Received January 25, 2019, accepted February 19, 2019, date of publication March 4, 2019, date of current version April 9, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2902902

RowBee: A Routing Protocol Based on Cross-Technology Communication for Energy-Harvesting Wireless Sensor Networks

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This work was supported in part by the National Natural Science Fund of China under Grant 31670554, in part by the Natural Science Foundation of Jiangsu Province of China under Grant BK20161527, in part by the project funded by the China Postdoctoral Science Foundation under Grant 2018T110505 and Grant 2017M611828, and in part by the Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions.

ABSTRACT Low and dynamic duty cycles cause that the E2E delay for packet delivery is more critical in energy-harvesting wireless sensor networks (EH-WSNs). The traditional routing protocols are constrained by the in-technology communication paradigm, where Wi-Fi devices can talk to the Wi-Fi devices only, and so on for ZigBee or wireless technology. This is, however, not necessary by recent advances in cross-technology communication (CTC). The CTC enables ZigBee nodes to be coordinated by a Wi-Fi node without any hardware changes or gateway equipment, which sheds the light on more efficient routing protocols design. In this paper, we introduce a new routing protocol based on a CTC technique called RowBee. RowBee takes the advantages of coordination from the Wi-Fi node to assist the ZigBee nodes for establishing routing paths and allows nodes to choose their duty cycles freely with finer duty-cycle granularity. A simple yet effective method is employed so that the ZigBee nodes are coordinately waked up simultaneously according to the beacons broadcasted by the Wi-Fi nodes. We implement RowBee based on a USRP-N210 and MICAz hybrid platform, and the experimental results show that RowBee can reduce the E2E delay greatly.

INDEX TERMS Wireless sensor networks, routing protocol, cross-technology communication, energy-harvesting wireless sensor networks.

I. INTRODUCTION

As an interesting strategy to extend the network lifetime of Wireless Sensor Networks (WSNs), Energy-Harvesting Wireless Sensor Networks (EH-WSNs) are more economical and useful in the long-term as they can operate for very long periods of time (perhaps more than ten years until hardware failure) relying on rechargeable technologies [1], which convert sources such as foot strike [2], body heat [3], finger strokes [4] and solar [5] into electricity. Assuming energy neutral operation [6], a sensor node[1] can operate perpetually if the energy used is always less than the energy harvested and the desired performance level can be supported in a given harvesting environment by using supercapacitors (in the order of a million cycles [7]) to store the harvested energy. However, in EH-WSNs, although their lifetime is less of an issue, the energy harvested from surrounding environment usually is not enough to power sensor nodes continually due to sporadic and limited availability of energy [8]. Therefore, nodes have to operate in a very low duty cycle [9], which means they activate shortly and stay at the sleep state most of the time for recharging themselves. At the same time, the available energy varies dramatically over time due to the varying environment conditions [10]. For regulating energy consumption, sensors have to adapt their duty cycle continuously according to

The associate editor coordinating the review of this manuscript and approving it for publication was Zhenyu Xiao.

[1]in this paper, we will use "node" and "sensor" and "sensor node" and "ZigBee node" interchangeable if no confusion

available energy [11]. Therefore, since an energy-harvesting sensor operates generally in a low and dynamic duty-cycles, it is critical to choose a node as a central coordinator to coordinate other sensors for data transmission.

A state-of-the-art routing protocols are fundamentally constrained by the in-technology communication paradigm. To be more precisely, a ZigBee node can communicate with other ZigBee devices only, and WiFi nodes can talk to other WiFi nodes as well. No direct communications between WiFi nodes and ZigBee nodes are allowed in traditional designs, which greatly limits the ZigBee devices to be assisted by other technology devices, for example, a WiFi node, which greatly limits the ZigBee devices to be assisted by other technology devices, for example, a WiFi node. This constraint is, however, not necessary and can be released by the help of the recent advances in Cross-Technology Communications (CTC), e.g., Freebee [12], HoWiEs [13]. CTC techniques are introduced in recent literatures [14] to provide direct communication across technologies. As a result, network coordination protocols, such as TDMA and RTC/CTS, can be extended to be globally applied across wireless technology.

It is notable that CTC not only alleviates the issue of interference, but also serves as a fundamental building block for collaborative applications via cross-technology cooperation. CTC allows direct communications between different wireless technologies when they are in the same spectrum band. For example, both of WiFi and ZigBee reside on the 2.4GHz ISM band and thus WEBee [15], TwinBee [16], LongBee [17] uses a high-speed WiFi radio to emulate the desired signals of a low-speed ZigBee radio. This is done by carefully selecting the payload of the WiFi packet and the data rate from the WiFi node to the ZigBee node is up to 126 Kbps. Fig. 1 illustrates the principle of WEBee. Notice that WEBee is purely a software-based solution, requiring no modification on WiFi or ZigBee hardware. It can work on Off-the-Shelf WiFi and ZigBee devices. The advances in these CTC technologies provide new opportunities for routing protocol of EH-WSNs.

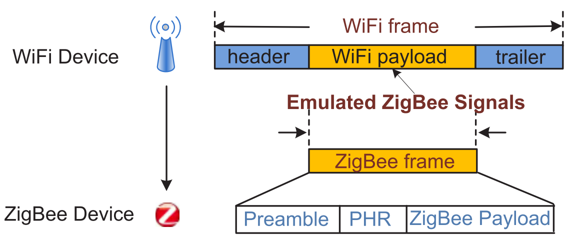

FIGURE 1. Cross-technology communication from WiFi to ZigBee.

In this paper, we will show how to leverage these new CTC advances to improve the routing protocol performance. We will introduce a new direction for routing protocol based on CTC technique, a physical-layer technique named RowBee, (A Routing protocol based on WiFi assisting ZigBee). In short, RowBee takes advantage of WiFi broadcasting with long distance to assist ZigBee-embedded devices to establish routing paths.

Our contributions are summarized as follows:

- We propose RowBee, a new routing protocol based on CTC technology. To the best of our knowledge, there is the first in literatures to study the problem of routing protocol based on CTC.
- We propose a simple yet effective routing protocol for reducing E2E delay, where, a WiFi device will be as a central coordinator for broadcasting beacons to ZigBee devices in vicinity. The ZigBee nodes will wake up simultaneously for data delivery according to these beacons for their rendezvous.
- The analysis results show that by RowBee's simple design, the data transmission latency can be reduced greatly. In particular, RowBee requires no changes on the node duty-cycle schedules, making it extremely power-efficient.
- To evaluate the performance of RowBee in real environments, we implement RowBee based on a USRP-N210 and MICAz hybrid platform. The USRP-N210 with 802.11 b/g PHY functions as the WiFi node, and 50 MiCAz nodes are employed to test our protocol.

The remainder of this paper is organized as follows. In section II we present a number of existing routing protocols. section III motivates the necessary of RowBee. Section IV we present our method and design. Section V contains experimental results. Conclusions are presented in section VI.

II. RELATED WORK

A great quantity of works were done for considering the interaction of various factors like the characteristics of the energy sources [18], energy storage device(s) used [19], time synchronization [20], routing protocols [21], and the applications requirements [22], [23] when designing energy harvesting circuits for WSNs. Shaikh and Zeadally [24] present a comprehensive taxonomy of the various energy harvesting sources that can be used by WSNs and discuss various recently proposed energy prediction models. These uncontrolled abient energy supplements are attributed to the unique characteristics of EH-WSNs, such as, sensors have to adapt their duty cycle continuously for regulating energy consumption [25] and operate in a low-duty-cycle due to sporadic availability of energy [26], which pose a high challenge for routing protocols design and time synchronization.

In order to solve a variety of EH-WSNs problems, especially utilize the harvesting energy as much as possible, most of researchers propose various routing protocols. Examples of which include energy-efficient medium access control (MAC) protocols [27], duty-cycling strategies [28], energy-efficient routing [8], and topology control mechanisms [29]. By considering the limited and dynamical energy supply for sensor nodes, various protocols for reducing E2E delay have been proposed; e.g., [30], [31]. Noh *et al.* [32] introduce a duty-cycle-based low-latency geographic routing for asynchronous EH-WSNs. Gu and He [33] introduce a method to increase duty cycle by strategically adding wake-up slots to nodes to reduce end-to-end delay within a given bound. In addition, since some application of EH-WSNs depending on a synchronized notion of time, as a traditional problem of WSNs and EH-WSNs, time synchronization is researched widely for achieving global or local time synchronized; e.g., RBS [34], TPSN [35], and SATS [20]. Other examples can be found in [36], [37], and references therein. Even though numbers approaches have been proposed for EH-WSNs, a single communication technology is utilized in these works for solving the problems of routing protocol and time synchronization.

CTC techniques are researched firstly for dealing with how to model network interference by conveying information across technologies via generating patterns embedded in the interference. The literatures for CTC are generally categorized into three main approaches: injecting dummy packet [38], generating customized signal [39], and exploring free channel [12]. ESence [38] injects data packets of specified length and encode CTC symbols and GSense [39] prepending a customized preamble in front of legacy data packets, while FreeBee [12] encodes CTC symbols in the timings of mandatory beacons without introducing dedicated packets. Currently, WEBee [15] has made a breakthrough, where allows direct communications from WiFi to ZigBee without any modification on hardware, besides many others such as WiFi-to-Bluetooth, LTE-to-ZigBee, and LTE-to-Bluetooth. In WEBee [15], Li and He encapsulate a ZigBee data frame into the WiFi packet payload. LongBee [17] extends the range of CTC by concentrating the effective TX power through down-clocked operations at the transmitter and improving the RX sensitivity at the receiver side. TwinBee [16] recovers the intrinsic errors of physical-layer CTC and improves the packet reception ratio to 99% by exploring chip-level error patterns. These works main focus on CTC technology improvement. As a new-fashioned technology, CTC provides the chance and challenge for routing protocol design and time synchronization in WSNs and EH-WSNs.

In a nutshell, different from all these previous works, which focus on routing protocol design utilizing single communication technology and all nodes are homogenous. In this work, we provide a promising solution for routing protocol design based on Cross-Technology Communication using WiFi devices assisting ZigBee devices to establish routing paths. To the best of our knowledge, this is the first generic work to study the problem of routing protocol based on Cross-Technology Communication technology for EH-WSNs.

III. MOTIVATION

In this section, we motivate our work by the following observations. We present the challenge we face in routing protocol design of EH-WSNs and new opportunities brought by the Cross-Technology Communications.

A. CHALLENGE OF EH-WSNs

Challenge 1 (Dynamic Duty-Cycle of EH-WSNs): The dynamic duty cycle of a sensor is the most intuitive characteristics of EH-WSNs. For a sensor powered by a solar panel (Fig. 2), the duty cycle achievable by the Crossbow MICAz can reach about 90% in direct sunlight at 12 am. However, in the evening about at 6 pm, the duty cycle is estimated about 0.08%. Therefore, the energy harvesting sensor networks is environment-dependent, which indicates that the duty cycle of a sensor will be adjusted continually according to the realistic environment. Dynamic duty-cycle in EH-WSNs causes that fixed routing path can not be sustained for a long time and it will be reestablished continually, which leads to serious data transmission delay and high challenge of routing protocol design.

FIGURE 2. A solar-powered sensor is deployed in outdoor.

Challenge 2 (Low-Duty-Cycle of EH-WSNs): Due to sporadic availability of energy and limited energy storage capacity, the harvesting energy is still significantly lower than the power consumption for a wireless sensor. Thus, a node has to operate in a very low duty-cycle, which means that a node has to activate shortly and stay at the sleep state most of the time in order to recharge itself. From our empirical measurement results, a node can only operate about 3.5 hours continuously if its duty cycle is over 20%. It is a long time before a packet reaches its destination in a low-duty-cycle network. Therefore, quality routing protocol is critical for reducing transmission time in EH-WSNs.

B. OPPORTUNITY FOR EH-WSNs

Opportunity 1 (Large Install Base and Longer Transmission Range of WiFi Devices): Currently, the WiFi hotspots have a large install base because of its low cost and efficient data transmissions. Reports show that WiFi can be accessed 53% of the time in large cities [40]. According to the forecast from Cisco [41], the WiFi hotspots will be more than double from 2018 to 2022, with about 600m public devices in world-wide (Fig. 3). All these WiFi hotspots can be employed and ZigBee nodes can easily join an existing WiFi network with nearly zero cost. In addition, the maximum transmission power of ZigBee device (i.e., MICAz) is 1 mw (0 dBm) and transmission range is about 70 m [42], while that of WiFi

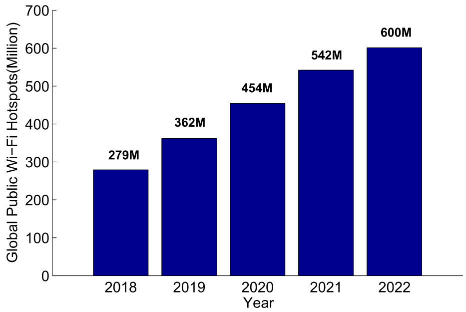

FIGURE 3. Million of Hotspots forecasted by Cisco.

is up to 100 mw (−20 dBm) and the transmission range for WiFi nodes to ZigBee nodes is near 300 m [17]. Therefore, the maximum transmission range of WiFi is much longer than that of ZigBee. A WiFi node can easily cover a region of ZigBee nodes.

Opportunity 2 (As a Central Coordinator for Command Distribution): In traditional WSNs and EH-WSNs, nodes are coordinated on their own. To the opposite, CTC allows a WiFi node to send messages to all nearby sensors, and this WiFi node can function as a central coordinator for sensors. Apparently, this central coordinator can greatly ease the coordinations among sensors and broadcast commands to all covered nodes directly without data forwarded, which reduce commands' distribution time extremely. As the node rendezvouses are guaranteed by the WiFi node's coordination, sensors can freely choose their duty-cycle ratio according to its harvesting energy.

Opportunity 3 (Energy Saving for ZigBee Devices): With the help of CTC, all ZigBee nodes can receive messages from the WiFi node directly, and thus the active nodes will do nothing but simply keep in listening mode, waiting for coordination messages from the WiFi node. To the contrast, the WiFi node will assist the ZigBee nodes to coordinate their rendezvous until they are able to discover each other. Since the WiFi nodes are usually powered by power cord and have no limitation on energy budget, the beacon messages of ZigBee nodes for coordination purposes can be greatly saved. Notice that CTC between WiFi and ZigBee nodes are one-way communications where WiFi nodes can send messages to ZigBee nodes but not the reverse one. And thus the coordination scheme from the WiFi nodes should be carefully designed to guarantee a successful data delivery.

IV. RowBee DESIGN

A. NETWORK MODEL

In EH-WSNs, duty cycling is used widely to control energy utilization and guarantee that a sensor has enough time to recharge itself. At any point of time, there are two states for any sensor node with duty-cycle: active and dormant. In the active state, a sensor node can generate data after sensing its surrounding environment, transmit the data to its neighbors or receive data from its neighbors. While a sensor node is in the dormant state, it turns off all its modules except for a timer to wake itself up.

For all sensors, since their neighboring nodes switch between active and dormant states regularly, the transmission between a pair of nodes becomes time-dependent strictly. In the paper, let the duration of periodic working schedules be t which can be divided into a sequence of time instances with length τ. The duration of τ is the unit of working time for an activity, which is a period time for data sent or received at least one time. In WSNs, the value of τ is about $200ms$, which is the time for a sensor to send a packet. We note that the practical value of τ is determined by the nature of hardware device. For a node, when it is in the active state within period time t, its working schedules contains one or multiple time instances with length τ.

For the purpose of explaining the active and dormant activities utilizing the working schedule and time instance, let t_α denotes the working schedule of node α, which indicates the time instances that node α will be in active state. Therefore, we can have $t_\alpha = \{t_\alpha^1, t_\alpha^2, \ldots, t_\alpha^n\}$ for node α when it is in the active state for working schedule t_α. For instance, a sensor node α with a period duration time 10τ and working schedule $t_\alpha = \{1, 3, 6, 7, 9\}$, which indicates that sensor α will be in active state in time instance $\{1, 3, 6, 7, 9\}$ and in dormant state in other time instances $\{2, 4, 5, 8, 10\}$, as shown in Fig. 4.

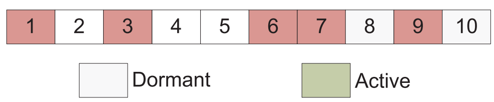

FIGURE 4. Example of working schedule of a sensor α.

B. DESCRIPTION OF THE DELAY PROBLEM FOR EH-WSNs WITHOUT CTC

In the process of packet delivery, a sender has to wait for its receiver switching to active state before it can send a packet. Hence, sleep latency is the main factor for causing the E2E delay problems of WSNs and EH-WSNs, especially when sensor nodes are in a low duty cycle which means sensor nodes are in a dormant state in most of the time in order to recharge the battery. To further illustrate the concept of sleep latency, we provide a simple walkthrough example of 2-hop liner network as shown in Fig. 5. The working schedules for nodes α, β, γ were set to $t_\alpha = \{2\}$, $t_\beta = \{7\}$, $t_\gamma = \{5\}$, respectively. If the sensor α has received a packet in time 2 and ready to send the packet to its neighboring node β at the

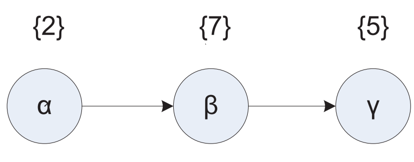

FIGURE 5. Three sensors with different active instances are deployed in a linear network.

next active instance, the sleep latency for the first attempted transmission from node α to node β is $d_{(\alpha,\beta)}(2,7) = 5$. Therefore, the E2E delay is $d_{(\alpha,\gamma)}(2,5) = 13$ when packet is transmitted from node α to node γ by the forwarding of node β.

The sleep latency between two sensors is on the influence of their duty cycles. We assume that m denotes the duration of periodic working schedules and k denotes the number of active instances in m. The value of k reflects the active intensity in a working-schedule for a sensor, where, high value represents a sensor activating frequently, and vice versa. Therefore, for the wireless sensor networks, the duty cycle can be calculated as the percentage of one period in which a signal is active. In our work, the duty cycle for a sensor α can be represented as:

$$D_\alpha = \frac{k}{m} \tag{1}$$

For EH-WSNs, even though the duty-cycle of a sensor is adjusted dynamically and very hard to be predicted due to unpredictable environment condition, there is still some regularity to follow. We can conclude the average delay for a long period time. The average delay for two adjacent nodes α and β is:

$$d^{\nu}_{(\alpha,\beta)} = \frac{1}{2 * D_\alpha} - 0.5 \tag{2}$$

where, $0 < D_\alpha \leq 1$, if $D_\alpha = 0$, it means that sensor α never wakes up and has broken down. An example is provided for further to illustrating the average delay calculated based on Eq. 2. We assume that the duration of periodic working-schedule is 10, for a sensor attempts to deliver a packet to its neighbor, when only one active instance exists for both sensors, the maximum delay is 9 and minimum delay is 0. Hence, the average delay is 4.5, as is shown in Fig. 6. If a node has 10 active instance, which means the node can work continually, $m = 10$, $k = 10$, the $d^{\nu}_{(\alpha,\beta)}$ is 0, which indicates that both of them wake up together and data is transmitted directly between them.

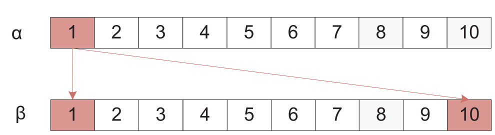

FIGURE 6. Three sensors with different active instances are deployed in a linear network.

Hence, the E2E delay can be concluded as:

$$d^{\nu}_{(\alpha,\gamma)} = \sum_{\alpha=1}^{m-1} d^{\nu}_{(\alpha,\beta)} \tag{3}$$

where, m denotes the hop counts from a source node to destination. Therefore, the Eq. 3 represents the E2E delay from a source to destination in traditional EH-WSNs without utilizing CTC. We will analyzing the E2E delay problem based on CTC for EH-WSNs in next section.

C. ROUTING PROTOCOL FOR EH-WSNs BASED ON CTC

With the help of WiFi-to-ZigBee CTC technology, a WiFi node can directly send message to nearby ZigBee nodes within its range.

Definition 1: Countdown Mechanism (CM): A WiFi node continually broadcasts beacon messages containing a beacon number $k, k \in N+$ in each time slot. This beacon number will decrease by one after each broadcast until it reaches 0.

The Countdown Mechanism is used for the WiFi node to coordinate other ZigBee nodes. For ZigBee nodes, upon receiving a beacon message, they will switch back to dormant state and wait for k time slots to rendezvous others. As the beacons are broadcasted continually, ZigBee nodes at different time slots will receiving different beacon numbers, and wake up together when $k = 0$.

Take Fig. 7 as an illustrative example. Suppose initially the WiFi node broadcasts the number $k = 8$. After one time slot, the node α is active according to its duty-cycle schedule, and receives the new beacon number $k = 7$. It will switch back to dormant state, waiting for the next 7 time slots. Notice that during these 7 slots, node α does not need to wake up regardless its original duty-cycle schedule. At the fourth slot, node β wakes up and receives the number 5. It will be in sleep for 5 time slots and rendezvous node α in the eighth time slot. In the eighth slot, both node α and β will open their radio and discover each other.

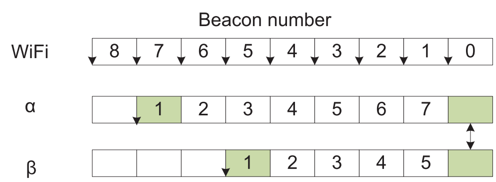

FIGURE 7. Two nodes attempt to discover each other assisted by a WiFi node.

By the simple examples, we can find that on one hand, a large initial beacon number, denoted as K, may help to discover more ZigBee nodes. When it is sufficiently large, all nodes can receive the beacon number at least once, and they will rendezvous at the last time slot. On the other hand, the countdown has to finish before ZigBee nodes rendezvous, and extra discovery latency will be introduced by a large initial beacon number. We thus prefer a minimal initial number while desire more nodes to be covered. The suitable initial beacon number K is our main design issue.

Let K_α be a completed duty period for node α, then we have $K_\alpha = 1/D_\alpha$. According to this definition, in K_α time, α shall wake up at least once. Assuming the WiFi beacons are perfectly received, when the initial beacon number is greater than the duty period, i.e., $K \geq K_\alpha$, the node α can surely receives a beacon message and the beacon number. Accordingly, two nodes α and β can discover each other if $K \geq \max(K_\alpha, K_\beta)$.

Similarly, for more general cases where there are N nodes deployed in the field, it is easy to see that the initial beacon number K should be set to the largest duty period, i.e.,

$$\begin{aligned} K &= \max\{K_{\alpha_i}, i = 1, \ldots, N\} \\ &= \max\{1/D_{\alpha_i}, i = 1, \ldots, N\} \end{aligned} \quad (4)$$

When the WiFi node selects the initial beacon number K as Eq. 4, all nodes will receive at least one beacon. When the countdown finishes, all nodes will wake up simultaneously and data transmission will be accomplished. According to Eq. 4, K is only determined by the minimum duty cycle of nodes and independent to the number of nodes N.

Therefore, the E2E delay for EH-WSNs based on CTC can be concluded as:

$$d^{v'}_{(\alpha,\gamma)} = K \quad (5)$$

According to Eq. 3 and Eq. 5, if a packet is forwarded from a source to its destination through more than three hop-count in a low-duty-cycle network, our routing protocol will provide better performance with lower E2E delay. Such as, we assume that all sensors with identical duty cycle D_α, in traditional EH-WSNs without CTC, according to Eq. 3 and Eq. 4, when $m = 3$, the E2E delay $d^{v}_{(\alpha,\gamma)} = \frac{3}{2*D_\alpha} - 1.5$. In EH-WSNs with CTC, the E2E delay $d^{v'}_{(\alpha,\gamma)} = \frac{1}{D_\alpha}$. When $D_\alpha < 1/3$, then, $d^{v'}_{(\alpha,\gamma)} < d^{v}_{(\alpha,\gamma)}$. When $m = 4, D_\alpha < 1/2$, the E2E delay $d^{v'}_{(\alpha,\gamma)} < d^{v}_{(\alpha,\gamma)}$. Therefore, our algorithm is suitable particularly for a large-scale and low-duty-cycles wireless sensor network.

D. GLOBAL TIME SYNCHRONIZATION

Time synchronization is a method which allows individual entities in a group to synchronize their clocks with respect to each other or to some coordinated universal time (UTC). As the different clock tick at different rates because of the difference of oscillating frequency, they may not remain synchronized always every if the start synchronized. All sensors have their own internal clock and own notion of time. This can cause serious problems to applications that depend on a synchronized notion of time. Currently, all algorithms for time synchronization utilizing single communication technology and it is expensive to achieve global time synchronization. Therefore, there is no global clock or common time in the distributed system in traditional WSNs and EH-WSNs.

Depending on CTC, since a WiFi node can send commands to sensors directly without other sensors forwarding, WiFi nodes can be as central coordinators and broadcast global time stamps to sensors directly. The process of time synchronization for EH-WSNs based on CTC is similar to RBS [34]. The difference to RBS for RowBee is that we use a WiFi node to replace a common sensor for broadcasting time information to all the nodes in the network as done in the traditional wireless system. Therefore, if all sensors are covered by multiple WiFi nodes, all of them will achieve global time synchronization simultaneously, as shown in Fig. 8. There are at least two significant advantages for the global time synchronization based on CTC. firstly, it is a simple yet effective method based on CTC for sensors achieving global time synchronization simultaneously. Secondly, since all sensors only need to listen to the channel and wait for the time stamps coming, the energy expenditure of sensors for time synchronization is lower than that of traditional WSNs and EH-WSNs without CTC.

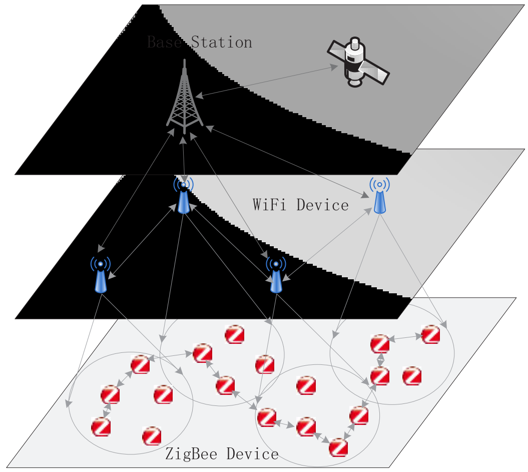

FIGURE 8. A hierarchical view of three layers for Base station, WiFi devices and ZigBee devices.

In our previous analysis, we assumes time slots of different ZigBee nodes are perfectly aligned. This is not always true in practice, and not a mandatory requirement for RowBee protocol either. Consider a non-alignment example in Fig. 9. Suppose the node α wakes up at the middle of the first slot, it will miss the first beacon and receives the second beacon message, containing the beacon number 7. Similarly, node β may be active since fourth slot, while it only receives the beacon number 4. Node α and β can still meet each other at last. Therefore, RowBee protocol will achieve slots aligned in the process of data transmission. By this case, we can find that the RowBee protocol is robust against time slot non-alignment.

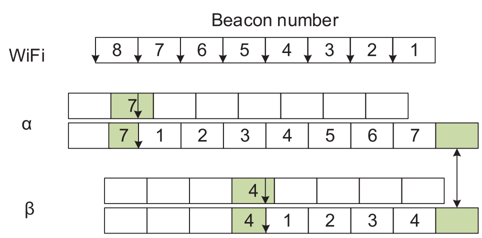

FIGURE 9. Two nodes achieve neighbor discovery regardless of the offset. After a node receiving a beacon, its slots are aligned with that of the WiFi node.

E. HOW TO HANDLE THE WiFi SIGNAL INTERFERING WITH ZigBee COMMUNICATION

Since WiFi node is no limitation on energy budget, it can broadcast command packets frequently to its covering area. These command packets can be utilized for global time synchronization and routing path establishment. Since the WiFi nodes can not distinguish ZigBee signal, at the same time, because it operates in the same ISM band and channel together with ZigBee nodes, WiFi signal will interfere with ZigBee communication, which indicates that ZigBee nodes can not communicate with other devices when WiFi node occupies the channel.

For handling the WiFi signal interfering with ZigBee communication, we analyze the time slot division for WiFi node and ZigBee nodes. According to previous analysis, after ZigBee nodes achieving neighbor discovery, their slots are aligned with that of the WiFi node, which indicates that a ZigBee node master the working schedule of WiFi node. Therefore, ZigBee nodes can switch to dormant state when WiFi node broadcasts commands until channel is idle. Take Figure. 10 as an illustrative example. When node α and β decide to exchange information in a time slot when WiFi node broadcasts command at the time slot 4, node α and β will turn off the radio in the beginning of the time slot until command broadcasting is finished. Therefore, ZigBee nodes can utilize the interval of command broadcasting for data transmission.

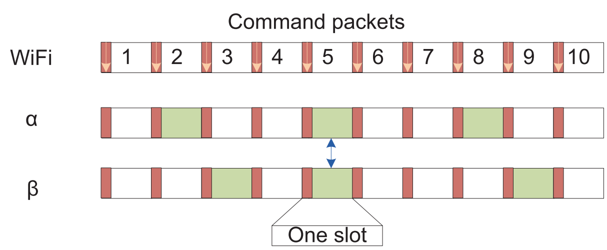

FIGURE 10. Two nodes can exchange information evading WiFi signal interference.

V. SIMULATION EVALUATION

In this section, we perform experiments on real-world testbed to evaluate RowBee's performance and compare it to other state of the art protocols.

A. EXPERIMENT SETUP

The RowBee testbed consists of two types of devices: (i) sender: the USRP-N210 platform with 802.11 b/g PHY, (ii) receiver: a commodity ZigBee receiver(i.e., MICAz). We note that RowBee is supported directly among commodity devices and USRP-N210 devices are used only for evaluation purposes to measure low-level PHY information, which are inaccessible by commodity devices, such as a commodity WiFi card Atheros AR2425 can replace USRP-N210 devices as the sender. For the receiver, we have implemented RowBee and other reference protocols on TinyOS 2.1.2. Fig. 11 shows the experiment setting of our design. We use a laptop as a data packet generator and it is connected to USRP N210. All nodes locate in the transmission range of the USRP-N210 device. Time slot is set to 10ms as Disco does.

In the experiments, beacons are implemented as small AM broadcast message with payloads. The length of the

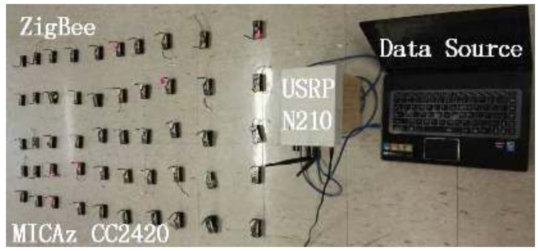

FIGURE 11. Experiment setting.

underlying physical message is 25 bytes(4B preamble + 1B SFD + 1B PHR + 4B preamble + 1B SFD + 1B PHR + 8B MAC header + 1B TinyOS AM type + 2B payloads + 2B CRC). As shown in Fig. 12, preamble repetition improves the chances of successful preamble detection. If the first preamble is identified successfully, the second is discarded. It takes about 0.8 ms (25*0.32) for an IEEE 802.11g-compatible radio to transmit and IEEE 802.15.4-compatible radio to receive a beacon.

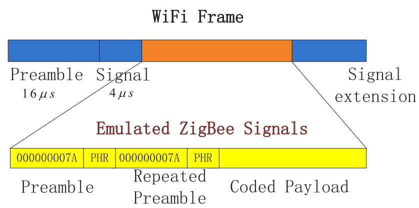

FIGURE 12. WiFi frame format.

B. RowBee BASED ON CTC

In the scenario, 50 nodes are deployed (as is shown in Fig. 11) in the field with duty cycles between 0.1% – 30% randomly. Therefore, the maximum initial number broadcasted by a WiFi node is 1000. We analyze the number of nodes waking up together when different beacons are broadcasted by a WiFi node, as is shown in Fig. 13. From Fig. 13, for guaranteeing 45 nodes (90% of total nodes) waking up together, we can

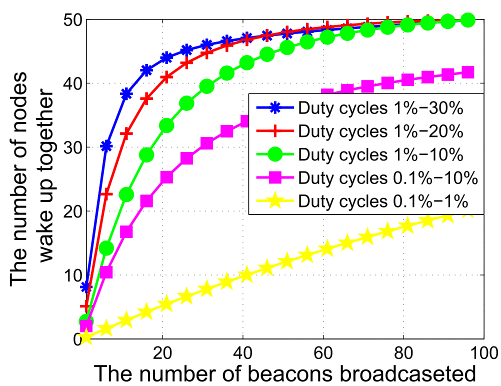

FIGURE 13. The number of nodes wake up together with beacons broadcasted number increasing when different duty cycles of nodes are adopted.

observe that at least 26, 32, 49 beacons should be broadcasted for duty-cycles distributed in $1-30\%$, $1-20\%$, $1-10\%$, respectively, and only 43, 20 nodes can wake up togher when 100 beacons are broadcasted when duty-cycles are distributed in $0.1-10\%$, $0.1-1\%$, respectively.

C. SYSTEM PERFORMANCE COMPARISON

In order to further understand of the performance of our algorithm (RowBee) under network settings, in this section, we provide a scheme for performance comparison, Plant-Bioenergy MAC (PB-MAC) [43], a novel asynchronous duty-cycling energy-efficient protocol. In PB-MAC, the authors propose an individual energy harvesting prediction algorithm to guarantee precise energy management and an optimized self-adaptive work-sleep duty cycle mechanism to provide optimal packet communications with lower data transmission delay. For system performance comparison, we provide numerical results to demonstrate the performance of the proposed algorithm. Simulation of our RowBee and PB-MAC were done by Matlab software, with up to 400 nodes are randomly deployed in a $1000m*1000m$ square field. The maximum communication range of each node is set to be $100m$. Time slot is set to 10ms. Every data point in simulation figures is obtained by averaging 50 runs with different random seeds, node deployment and node working schedules.

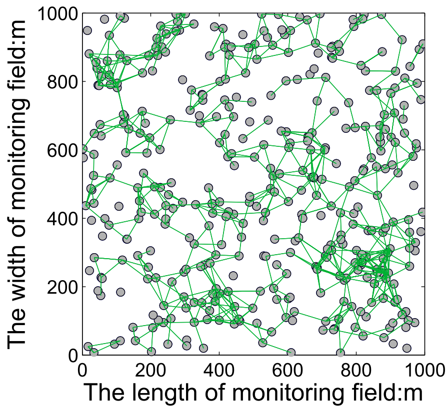

FIGURE 14. For PB-MAC, the routing protocol for data link paths established with duty cycles distributed randomly in [1% – 10%] after system initiates 1000ms (100 slots) later.

Let us start with the example for PB-MAC shown in Fig. 14, where shows the status for communication links established by sensors when system initiates $1000ms$ (100 slots) later with the duty cycles distributed randomly in $[1\% - 10\%]$. In our work, we said that a sensor discovers its neighbors or establishes communication link if the sensor has found at least one neighbor, although the sensor generally obtains more than one adjacent neighbors. From Fig. 14, for PB-MAC protocol, we can observe that about 352 sensors find at least one neighbor sensor and establish about 1562 linking-paths between two nodes. For RowBee protocol, since the minimum duty-cycle is 1%, if the initial number broadcasted by a WiFi node is 100, all sensors will wake up together. In other word, after 100 slots, all sensors will find their neighbors, the result is shown in Fig. 15, where 4574 links between these sensors and their adjacent neighbors are established for RowBee.

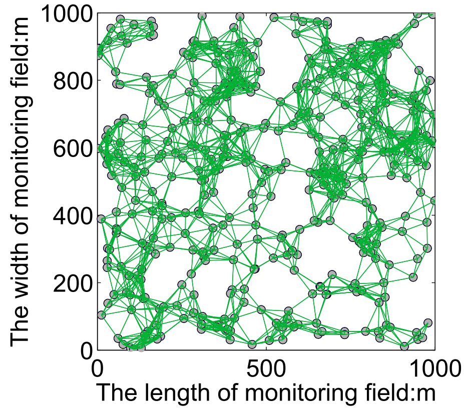

FIGURE 15. For RowBee, the routing protocol for data link paths established with duty cycles distributed randomly in [1% – 10%] after system initiates 1000ms (100 slots) later.

For PB-MAC, RowBee, since all sensors' duty-cycles are distributed in $[1\% - 10\%]$, it means that all sensors wake up the same times generally. However, from Fig. 14 and Fig. 15, we can find a big gap between the two protocols for establishing connection links. The main reason is that two sensors should wake up together and lay in the transmission range of each other if they want to build a routing path. In PB-MAC, although two sensors perhaps wake up simultaneously, they can not talk to each other if they are without each other's communication range. While in RowBee, since all sensors will wake up together, they will find all their neighbors and establish all communication paths.

In order to further insight the performance of our algorithm and PB-MAC, we compare the average E2E delay for different nodes duty-cycles, number of sensor, respectively, as shown in Fig. 16. From Fig. 16, we observe that the average E2E delay decreases greatly for two algorithms

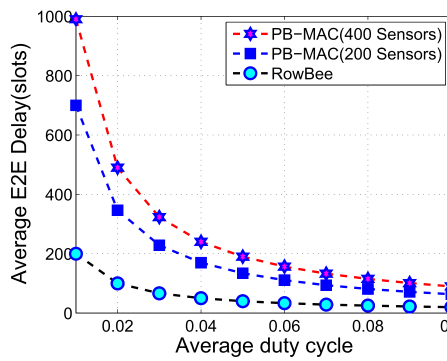

FIGURE 16. The average E2E delay for PB-MAC (200 sensor deployed and 400 sensors deployed) and RowBee with nodes' duty-cycles increased from 1% to 10%.

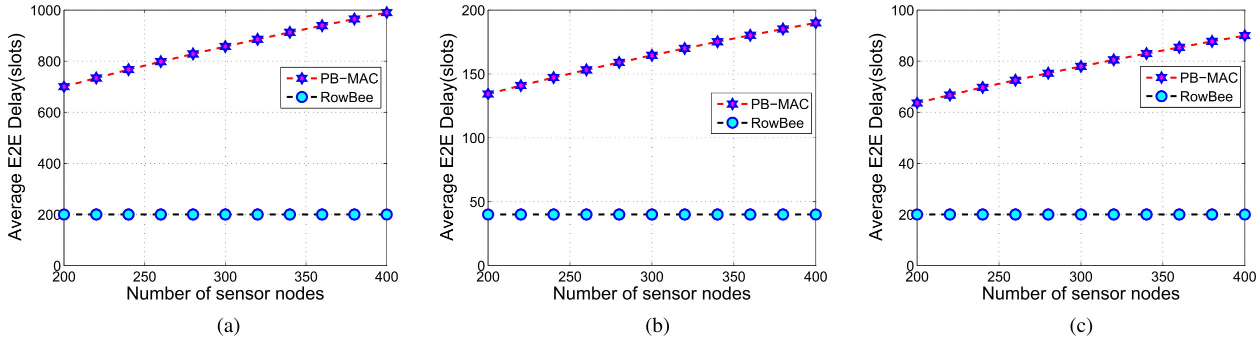

FIGURE 17. The average E2E Delay for PB-MAC and RowBee when the number of nodes increases from 200 to 400 with nodes' duty-cycle 1%, 5%, 10%, respectively. (a) The duty cycle is 1%. (b) The duty cycle is 5%. (c) The duty cycle is 10%.

