Abstract—In wireless ad hoc networks, IEEE 802.11 power management may completely fail if power-saving (PS for short) stations are out of synchronization. To fix this problem, [5]–[8] proposed various cyclic quorum-based power management (CQPM) protocols, which, however, may also completely fail if some PS stations have different schedule repetition intervals (SRIs). To conquer these problems, we propose the OAPM protocol, which has the following attractive features. (i) By means of novel factor-hereditary quorum space techniques, OAPM ensures that two PS neighbors can discover each other in finite time regardless of their clock difference and their individual SRIs. (ii) Given the maximum value of SRI, $S_{\text{max}}$, the number of tunable SRIs for every PS station is $S_{\text{max}}$. (iii) The idle duty cycles for all SRIs are minimal. (iv) The time complexity of OAPM neighbor maintenance is constant. (v) A cross-layer SRI adjustment scheme is proposed such that a PS station can adaptively tune its SRI according to traffic QoS requirements. