Remainder Theorem (CRT) [10], we can obtain the following theorem.

Theorem 2. *A co-primality can guarantee that the sink s and node a wake up in the same time slot for any amount of clock drift if the associated integer sets satisfy the co-prime pair property. And the broadcast delay between s and a is bounded by the product of the two smallest co-prime numbers, one from each set, i.e.:*

$$\min_{\gcd(d_i^s, d_j^a)=1, 1\leq i\leq D_s, 1\leq j\leq D_a} \{d_i^s \cdot d_j^a\},$$

where $\gcd(\cdot,\cdot)$ is the greatest common divisor.

Suppose that s and a with duty cycles $\delta_s = \frac{1}{d_s}$ and $\delta_a = \frac{1}{d_a}$, wake up every d_s and d_a slots, i.e., $x_s^t = 1$ for $t = kd_s$ and $x_a^t = 1$ for $t = kd_a + \delta_{sa}$ where δ_{sa} is the clock drift between s and a, $k = 1, 2, \cdots$, the following congruence system w.r.t. t applies:

$$\begin{cases} t \equiv 0 & (\bmod\ d_s) \\ t + \delta_{sa} \equiv 0 & (\bmod\ d_a). \end{cases} \tag{3}$$

If t is a solution to Eq.(3), then the sink s will deliver the broadcast message to node a in t-th time slot of the sink (i.e., node a's $(t+\delta_{sa})$-th time slot). It follows from the CRT that if d_s and d_a are co-prime with each other, the broadcast delivery is ensured regardless of δ_{sa}, i.e., there exists a solution $t \equiv t_d$ (mod lcm(d_s, d_a)) such that $x_s^{t_d} = x_a^{t_d}(\delta_{sa}) = 1$, $\forall \delta_{sa}$.

B. MCB Protocol Design

Robust broadcast protocol in multi-channel case needs to ensure that the sink and nodes activate in the same slot and switch to the same channel and fulfill the full broadcast diversity. Motivated by the co-prime pair property, a commonly adopted solution is to use only prime numbers because two distinct prime numbers are definitely co-prime to each other, which, however, limits the choices to prime numbers and fails to support all the duty cycle due to the limited number of prime numbers. Note that there are only $\frac{1}{6}$ prime numbers among natural numbers smaller than 1000. To break the limit, we devise the following wake-up schedule in MCB, by using two consecutive odd integers.

Moreover, to ensure that any node z can hop to every channel h ($h \in \mathcal{N}$) in one period, we extend the length of the wake-up schedule sequence to $(2Nd_z+1)(2Nd_z-1)$ and let the node hop to another channel every d_z slots, where d_z is the reciprocal of its duty cycle. Thus, for any node z, it can wake up and hop across different channels based on the following schedule:

$$x_z^t = \begin{cases} h & t - hd_z \text{ is divisible by } 2Nd_z \pm 1, \\ 0 & \text{otherwise,} \end{cases}$$

where $x_z^t = h$ signifies that node z wakes up on channel h in slot t while $x_z^t = 0$ indicates that z sleeps in the slot.

In a duty cycling WBAN, we need to guarantee that the successful broadcast with full diversity between the sink s and any node a occurs for any initial time offset t_s^0 and t_a^0 within a bounded delay. To that end, we should make sure that at least one of $2Nd_s \pm 1$ is co-prime with at least one of $2Nd_a \pm 1$ based on the CRT and Theorem 2. Example 2 illustrates the wake-up schedule in our MCB protocol for s and a.

Example 2. *Consider a WBAN of two channels (i.e., $N = 2$), the sink s and the node a with duty cycles $\delta_s = \frac{1}{2}$ and $\delta_a = \frac{1}{3}$ respectively. Under the above multi-channel broadcast schedule, s wakes up on channel h_1 in slots $7k + 2$ and $9k + 2$, i.e., $9, 11, 16, 20, 23, 29, \ldots$, and on channel h_2 in slots $7k + 4$ and $9k + 4$, i.e., $11, 13, 18, 22, 25, 31, \ldots$. Similarly, a wakes up on channel h_1 in slots $11k + 3$ and $13k + 3$, i.e.,$14, 16, 25, 29, 36, 42, \ldots$, and on channel h_2 in slots $11k + 6$ and $13k + 6$, i.e.,$17, 19, 28, 32, 39, 45, \ldots$, as illustrated in Fig. 2. The broadcast delivery with full diversity happens between s and a at the 32nd slot.*

Note that the above construction of x_a does not take into account the case where there exist two different channels h_c ($c = 1, 2$) such that node a needs to hop to two different channels at the same time slot t, when $(t - h_1 d_a) \equiv 0 \pmod{2Nd_a+1}$ and $(t - h_2 d_a) \equiv 0 \pmod{2Nd_a - 1}$. Once the conflict happens, node a will select the channel h_c which differs from the one that it picked in last wake-up slot. For example, the sink s needs to hop to channel h_1 and h_2 in slot 11 based on the multi-channel schedule, since $(11 - 2)$ is divisible by 9 and $(11 - 4)$ is also divisible by 7. In order to resolve this conflict, the node picks channel h_2 in slot 11 because it stayed on h_1 in the last wake-up slot 9, as shown in Fig. 2 (a).

