Asynchronous Power Management Protocols With Minimum Duty Cycle and Maximum Adaptiveness for Multihop Ad Hoc Networks

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***Abstract*—IEEE 802.11 is currently the *de facto* medium access control (MAC) standard for mobile ad hoc networks (MANETs). However, in a multihop MANET, 802.11 power management may completely fail if stations are out of synchronization. To fix this problem, several papers have proposed various cyclic quorum-based power management (CQPM) protocols, which, however, may also fail if stations have different schedule repetition intervals (SRIs). Hence, adaptive CQPM protocols, namely, adaptive quorum-based energy conserving (AQEC) and hyper quorum system (HQS), were proposed to overcome this drawback. However, the duty cycles of AQEC and HQS are far from optimal. In this paper, we propose the optimal fully adaptive and asynchronous (OFAA) power management protocol for a multihop MANET, which has the following attractive features: 1) By means of factor-hereditary quorum space, the OFAA protocol guarantees that two neighboring stations can discover each other in bounded time, regardless of their clock difference and individual SRIs; 2) given the length of SRI, the duty cycle of a station reaches the theoretical minimum; 3) the number of tunable SRIs of every station reaches the theoretical maximum; 4) the time complexity of OFAA neighbor maintenance is $O(1)$; 5) a cross-layer SRI adjustment scheme is proposed such that a station can adaptively tune the values of SRI to maximize energy conservation according to flow timeliness requirements. Both theoretical analysis and simulation results demonstrate that the OFAA protocol is much more energy efficient than AQEC and HQS protocols.**

***Index Terms*—IEEE 802.11, medium access control (MAC), mobile ad hoc network (MANET), power management, quorum.**

I. Introduction

A MOBILE ad hoc network (MANET) consists of a collection of mobile stations, which communicate with each other either directly or indirectly through multiple hops, without the aid of any infrastructure (e.g., base stations or access points). Since mobile stations are typically powered by batteries, the success of MANETs strongly relies on energy-efficient communications. The radio of a mobile station can be in one of three *awake* states, namely, transmitting, receiving, and idle listening, or in the *doze* state. Studies in [6] have shown that power consumption in the idle state is only *slightly* lower than that in the transmitting and receiving states. Hence, to save power, a mobile station has to put itself in the doze state. However, in this state, it cannot transmit nor receive. This implies that if a station sleeps but there are data frames for it, then the latency to obtain those frames will become larger. On the other hand, if a station wakes up and finds no data for it, that station obviously wastes energy. The problem, therefore, is to design a good *power management* protocol by which a station can decide when to sleep and when to wake up such that the energy–latency tradeoff can be properly managed.

A. IEEE 802.11 Power Management

IEEE 802.11 [8] is currently the *de facto medium access control* (MAC) standard for MANETs. As shown in Fig. 1(a), in 802.11, time is divided into fixed-sized *beacon intervals* (BIs). Mobile stations operating in the *power-saving* (PS) mode should wake up prior to each *target beacon transmission time* (TBTT) and wait for a random backoff time to contend for broadcasting a beacon frame, which is mainly used for clock synchronization. All PS stations should keep awake during the entire *announcement traffic indication message* (ATIM) window. If station P intends to send buffered data frames to destination Q currently operating in the PS mode, P shall first unicast an ATIM frame to Q during the ATIM window. Upon reception of that ATIM frame, PS destination Q replies an ATIM-ACK to P, and then, both P and Q stay awake for the entire BI. PS stations that neither transmitted nor received an ATIM frame may return to the *doze* state at the end of the ATIM window. After the ATIM window concludes, station P sends buffered data to Q, and Q then acknowledges its receipts. Note that the transmission and retransmission of ATIM/data frames should follow the *distributed coordination function* procedure [8].

B. Challenges

When designing power management protocols for a multihop MANET, we inevitably need to face two major challenges.

1) *Timing synchronization*. Because of beacon contention, radio interference, and frequent topology change, it is very difficult or costly for all stations to keep synchronized at all times [16]. In Fig. 1(b), we can see that once PS stations get out of synchronization, 802.11 power management may completely fail since PS neighbors may forever lose each other's beacons or ATIM frames.

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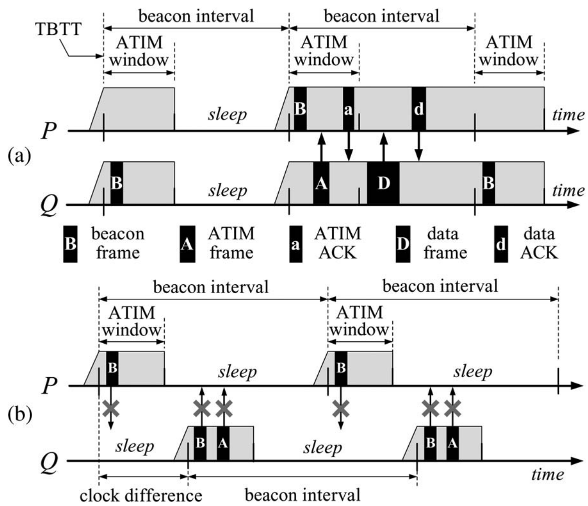

Fig. 1. (a) Example of 802.11 power management operation in a MANET. (b) Because of out of synchronization, PS neighbors P and Q are unable to receive each other's beacons or ATIM frames.

2) *Neighbor maintenance*. An active station may not detect some PS neighbors since they purposely reduce their transmitting activities. In an asynchronous MANET, a PS station may wake up too late to hear neighbors' beacons. Such incorrect neighbor information may be an obstacle to existing protocols, such as the zone routing protocol [7] and the neighbor coverage-based broadcasting protocol [17], whose success relies on accurate neighbor table. Worse, if some PS stations constitute a *vertex cutset*, whose removal will disconnect the network, then a *PS-induced network partition* problem [16], [21] may arise.

C. Related Work

Tseng *et al.* [16] proposed the first *asynchronous* power management protocols that can correctly operate in an 802.11-based MANET without need for synchronization. Then, Jiang *et al.* in [9], Zheng *et al.* in [23], and Chou *et al.* in [21] concurrently and independently proposed similar *cyclic quorum*-based power management (CQPM) protocols to improve the performances in [16]. In these CQPM protocols [9], [16], [21], [23], there are two types of BIs, namely, *fully awake BI* (FBI) and *normal BI* (NBI). In Fig. 2(a), the FBI starts with the *beacon window* followed by the *data window*. Every station shall broadcast its beacons *only* in its beacon windows. After the close of the beacon window, a PS station needs to remain awake during the *entire* data window. The design purpose of the FBI [16] is to impose a PS station to stay awake sufficiently long so as to ensure that neighboring stations have chance to receive each other's beacons (and thus *discover* each other) even if their clocks are different. On the other hand, the NBI[1] starts with

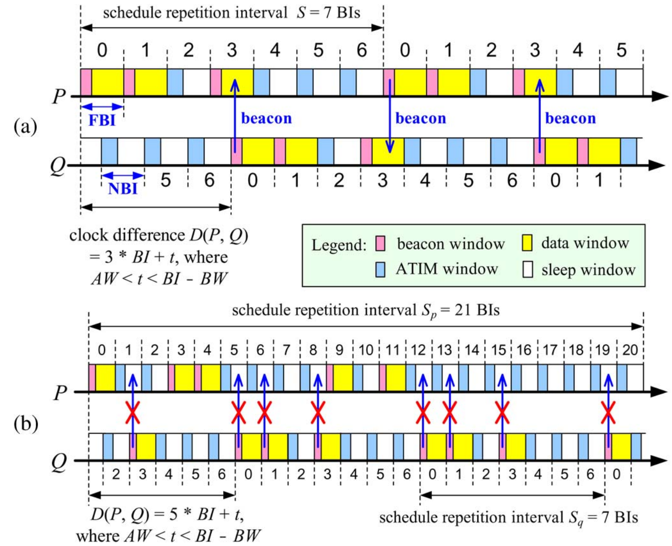

Fig. 2. (a) Example of the neighbor maintenance in CQPM. (b) P forever loses Q's beacons when P's clock leads Q's clock by $5 \times BI + t$, where $AW < t < BI - BW$. Note that some arrows representing the beacon frames are ignored for clarity.

an ATIM window. After the ATIM window ends, a PS station may doze off during the *sleep window*. Let the lengths of the beacon window, the ATIM window, and the BI be denoted by BW, AW, and BI, respectively. CQPM protocols require that $AW \geq BW$. Importantly, in CQPM, when a station switches to the PS mode, it selects a quorum $q_i \subseteq \{0, 1, \ldots, S-1\}$ from the cyclic quorum system $\mathcal{Q} = \{q_i\}_{0 \leq i \leq S-1}$ as its FBIs in a *schedule repetition interval* (SRI), whereas the residual BIs are NBIs, where SRI $= S$ means that these S consecutive BIs that constitute the specific awake/sleep schedule regularly repeat. In Fig. 2(a) for example, $S = 7$ and $\mathcal{Q} = \{q_0 = \{0,1,3\},\ q_1 = \{1,2,4\},\ q_2 = \{2,3,5\},\ q_3 = \{3,4,6\},\ q_4 = \{4,5,0\},\ q_5 = \{5,6,1\},\ q_6 = \{6,0,2\}\}$, both PS stations P and Q select the $q_0 = \{0,1,3\}$th BIs as their FBIs in every consecutive seven BIs. To keep the analysis and presentation simple, we assume that no collisions occur in beacon broadcast throughout this paper except for simulations. Under this assumption, [9], [21], and [23] have proven that two PS neighbors, i.e., P and Q, are able to discover each other in finite time, regardless of their clock difference $D(P,Q)$.

We define *duty cycle* as the minimum fraction of time during which the PS station must stay awake. Intuitively, the lower the duty cycle, the less frequent the station wakes up, the more battery power the station can save. On the flip side, the higher the duty cycle, the more frequent the station wakes up, the shorter data reception delay and neighbor discovery time the station may perceive. Hence, we hope that a PS station can adaptively adjust its duty cycle according to its residual battery power or other quality-of-service (QoS) considerations. The common drawback of existing CQPM protocols [9], [21], [23] is they require that all PS stations must have the *same* SRI. Let *FBI-set* $\mathcal{F}(S)$ be the *positions* of the FBIs in SRI S. Fig. 2(b) shows that although stations P and Q obey the rotation closure rule [9], [21], [23] to set their respective FBI-sets [namely, $(S_p, \mathcal{F}(S_p)) = (21, \{0,3,4,9,11\})$ and $(S_q, \mathcal{F}(S_q)) = (7, \{0,1,3\})$], yet these protocols [9], [21], [23]

[1]Note that the NBI in CQPM protocols is slightly different from the BI in 802.11. More specifically, to reduce power consumption and beacon collision probability, existing CQPM protocols [9], [16], [21], [23] require that a PS station should *not* send its beacon in the NBI. On the other hand, in Fig. 2(a), if the NBI is replaced by the sleep BI (SBI), during which a PS station *entirely* dozes off, station P may forever fail to discover its PS neighbor Q when the clock of P leads that of Q by $4 \times BI - t$, where $0 < t < BW$, since none of Q's beacon windows can be *fully* covered by any P's active windows, during which station P stays awake.

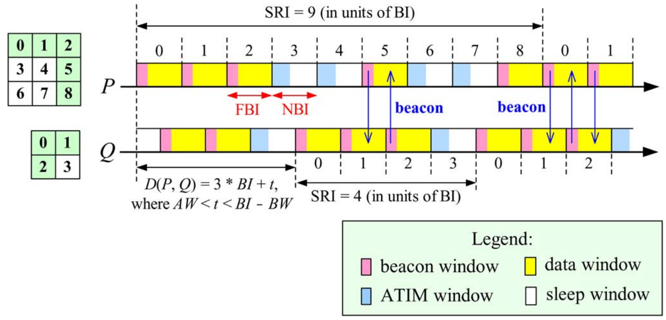

Fig. 3. Example of the neighbor maintenance in AQEC.

may completely fail when P and Q have different values of SRI. This implies that, from the viewpoint of the duty cycle, they are *nonadaptive*.

To support SRI adaptation, Chao *et al.* [3] proposed the first *adaptive* power management protocol, which is called adaptive quorum-based energy conserving (AQEC), for 802.11-based MANETs. In Fig. 3, in AQEC, the consecutive BIs in SRI S are arranged as a $\sqrt{S} \times \sqrt{S}$ grid in a row-major fashion, where $\sqrt{S}$ is an integer. Each PS station selects one row and one column from a grid of *arbitrary* size $\sqrt{S} \times \sqrt{S}$ as its FBIs, whereas the residual BIs are NBIs. In Fig. 3 for example, station P chooses SRI $S = 9$ and sets the jth BIs, where $j \in \{0, 1, 2, 5, 8\}$, as its FBIs in an SRI. By the grid-quorum property [3], AQEC ensures that two neighbors, i.e., P and Q, can discover each other in bounded time regardless of their clock difference $D(P, Q)$ and *individual* SRIs. The duty cycle of AQEC is close to $AW/BI + 2(1 - AW/BI)/\sqrt{S}$ and bounded by AW/BI. In addition, given the maximum value of SRI $S_{\max}$, the number of adjustable SRIs in AQEC is only $\lfloor\sqrt{S_{\max}}\rfloor$. Intuitively, the larger the number of tunable SRIs, the more flexible PS stations are to fine tune their duty cycles to achieve high energy efficiency. Therefore, Wu *et al.* [20] proposed *fully* adaptive power management protocols, which are called hyper quorum system (HQS), in which each PS station can select an *arbitrary* value of SRI. More specifically, given the value of SRI $1 \leq S \leq S_{\max}$, the FBI-set $\mathcal{F}(S)$ in an HQS is constructed as follows. Let us first define

$$\mathcal{D}(S) = \{0, 1, \ldots, \phi - 1, d_1, d_2, \ldots, d_{g-1}\} \quad (1)$$

where $\phi = \lceil\sqrt{(S_{\max}+1)/2}\rceil$, $g = \lceil S + 1/2\phi\rceil$, $\phi - 1 < d_1 \leq 2\phi - 1$, $d_{g-1} \geq (S-1)/2$, and $0 < d_{j+1} - d_j \leq \phi$ for all $1 \leq j \leq g-2$. Then

$$\mathcal{F}(S) = \{i \bmod S \mid i \in \mathcal{D}(S)\}. \quad (2)$$

When $S = S_{\max}$, the duty cycle of the HQS is close to $AW/BI + (1 - AW/BI)\sqrt{2/S}$ and bounded by AW/BI.

After comparing with 802.11, AQEC, and HQS, we can make the following observations: 1) From the viewpoint of *synchronization requirement* and *adaptiveness*, both AQEC and HQS protocols outperform 802.11 since 802.11 requires *global* clock synchronization and the duty cycle of 802.11 is fixed. 2) The duty cycle of 802.11 is only AW/BI. Thus, from the viewpoint of *power consumption*, 802.11 outperforms both AQEC and HQS protocols. This is because PS stations in all existing asynchronous CQPM protocols [3], [9], [16], [20], [21], [23] are required to have a much higher duty cycle than those in 802.11 to overhear neighbors' beacons and, thus, maintain neighbor connectivity.

D. Objective and Contributions

The main objective of this paper is to design an optimal fully adaptive power management protocol for an asynchronous MANET. Specifically, in Section III, we will show that if an asynchronous power management protocol $\mathcal{X}$ is said *optimal* and *fully adaptive*, it must satisfy the following requirements.

R1. *Minimum duty cycle requirement*. Given the value of SRI S, the duty cycle of a PS station in $\mathcal{X}$ is no more than $(1/2 + BW/BI)(\lceil\sqrt{S}\rceil + 1)/S$, which is only about $1/(2\sqrt{S})$ when BW/BI is small.

R2. *Maximum adaptiveness requirement*. Given the maximum value of SRI $S_{\max}$, the number of tunable SRIs of every station in $\mathcal{X}$ is $S_{\max}$.

In [23], Zheng *et al.* conjectured that the problem of finding an adaptive and optimal awake/sleep schedule for asynchronous MANETs is NP-complete. In this paper, we disprove this conjecture by providing a simple yet novel $O(1)$ optimal fully adaptive and asynchronous (OFAA) power management protocol for the practical value of $S_{\max}$, e.g., 25. The major technical innovations of an OFAA protocol include 1) newly designed structures of BIs, and 2) a topology-independent neighbor maintenance scheme by using the *factor-hereditary quorum space* (defined in Section II-B), such that two PS neighbors can discover each other in bounded time, regardless of their clock difference and individual SRIs. To the best of our knowledge, the OFAA protocol is the first asynchronous quorum-based power management protocol where the duty cycle of every station can be lower than that in 802.11. On the other hand, since a PS station may often doze off, the OFAA protocol employs the awake/sleep pattern prediction method such that the source station can predict when the PS destination will wake up, thus delivering data frames to it at the right time. Then, on the basis of the OFAA protocol, we design a cross-layer SRI adjustment scheme such that PS stations along the routing path can adaptively adjust the values of SRI to minimize power consumption while satisfying end-to-end flow delay requirements. Finally, through theoretical analysis and simulation results, we will quantitatively demonstrate that the OFAA protocol is much more energy efficient than AQEC and HQS protocols.

The rest of this paper is organized as follows: In Sections II and III, we present and analyze the OFAA protocol in detail. Section IV presents the cross-layer SRI adjustment scheme for the OFAA protocol. Extensive simulations are conducted in Section V. Final conclusions are drawn in Section VI.

II. Optimal Fully Adaptive and Asynchronous Protocol

The OFAA protocol contains four parts: 1) new structures of BIs; 2) a neighbor maintenance procedure; 3) an awake/sleep

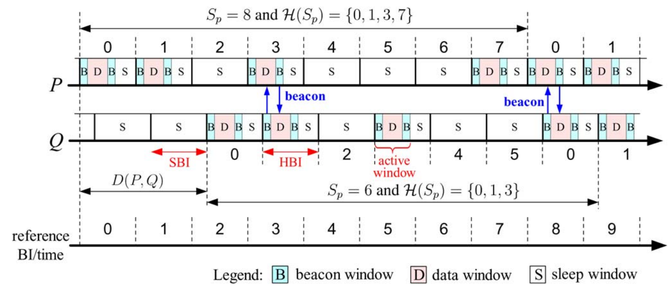

Fig. 4. Example of the neighbor maintenance in OFAA.

pattern prediction method; and 4) a data frame transfer procedure.

A. New Structures of BIs

As shown in Fig. 4, we design two types of BIs for the OFAA protocol, namely, *half-awake BI* (HBI) and SBI. The structures of these BIs are defined as follows.

- The *HBI* starts with the beacon window and followed by the data window. After the second beacon window ends, a PS station may enter the doze state. To announce its presence for neighbor maintenance, every PS station shall broadcast two beacon frames, i.e., one in each of the two beacon windows, in an HBI. Let $actW$ be the length of the active window in a BI, during which a PS station must stay awake. The OFAA protocol requires that in an HBI, $actW = BW + DW + BW \geq BW + BI/2$.
- During the *entire SBI*, a PS station may doze off.

Remark 1: Note that the original design purpose of the HBI is for a PS station to save more energy than the FBI since the duty cycle of the former is only about *half* that of the latter. A positive by-product of this design is that, since there are two beacon windows in an HBI, a CQPM protocol that replaces FBIs with HBIs may have shorter average neighbor discovery time.

B. Neighbor Maintenance Procedure

Before presenting the OFAA protocol, we need to first introduce the generalized Chinese remainder theorem [5] and then provide the definition of factor-hereditary quorum space.

Theorem 1 (Generalized Chinese Remainder Theorem): Let $S_1, S_2, \ldots, S_n$ be positive integers. Let $h, b_1, b_2, \ldots, b_n$ be any integer. The following system of congruences, i.e.,

$$x \equiv b_i (\bmod S_i), \qquad i = 1, 2, \ldots, n \tag{3}$$

has infinitely many integer solutions if and only if

$$b_i \equiv b_j \; (\bmod \gcd(S_i, S_j)) \,, \text{ for all } i \neq j \text{ and } 1 \leq i, \; j \leq n. \tag{4}$$

When conditions (4) hold, the solution $h \leq x \leq h + \ell - 1$ is unique modulo $\ell = \operatorname{lcm}(S_1, S_2, \ldots, S_n)$.

Definition 1: Given a positive integer $S_{\max}$, let $\mathcal{S} = \{1, 2, \ldots, S_{\max}\}$. Let $S_i \in \mathcal{S}$ and $\mathcal{H}(S_i) = \{b_1, \ldots, b_k\}$ be a subset of $\{0, 1, \ldots, S_i - 1\}$. A collection of pairs $\mathcal{C} = \{(S_i, \mathcal{H}(S_i))\}_{1 \leq S_i \leq S_{\max}}$ is called a *factor-hereditary quorum space* if it satisfies the following properties: **P1**) For any integer h, we define $h \oplus \mathcal{H}(S_i) = \{h + b_j \bmod S_i | \text{ for all } b_j \in \mathcal{H}(S_i)\}$. Then, for all S_i, we require $\mathcal{H}(S_i) \cap (h \oplus \mathcal{H}(S_i)) \neq \varnothing$. **P2**) Given the integer S_i, let $f_1, f_2, \ldots, f_m$ be the factors (also called divisors) of S_i. Then, we require $\bigcup_{j=1}^{m} \mathcal{H}(f_j) \subseteq \mathcal{H}(S_i)$.

SRI	Positions of HBIs				SRI	Positions of HBIs					
2	0	1			14	0	1	2	3	7	
3	0	1			15	0	1	2	3	7	
4	0	1	3		16	0	1	3	7	11	
5	0	1	3		17	0	1	2	4	12	
6	0	1	3		18	0	1	3	8	12	
7	0	1	3		19	0	1	2	6	9	
8	0	1	3	7	20	0	1	2	3	6	10
9	0	1	3	8	21	0	1	3	4	14	16
10	0	1	3	6	22	0	1	2	5	8	13
11	0	1	2	5	23	0	1	2	3	7	11
12	0	1	3	7	24	0	1	2	3	7	15
13	0	1	3	9	25	0	1	2	3	8	12

Fig. 5. Example of the HBI/SBI schedule table stored in a mobile station.

The neighbor maintenance of the OFAA protocol operates as follows. Every mobile station stores the same HBI/SBI schedule table, as shown in Fig. 5, which is, in fact, a factor-hereditary quorum space $\mathcal{C} = \{(S_i, \mathcal{H}(S_i))\}_{1 \leq S_i \leq S_{\max}}$. Note that in Fig. 5, we set $S_{\max} = 25$. In Fig. 4, a PS station in the OFAA protocol can adjust the length of SRI only at the *start* of each SRI. Once the value of SRI S_i is determined, that PS station should look up the HBI/SBI schedule table to set the positions of HBIs and SBIs in the SRI. For example, as shown in Fig. 4, station P selects the $\{0, 1, 3, 7\}$th BIs as its HBIs in every consecutive eight BIs. Fig. 4 also shows that PS neighbors P and Q can discover each other at the third and eighth reference BIs when their clock difference $D(P, Q)$ is $2 \times BI + t$, where $BW < t < BW + DW$. Importantly, we have the following general result.

Theorem 2: The OFAA protocol guarantees that any two PS neighbors, i.e., P and Q, can discover each other in bounded time regardless of their clock difference $D(P, Q)$ and their individual SRIs, i.e., S_p and S_q.

Proof: Without loss of generality, we assume that the clock of P leads that of Q by $h \times BI + t$, where $h \geq 0$ is an integer, and $0 \leq t < BI$. In addition, P and Q select $(S_p, \mathcal{H}(S_p))$ and $(S_q, \mathcal{H}(S_q))$ as their respective (SRI, HBI-set), where the *HBI-set* is the set of the positions of HBIs in an SRI. Before proceeding with the proof, we need the following lemma.

Lemma 1: Let $\mathcal{C} = \{(S_i, \mathcal{H}(S_i))\}_{1 \leq S_i \leq S_{\max}}$ be a factor-hereditary quorum space. Given two integers h and S_i, there must exist two integers β_1 and β_2 in S_i such that $\beta_1 - \beta_2 = h (\bmod S_i)$.

Proof: By **P1**, $\mathcal{H}(S_i) \cap (-h \oplus \mathcal{H}(S_i)) \neq \varnothing$. Hence, we assume that $\beta \in \{\mathcal{H}(S_i) \cap (-h \oplus \mathcal{H}(S_i))\}$. This implies that there must exist an element β^* in $\mathcal{H}(S_i)$ such that $\beta = -h + \beta^* (\bmod S_i)$. Let $\beta_1 = \beta^*$ and $\beta_2 = \beta$. This lemma thus follows. ■

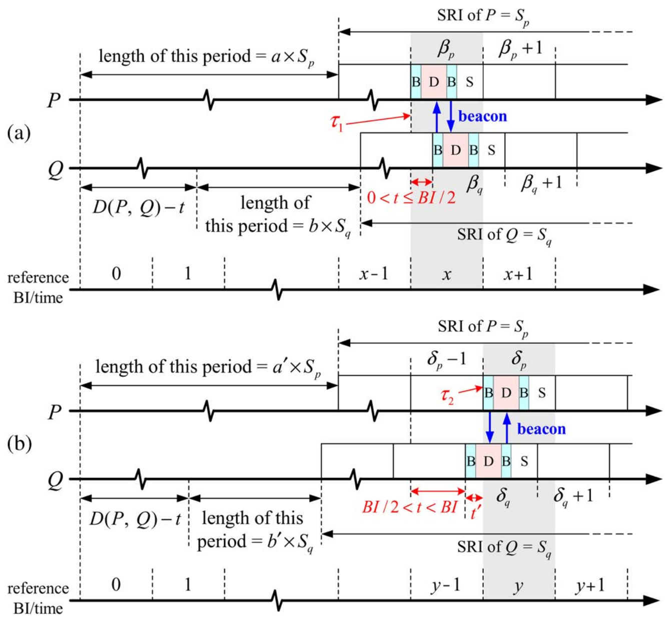

Fig. 6. Stations P and Q can discover each other, even when their clock difference is $D(P,Q) = h \times BI + t$. (a) $0 < t \leq BI/2$. (b) $BI/2 < t < BI$.

The proof of Theorem 2 can be divided into three cases.

Case 1) $t = 0$. In Fig. 4, we can understand that, when $t = 0$, the chance for PS neighbors to discover each other relies on the *encounter* of their HBIs. Hence, if P and Q can discover each other, there must exist some $\beta_p \in \mathcal{H}(S_p)$ and $\beta_q \in \mathcal{H}(S_q)$, such that the following system of congruences has positive integer solutions x:

$$\begin{cases} x \equiv \beta_p (\bmod S_p) \\ x \equiv h + \beta_q (\bmod S_q). \end{cases} \tag{5}$$

In Fig. 4 for example, P's zeroth BI (also HBI) and Q's zeroth BI (also HBI) can meet each other at the eighth reference BI since $8 \equiv 0 (\bmod 8)$ and $8 \equiv 2 + 0 (\bmod 6)$. Let $g = \gcd(S_p, S_q)$. According to the generalized Chinese remainder theorem, (5) has infinitely many positive integer solutions if and only if $\beta_p \equiv h + \beta_q (\bmod g)$. By Lemma 1, we know that, for any integer h, there must exist two integers β_1 and β_2 in $\mathcal{H}(g)$ such that $\beta_1 \equiv h + \beta_2 (\bmod g)$. By **P2**, we have $\mathcal{H}(g) \subseteq \mathcal{H}(S_p)$ and $\mathcal{H}(g) \subseteq \mathcal{H}(S_q)$. Hence, the proof of this case follows by letting $\beta_p = \beta_1 \in \mathcal{H}(S_p)$ and $\beta_q = \beta_2 \in \mathcal{H}(S_q)$.In **Case 2** and **Case 3**, we will prove that, in bounded time, at least one of P's entire beacon windows is fully covered by one of Q's active windows, and *vice versa*.

Case 2) $0 < t \leq BI/2$. In this case, the clock of Q falls behind that of Q in **Case 1** by an additional delay t. We use P's time as the reference time. In Fig. 6(a), the second beacon window of P in the xth reference BI (also the β_pth BI in SRI S_p) falls in the range $R_1 = [\tau_1 + BI/2, \tau_1 + BI/2 + BW]$, where x is one of the solutions of (5), and τ_1 is the TBTT of the xth reference BI. Note that, in Fig. 6(a), $a = \lfloor x/S_p \rfloor$ and $b = \lfloor (x-h)/S_q \rfloor$. Moreover, the range of Q's active window in the β_qth BI is $R_2 = [\tau_1 + t, \tau_1 + t + BI/2 + BW]$. Obviously, $R_1 \subseteq R_2$. On the other hand, the first beacon window of Q in the β_qth BI falls in the range $R_3 = [\tau_1 + t, \tau_1 + t + BW]$. In addition, the range of P's active window in the β_pth BI is $R_4 = [\tau_1, \tau_1 + BI/2 + BW]$. Clearly, $R_3 \subseteq R_4$. This case is thus proved.

Case 3) $BI/2 < t < BI$. In this case, the clock difference between P and Q is $D(P,Q) = h \times BI + t = h' \times BI - t'$, where $h' = h + 1$, $t' = BI - t$, and $0 < t' < BI/2$. From the proof of **Case 1**, we know that, for any integer h', there always exist $\delta_p \in \mathcal{H}(S_p)$ and $\delta_q \in \mathcal{H}(S_q)$ such that the following system of congruences has positive integer solutions y:

$$\begin{cases} y \equiv \delta_p (\bmod S_p) \\ y \equiv h' + \delta_q (\bmod S_q). \end{cases} \tag{6}$$

We use P's time as the reference time. In Fig. 6(b), we can observe that if $t = 0$, the δ_pth BI of P (in SRI S_p) and the δ_qth BI of Q (in SRI S_q) can meet each other at the yth reference BI. Note that, in Fig. 6(b), $a' = \lfloor y/S_p \rfloor$ and $b' = \lfloor (y-h-1)/S_q \rfloor$. However, the clock of Q now leads that of Q in the case where $t = 0$ by $t' = BI - t$. Under such circumstances, the range of Q's active window in the δ_qth BI is $R_6 = [\tau_2 - t', \tau_2 - t' + BI/2 + BW]$, where τ_2 is the TBTT of the yth reference BI. In addition, the first beacon window of P in the δ_pth BI falls in the range $R_5 = [\tau_2, \tau_2 + BW]$. Since $-t' + BI/2 > 0$, we have $R_5 \subseteq R_6$. On the other hand, the second beacon window of Q in the δ_qth BI falls in the range $R_7 = [\tau_2 - t' + BI/2, \tau_2 - t' + BI/2 + BW]$. In addition, the range of P's active window in the δ_pth BI is $R_8 = [\tau_2, \tau_2 + BI/2 + BW]$. Clearly, $R_7 \subseteq R_8$. This theorem thus follows. ■

Remark 2: Deriving the minimum HBI-set $\mathcal{H}(S_i)$, for all $1 \leq S_i \leq S_{\max}$, that satisfies **P1** and **P2** may need exhaustive search whose time complexity is $O(S_{\max}^{\sqrt{S_{\max}}+O(1)})$. Fortunately, we know that the practical value of $S_{\max}$ is small, e.g., $S_{\max} = 25$ [3], [20]. Hence, we can compute the optimal HBI/SBI schedule table just *once* and then store it in a mobile device, thereby avoiding the work of recomputing the HBI-set every time when a station needs to adjust the value of SRI. By means of such a *memoization* technique, the time complexity of OFAA neighbor maintenance is $O(1)$ since it only involves table lookup operations and the table size is *constant*.

C. Data Frame Transfer Procedure

This section presents how a station in the OFAA protocol sends data frames to its PS neighbor. Since the PS station is

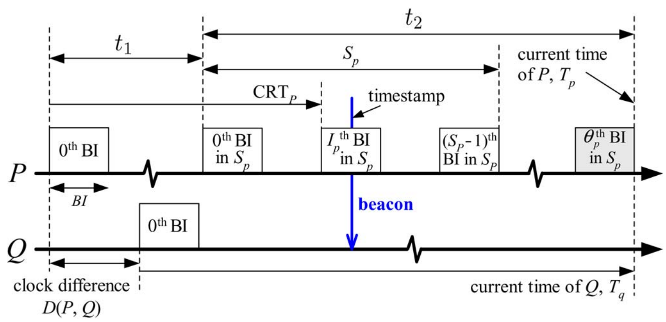

Fig. 7. Example of the HBI/SBI pattern prediction method.

not always awake, the sending station must predict when the PS destination will wake up. To achieve this goal, each beacon frame should contain a MAC address, a sequence number, a timestamp, the TBTT of the current BI, the value of the SRI, and the position of the current BI in the SRI, in addition to other 802.11 management parameters. In Fig. 7, once station Q has a cached record about its PS neighbor P, Q can use the timestamp record to deduce their clock difference $D(P, Q)$. Accordingly, P's current time t_p is $t_q + D(P, Q)$ if Q finds that P's clock leads its clock. In Fig. 7, let CRT_p be the cached record about the TBTT of the BI, during which Q received the beacon frame from its neighbor P. Moreover, let I_p denote the position of the BI in P's SRI S_p in that record. Then, we have $t_2 = t_p - t_1$ and $t_1 = \text{CRT}_p - I_p \times BI$; above all, at time t_q, the current position of BI θ_p in P's SRI S_p can be derived via the following formula:

$$\theta_p = \left\lfloor \frac{(t_p - \text{CRT}_p + I_p \times BI) \bmod (S_p \times BI)}{BI} \right\rfloor \quad (7)$$

where $a \bmod b = a - b\lfloor a/b \rfloor$, if both a and $b \neq 0$ are any *real* numbers. By comparing θ_p and S_p with the HBI/SBI schedule table (e.g., Fig. 5), Q can hence infer whether P is currently in the ABI or the SBI.

When station Q intends to transmit data frames to its PS neighbor P, Q should first employ the aforementioned HBI/SBI pattern prediction method to judge whether P is currently in the HBI or the SBI. If P is currently in the HBI, Q can directly send data frames to P in P's data window. If P is currently in the SBI, Q should buffer data frames and wait for the coming of P's data window. Moreover, when sending data frames to P, if the data queue for P is not empty, Q will set the *more* data bit to 1 in the frame control filed [8] of the data frame. If Q's data transmissions for P cannot be completed within a data window due to congestion or large amount of buffered data, both P and Q will remain awake across multiple BIs (some of which may be originally SBIs) until communication is not needed.

III. Protocol Analysis

From the viewpoint of MAC layer, the duty cycle and average neighbor discovery time are used to judge the goodness of a power management protocol [3], [9], [21]. Here, we provide performance comparisons among the AQEC, HQS, and OFAA protocols with regard to these metrics.

A. Duty Cycle

Theorem 3: The OFAA protocol is optimal in terms of duty cycle. Specifically, given the value of SRI S, where $1 \leq S \leq S_{\max} = 25$, the duty cycle of the OFAA protocol is given by (8), shown at the bottom of the page.

Proof: Since a PS station cannot transmit nor receive in the doze state, we first claim that, for any quorum-based asynchronous power management protocol $\mathcal{X}$, there must exist at least one kind of BI, which is called *awake BI* (ABI), in which the length of active window $actW$ is at least $BI/2 + BW$.

We denote by S_p and S_q the SRIs of stations P and Q, respectively. Let us consider the condition that $S_p = S_q = 1$ and $D(P, Q) = BI/2$. It can be shown that if $actW \leq BI/2$, stations P and Q are unable to discover each other since when P wakes up, Q goes to sleep, and *vice versa*. Thus, we have $actW > BI/2$. Further, from the proof of Theorem 2, we know that the necessary condition for stations P and Q discovering each other is that the overlapping length of their active windows should be at least BW. Hence, $actW$ should be at least $BI/2 + BW$.

In the OFAA protocol, there exists only one kind of ABI, which is called HBI, in which the length of the active window is just $BI/2 + BW$. Let $\mathcal{H}(S)$ be the set of the positions of HBIs in SRI S. Jiang *et al.* [9] have proved that, given the value of SRI S, the cardinality of a quorum in any quorum system that satisfies **P1** can be no less than $\lceil \sqrt{S} \rceil$. Thus, the minimum value of $|\mathcal{H}(S)|$ is at least $\lceil \sqrt{S} \rceil$. In what follows, we derive the value of $|\mathcal{H}(S)|$ in the OFAA protocol. Let the *span* of set $\mathcal{H}(S_i)$ be $span(\mathcal{H}(S)) = \{L_j | L_j = j \oplus \mathcal{H}(S)$ and $0 \leq j \leq S - 1\}$. Let $\mathcal{U}_S = \{0, 1, \ldots, S - 1\}$. By **P1, P2**, and Definition 3 in [21], when S is a prime and of the form $\kappa^2 + \kappa + 1$, where κ is a prime power, $(\mathcal{U}_S, span(\mathcal{H}(S)))$ constitutes a special kind of quorum system, which is called the *cyclic finite projective plane* (CFPP) [21]. By [21, Th. 3], we have $|\mathcal{H}(S)| = \kappa + 1 = \lceil \sqrt{\kappa^2 + \kappa + 1} \rceil = \lceil \sqrt{S} \rceil$ in the CFPP. Above all, we are certain that the value of $|\mathcal{H}(S)|$ in the OFAA protocol is minimum since the HBI/SBI schedule table is generated by exhaustive search. In Fig. 5, we can verify that $|\mathcal{H}(S)| \leq \lceil \sqrt{S} \rceil + 1$, for all $1 \leq S \leq S_{\max} = 25$, and (8) therefore follows. ■

Theorem 4: The OFAA protocol is optimal and fully adaptive.

$$\begin{cases} duty\_cycle(\text{OFAA}) = \frac{\lceil \sqrt{S} \rceil}{S} \left(\frac{1}{2} + \frac{BW}{BI} \right), & \text{if } S \text{ is a prime and of the form } \kappa^2 + \kappa + 1 \\ & \quad \text{where } \kappa \text{ is the power of a prime} \\ duty\_cycle(\text{OFAA}) \leq \frac{\lceil \sqrt{S} \rceil + 1}{S} \left(\frac{1}{2} + \frac{BW}{BI} \right), & \text{otherwise} \end{cases} \quad (8)$$

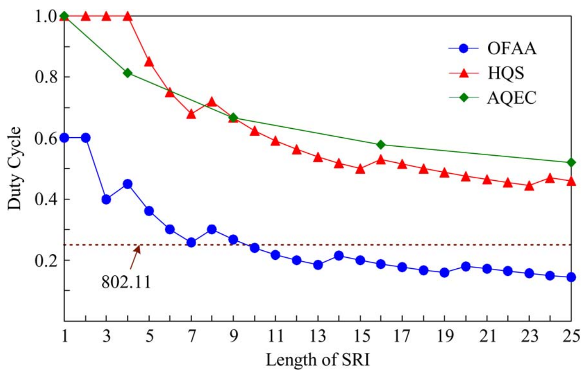

Fig. 8. Length of SRI versus the duty cycle. Note that the duty cycle of 802.11 is fixed at AW/BI.

Proof: This is a direct consequence of Theorem 3 and the fact that, in the OFAA protocol, given the maximum value of SRI $S_{\max}$, the number of tunable SRIs of every station is $S_{\max}$. ■

Theorem 5: Let $\omega = 2AW/(BI + 2BW)$. When the value of SRI S is greater than $((1 + \sqrt{1 + 8\omega})/2\omega)^2$, the duty cycle of the OFAA protocol is smaller than that of 802.11.

Proof: Given the value of SRI S, the duty cycle of the OFAA protocol is smaller than that of 802.11 when (9), shown below, holds. Thus

$$duty\_cycle(\text{OFAA}) \leq \frac{\lceil\sqrt{S}\rceil + 1}{S}\left(\frac{1}{2} + \frac{BW}{BI}\right) < \frac{AW}{BI} = duty\_cycle(802.11). \quad (9)$$

Since $\lceil\sqrt{S}\rceil \leq \sqrt{S} + 1$, if (10) is satisfied, so does (9). Thus

$$\frac{\sqrt{S} + 2}{S}\left(\frac{1}{2} + \frac{BW}{BI}\right) < \frac{AW}{BI}. \quad (10)$$

Let $x = \sqrt{S} > 0$, we have

$$(10) \Leftrightarrow \frac{\sqrt{S} + 2}{S} < \omega \Leftrightarrow \omega x^2 - x - 2 > 0. \quad (11)$$

Hence, the solution of (11) is $x = \sqrt{S} > (1 + \sqrt{1 + 8\omega})/2\omega$. ■

Let $BI = 100$ ms, $AW = 25$ ms, and $BW = 10$ ms. Fig. 8 shows the duty cycle comparison among the AQEC, HQS, and OFAA protocols. We can see that the duty cycle of the OFAA protocol is much lower than those of HQS and AQEC protocols. To the best of our knowledge, the OFAA protocol is the first asynchronous CQPM protocol where every station can have a lower duty cycle than that in 802.11.

B. Average Neighbor Discovery Time

Now, we investigate the average neighbor discovery time in the OFAA protocol. Suppose that the SRIs of two PS neighbors P and Q are S_p and S_q, respectively. Let k be a positive integer and $BW_{P\to Q}(x, x + k \times BI \mid S_p, S_q)$ denote the number of P's beacon windows that are fully covered by Q's active windows from any reference time x to $x + k \times BI$. From the proof of Theorem 2, we can find that in a reference BI, the number of P's beacon windows fully covered by Q's active window is equal to the number of Q's beacon windows fully covered by P's active window. Thus, we have $BW_{P\to Q}(x, x + k \times BI \mid S_p, S_q) = BW_{Q\to P}(x, x + k \times BI \mid S_p, S_q)$. For brevity, we denote $BW_{P\to Q}(x, x + k \times BI \mid S_p, S_q)$ as $BW(x, x + k \times BI)$. The average neighbor discovery time $\tau(P, Q)$ between P and Q is formally defined as follows:

$$\tau(P, Q) = \lim_{k\to\infty} \frac{k \times BI}{BW(x, x + k \times BI)}.$$

Theorem 6: In the OFAA protocol, the average neighbor discovery time between two PS neighbors P and Q is

$$\tau(P, Q) = \frac{S_p \times S_q \times BI}{|\mathcal{H}(S_p)| \times |\mathcal{H}(S_q)|} \approx \sqrt{S_p \times S_q} \times BI \leq S_{\max} \times BI.$$

Proof: Without loss of generality, we assume that the clock of P leads that of Q by $D(P, Q) = h \times BI + t$, where $h \geq 0$ is an integer, and $0 \leq t < BI$. Let us consider two cases.

Case 1. $0 < t < BI/2$. We define the *common ABI* (CABI) between P and Q as the reference BI in which P and Q can discover each other. Let $g = \gcd(S_p, S_q)$, $\mathcal{B}_{[i]}(S_p) = \{b \mid b \equiv i (\mathrm{mod}\, g)$ and $b \in \mathcal{H}(S_p)\}$, and $\mathcal{B}_{[i-h]}(S_q) = \{b \mid b \equiv i - h (\mathrm{mod}\, g)$ and $b \in \mathcal{H}(S_q)\}$. If both $\mathcal{B}_{[i]}(S_p)$ and $\mathcal{B}_{[i-h]}(S_q)$ are nonempty sets, then given $\beta_1 \in \mathcal{B}_{[i]}(S_p)$ and $\beta_2 \in \mathcal{B}_{[i-h]}(S_q)$, we claim that the following system of congruences always has solutions:

$$\begin{cases} z \equiv \beta_1 (\mathrm{mod}\, S_p) \\ z \equiv h + \beta_2 (\mathrm{mod}\, S_q). \end{cases} \quad (12)$$

Clearly, the solutions of z are the CABIs between P and Q. Since $\beta_1 \in \mathcal{B}_{[i]}(S_p)$ and $\beta_2 \in \mathcal{B}_{[i-h]}(S_q)$, we have $\beta_1 (\mathrm{mod}\, S_p) \equiv i (\mathrm{mod}\, g)$ and $h + \beta_2 (\mathrm{mod}\, S_q) \equiv h + i - h (\mathrm{mod}\, g) \equiv i (\mathrm{mod}\, g)$. Thus, we have $\beta_1 \equiv h + \beta_2 (\mathrm{mod}\, g)$. By the generalized Chinese remainder theorem, (12) has a unique solution z modulo ℓ, where $h \leq z \leq h + \ell - 1$ and $\ell = \mathrm{lcm}(S_p, S_q)$. The given derivation leads to the following conclusions: 1) The pattern of the CABIs between P and Q repeats every ℓ BIs. 2) Let $N_{\mathrm{CABI}}[h, h+\ell-1 \mid 0 < t < BI/2]$ denote the number of CABIs between the hth reference BI and the $(h+\ell-1)$th reference BI under the condition that $0 < t < BI/2$. Then, for $0 < t < BI/2$, we have $BW(D(P,Q), D(P,Q) + \ell \times BI) = N_{\mathrm{CABI}}[h, h+\ell-1 \mid 0 < t < BI/2] = \sum_{i=0}^{g-1} |\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-h]}(S_q)|$.

Case 2. $BI/2 < t < BI$. In this case, $D(P, Q) = (h + 1) \times BI - t'$, where $0 < t' < BI/2$. By similar arguments in **Case 1**, we can derive that for $BI/2 < t < BI$, $BW(D(P, Q), D(P, Q) + \ell \times BI) = N_{\mathrm{CABI}}[h + 1, h + \ell \mid BI/2 < t < BI] = \sum_{i=0}^{g-1} |\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-h-1]}(S_q)|$.

Let H_g be the discrete uniform random variable on set $G = \{0, 1, \ldots, g - 1\}$ with probability mass function $f_{H_g}(k) = 1/g$

for all $k \in G$. Let T be the continuous uniform random variable over interval $[0, BI)$ with probability density function $f_T(t) = 1/BI$ for all $t \in [0, BI)$. Let $[k]_g = \{h \mid h \geq 0$ is an integer and $h \equiv k (\bmod g)\}$. We can regard $D(P,Q)$ as a function of two random variables, i.e., H_g and T, and its mixed probability density function $f_{H_g,T}(h,t)$ is defined as $f_{H_g}(k) f_T(t) = 1/g \times 1/BI$ if the value of $D(P,Q) = x$ belongs to set $\{h \times BI + t \mid h \in [k]_g$ and $0 \leq t < BI\}$. Since the pattern of the CABIs between P and Q repeats every ℓ BIs, we have

$$\tau(P,Q) = \frac{\ell \times BI}{E\left[BW(x, x + \ell \times BI)\right]}$$

$$E\left[BW(x, x+\ell \times BI)\right] = \sum_{h=0}^{\infty} \int_0^{BI} f_{H_g,T}(h,t) \times BW(x, x+\ell \times BI) dt$$

$$= \sum_{k=0}^{g-1} f_{H_g}(k) \int_0^{BI} f_T(t) \times BW(x, x+\ell \times BI) dt$$

$$= \sum_{k=0}^{g-1} \frac{1}{g} \Big[\Pr[0 < t < BI/2 \mid 0 \leq t < BI] \times N_{\mathrm{CABI}}[h, h+\ell-1 \mid 0 < t < BI/2] + \Pr[BI/2 < t < BI \mid 0 \leq t < BI] \times N_{\mathrm{CABI}}[h+1, h+\ell \mid BI/2 < t < BI] \Big]$$

$$= \sum_{k=0}^{g-1} \frac{1}{g} \left[\frac{1}{2} \sum_{i=0}^{g-1} \left(|\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-k]}(S_q)| \right) + \frac{1}{2} \sum_{i=0}^{g-1} \left(|\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-k-1]}(S_q)| \right) \right]$$

$$= \frac{|\mathcal{H}(S_p)| \times |\mathcal{H}(S_q)|}{g}.$$

The last three equations follow by the following facts: 1) $\Pr[t = 0] = \Pr[t = BI/2] = 0$ since T is a continuous random variable; 2) $\mathcal{B}_{[i]}(S_p) \cap \mathcal{B}_{[j]}(S_q) = \varnothing$, if $i \not\equiv j (\bmod g)$; 3) $\sum_{i=0}^{g-1} (|\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-k]}(S_q)|) = \sum_{i=0}^{g-1} (|\mathcal{B}_{[i]}(S_p)| \times |\mathcal{B}_{[i-k-1]}(S_q)|)$; 4) $\mathcal{H}(S_p) = \bigcup_{i=0}^{g-1} \mathcal{B}_{[i]}(S_p)$; and 5) $|\mathcal{H}(S_p)| = \sum_{i=0}^{g-1} |\mathcal{B}_{[i]}(S_p)|$. Finally, according to the proof of Theorem 3 and the fact that $\ell \times g = S_p \times S_q$, we have

$$\tau(P,Q) = \frac{S_p \times S_q \times BI}{|\mathcal{H}(S_p)| \times |\mathcal{H}(S_q)|} \approx \sqrt{S_p \times S_q} \times BI \leq S_{\max} \times BI. \qquad \blacksquare$$

Theorem 6 shows that given bounded value of $S_{\max}$, the average neighbor discovery time in the OFAA protocol is also bounded and only sublinearly increases with the increasing value of the SRI. On the other hand, due to the fluctuation in parameters $\phi - 1 < d_1 \leq 2\phi - 1$ and $0 < d_{j+1} - d_j \leq \phi$ in (1), the neighbor discovery time of HQS is unpredictable.

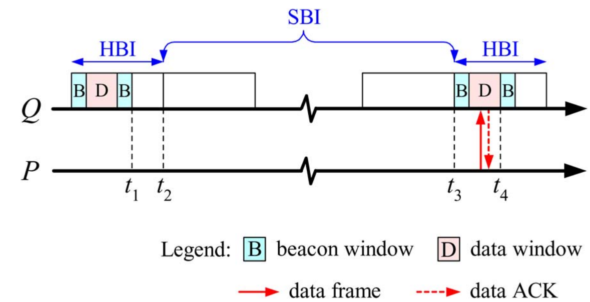

Fig. 9. By Lemma 2, there are, at most, $(\lceil S_q/2 \rceil - 1)$ SBIs between Q's adjacent HBIs.

IV. Cross-Layer Schedule Repetition Interval Adjustment Procedure

To illuminate the power of SRI adaptation, we design a cross-layer SRI adjustment scheme for the OFAA protocol such that PS stations can adaptively adjust the values of the SRI to minimize the power consumption of the whole MANET while satisfying end-to-end flow timeliness requirements. Before proceeding, we need the following lemma and theorem.

Lemma 2: Let $\{(S_i, \mathcal{H}(S_i))\}_{1 \leq S_i \leq S_{\max}}$ be the HBI/SBI schedule table (i.e., factor-hereditary quorum space) in the OFAA protocol and $\xi(S_i)$ be the maximum difference between two cyclic consecutive elements in $\mathcal{H}(S_i)$. More specifically, given $\mathcal{H}(S_i) = \{b_1, \ldots, b_k \mid b_j < b_{j+1}$ for all $1 \leq j \leq k-1\}$, $\xi(S_i) = \max\{b_{j+1} - b_j$ and $(b_1 - b_k) \bmod S_i \mid 1 \leq j \leq k - 1\}$. Then, for all S_i, we have $\xi(S_i) \leq \lceil S_i/2 \rceil$.

Proof: See the Appendix. $\blacksquare$

Theorem 7: Assume that in a light-loaded MANET, a data frame sent from a station to its neighbor can be completed in a single data window when they are simultaneously awake. Then, in a light-loaded MANET, the maximum data frame transfer delay $\mu(S_q)$ from station P to its *discovered* neighbor Q that selects S_q as its SRI is no more than $\lceil S_q/2 \rceil BI - BW$, where BI and BW are the lengths of the BI and the beacon window, respectively.

Proof: Once station P discovered its neighbor Q, P can henceforth predict when Q will wake up. In Fig. 9, in a light-loaded MANET, the maximum data frame transfer delay from P to Q occurs when P has data for Q just after the close of Q's active window (at time t_1), P waits for the maximum number of consecutive SBIs (from time t_2 to t_3), and finally, finishes the data transfer before the end of Q's next data window (at time t_4). Under such circumstances, we have

$$\begin{aligned} \mu(S_q) &= (t_2 - t_1) + (t_3 - t_2) + (t_4 - t_3) \\ &= (BI/2 - BW) + (\xi(S_q) - 1) BI + BI/2 \\ &\leq \lceil S_q/2 \rceil BI - BW \end{aligned}$$

where $\xi(S_q) \leq \lceil S_q/2 \rceil$ follows by Lemma 2. $\blacksquare$

Theorem 7 provides the data transfer delay bound only for a light-loaded MANET. In other words, we focus only on the delay induced by the power management protocol since this delay tends to be large (e.g., thousands of milliseconds) relative to contention and queuing delay in a light-loaded MANET. In a heavy-loaded MANET, power management protocols would most likely not be used [13]. A large body of QoS research has dealt with congestion and queuing delay, such as [1], [2], and [14], which can be viewed as orthogonal and complementary to our work.

Now, we show how to integrate the OFAA protocol with dynamic source routing (DSR) [10] so that PS stations along the routing path can adjust the values of the SRI in response to the flow timeliness requirement. Theoretically, since the OFAA protocol regulates the behavior of MAC layer and routing protocols regulate only the behavior of network layer, the OFAA protocol can integrate with any existing ad hoc routing protocols. The choice of DSR is mainly because it is simple, and its route discovery procedure can serve as a flow-setup signaling mechanism. In the OFAA protocol, every station by default sets its SRI $S_{\max}$. When source station X intends to transmit data flow to destination Y, it initiates a *route request* (RREQ) packet, which specifies the sequence number, the address of Y, and flow tolerable delay T_{delay}. This RREQ is then flooded throughout the network. Upon reception of the RREQ packet, if the receiving station is not the destination, it appends its address and current SRI value to the RREQ, and then rebroadcasts that RREQ only once to its neighbors. When destination Y receives the first RREQ from X, it will set a timer and continuously collect all RREQ packets with the same sequence number from X until that timer expires. Assume that Y has collected m paths $P_1, P_2, \ldots, P_m$ from received RREQ packets and the lengths of these paths are $k_1, \ldots, k_m$, respectively. Assume that path P_i starts from source X, through stations $Z_1^i, Z_2^i, \ldots, Z_{k_i-1}^i$, to the destination $Z_{k_i}^i = Y$, for all $1 \le i \le m$. Then, Y performs *admission control* checking whether the following inequality can be satisfied:

$$\Phi = \min_{1\le i\le m}\{k_i \times \mu(1)\} = (BI - BW) \times \min_{1\le i\le m}\{k_i\} \le T_{\text{delay}}.$$

If not, this means that even if all stations along the shortest routing path set the SRI value to 1, tolerable delay T_{delay} still cannot be fulfilled. In this case, Y replies the *route rejection* (RREJ) packet, attaching Φ along that path back to the source. The source station can either abort the flow setup or revise the value T_{delay} based on Φ and then attempts the given procedure again.

If so, Y should determine which path can achieve the desired latency T_{delay} while increasing power consumption in the network the least. Unfortunately, Miller and Vaidya in [13] and Wang *et al.* in [18] have proven that the problem of finding minimum energy routes in a multihop MANET without violating delay constraints is NP-complete. In what follows, we present a simple heuristic method to efficiently find out the near-optimal solution. Specifically, the job of Y is to select path P_j from set $\mathcal{P} = \{P_i \mid 1 \le i \le m \text{ and } k_i \times \mu(1) \le T_{\text{delay}}\}$ and determine the SRI value $S(Z_h^j)$ of each station Z_h^j on P_j, where $1 \le h \le k_j$, such that the sum of the duty cycles of all stations in the network is minimized, subject to the following constraint:

$$\mu\left(S\left(Z_1^j\right)\right) + \cdots + \mu\left(S\left(Z_{k_j}^j\right)\right) \le T_{\text{delay}}. \tag{13}$$

If path P_j is selected as the routing path, we hope that all stations on P_j use roughly the same SRI to balance power consumption. If $S(Z_h^j) = \mathcal{S}_j$ for all $1 \le h \le k_j$, then by Theorem 7, inequality (13) can be rephrased as follows:

$$k_j\left(\lceil \mathcal{S}_j/2 \rceil BI - BW\right) \le T_{\text{delay}}.$$

Let $\mathbb{S} = \{1, \ldots, S_{\max}\}$. To minimize the duty cycle of every station on path P_j, we have

$$\mathcal{S}_j = \arg\min_{S\in\mathbb{S}}\left\{duty\_cycle(S) | S \le 2\left\lfloor \frac{BW + T_{\text{delay}}/k_j}{BI} \right\rfloor\right\}$$

where $duty\_cycle(S) = |\mathcal{H}(S)|/S(1/2 + BW/BI)$. Assume that the current SRI value of station Z_h^j is $S_{\text{cur}}(Z_h^j)$. Then, station Z_h^j should set its new SRI value $S_{\text{new}}(Z_h^j)$ according to the following rule to satisfy T_{delay} and the delay requirements of other flows passing through Z_h^j. Thus

$$S_{\text{new}}\left(Z_h^j\right) = \begin{cases} S_{\text{cur}}\left(Z_h^j\right), & \text{if } S_{\text{cur}}\left(Z_h^j\right) \le \mathcal{S}_j \\ \mathcal{S}_j, & \text{otherwise.} \end{cases}$$

Under such circumstances, increased power consumption by routing path P_j would be proportional to $\Omega(P_j)$ and

$$\Omega(P_j) = \sum_{h=1}^{k_j}\left[duty\_cycle\left(S_{\text{new}}\left(Z_h^j\right)\right) - duty\_cycle\left(S_{\text{cur}}\left(Z_h^j\right)\right)\right].$$

Accordingly, destination Y should select path P_χ as the routing path, where

$$\chi = \arg\min_{1\le j\le m}\left\{\Omega(P_j) \mid P_j \in \mathcal{P}\right\}.$$

After determining routing path P_χ, destination station Y replies the *route reply* (RREP) packet, attaching $\mathcal{S}_\chi$ back to the source station in the reverse direction. Hence, each station along path P_χ changes the SRI value to $\mathcal{S}_\chi$ *only* when its current SRI is larger than $\mathcal{S}_\chi$. Once the source station received the RREP packet, it can commence data flow transmission. After finishing the data flow transmission, the source station sends the *route release* (RREL) packet to the destination. Upon receipt of the RREL packet, if a station does not need to forward any flows, it can switch the value of the SRI to $S_{\max}$.

V. Performance Evaluation

A. Simulation Model

We follow the event-driven approach [12] to build simulators to compare the performances of the OFAA protocol with those of the AQEC [3] and HQS [20] protocols. The simulation area of the whole MANET is 2000 m × 2000 m. The transmission

TABLE I
SYSTEM PARAMETERS USED IN THE SIMULATION

Parameter	Value
Channel bit rate	2 Mbps
DIFS (DCF Inter Frame Space)	50 μs
SlotTime	20 μs
$\mathrm{CW}_{\min}/\mathrm{CW}_{\max}$	31/1023 slots
length of BI	100 ms
Beacon window length	10 ms
Beacon frame size	65 bytes
ATIM frame size	28 bytes
ACK frame size	14 bytes
Power consumption in TRANSMIT state	1.65 Watt
Power consumption in RECEIVE state	1.4 Watt
Power consumption in LISTEN state	1.15 Watt
Power consumption in DOZE state	0.045 Watt
Power consumption of DOZE/AWAKE transition	0.575 mJ

radius of a station is 250 m. We assume that the clock difference between any two stations ranges from 0 to 5000 ms. Station mobility follows the random way-point model [22]. More specifically, all stations alternate between pausing and then move to a randomly chosen location at a fixed speed. The pause time is fixed at 30 s. For fair comparison, OFAA, AQEC, and HQS protocols use the same routing protocol (i.e., DSR), except that the RREQ/RREP procedure in the OFAA protocol is used to find the *least incremental power* path, whereas the RREQ/RREP procedure in AQEC and HQS protocols is used to find the shortest path.

In our simulations, a total of k data flows are established between randomly selected source–destination pairs, where $2 \leq k \leq 14$. Traditionally, data traffic processes are often assumed to be Poissonian. However, this model cannot capture any correlation between consecutive packet arrivals. Hence, we adopt the two-state (ON/OFF) *Markov-modulated Poisson process* data traffic model [4] to recover from this problem. Specifically, each sender is an ON–OFF Poisson traffic source with interleaved ON and OFF periods of length 10 and 15 s, respectively. During the ON period, the average data arrival rate is λ kb/s, where $2 \leq \lambda \leq 14$, and the data packet size is 256 bytes. During the OFF period, no traffic is generated. We fix the length of a BI as 100 ms. Determining the appropriate ATIM window length is a nontrivial issue. As suggested in [19], we set the ATIM window length as 25 ms, which is one fourth of a BI. Table I summarizes the system parameter values, which follow the IEEE 802.11 specification for the direct-sequence spread-spectrum physical layer [8]. The power consumption parameters in Table I follow the specifications adopted in [11].

