Multichannel Broadcast in Duty-Cycling WBANs via Channel Hopping

Rongrong Zhang, Hassine Moungla, Jihong Yu, Lin Chen, and Ahmed Mehaoua

***Abstract*—We formulate and study a broadcast problem arising in multichannel duty-cycling wireless body area networks (WBANs) which the sink needs to broadcast control information to all sensor nodes on or implanted in the human body. Despite its fundamental importance for the network configuration and secure key management, the multichannel broadcast problem is largely unaddressed in duty-cycling WBANs. In this paper, we devise novel 2-D scheduling specifying the rule of channel hopping and wake-up time slot selection, which achieves the order-minimal worst-case broadcast delay while guaranteeing the full broadcast diversity regardless of clock drifts and asymmetric duty cycles and channel perceptions. Specifically, we first employ the Chinese remainder theorem to design an effective multichannel broadcast (MCB) algorithm and further propose improved MCB that enhances the granularity of MCB in matching actual duty cycles and number of channels, reducing the theoretically worst-case broadcast delay of MCB by up to 75%. We demonstrate the performance of the proposed algorithms through theoretical analysis and extensive simulations.**

***Index Terms*—Channel hopping, duty cycle, multichannel broadcast, wireless body area networks (WBANs).**

I. INTRODUCTION

WIRELESS body area networks (WBANs) are the emerging networks designed and developed for human body to monitor, manage, and transmit the physiological parameters [1]. Due to the highly extensive potential applications ranging from medical to nonmedical applications, such as health-care monitoring, rehabilitation, fitness, military, and defense [2], WBANs have attracted considerable attentions in recent years. A typical WBAN consists of one sink and several sensor nodes on, around or implanted in the human body, wherein the sink can collect all sensed data from sensor nodes and send it to users via an external gateway [3].

Broadcast that the sink disseminates the control message to all sensor nodes is an essential/fundamental operation in WBANs for network configuration [4], data collection [5], secure key management [6], and privacy protection [7]. There are three main challenges, however, in designing broadcast algorithm for multichannel duty-cycling WBANs.

1) *Duty Cycles:* The sink cannot know duty cycle schedules of sensor nodes. Specifically, the sink and each sensor node in WBANs work in duty-cycling mode for energy conservation by alternating between the shorter active and the longer sleep states [8]. In such a duty-cycling WBAN, the broadcast message can be delivered to a sensor node if and only if the sink and the sensor node wake up in the same time slot. But due to their independent energy constraint and individual applications [9], they have heterogeneous desired duty cycles and may fail to activate in the same time slots, it is thus a challenging problem that how to schedule wake-up slots to guarantee the required duty cycles and successful broadcast delivery without any prior coordination.
2) *Clock Synchronization:* It is difficult to maintain tight synchronization [10] among local clocks of the sink and the sensor nodes in a distributed system. If their clocks drift away from each other, the broadcast will fail though they wake up in the same time slot number in the sense of their individual local clocks, which makes the broadcast problem more difficult.
3) *Multiple Channels:* The sink cannot know channel-hopping schedules of sensor nodes. To alleviate bandwidth limitations and improve the reliability and stability in wireless communications, the sink and sensor nodes are allowed operate on multiple frequency channels as specified in IEEE 802.15.6 standard [11]. In such a multichannel WBAN, the sink can communicate with a sensor node if and only if they hop to the same channel in the same time slot. On the other hand, from the perspective of the notorious instability of wireless channels in both time and space domains, the sink and sensor nodes may experience different channel perceptions due to their locations, interference and noises. In this case, the broadcast will fail though the sink and sensor nodes hop to the channel with the same number in the same time slot, challenging the network robustness which is of great importance in the health-care monitoring applications of WBANs.

Albeit considerable research effort has been devoted to studying broadcast problem in wireless sensor networks or ad hoc networks, they just address one of the three challenges (Section II). In contrast, this paper aims at addressing all the challenges above arising from multichannel broadcast (MCB) problem in duty-cycling WBANs: when the sink and sensor

Manuscript received September 3, 2017; revised October 12, 2017; accepted October 21, 2017. Date of publication October 26, 2017; date of current version December 11, 2017. *(Corresponding author: Jihong Yu.)*

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Digital Object Identifier 10.1109/JIOT.2017.2767018

nodes with heterogenous duty cycles and asynchronous clocks operate on multiple channels, the sink can achieve successful broadcast delivery and full broadcast diversity (maximum robustness) with bounded worst-case delay.

Specifically, we develop 2-D scheduling containing wake-up time slot schedules and channel-hopping sequences for the sink and sensor nodes. The main contributions of this paper can be articulated as follows.

1) We establish a theoretical MCB framework and exploit the Chinese remainder theorem (CRT) to design an MCB algorithm with power-multiple of two used to approximate actual duty cycles and number of channels.
2) We develop an improved algorithm, referred to as improved MCB, to further reduce the broadcast delay in the worst case by enhancing the granularity of MCB.
3) We demonstrate theoretically and experimentally that the proposed algorithms achieve the successful broadcast delivery with full diversity within the order-minimal worst-case delay regardless of heterogenous duty cycles and asynchronous clocks and asymmetric channel perceptions.

The remainder of this paper is organized as follows. Section II gives an overview of related work. Section III presents the system model and formulates the MCB problem. Sections IV and V introduce the MCB and its improved algorithm, respectively, as well as the theoretical performance analysis. In Section VII, we conduct extensive simulations for performance evaluation, and finally conclude this paper in Section VIII.

II. Related Work

The MCB problem has not yet been studied in the context of duty-cycling scenarios. To the best of our knowledge, this is the first contribution so far to design the MCB algorithms in duty-cycling WBANs. Albeit, a number of algorithms, have been proposed to address the broadcast problem in wireless sensor networks or ad hoc networks, they do not involve two dimensions simultaneously, i.e., duty cycles and multiple channels.

Broadcast in duty-cycling networks. As a representative of the groundbreaking work, Wang and Liu [12] formulated a broadcast problem in duty-cycling wireless sensor networks and presented a centralized optimal solution. Jiao *et al.* [13], [14] proved NP hardness of the minimum latency broadcast problem in duty-cycling ad hoc networks. Then they proposed a suit of order-optimal approximate algorithms to solve this problem. Guo *et al.* [15] proposed a probabilistic flooding scheme to deal with the duty-cycling broadcast problem based on the delay distribution of next-hop receivers. Xu *et al.* [16], [17] utilized the spatiotemporal locality of broadcast to reduce the total number of broadcast messages transmission in wireless sensor networks. They reduced energy cost by having early wake-up nodes that can overhear the broadcast message postpone their wake-up slots. They also revealed NP hardness of the problem and proposed an algorithm of a polylogarithmic approximation ratio. Recently, Xu *et al.* [18] studied the broadcast problem from the perspective of load balance and proposed a λ-approximation assignment algorithm, where λ is the maximum number of neighbors scheduled to wake up together.

Nevertheless, in all the work above, each node needs to know the scheduling information of others *a priori*, which is unrealistic and does not differ their duty-cycling broadcast from the traditional one essentially. In addition, none of them take into account multichannel setting.

Broadcast in multichannel environment. Song and Xie [19], [20] proposed a distributed broadcast scheme that constructed the broadcasting sequences for both sender and receiver without requirement of clock synchronization. Dabideen *et al.* [21] group the modes with at least one same channel to reduce the number of transmission. None of the algorithms above, however, can guarantee successful broadcast delivery on all common channels (full diversity), which may render the flop of the broadcast task once the would-be delivery channel is unavailable due to the interference or noises. Lim *et al.* [22] devised a signal processing mechanism for WLAN to decode information transmitted on the subchannels in the overlapped band of adjacent channels between the sender and the receiver, reducing transmissions to multiple channels. This paper, however, requires higher capability of nodes, which goes against the lightweight nature of WBANs. Moreover, it cannot work with asynchronous clocks and asymmetrical channel perceptions. The most similar works were done by Lin *et al.* [23] and by Chen *et al.* [24], [25], respectively. Specifically, Lin *et al.* [23] proposed a channel-hopping scheme based on the properties of Galois Field, in which the nodes could independently decide their own channel schedules and ensure network connectivity at the same time. Chen *et al.* [24], [25] addressed the MCB problem in one-hop infrastructure-based cognitive radio networks by using Langford Paring and Skolem Sequence to design channel-hopping sequences, respectively. These algorithms, however, cannot be applied in duty-cycling WBANs where the desired properties of Galois Field, and Langford Paring and Skolem Sequence cannot be satisfied. Besides, they cannot work in practical scenarios with asymmetrical channel perceptions where nodes are unaware of the available channel sets of each other.

In summary, no existing work has been done on the broadcast problem with the consideration of two dimensions of multiple channels and duty cycles despite their considerable applications in practical networks. In order to bridge this gap, we devote this paper to addressing the MCB problem in duty-cycling WBANs from the perspectives of theoretical framework and algorithm design.

III. System Model and Problem Formulation

In this section, we first introduce the system model and then define the MCB problem formally.

A. System Model

We consider a time-slotted duty-cycling WBAN which consists of one sink and a set $\mathcal{R}$ of R sensor nodes of a single half-duplex radio interface operating on N frequency channels in a channel set $\mathcal{N}$, i.e., $N \triangleq |\mathcal{N}|$. In a generic WBAN, the

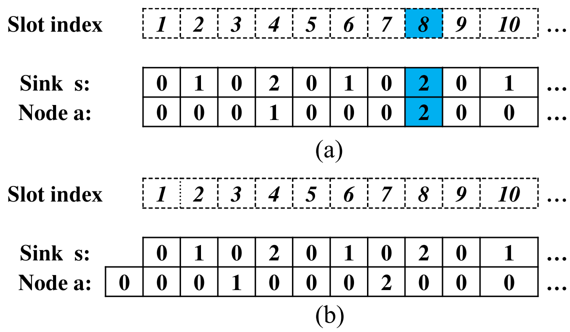

Fig. 1. Example of MCB. (a) Without clock drift. (b) Node a drifts by 1 time slot to the left.

sensor nodes can communicate with the sink by single hop as specified in IEEE 802.15.6 [11]. In multichannel environment, the sink and each node wake up periodically based on their individual duty cycles and can switch across multiple channels. For analytical tractability, we assume that node a has the smallest duty cycle in $\mathcal{R}$, i.e., the successful broadcast delivery can be achieved between the sink and all nodes if it is ensured between the sink and node a. Given such a WBAN, the objective of this paper is to design reliable and efficient algorithms to guarantee successful broadcast between the sink and node a.

As mentioned in Section I, the main challenges in the algorithm design lie in the following.

1) *Lack of Clock Synchronization:* The clocks of the sink and nodes may drift away from each other by an arbitrary amount of time.
2) *Heterogenous Duty Cycles:* The sink and nodes do not know duty cycles of each other.
3) *Asymmetric Channel Perceptions:* The sink and nodes do not know channel-hopping sequences of each other, and they may also experience different channel perceptions.

For clearness, we illustrate an example with two orthogonal channels as shown in Fig. 1 where the sink s and node a wake up based on their duty cycles and switch to a channel following their channel-hopping sequences. Without clock drift, the broadcast succeeds in 8th time slot on channel 2 as shown in Fig. 1(a). Unfortunately, once node a drifts by 1 time slot to the left, the sink s can never broadcast message to node a as depicted in Fig. 1(b). Thus, the first problem we face is *how to schedule channel hopping for the sink and nodes to ensure the successful broadcast delivery regardless of their duty cycles and clock drifts?* On the other hand, the sink s can only broadcast message to node a on channel 2 not on channel 1 in Fig. 1(a). While wireless channel condition experiences spatiotemporal variation. Once channel 2 is unavailable, the broadcast will fail. In order to improve the reliability and robustness, the successful broadcast delivery should be achieved on every common channel. Therefore, the second problem we need to solve is *how to devise the channel-hopping sequences for the sink and nodes to achieve full broadcast diversity in multichannel environment?*

Based on these observations, we will develop MCB algorithms to address the two problems. Before the algorithm design, we first introduce the following definitions for an arbitrary node u in a WBAN for mathematically formulating the MCB problem.

Definition 1 (Channel-Hopping Schedule): The channel-hopping schedule of a node u is defined as a integer sequence $x_u \triangleq \{x_u^t\}_{1\le t\le T_u}$, where T_u is the period of the sequence, and

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

The channel-hopping sequence for node u is represented as

$$x_u = \left\{x_u^1, x_u^2, \ldots, x_u^i, \ldots, x_u^{T_u}\right\}$$

where integer $x_u^t \in [0, N]$. If $x_u^i = x_u^{i+1}$, $\forall i \in [1, T_u - 1]$, node u stays on the same channel and does not hop.

Consider that the sink s intends to broadcast messages to each of the sensor nodes named u without loss of generality. Given two channel hopping sequences of x_u and x_s whose periods are T_u and T_s, respectively, if there exists $t \in [1, T_u T_s]$ such that $x_u^t = x_s^t = h$, where $h \in [1, N]$, we say that s can deliver message to u in the tth time slot on broadcast channel h. The tth time slot is called a *broadcast delivery slot* and channel h is called a *broadcast delivery channel* between u and s. In Fig. 1(a), we have $x_a = \{0, 0, 0, 1, 0, 0, 0, 2\}$ and $x_s = \{0, 1, 0, 2\}$, and the periods T_a and T_s are 8 and 4, respectively. As $x_a^8 = x_s^8 = 2$, the corresponding broadcast delivery slot and broadcast delivery channel are 8th slot and channel 2.

Let $\mathcal{T}(x_u, x_s)$ denote the *set of broadcast delivery slots* between two channel-hopping sequences x_u and x_s, and $|\mathcal{T}(x_u, x_s)| \in [1, T_u T_s]$. The element of $\mathcal{T}(x_u, x_s)$ reflects time slot number when broadcast succeeds within a period, such as $\mathcal{T}(x_a, x_s) = \{8, 16, 24, 32\}$ in Fig. 1(a).

Given N broadcast channels, let $\mathcal{C}(x_u, x_s)$ denote the *set of broadcast delivery channels* between two channel-hopping sequences x_u and x_s. The cardinality of $\mathcal{C}(x_u, x_s)$ denotes the number of broadcast delivery channels, i.e., $|\mathcal{C}(x_u, x_s)| \in [0, N]$, which measures the broadcast diversity, i.e., the number of channels in which the successful broadcast delivery occurs. Recall Fig. 1(a), we have $\mathcal{C}(x_a, x_s) = \{2\}$.

Definition 2 (Duty Cycle): The duty cycle of a node u, denoted by δ_u, is defined as the percentage of active time slots per period of the channel-hopping schedule x_u. Formally

$$\delta_u \triangleq \frac{|t \in [1, T_u] : x_u^t \neq 0|}{T_u}.$$

The reciprocal of δ_u is denoted by d_u.

As illustrated in Fig. 1(a), the duty cycles of the sink and node a are $\delta_s = (1/2)$ and $\delta_a = (1/4)$, respectively.

Definition 3 (Clock Drift): We apply *cyclic rotation* to model the situation that the clocks of different nodes are not synchronized. Specifically, given a channel-hopping schedule x_u, we define a cyclic rotation of x_u by k slots as $x_u(k)$, that is,

$$x_u(k) = \{r_u^t\}_{1\le t\le T_u}$$

where $r_u^t = x_u^{(t+k) \bmod T_u}$.

For example, $x_a(1) = \{0, 0, 1, 0, 0, 0, 2, 0\}$ in Fig. 1(b). In order to guarantee successful broadcast delivery, the channel-hopping sequences of x_u and x_s must satisfy that the number of broadcast delivery channels is greater than or equal to 1 for all possible clock drifts, i.e., $|\mathcal{C}(x_u(k), x_s(l))| \geq 1, \forall k, l \in \mathbb{Z}$.

B. Performance Metrics

Given an MCB algorithm for WBANs, we introduce the following metrics for evaluating its performance.

1) *Broadcast Diversity:* The broadcast diversity characterizes the capability of an MCB algorithm of delivering a broadcast message regardless of its operational channel, which measures the lower bound of broadcast delivery channel set size between the sink and an arbitrary sensor node with any duty cycle and clock drift. The broadcast diversity is thus expressed as

$$\text{DIV} = \min_{\forall \delta_u, \delta_s, \forall k, l \in \mathbb{Z}} |\mathcal{C}(x_u(k), x_s(l))|.$$

We say that an MCB algorithm achieves *full* broadcast diversity if the broadcast delivery between the sink and an arbitrary sensor node is guaranteed on *every* common channel they can access, i.e., DIV $= N$, where N is the number of the common channels.

2) *Broadcast Delay With Full Diversity:* Full diversity implies the robustness of an MCB algorithm. Thereby, we further define the second metric, *broadcast delay with full diversity* (BD-FD), as the upper bound of the worst-case delay before the full broadcast diversity is achieved at the first time, which is given by

$$\begin{aligned} \max_{u \in \mathcal{R}, \forall \delta_u, \delta_s, \forall k, l \in \mathbb{Z}} \quad & (\min \mathcal{T}(x_u(k), x_s(l))) \\ \text{subject to} \quad & \text{DIV} = N. \end{aligned}$$

C. Multichannel Broadcast Problem

In order to ensure the reliable broadcast delivery between the sink and any sensor node in a WBAN, we need to ensure that an MCB algorithm achieves full broadcast diversity. Thus, the MCB problem in this paper can be formally defined as follows.

Problem 1 (MCB Problem): Consider a WBAN of one sink and multiple sensor nodes with asymmetric duty cycles, operating on multiple channels, without clock synchronization, how can the sink successfully broadcast control information to all sensor nodes over every common channel within a bounded delay?

For any duty cycle pair (δ_u, δ_s), any initial time offset t_u^0 and t_s^0 (i.e., any clock drifts) and any channel set $\mathcal{N}$, the MCB problem can be formulated as

$$\begin{aligned} \text{minimize} \quad & \max_{u \in \mathcal{R}} (\min \mathcal{T}(x_u(k), x_s(l))) \\ \text{s.t.:} \quad & \min |\mathcal{C}(x_u(k), x_s(l))| = N \\ & \forall t_u^0 \in [1, T_u], t_s^0 \in [1, T_s], \forall \delta_u, \delta_s, \exists t \leq T \\ & \text{such that } x_u^t\left(t_u^0\right) = x_s^t\left(t_s^0\right) = h \quad \forall h \in \mathcal{N}. \end{aligned} \tag{1}$$

The problem formulation suggests that our objective is to devise algorithms specifying wake-up time sequences and channel-hopping sequences for the sink and all sensor nodes such that the broadcast succeeds with the minimum broadcast delay and the maximum broadcast diversity.

D. Multichannel Broadcast Delay Bound

In this section, we present the generalized lower-bound for the MCB Problem 1.

Theorem 1: For any MCB algorithm solving the Problem 1, the BD-FD, denoted by L, is lower-bounded by $N^2 d_a d_s$ where s is the sink and a is the sensor node with the smallest duty cycle in $\mathcal{R}$ and $d_a = (1/\delta_a)$ and $d_v = (1/\delta_s)$.

Proof: The method used in the proof is similar to [26]. ■

Theorem 1 implies that the performance of any MCB algorithm is determined by the sink and the sensor node with the smallest duty cycle. As further explained in the following remark, we can guarantee the successful broadcast delivery from the sink s to all sensor nodes if the delivery can be achieved between s and a of the smallest duty cycle. Therefore, we focus on the analysis between s and a in what follows. Note that the properties of a in the rest of paper also hold for the other sensor nodes.

Remark 1: For a WBAN with one sink s and R sensor nodes operating on N broadcast channels, The worst-case BD-FD happens on the broadcast from the sink to the node a of the smallest duty cycle for any MCB algorithm, which is asymptotically $L \simeq O(N^2 d^2)$ when $d_s \simeq d_a \simeq O(d)$.

With the guidance of the performance bound above, we next design MCB algorithms that achieve the lower-bound of Problem 1.

IV. Multichannel Broadcast Algorithm

In this section, we first introduce the CRT which is the methodology of this paper. We then elaborate the design of MCB algorithm that achieves the full broadcast diversity within the order-minimum BD-FD.

A. Technical Background

The CRT: let $m_1, \ldots, m_k$ be positive integers that are pairwise co-prime. Then, for any given sequence of integers $b_1, \ldots, b_k$, there exists an integer x solving the following system of simultaneous congruences:

$$\begin{cases} t \equiv b_1 \pmod{m_1} \\ t \equiv b_2 \pmod{m_2} \\ \quad \vdots \\ t \equiv b_k \pmod{m_k}. \end{cases}$$

Furthermore, any two solutions of this system are congruent modulo the product $M = \prod_{i=1}^{k} m_i$. Hence, there is a unique (non-negative) solution less than M. The detailed proof can refer to [27].

In a network, for any two distinct nodes u and v with sets of integers $D_u = \{d_1^u, d_2^u, \ldots, d_{|D_u|}^u\}$ and $D_v = \{d_1^v, d_2^v, \ldots, d_{|D_v|}^v\}$, respectively, the wake-up sequence $x_u \triangleq \{x_u^t\}_{1 \leq t \leq T_u}$ of node u can be expressed as

$$x_u^t = \begin{cases} 1, & t \text{ is divisible by some } d_i^u \in D_u \\ 0, & \text{otherwise.} \end{cases}$$

The period length is $T_u = \text{lcm}(d_1^u, d_2^u, \ldots, d_{|D_u|}^u)$ where $\text{lcm}(\cdot, \cdot)$ defines the least common multiple. And, its duty cycle

δ_u according to the Definition 2 is given by

$$\delta_u = \sum_{1 \le i_1 \le |D_u|} \frac{1}{d^u_{i_1}} - \sum_{1 \le i_1 < i_2 \le |D_u|} \frac{1}{\mathrm{lcm}\left(d^u_{i_1}, d^u_{i_2}\right)} \cdots + (-1)^{|D_u|+1} \frac{1}{\mathrm{lcm}\left(d^u_1, d^u_2, \ldots, d^u_{|D_u|}\right)}.$$

Correspondingly, the same results hold for node v. Following the CRT, if there exists an integer in D_u that is co-prime to an integer in D_v, i.e., $\exists d^u_{i_0} \in D_u$ and $\exists d^v_{j_0} \in D_v$, such that $d^u_{i_0}$ and $d^v_{j_0}$ are co-prime, then they can wake up at the same time slot. Moreover, we can further obtain the following theorem from the CRT and co-primality.

Theorem 2: If the associated integer sets of the nodes satisfy the co-prime to each other, it can be guaranteed that any pair of nodes u and v wake up in the same time slot for any amount of clock drifts. And *the delay* is bounded by the product of the two smallest co-prime numbers, one from each set, that is,

$$\min_{\gcd\left(d^u_i, d^v_j\right)=1, 1 \le i \le D_u, 1 \le j \le D_v} \left\{ d^u_i \cdot d^v_j \right\}$$

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

Proof: Assume that the clock of node u is δ_{uv} time slots ahead of that of node v, i.e., node v's tth time slot is the $(t + \delta_{uv})$th time slot of node u, where δ_{uv} is the clock drift. That is, for the following congruence system:

$$\begin{cases} t \equiv 0 & (\mathrm{mod}\ d_u) \\ t \equiv \delta_{uv} & (\mathrm{mod}\ d_v) \end{cases} \tag{2}$$

if t is a solution to (2), then node u and v will both wake up in node u's tth time slot [i.e., node v's $(t - \delta_{uv})$th time slot]. By CRT, since d_u and d_v are co-prime to each other, there exactly exists a solution $t \equiv t_d$ (mod $d_u d_v$) in every period $d = d_u d_v$ such that $x^{t_d}_u = x^{t_d}_v(\delta_{uv}) = 1$, $\forall \delta_{uv} \in \mathbb{Z}$. ■

This theorem states that if $t_d \in [1, d_u d_v]$ is such a solution, then an integer t satisfies the congruences if and only if t can be expressed as $t = t_d + kd$ for $k = 1, 2, \ldots$.

B. MCB: Algorithm Design

From the CRT and Theorem 2, we know that given the desired duty cycles of the sink and any sensor node in WBANs, if their designed reciprocals of duty cycles are co-prime to each other, they can wake up in the same time slot for any amount of clock drifts. However, in multichannel environment, a reliable MCB algorithm needs to ensure that the sink and nodes not only wake up in the same time slot but also hop to the same channel while achieving the full diversity. Thus, consider a WBAN of N channels, where the sink and sensor nodes can hop across all the N channels based on their individual duty cycles, respectively, we need to design both wake-up time slot sequences and the channel-hopping sequences for the sink and nodes to guarantee the successful broadcast delivery with full diversity within the bounded broadcast delay.

Fortunately, we can exploit CRT in the two dimensions. Specifically, based on the CRT and Theorem 2, if the wake-up intervals of the sink and nodes are co-prime with each other meanwhile the interval of a sensor node hops to the same channel is also co-prime with that of the sink, the successful broadcast delivery will be guaranteed within bounded broadcast delay. Motivated by this observation, we devise the MCB containing weak-up and channel-hopping schedules for the sink and all sensor nodes, and will confirm its correctness in Theorem 3.

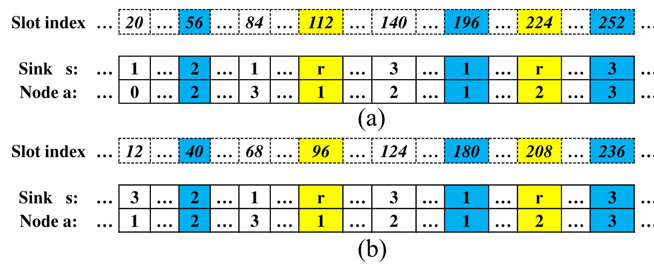

Fig. 2. Illustrating MCB: $d_s = 3$ and $d_a = 6$. (a) Without clock drift. (b) Node a drifts by 5 time slots to the right.

More specifically, given the required duty cycle of the sink $\delta_s = (1/d_s)$, denote by $p_s = 2^k$ with $k = \lceil \log_2 d_s \rceil$ the actual wake-up period of the sink. Correspondingly, consider the number of broadcast channels N, denote by $q_s = 2^m$ the period of channel polling for the sink s in active slots. In order to guarantee that each channel is visited at least once in a cycle, we set m as the smallest integer satisfying $2^m \ge N$ and construct the channel-hopping sequence of the sink s as

$$x^t_s = \begin{cases} h_i, & t - ip_s \text{ is divisible by } p_s q_s, 0 < i \le N \\ h_r, & t - ip_s \text{ is divisible by } p_s q_s, N < i \le q_s \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where h_r denotes a channel randomly selected in $[1, N]$. It can be noted that the whole period of the channel hopping sequence x_s is $p_s q_s$.

Similarly, for node a with the smallest duty cycle $\delta_a = (1/d_a)$ in $\mathcal{R}$, its wake-up interval is defined as the smallest odd integer p_a which minimizes $|p_a - d_a|$. Then, let q_a denote the period of channel polling for node a in active slots, we set it to the smallest odd integer which is not smaller than N. Correspondingly, the channel-hopping sequence of a is generated as

$$x^t_a = \begin{cases} h_i, & t - ip_a \text{ is divisible by } p_a q_a, 0 < i \le N \\ h_r, & t - ip_a \text{ is divisible by } p_a q_a, N < i \le q_a \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

and the period of x_a is $p_a q_a$.

Therefore, the broadcast delivery with full diversity between s and a occurs successfully regardless of their clock drifts, as the $p_s q_s$ and $p_a q_a$ are co-prime following from the CRT and Theorem 2, which will be explained in Theorem 3. Example 1 illustrates the MCB algorithm in multichannel case.

Example 1: Consider the sink s and node a with duty cycles $\delta_s = (1/3)$ and $\delta_a = (1/6)$, respectively, operating on three common channels (i.e., $N = 3$). Under the above MCB channel hopping schedules, we can derive that $p_s = 4$, $q_s = 4$, $p_a = 7$, and $q_a = 3$. Using the time of s as a reference, s wakes up on channel h_1 in slots $4 + 16k$, i.e., $4, 20, 36, \ldots$, on channel h_2 in slots $8+16k$, i.e., 8, 24, 40, ..., and on channel h_3 in slots $12+16k$, i.e., 12, 28, 44, ... It can be noted that s wakes up and randomly hops to one channel in the slots $16+16k$, $k=0,1,2,3,\ldots$. Similarly, a wakes up on channel h_1 in slots $7+21k$, on channel h_2 in slots $14+21k$ and on channel h_3 in slots $21+21k$, $k=0,1,2,3,\ldots$, as illustrated in Fig. 2(a). The first successful broadcast delivery happens at the 56th slot, and the broadcast delivery with full diversity achieves at the 252nd slot between s and a. Correspondingly, if there exists a clock drift offset, such as $\delta_{sa}=5$, the broadcast delivery first occurs at the 40th slot, and the broadcast delivery with full diversity can also be ensured at the 236th slot between s and a as shown in Fig. 2(b). Note that the entries with value r indicates a random number in $[1,N]$, thus the broadcast delivery may also occur in the 112nd and 234th slots as shown in Fig. 2(a).

C. MCB: Granularity

Here, we discuss the granularity of the MCB in matching any desired duty cycle and the actual number of channels in practical applications.

Duty cycle granularity. Consider the desired duty cycle of node u is δ_u and its actual value $\hat{\delta_u}$, the relative error $\epsilon(\delta_u)$ between δ_u and $\hat{\delta_u}$ is defined by

$$\epsilon(\delta_u)=\frac{|\hat{\delta_u}-\delta_u|}{\delta_u}. \tag{5}$$

Following the wake-up schedule in MCB, the actual duty cycle of the sink s is $\hat{\delta_s}=(1/2^k)$ while the required one is $\delta_s=(1/d_s)$. According to the definition of the relative error, we have

$$\epsilon(\delta_s)=\frac{|\hat{\delta_s}-\delta_s|}{\delta_s}=\left|\frac{1}{2^{\lceil\log_2 d_s\rceil}}-\frac{1}{d_s}\right|\Big/\frac{1}{d_s}<\frac{1}{2}. \tag{6}$$

Similarly, we can also derive the relative error of node a between $\hat{\delta_a}$ and δ_a as

$$\epsilon(\delta_a)=\left|\frac{1}{p_a}-\frac{1}{d_a}\right|\Big/\frac{1}{d_a}\le\frac{1}{d_a-1}. \tag{7}$$

As shown in (7), the relative error of node a decreases with the decline of the desired duty cycle δ_a. In practical applications of WBANs, δ_a is typically very low, thus $\epsilon(\delta_a)$ is small enough. However, the relative error $\epsilon(\delta_s)$ is not very stringent to approach the required duty cycle as in (6). The same granularity results can be conducted for the number of broadcast channels. In order to improve the granularity of the sink, we will propose an improved MCB design in Section V.

Channel Granularity: Similar as the analysis of duty cycle granularity, denote by $\epsilon(N_s)$ and $\epsilon(N_a)$ the relative errors between the channel polling period and the actual number of channels for the sink s and node a, we have

$$\epsilon(N_s)=\frac{|q_s-N|}{N}<1, \tag{8}$$

$$\epsilon(N_a)=\frac{|q_a-N|}{N}\le\frac{1}{N}. \tag{9}$$

D. MCB: Performance Analysis

In this section, we conduct theoretical analysis to demonstrate the effectiveness of MCB in terms of BD-FD.

Theorem 3: Given the duty cycles of the sink $(1/d_s)$ and node a $(1/d_a)$ and the number of broadcast channels N in a WBAN, as p_sq_s and p_aq_a are co-prime with each other, the successful broadcast delivery with full diversity is ensure to occur within at most $p_sq_sp_aq_a$ time slots for any amount of clock drifts. Asymptotically, when $q_s\simeq q_a\simeq O(N)$, BD-FD $\simeq O(N^2p_sp_a)$.

Proof: Following the algorithm design of MCB, the period of the channel hopping sequence of the sink x_s is $p_sq_s=2^{k+m}$ which is an even integer, and the period of x_a is p_aq_a which is an odd integer. It is well known that the even integer and odd integer are co-prime. It then follows from the CRT and Theorem 2 that there exists $t_0<p_sq_sp_aq_a$ 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 $t_k=t_0+kp_sq_sp_aq_a$, the broadcast delivery can be ensured to occur between the sink s and node a. Therefore, MCB achieves the full diversity within at most $O(N^2p_sp_a)$ time slots. ■

V. IMPROVED MCB

In this section, we propose improved MCB to enhance the granularity of MCB and thus decrease the broadcast delay in the worst case.

A. Motivation

Recall the analysis of duty cycle granularity in Section IV-C, the relative error of a sensor node $\epsilon(\delta_a)$ is typically very small, as the p_a is the smallest odd integer not smaller than d_a in our design and it is well-known that we can find p_a which is very close to d_a for any d_a. However, the relative error of the sink $\epsilon(\delta_s)$ may be up to $(1/2)$ as shown in (6). The main reason is that we design p_s as a power-multiple of 2 to approximate the desired d_s. In the extremely unlucky case where d_s is in the form of 2^n+1, we may have $p_s\simeq 2d_s$ when the broadcast delay in the worst-case is $p_sp_a\simeq 2d_sd_a$. Similarly, as q_s in MCB needs to be a power-multiple of 2, we may also have $q_s\simeq 2N$ in the worst case, thus leading to larger BD-FD, i.e., $p_sq_sp_aq_a\simeq 2N^2p_sp_a\simeq 4N^2d_sd_a$.

This motives us to wonder: *can we improve the granularity of MCB and further reduce the BD-FD toward the lower bound?* Following this motivation, we propose improved MCB with more fine-grained control.

B. Improved MCB: Algorithm Design and Analysis

Instead of using only power-multiple of 2 to approximate required duty cycles and actual number of channels in MCB, given the required duty cycle δ_s of the sink s, improved MCB set $p_s=2^{k_1}3^{k_2}$ with integers k_1 and k_2 chosen from $[0,\lceil\log_2 d_s\rceil]$ and $[0,\lceil\log_3 d_s\rceil]$, respectively, such that p_s-d_s is minimized under the constraint $p_s\ge d_s$, that is,

$$(k_1,k_2)=\underset{k_1,k_2}{\operatorname{argmin}}\left(2^{k_1}3^{k_2}-d_s\right),\quad \text{s.t.}\quad 2^{k_1}3^{k_2}\ge d_s.$$

The rationale behind such setting is detailed in Lemma 1 proving that p_s is asymptotically close to d_s.

Lemma 1: For any $\epsilon > 0$, given d_s sufficiently large, there exist $k_1 \in [0, \lceil \log_2 d_s \rceil]$ and $k_2 \in [0, \lceil \log_3 d_s \rceil]$ so that $p_s = 2^{k_1}3^{k_2} \geq d_s$ and $p_s - d_s \leq \epsilon$, i.e., d_s can be arbitrarily closely approximated by q_s.

Proof: We give the proof sketch. We prove the lemma by showing for large enough d_s that there exist $k_1 \in [0, \lceil \log_2 d_s \rceil]$ and $k_2 \in [0, \lceil \log_3 d_s \rceil]$ such that

$$\log_2 d_s \leq k_1 + k_2 \log_2 3 < \log_2 d_s + \epsilon.$$

This follows from the fact that the fractional parts of $x\log_2 3$ for $x \in \mathbb{N}$, i.e., $x\log_2 3 - \lfloor x\log_2 3 \rfloor$, are dense in [0, 1]. In fact, given any $\epsilon > 0$, if we choose non-negative integers $\{x_i\}$ so that fractional parts of $x\log_2 3$ form an $(\epsilon/2)$ set of [0, 1], then we can choose the appropriate integer k_2 and then k_1, which is feasible provided that d_s is large enough. ■

Similarly, given the number of broadcast channels N, the sink s can set $q_s = 2^{m_1}3^{m_2}$ where m_1 and m_2 are integers chosen from $[0, \lceil \log_2 N \rceil]$ and $[0, \lceil \log_3 N \rceil]$, respectively, so that $q_s - N$ is minimized under the constraint $q_s \geq N$, that is,

$$(m_1, m_2) = \operatorname*{argmin}_{m_1, m_2} \left(2^{m_1}3^{m_2} - N\right), \quad \text{s.t.} \quad 2^{m_1}3^{m_2} \geq N.$$

Correspondingly, following from the CRT and Theorem 2, the successful broadcast delivery between the sink s and node a can be guaranteed as long as $p_s q_s$ is co-prime with $p_a q_a$. Therefore, p_a and q_a need to be co-prime to 2 (or 3) and/or 3 (or 2) depending on k_1, k_2, m_1, m_2 in the improved MCB. Specifically, given p_s and q_s, we can pick p_a and q_a by solving the following optimization problems:

$$\begin{aligned} &\text{obj: } \min |p_a - d_a| \quad \text{obj: } \min(q_a - N) \\ &\text{s.t.: } p_a > 0 \text{ (mod 2 or/and 3) s.t.: } q_a \geq N \\ &\qquad q_a > 0 \text{ (mod 2 or/and 3).} \end{aligned}$$

If the system parameters on duty cycle and channel set are given, we can obtain p_s, q_s first, and then p_a, q_a and finally the channel hopping sequences as in (3) and (4).

Remark: The theoretical property in Theorem 3 can be also conducted for the improved MCB algorithm. With the more fine-grained control, improved MCB can reduce the BD-FD to a quarter of baseline MCB at most.

VI. Robustness Against Asymmetrical Channel Perception

In the previous analysis, we implicitly assume that the sink and sensor nodes have the same channel perceptions, i.e., they have symmetrical knowledge on $\mathcal{N}$. In this section, we relax this assumption to study the robustness of our algorithms against asymmetrical channel scenario where the sink s and sensor nodes have different perceptions on $\mathcal{N}$. For clarity, we, without loss of generality, assume node a has the smallest channel perception and the smallest duty cycle among all sensor nodes.

Denoted by $\mathcal{N}_s$ and $\mathcal{N}_a$ which are subsets of $\mathcal{N}$ the channel perceptions of s and a, respectively. Specifically, the channel perception asymmetry between s and a can be characterized at two levels.

1) *Asymmetry on Accessible Channel Set:* They have asymmetrical perceptions on the global channel set $\mathcal{N}$, i.e., $\mathcal{N}_s \neq \mathcal{N}_a$ and $\mathcal{N}_s \cap \mathcal{N}_a \neq \emptyset$.
2) *Asymmetry on Channel Index:* They have asymmetrical perceptions on the channel index, i.e., channel $h \in \mathcal{N}$ is indexed by h_i by s and h_j by a where $h_i \in \mathcal{N}_s$ and $h_j \in \mathcal{N}_a$ but $h_i \neq h_j$.

The channel-hopping schedule of s in MCB (or improved MCB) thus becomes to

$$x_s^t = \begin{cases} h_i, & t - ip_s \text{ is divisible by } p_s q_s, 0 < i \leq N_s \\ h_r, & t - ip_s \text{ is divisible by } p_s q_s, N_s < i \leq q_s \\ 0, & \text{otherwise} \end{cases}$$

where h_r represents a channel randomly picked by s from $[1, N_s]$. Correspondingly, the channel hopping sequence of a becomes to

$$x_a^t = \begin{cases} h_i, & t - ip_a \text{ is divisible by } p_a q_a, 0 < i \leq N_a \\ h_r, & t - ip_a \text{ is divisible by } p_a q_a, N_a < i \leq q_a \\ 0, & \text{otherwise} \end{cases}$$

where h_r denotes a channel randomly selected from $[1, N_a]$.

Next, we show our algorithm performance in such context.

Theorem 4: MCB/improved MCB under asymmetrical channel perceptions achieves the same BD-FD as under symmetrical channel perceptions, i.e., within at most $O(N_s N_a d_s d_a)$ [specifically, $O(N^2 d^2)$ if $d_s \simeq d_a \simeq O(d)$ and $N_s \simeq N_a \simeq O(N)$] slots, the successful broadcast delivery from the sink s to all sensor nodes occurs on each common channel $h \in \mathcal{N}_s \cap \mathcal{N}_a$.

Proof: Since $p_s q_s$ is co-prime with $p_a q_a$ in our original and improved MCB algorithms, it thus holds following from CRT that there exists $t_0 < p_s q_s p_a q_a$ such that $x_s^{t_0}(t_s^0) = h_i$ and $x_a^{t_0}(t_b^0) = h_j$ for any channel h indexed as h_i (h_j) by s (a). Then by the similar analysis as the proof of Theorem 3, we can prove the BD-FD to be $O(N_s N_a d_s d_a)$. ■

Theorem 4 shows that our algorithms are robust against asymmetrical channel perceptions, either on the channel set or index. Example 2 exemplifies the capability of improved MCB against asymmetrical channel perceptions.

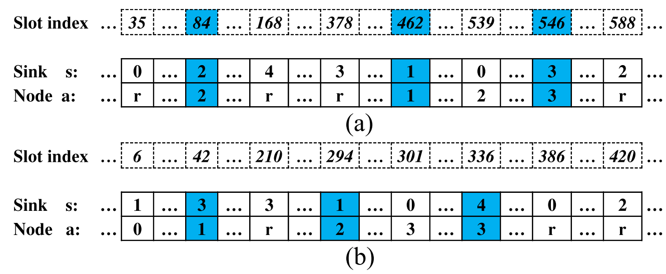

Fig. 3. Improved MCB versus asymmetrical channel perceptions.

Example 2: Consider a WBAN of four broadcast channels (i.e., $N = 4$), the sink s with desired duty cycle $\delta_s = (1/5)$ can hop across all the four channels, i.e., $N_s = 4$, and node a with required duty cycle $\delta_a = (1/8)$ can access three channels, i.e.,

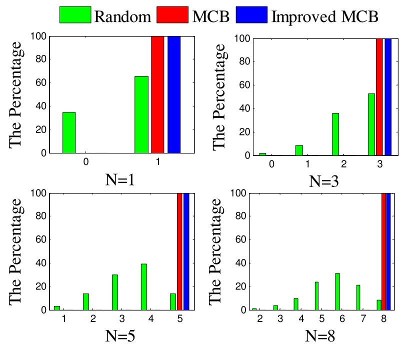

Fig. 4. Broadcast diversity.

$N_a = 3$. Under the schedules of improved MCB, we can derive that the actual wake-up period of s is $p_s = 6$ as $k_1 = 1, k_2 = 1$, and the actual period of channel hopping is $q_s = 4$ as $m_1 = 2, m_2 = 0$. Correspondingly, we have $p_a = 7$ and $q_a = 5$. Note that the value r denotes a random number in $[1, N]$. For the asymmetry on accessible channel set, the broadcast delivery with full diversity (i.e., $\mathcal{N}_s \cap \mathcal{N}_a = 3$ and the common channels are h_1, h_2, and h_3) achieves at the 546th slot between s and a as illustrated in Fig. 3(a). For the asymmetry on channel index, without loss of generality, assume that the channel h_1 indexed by s is indexed by a as h_2, h_3 for s is denoted by a as h_1, and h_4 for s is indexed as h_3 for a. In this case, the successful broadcast delivery with full diversity also happens at 336th slot as shown in Fig. 3(b).

VII. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithms through MATLAB. In the simulation, node a has the smallest duty cycle among all sensor nodes. We set the number of the channels $N = 3, 5, 8$ corresponding to IEEE 802.15.6 [11] on low and high bands of UWB, respectively. Because no existing work handles the MCB problem in duty-cycling context, we choose the random broadcast algorithm, referred to as Random, as a benchmark, where the sink and each node select their individual active slots and a channel at random.

In what follows, we first evaluate the algorithm performance in terms of the broadcast diversity and BD-FD in several typical multichannel scenarios. We then illustrate the capability of the algorithms against the asymmetrical channel perceptions. Note that the delay is presented in the number of time slots, and all results are calculated from 1000 independent experiments.

A. Broadcast Diversity

Broadcast diversity indicates the capability of an algorithm of delivering broadcast messages regardless of the sink's and nodes' operation channels. To evaluate this metric, we conduct 1000 independent experiments with the simulation settings in Sections VII-B and VII-C, and plot the average percentage of the broadcast diversity achieved by Random, MCB and improved MCB in Fig. 4. As shown in the figure, the proposed MCB and improved MCB can guarantee the 100% full broadcast diversity in any multichannel case. Random, however, cannot achieve this in each case due to its probabilistic nature. Moreover, the percentage of the full broadcast diversity decreases as the increase of the number of broadcast channels in Random.

TABLE I
Reliability Comparison

Algorithms	Reliability		
	$N = 3$	$N = 5$	$N = 8$
Random	0.536	0.14	0.087
MCB	1	1	1
Improved MCB	1	1	1

Obviously, the percentage of full broadcast diversity implies the reliability and robustness of an MCB algorithm. Define the percent of successful broadcast delivery with full diversity within bounded time as reliability in this paper. We explicitly list the reliability of the three algorithms in Table I. The proposed MCB and improved MCB are able to achieve 100% reliability, while the reliability of Random dramatically decreases as the increase of the broadcast channel number, meaning that Random never ensures the successful broadcast delivery within bounded time. Specifically, when there are 8 broadcast channels, Random only succeeds in 87 out of the 1000 experimentations.

One thing worth noting is that MCB and improved MCB achieve 100% reliability, but improved MCB is more time-efficient than MCB, which will be shown in the following.

B. Broadcast Delay With Full Diversity

In this section, we evaluate the BD-FD of Random, MCB and improved MCB. In order to better assess the impact of duty cycles of the sink s and node a on BD-FD, four representative scenarios are considered.

1) Both s and a have large duty cycles: $d_s = 10$, $d_a = 16$.
2) Both of them have small duty cycles: $d_s = 50$, $d_a = 60$ and $d_s = 70$, $d_a = 90$.
3) s has large duty cycle while a has small duty cycle: $d_s = 10$, $d_a = 60$.

Noth that the duty cycles of the other sensor nodes are not less than δ_a. Moreover, the amount of clock drifts is randomly distributed in $[1,\ T_sT_a]$.

Figs. 5 and 6 where we set the number of channels $N = 3$ illustrate the worst-case and average BD-FD. From the results, we can make the following observations.

1) The BD-FD increases in proportion to the product of the reciprocals of duty cycles of s or/and a, which is in accordance with our theoretical results in Theorem 3.
2) The BD-FD of our proposed MCB and improved MCB is bounded. And Random is very time-consuming in each case, because it cannot guarantee 100% reliability such that more time is needed, for instance, up to 5 times that of improved MCB in Fig. 5, to achieve full diversity.
3) Improved MCB works faster than MCB in terms of both the worst-case and average BD-FD. The main reason lies in the rough granularity of MCB that uses only one

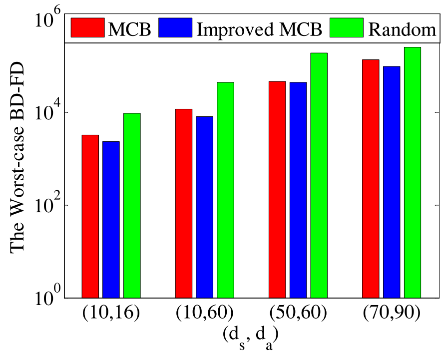

Fig. 5. Worst-case BD-FD: $N = 3$.

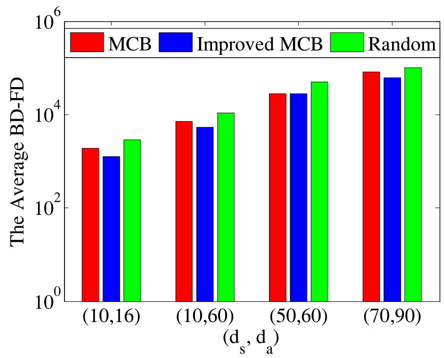

Fig. 6. Average BD-FD: $N = 3$.

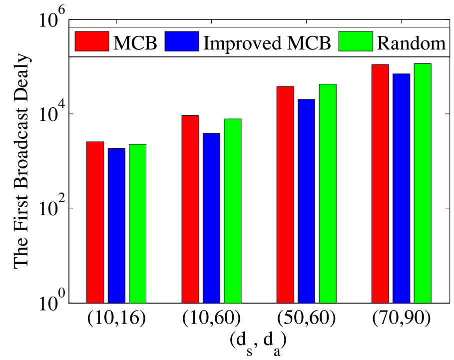

Fig. 7. First broadcast delay.

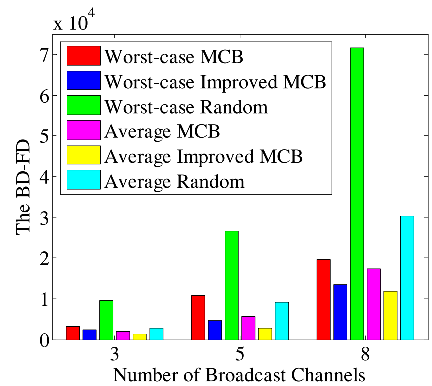

Fig. 8. BD-FD versus channel number.

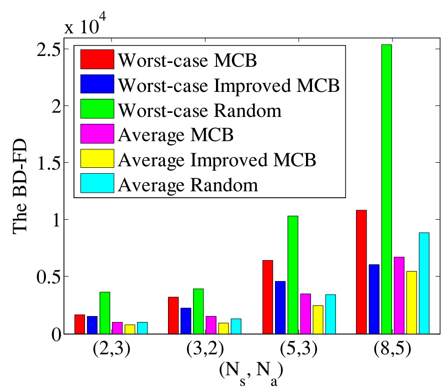

Fig. 9. BD-FD-channel perceptions.

pair of co-prime numbers. Specifically, for the limited choices of co-prime numbers, the MCB restricts the duty cycle reciprocal of s to a power-multiple of two, i.e., 2, 4, 8, etc. As a natural consequence, when the required duty cycle reciprocal deviates from the power-multiples, the related error increases, leading to a larger broadcast delay of MCB. In contrast, improved MCB exploits two pairs of co-prime numbers to improve the granularity as proved in Lemma 1 and thus can decrease the broadcast delay.

4) The differences between the worst-case and average broadcast delay of MCB and improved MCB are slight under small duty cycles while becoming relatively significant under large duty cycles, which is due to the negative impact of approximating the duty cycle reciprocal of 10 by a power-multiple 16 on the broadcast delay.

Moreover, we proceed by evaluating the first successful broadcast delay which is the most time needed by the sink s to successfully broadcast to all sensor nodes for the first time among the 1000 experiments. From Fig. 7, we can also draw that improved MCB performs best for all different duty cycles, while the basic MCB needs more time than Random in some scenarios. This is resulted from their different objectives, which can be interpreted as follows: Random is not designed to guarantee 100% reliability such that the sink and nodes strictly follow their original duty cycles, thus they may hop to one common channel in the first same wake-up time slot in a quite lucky case. In contrast, in order to ensure the full broadcast delivery, MCB has to magnify the original duty cycles of the sink and nodes as the limited choices of the co-prime numbers. In order to overcome this drawback, we proposed improved MCB to improve the granularity by two pairs of co-prime numbers.

In addition, we also evaluate the impact of the number of broadcast channels on the BD-FD. To this end, we set the pair of duty cycles to (10, 16) and vary the number of channels from $N = 3$ to 5 and 8. The results are shown in Fig. 8, from which we can make the following observations.

1) As the channel set size N scales, the BD-FD increases at the square speed, which is in accordance with the analytical results in Theorem 3.
2) In all the simulated cases, improved MCB significantly outperforms the others and achieves higher performance

gain with the increase of N, which further demonstrates the correctness of the theoretical results. Quantitatively, the worst-case delay of improved MCB when $N = 5$ is less than one fourth of Random, while this number reduces to nearly one sixth when $N = 8$.

C. Asymmetrical Channel Perceptions

Here, we assess the robustness of our algorithms against the asymmetrical channel perceptions. In the experiments, we set the pair of duty cycles to (10, 16) and vary the number of individual channels N_s and N_a.

Fig. 9 illustrates the BD-FD under the different channel perceptions. As shown in the figure, the proposed MCB and improved MCB can still fulfill the successful broadcast delivery on each common channel though in the presence of asymmetrical channel perceptions, which verifies the theoretical result established in the Theorem 4. And improved MCB still works best in each case, proving it especially appropriate for the decentralized applications of WBANs with heterogeneity between the sink and sensor nodes.

VIII. Conclusion

In this paper, we have studied the MCB problem in duty-cycling WBANs. We first introduced the performance bound of any MCB algorithm. With the guidance of this theoretical result, we designed the algorithm MCB and its improved version, namely improved MCB that enhances the granularity of MCB. We also conducted theoretical analysis and extensive simulations. The results demonstrate that the proposed algorithms can guarantee the successful broadcast delivery with full diversity regardless of the clock drifts and duty cycles and asymmetric channel perceptions within the order-minimal worst-case delay.

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