C. Granularity of MCB

Granularity of MCB in matching any required duty cycle in practical applications. Following the wake-up schedule in MCB, the period of x_z is $(2Nd_z-1)(2Nd_z+1)$, in which there are $N(4Nd_z-1)$ active slots. Hence, the actual average duty cycle $\hat{\delta_z}$ is $\frac{N(4Nd_a-1)}{(2Nd_z-1)(2Nd_z+1)}$, which is different from the required duty cycle $\delta_z = \frac{1}{d_z}$.

In order to evaluate the accuracy between actual duty cycle and the expected duty cycle in practical applications, we next discuss the granularity of MCB. Consider the expected duty cycle δ_z of node z and its actual value $\hat{\delta_z}$, we define the relative error $\epsilon(\delta_z)$ between δ_z and $\hat{\delta_z}$ as

$$\epsilon(\delta_z) = \frac{|\hat{\delta_z} - \delta_z|}{\delta_z}, \tag{4}$$

which is formally derived in the following lemma. Note that the relative error of other nodes can be also derived in the similar way.

Lemma 1. *The relative error between the duty cycle of the actual wake-up schedule $\hat{\delta_z}$ and the required duty cycle δ_z is upper-bounded by $\frac{1}{4Nd_z}$, where N is the number of channels.*

Proof: As $d_z = \frac{1}{\delta_z} \geq 1$, following the definition of the relative error $\epsilon(\delta_z)$, we have:

$$\begin{aligned} \epsilon(\delta_z) &= \left| \frac{N(4Nd_z - 1)}{(2Nd_z - 1)(2d_z + 1)} - \frac{1}{d_z} \right| / \frac{1}{d_z} \\ &= \frac{Nd_z - 1}{4N^2 d_z^2 - 1} < \frac{1}{4Nd_z}. \end{aligned}$$

■

Lemma 1 implies that the relative error decreases with the decline of the desired duty cycle and the number of channels. In practical applications of WBANs, δ_z is typically smaller than 10% and thus ϵ is upper bounded by 2.5%, which is a very small relative error. Therefore, in multi-channel case, the MCB protocol can provide fine duty cycle granularity.

Granularity of MCB in supporting duty cycle in practical applications. Following the CRT, the broadcast delivery between the sink and all nodes in MCB, regardless of their clock drifts, requires at least one of $2Nd_s \pm 1$ to be co-prime with at least one of $2Nd_a \pm 1$, which can be satisfied in the vast

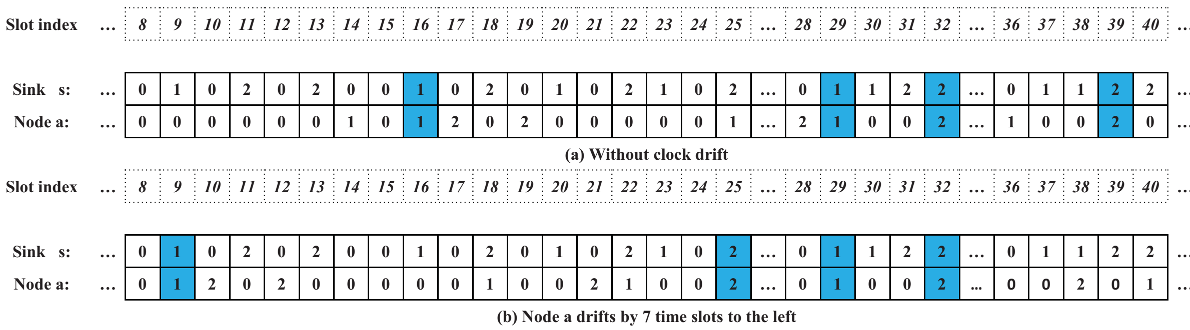

Fig. 2. MCB in multi-channel case: $d_s = 2$, $d_a = 3$

majority of cases. To prove this, we take two examples with the maximum duty cycle reciprocal $D = 100$ and $D = 1000$. When $D = 100$, all duty cycle $\frac{1}{d}$ except $d = 17$ and 38 can be supported by MCB; when $D = 1000$, only 43 duty cycles cannot be supported, i.e., MCB can support nearly 96% of all duty cycles.