In AQEC and HQS protocols, each PS station adaptively adjusts the SRI value S according to its *observed* traffic load [3]. Specifically, let $S_{\max} = 25$, $\lambda_{\max} = 14$ kb/s, and $\{s_1, \ldots, s_n\}$ be the permutation of the subset of $\{1, \ldots, S_{\max}\}$ such that $duty\_cycle(s_1) \geq \cdots \geq duty\_cycle(s_n)$. The SRI adaptation rules of AQEC/HQS are as follows:

$$S = \begin{cases} s_1, & \text{if traffic load} \geq duty\_cycle(s_1) \times \lambda_{\max} \\ s_i, & \text{if } duty\_cycle(s_{i+1}) \times \lambda_{\max} \leq \text{traffic load} \\ & \quad \text{and traffic load} < duty\_cycle(s_i) \times \lambda_{\max} \\ s_n, & \text{if traffic load} < duty\_cycle(s_n) \times \lambda_{\max}. \end{cases}$$

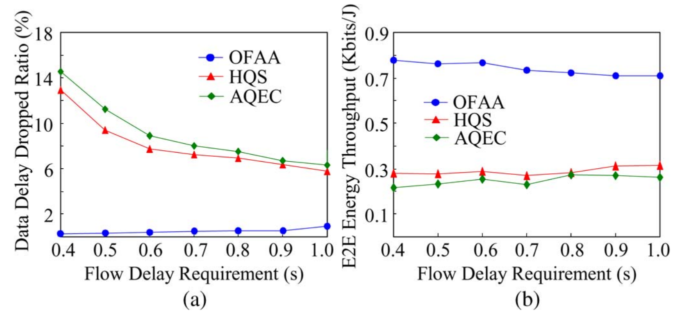

Fig. 10. (a) DDDR versus flow delay requirements. (b) End-to-end energy throughput versus flow delay requirements.

For example, in the AQEC protocol, we have $s_i = i^2$ for all $1 \leq i \leq 5$ and $duty\_cycle(s_i) = AW/BI + (1 - AW/BI)(2i - 1)/i^2$. In (1), we set $\phi = \lceil \sqrt{(S_{\max} + 1)/2} \rceil$, $d_1 = 2\phi - 1$, and $d_{j+1} - d_j = \phi$ for all $1 \leq j \leq g - 2$ in the HQS protocol [20]. Note that all simulation runs are carried out for a duration of 1.5×10^9 μs. The simulation warm-up time is 100 BIs, and each simulation result is obtained from the average of 20 runs.

B. *Effect of Flow Delay Requirement*

To examine the ability of the OFAA adaptive SRI adjustment procedure, we measure the *data delay dropped ratio* (DDDR) by varying the flow delay requirement from 0.4 to 1.0 s, where the DDDR is defined as the fraction of dropped data packets caused by violating the end-to-end delay constraints. In the experiments in Fig. 10, we assume that 1) the total number of stations is 125, 2) the whole MANET is static, 3) $\lambda = 6$ kb/s, and 4) the total number of flows is 6. In Fig. 10(a), we can observe that when the whole MANET is static, the DDDR of the OFAA protocol is no more than 1% regardless of flow delay requirements. These results justify the superiority of our adaptive SRI adjustment scheme.

On the other hand, although AQEC and HQS protocols adopt the shortest path, their DDDRs are still high even in the static MANET. The reasons are as follows. In HQS and AQEC protocols, stations adjust the SRI values according to the *observed* traffic load. Since PS stations do not wake up very often, they can hardly derive the *actual* arrival rates of the flows. Fig. 11 shows that during the ON periods of a flow, the SRI value of a station in HQS and AQEC protocols oscillates rapidly and sharply. (Note that in the experiments in Fig. 11, we assume that the delay requirement of each flow is 0.7 s.) Such phenomenon easily leads to the situation that the upstream station *frequently* predicts the wrong awake/sleep schedule of the downstream station, causing the large DDDR.

Next, we investigate the end-to-end energy throughputs of AQEC, HQS, and OFAA protocols under various flow delay requirements. The *end-to-end energy throughput* is defined by dividing the amount of data sent from sources to destinations in flow delay constraints by the total energy consumption of all stations. Jung and Vaidya [11] pointed out that using energy throughput to judge the goodness of a power management protocol is more fair than using total power consumption since

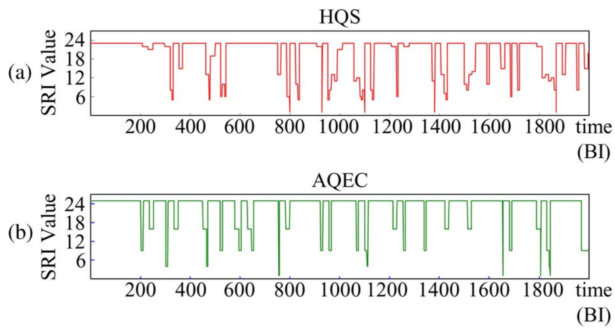

Fig. 11. Snapshot of the evolution of SRI of a station on a routing path in (a) HQS and (b) AQEC.

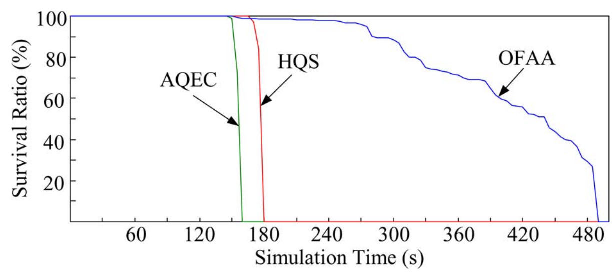

Fig. 12. Survival ratio.

some power management protocols may not only consume very little energy but attain very little throughput as well. In Fig. 10(a), we find that when the flow delay requirement increases from 0.4 to 1.0 s, the DDDRs of HQS and AQEC protocols drop by only about 7% and 8%, respectively. Hence, Fig. 10(b) shows that the end-to-end energy throughputs of HQS and AQEC protocols do not significantly change when the flow delay requirement varies. On the other hand, the end-to-end energy throughput of the OFAA protocol is much higher than those of AQEC and HQS protocols. This is because in the OFAA protocol, the stations on the routing paths achieve low DDDR via adaptive SRI control, and the stations that cannot partake in forwarding packets have much lower duty cycles than those in AQEC and HQS protocols.

C. Survival Ratio

We use the survival ratio to measure the energy-saving ability of a power management protocol, where the *survival ratio* is defined as the number of surviving stations (with nonzero energy) over the total number of stations. In the experiments in Fig. 12, we assume that 1) the total number of stations is 125, 2) the whole MANET is static, 3) the total number of flows is 6, 4) $\lambda = 6$ kb/s, 5) the delay requirement of each flow is 0.7 s, and 6) the initial energy of every station is 100 J. In Fig. 12, we find that since given the value of SRI, the duty cycle of a station in the OFAA protocol reaches the theoretical minimum, the network lifetime of the OFAA protocol could be about 2.72 and 3.06 times that of HQS and AQEC protocols, respectively. This implies that the OFAA protocol is more suitable than HQS and AQEC protocols for energy-limited applications, in which stations are subject to hard constraints on available battery energy. On the other hand, although HQS has full flexibility to tune the SRI value, Fig. 8 shows that the duty cycle of HQS is merely slightly lower than that of AQEC. Hence, the network lifetime of HQS is not significantly longer than that of AQEC.

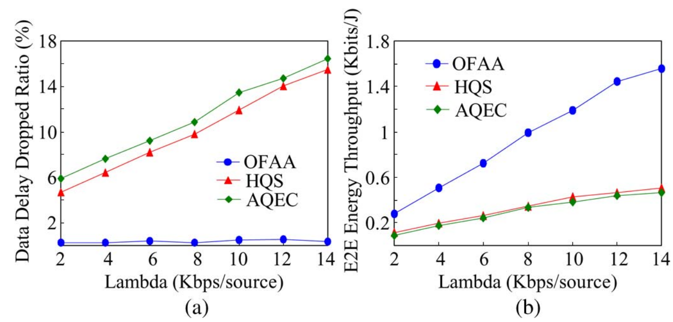

Fig. 13. (a) DDDR versus data traffic load. (b) End-to-end energy throughput versus data traffic load.

D. Effect of Data Traffic Load

To see the effect of traffic load, we first vary the traffic load λ of each source station from 2 to 14 kb/s. Note that in the experiments in Fig. 13, we assume that 1) the delay requirement of each flow is 0.7 s, 2) the whole MANET is static, 3) the total number of flows is 6, and 4) the total number of stations is 125. In Fig. 13(a), we can see that the DDDRs of both HQS and AQEC protocols quickly rise as λ increases. The reasons are similar to those mentioned in Section V-B. In our simulations, each source generates data packets according to the ON–OFF Poisson process. In AQEC and HQS protocols, all stations adjust the SRI values according to the *observed* traffic load. Thus, during the OFF periods, the downstream stations will rarely wake up. Once the ON periods arrive, the upstream stations easily accumulate a large amount of data, causing higher DDDR when λ becomes larger. On the other hand, due to admission control and the adaptive SRI adjustment procedure, the DDDR of the OFAA protocol can be no more than 1% when $\lambda \leq 14$ kb/s.

Fig. 13(b) shows that the end-to-end energy throughput of all protocols increases as λ increases. However, since the DDDRs of HQS and AQEC protocols are much larger than that of the OFAA protocol, hence, as λ increases, the end-to-end energy throughput of HQS and AQEC protocols grows more slowly than that of the OFAA protocol.

Then, we fix the traffic load λ of each source station as 6 kb/s and vary the total number of flows from 2 to 14 to observe its effect on the DDDR and the end-to-end energy throughput. Note that in the experiments in Fig. 14, we assume that 1) the delay requirement of each flow is 0.7 s, 2) the whole MANET is static, 3) $\lambda = 6$ kb/s, and 4) the total number of stations is 125. In Fig. 14(a) and (b), we can find that the effect of the total number of flows (when λ is fixed) is similar to that of the data traffic load (when the total number of flows is fixed). Note that when the total number of flows is 14, the DDDR of the OFAA protocol rises to about 2.6% since the medium access contention becomes severer in this case.

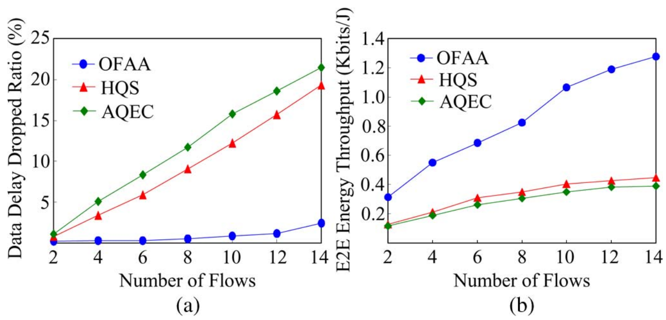

Fig. 14. (a) DDDR versus number of flows. (b) End-to-end energy throughput versus number of flows.

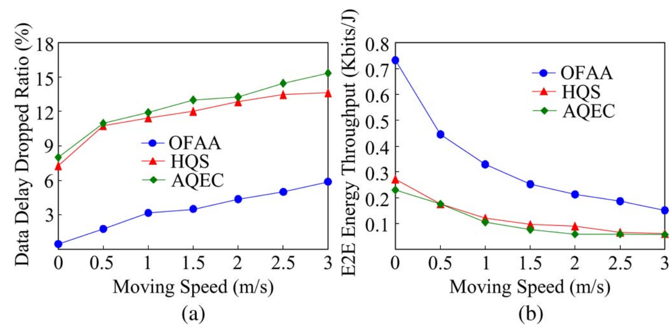

Fig. 16. (a) DDDR versus mobility. (b) End-to-end energy throughput versus mobility.

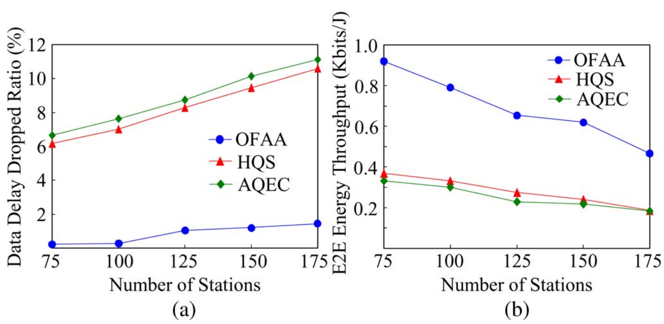

Fig. 15. (a) DDDR versus total number of stations. (b) End-to-end energy throughput versus total number of stations.

E. *Effect of Station Density*

In the experiments here, we vary the total number of stations from 75 to 175. Moreover, we assume that 1) the delay requirement of each flow is 0.7 s, 2) the whole MANET is static, 3) $\lambda = 6$ kb/s, and 4) the total number of flows is 6. Since the simulated network area is fixed, this parameter (i.e., total number of stations) reflects the station density of the network. On the other hand, since the data traffic load is fixed and only stations on the routing paths can forward packets, such experiments are equivalent to examine the impact of beacon contention. Since the whole MANET is asynchronous and all stations need to periodically broadcast their beacons, the data frames are more easily to be corrupted or delayed by beacon frames when the total number of stations becomes larger. Hence, Fig. 15(a) confirms that the DDDRs of all protocols increase with the increasing number of stations. Fig. 15(b) shows that the end-to-end energy throughput of all protocols significantly decreases as the number of stations increases. The reasons are as follows. On one hand, this just reflects the fact that the DDDRs of all three protocols increase with the increasing number of stations. On the other hand, since the number of flows is fixed, when the total number of stations becomes larger, the number of stations that cannot partake in forwarding packets also becomes larger, causing higher power consumption of the whole network.

F. *Effect of Mobility*

This section evaluates the performances of AQEC, HQS, and OFAA protocols under various moving speeds. Note that in the experiments in Fig. 16, we assume that 1) the total number of stations is 125, 2) the delay requirement of each flow is 0.7 s, 3) the total number of flows is 6, and 4) $\lambda = 6$ kb/s. Fig. 16(a) shows that a higher moving speed has a severely negative effect on the DDDR of all protocols. This is because in a higher mobility environment, it is more difficult for data packets to successfully traverse from the source to the destination due to less success probability of path construction and higher frequency of path breakage. Fig. 16(b) shows that the end-to-end energy throughput of all three protocols significantly decreases as moving speed becomes higher. Clearly, once a routing path is broken due to mobility, stations will waste a large amount of energy to perform the flooding-based route discovery procedure to reestablish the routing path, thus decreasing the end-to-end energy throughput in a higher mobility environment.

VI. Conclusion

IEEE 802.11 has become the de facto MAC standard for multihop MANETs. However, Fig. 1(b) shows that once PS stations get out of synchronization, 802.11 power management may completely fail. Thus, [9], [16], [21], and [23] proposed various CQPM protocols to overcome this problem. However, these protocols require that all PS stations must have the same SRI. This implies that, from the viewpoint of duty cycle, they are nonadaptive. Although AQEC [3] and HQS [20] protocols are adaptive, their duty cycles are far from optimal.

In this paper, we have proposed the OFAA protocol, which adopts the new structures of BIs and the novel factor-hereditary quorum space to ensure that any two PS neighbors can discover each other in bounded time regardless of their clock difference and individual SRIs. The time complexity of OFAA neighbor maintenance is $O(1)$. Importantly, the OFAA protocol achieves minimum duty cycle and maximum adaptiveness for IEEE 802.11-based multihop MANETs. To the best of our knowledge, the OFAA protocol is currently the only known asynchronous quorum-based power management protocol where the duty cycle of every station can be lower than that in 802.11. To further illuminate the power of the OFAA protocol, we have proposed a cross-layer SRI adjustment scheme such that PS stations can adaptively adjust the values of SRI to maximize energy conservation and minimize the violation of flow delay constraints. However, cross-layer design is a double-blade sword. The route discovery procedure of our modified DSR consumes more power than that of the original one since our RREQ and RREP packets include additional fields, such as T_{delay}, target SRI ($\mathcal{S}_\chi$), and the SRI values of each stations on the path from the source to the destination. Fortunately, the route discovery procedure will be performed only when the source intends to establish a routing path to the destination. Extensive simulation results have shown that "OFAA + modified DSR" greatly outperforms "AQEC + traditional DSR" and "HQS + traditional DSR" in terms of survival ratio, DDDR, and end-to-end energy throughput.

APPENDIX

We prove Lemma 2 by contradiction. Let $\{(S_i, \mathcal{H}(S_i))\}$ be the HBI/SBI schedule table (i.e., factor-hereditary quorum space) used in the OFAA protocol. Since $\mathcal{H}(1)$ contains 0, by **P2**, $\mathcal{H}(S_i)$ must contain $b_1 = 0$ for all $S_i \geq 2$. This means that $\mathcal{H}(S_i)$ must be of the form $\{b_1, \ldots, b_k \,|\, b_1 = 0 < b_j < b_{j+1} < b_k \leq S_i - 1 \text{ for all } 2 \leq j \leq k-2\}$. Assume that $\xi(S_i) > \lceil S_i/2 \rceil$. Let us consider two cases.

Case 1. $b_{i+1} - b_i > \lceil S_i/2 \rceil$ for some $1 \leq i \leq k-1$. In this case, we claim that $(-\lceil S_i/2 \rceil \oplus \mathcal{H}(S_i)) \cap \mathcal{H}(S_i) = \varnothing$. Let $\mathcal{H}_1(S_i) = \{0, b_2, \ldots, b_i\}$ and $\mathcal{H}_2(S_i) = \{b_{i+1}, \ldots, b_k\}$. Clearly, $\mathcal{H}(S_i) = \mathcal{H}_1(S_i) \cup \mathcal{H}_2(S_i)$. Moreover, all elements in $\mathcal{H}_1(S_i)$ are smaller than or equal to b_i, whereas all elements in $\mathcal{H}_2(S_i)$ are greater than or equal to b_{i+1}. Let $\mathcal{H}_3(S_i) = -\lceil S_i/2 \rceil \oplus \mathcal{H}_1(S_i) = \{c_j = \lfloor S_i/2 \rfloor + b_j \,|\, 1 \leq j \leq i\}$ and $\mathcal{H}_4(S_i) = -\lceil S_i/2 \rceil \oplus \mathcal{H}_2(S_i) = \{d_j = b_j - \lceil S_i/2 \rceil \,|\, i+1 \leq j \leq k\}$. Obviously, $-\lceil S_i/2 \rceil \oplus \mathcal{H}(S_i) = \mathcal{H}_3(S_i) \cup \mathcal{H}_4(S_i)$. Above all, for all $1 \leq j \leq i$, we have

$$b_i < \lfloor S_i/2 \rfloor \leq c_j \leq b_i + \lfloor S_i/2 \rfloor < b_{i+1}. \tag{14}$$

Note that b_i must be smaller than $\lfloor S_i/2 \rfloor$; otherwise, $b_{i+1} > b_i + \lceil S_i/2 \rceil \geq \lfloor S_i/2 \rfloor + \lceil S_i/2 \rceil = S_i$, which contradicts the definition of $\mathcal{H}(S_i)$. Moreover, for all $i+1 \leq j \leq k$, we have

$$b_i < b_{i+1} - \lceil S_i/2 \rceil \leq d_j \leq b_k - \lceil S_i/2 \rceil < b_{i+1}. \tag{15}$$

Note that $b_k - \lceil S_i/2 \rceil$ must be smaller than b_{i+1}; otherwise, $b_k \geq b_{i+1} + \lceil S_i/2 \rceil > b_i + \lceil S_i/2 \rceil + \lceil S_i/2 \rceil \geq S_i$, which contradicts the definition of $\mathcal{H}(S_i)$. From inequalities (14) and (15), we can know that all elements in both $\mathcal{H}_3(S_i)$ and $\mathcal{H}_4(S_i)$ fall in the open-interval (b_i, b_{i+1}). This implies that $(-\lceil S_i/2 \rceil \oplus \mathcal{H}(S_i)) \cap \mathcal{H}(S_i) = \varnothing$, which contradicts the property **P1** of $\mathcal{H}(S_i)$. The proof of this case thus follows.

Case 2. $(b_1 - b_k) \bmod S_i = S_i - b_k > \lceil S_i/2 \rceil$. This implies that $b_k < S_i - \lceil S_i/2 \rceil = \lfloor S_i/2 \rfloor$. Moreover, all elements in $\mathcal{H}(S_i)$ are smaller than or equal to b_k. Let $\lceil S_i/2 \rceil \oplus \mathcal{H}(S_i) = \{e_j = \lceil S_i/2 \rceil + b_j \,|\, 1 \leq j \leq k\}$. For all $1 \leq j \leq k$, we have

$$b_k < \lfloor S_i/2 \rfloor \leq \lceil S_i/2 \rceil \leq e_j \leq b_k + \lceil S_i/2 \rceil < S_i. \tag{16}$$

This implies that $(\lceil S_i/2 \rceil \oplus \mathcal{H}(S_i)) \cap \mathcal{H}(S_i) = \varnothing$, which contradicts the property **P1** of $\mathcal{H}(S_i)$. The proof of this lemma is thus complete. ■

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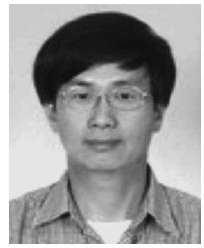

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