because a sensor has more chance to establish routing paths when nodes' duty-cycles increases. For all different duty-cycles, the average E2E delay in our algorithm is always lower than that of PB-MAC significantly. For example, when average duty-cycles are set to 0.04, the average E2E delay for RowBee, PB-MAC (when 200 sensors are deployed) and PB-MAC (when 400 sensors are deployed) are 50, 169, 240, respectively.

Fig. 17 shows the average E2E delay for PB-MAC and RowBee protocols when the density of sensors increases and the average nodes' duty-cycle is set to 1%, 5%, 10%, respectively. From Fig. 17, we can know that the average E2E delay for RowBee and PB-MAC decreases when nodes' duty-cycles improved from 1% to 10%. In a high-duty-cycle network, a sensor operates more active and is easer to build a routing-path reaching a destination, vice versa. Fig. 17 shows our algorithm is always lower than that of PM-MAC greatly. At the same time, the curve of our algorithm is quite smooth, which means the routing protocol is more stable, while, the curves of PB-MAC appear wide fluctuation. The average E2E delay of RowBee is only on the influence of the minimum duty-cycle of nodes and independent to the number of nodes. For PB-MAC, with the density of sensors increasing, a packet will be forwarded with longer distance before reaching a destination, which leads to higher E2E delay. The data from Fig. 17 tests and verifies our analysis.

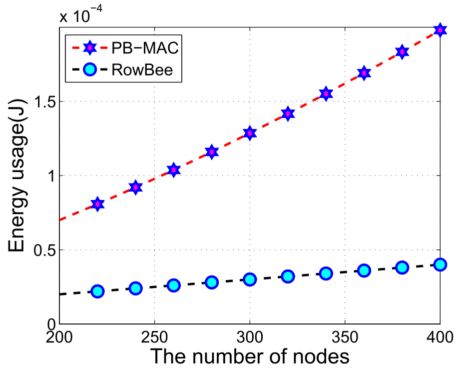

FIGURE 18. The energy usage with the number of nodes increasing when them operate at 1%.

TABLE 1. Simulation parameters.

Parameter Name	Value
Network area	$1000 \times 1000\ meter^2$
Number of sensor nodes	400
Beacon size	25 $bytes$
E_{elec}	50 nJ/bit
ε_{fs}	10 $pJ/bit/m^2$
ε_{amp}	0.0013 $pJ/bit/m^4$
d	100 $meters$
MAC protocol	BoX-MAC [45]

D. ENERGY USAGE COMPARISON

We analyze the energy depletion for RowBee and PB-MAC with the number of nodes increasing when the duty cycle is 10%, as shown in Fig. 18. This is the total amount of energy consumed for all nodes due to transmission and reception of beacons. The intensive set of simulation is performed based on the parameter illustrated in Table 1. In our experiment, Box-MAC is utilized as communication protocol of ZigBee devices. BoX-MAC continuously transmits a data packet until the packet received by neighbors rather than transmit a wakeup preamble.

From Fig. 18, we can observe that the energy consumption increases gradually with the number of sensors increasing and smaller energy is consumed in our algorithm than that of PB-MAC for any number of nodes. Especially, more sensors added to the scenario, the energy expenditure gap grows gradually. When the number of nodes is 200, the energy usage are 0.2 for RowBee and 0.7 for PB-MAC. While more 300 nodes are appended to the scenario, the energy expenditure are 0.3, 1.2 for RowBee and PB-MAC. Furthering to illustrate the reason of energy expenditure difference, when PB-MAC wants to establish routing paths for achieving a 1% duty cycle, a node will wake up about 7 times to broadcast beacons for worst-case discovery latency with 200 sensors deployed. From Fig. 17, about 700 slots are needed for linking-paths built with 200 sensors. Hence, a sensor will wake up 7 times with 1% duty-cycle in 700 slots. While for RowBee, a node only wakes up 2 times for establishing routing path, where, it receives a beacon firstly and broadcasts beacons for identifying neighbors secondly. Therefore, RowBee protocol achieves a better performance for saving energy.

VI. CONCLUSION

We have present RowBee, a routing protocol based on Cross-Technology Communication. The breakthrough on CTC, where, WiFi-equipped devices can transmit messages to ZigBee-embedded devices directly, sheds the light on the opportunities for a node identifies nearby devices. RowBee takes the advantage of WiFi broadcasting with long distance to assist ZigBee-embedded devices for establishing routing path. Firstly, we introduce the delay problem for EH-WSNs without CTC. Subsequently, we propose a method for WiFi nodes to broadcast beacons waking up ZigBee devices simultaneously for establishing routing paths and analyze how to handle the WiFi signal interfering with ZigBee communication. Finally, we provide a simple yet effective scheme for global time synchronization and time slots aligned. RowBee allows nodes to choose their duty-cycles freely and enables finer duty-cycle granularity. The analytical and real-world experiment results show that RowBee is significantly better than the state of the art protocols and reduces E2E delay greatly.

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