To tackle the case that the integer sets of s and a based on their desired duty cycles coincidentally do not satisfy the co-prime pair property, we can let s (or a) operate on $\frac{1}{d_s \pm 1}$ (or $\frac{1}{d_a \pm 1}$), because at least one from $\frac{1}{d_s \pm 1}$ (or $\frac{1}{d_a \pm 1}$) is co-prime with $\frac{1}{d_a}$ (or $\frac{1}{d_s}$). For example, when $D_s = \{33, 35\}$ and $D_a = \{75, 77\}$, where for $\forall d_i^s \in D_a, \forall d_j^a \in D_a$, we have $\gcd(d_i^s, d_j^a) > 1$, we can let s operate on $D_s = \{31, 33\}$ or $\{35, 37\}$ any of which satisfies the co-prime pair property with $D_a = \{75, 77\}$. Similarly, the co-prime pair property can be satisfied by revising the integer set of a.

Specifically, take an example with the revised duty-cycle $\frac{1}{d_a - 1}$ for a, its actual duty cycle is $\frac{4N^2(d_a-1)-N}{(2N(d_a-1)-1)(2N(d_a-1)+1)}$. The relative error between the actual duty cycle and the required duty cycle can be computed as

$$\begin{aligned}\epsilon'(\delta_a) &= \left| \frac{4N^2(d_a-1)-N}{(2N(d_a-1)-1)(2N(d_a-1)+1)} - \frac{1}{d_a} \right| / \frac{1}{d_a} \\ &\approx \frac{Nd_a - 1}{4N^2(d_a-1)^2 - 1}.\end{aligned}$$

D. MBD-FD of MCB

This subsection studies the theoretical performance of our proposed multi-channel broadcast schedule MCB, specifically, the second performance metric on MBD-FD. As the MBD-FD is ensured, the MBD can be achieved.

Theorem 3. *If $\frac{1}{d_s}$ and $\frac{1}{d_a}$ are the available duty cycles of the sink s and the node a, respectively, the broadcast with full diversity is achieved within at most $(2Nd_s + 1)(2Nd_a + 1)$ slots, regardless of their clock drifts, specifically, $O(N^2 d^2)$ if $d_s \simeq d_a \simeq O(d)$.*

Proof: Recall the co-prime pair property, we have that at least one of $2Nd_s \pm 1$ is co-prime with at least one of $2Nd_a \pm 1$. Without loss of generality, assume that $2Nd_s + 1$ is co-prime with $2Nd_a + 1$. It follows from the CRT that there exists $t_0 < (2Nd_s + 1)(2Nd_a + 1)$ such that $x_s^{t_0}(t_s^0) = x_a^{t_0}(t_a^0) = h$ for any channel h and it holds that on slots $t_k = t_0 + k(2Nd_s + 1)(2Nd_a + 1)$, the broadcast delivery can be ensured to occur between the sink s and node a. Therefore, the MBD-FD is ensured within at most $(2Nd_s + 1)(2Nd_a + 1)$. ■

Take the example 2 with $N = 2$, $d_s = 2$ and $d_a = 3$, the broadcast delay with full diversity is 32 slots without clock drift and 25 slots with clock drift $k = 7$, as shown in Fig. 2 (a) and (b), which are less than MBD-FD=117.

The capability to achieve broadcast delivery on every channel within bounded delay significantly improves robustness of multi-channel broadcast protocol in wireless environment where channel conditions are unpredictable and dynamic in both time and space.

V. Performance Evaluation

In this section, we evaluate the performance of MCB in terms of reliability and broadcast delay in several typical application scenarios. Since no prior work handles multi-channel broadcast problem in duty cycling WBANs, we compare with the naive random scheme, referred to as Random, as a benchmark where the sink and node randomly choose their active slots based on their individual duty cycles and hop to a random channel among their channel sets.

Specifically, we first illustrate the reliability of Random and the proposed MCB protocol. Then, we investigate the impact of duty cycles of nodes on the broadcast delay and show the robustness of MCB against the clock drift, subsequently. Note that the broadcast delay is calculated by the number of time slots.

A. Reliability Comparison

To comprehensively evaluate the performance of MCB, we simulate the multi-channel scenarios for a WBAN of one sink and 10 sensor nodes. Specifically, the number of channel in the simulation varies among $N = 1, 3, 5, 8$ corresponding to IEEE 802.15.6 [5] on low band of UWB and high band of UWB. Moreover, asymmetrical duty cycles, $\frac{1}{75}$ and $\frac{1}{80}$, are set for the sink and nodes, respectively. Quantitatively, we present the reliability of MCB and Random in Tab. I where all results are calculated from 1000 independent experiments.

It is noticed that MCB can achieve 100% reliability, demonstrating that MCB achieves the successful multi-channel broadcast with full diversity between the sink and all sensor nodes within bounded broadcast delay. However, the reliability

TABLE I
RELIABILITY COMPARISON OF MCB AND RANDOM

Protocols	Reliability			
	$N=1$	$N=3$	$N=5$	$N=8$
Random	0.655	0.556	0.19	0.09
MCB	1	1	1	1

of Random is only 65.5% when $N = 1$ and it dramatically decreases with the increase of N. The main reason lies in that MCB carefully tunes the wake-up and channel hopping sequence according to the co-prime pair property to ensure that the sink and nodes can active at a same time slot and hop to a same channel.

Due to the severe unreliability of Random, we next focus on the performance evaluation of MCB in a series of typical application scenarios.

B. Broadcast Delay

MBD-FD under asymmetric duty cycles: the duty cycles of the sink and nodes are randomly chosen from $[\frac{1}{10i}, \frac{1}{10(i+1)}]$ with $i = 1, 3, 5, 7$, that is, the duty cycle varies from 10% (large) to 1.25% (small).

From the simulation results shown in Fig. 3, we make the following observations: First, MCB protocol can not only support almost all duty cycles but also ensure the successful broadcast delivery with full diversity within bounded broadcast delay as proved in Theorem 3 despite the asymmetric duty cycles. Second, the broadcast delay increases with the scale of the channel set size and the reciprocal of duty cycle, which is in accordance with the analytical results. This property makes MCB especially adaptive for duty cycling WBANs of heterogeneous nodes.

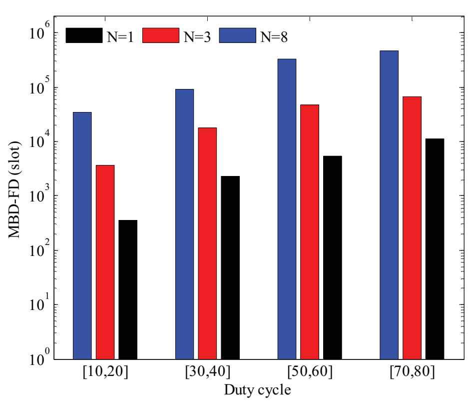

Fig. 3. MBD-FD under different duty cycles.

MBD-FD with clock drifts: to investigate the impact of clock drift on the performance of MCB, we set the small duty cycles of the sink and nodes to $\frac{1}{75}$ and $\frac{1}{80}$, respectively, and randomly select the clock drift k from $[0.1i, 0.1(i+1)] * T_s T_a$ with $i = 1, 3, 5, 7, 9$ where the period $T_s T_a = (2Nd_s + 1)(2Nd_a + 1)$.

As illustrated in Fig. 4, MCB can achieve full diversity within the theoretically derived MBD-FD under any clock drift between the sink and the nodes. MCB thus can work efficiently without the tight clock synchronization, which makes MCB appropriate for energy-constrained WBANs.

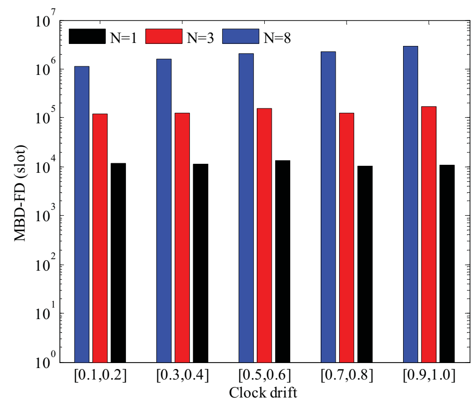

Fig. 4. MBD-FD under different clock drifts.

VI. CONCLUSION

In this paper, we have investigated the multi-channel broadcast problem in duty cycling WBANs. The performance bounded of any multi-broadcast protocol has been derived. Moreover, an effective MCB has been proposed to guarantees the successful broadcast delivery with full diversity regardless of the clock drifts and asymmetric duty cycles. Furthermore, we have derived the theoretical characteristic of maximum broadcast delay to full diversity. Finally, the simulation results have demonstrated the capability of MCB in ensuring broadcast delay in several typical application scenarios.

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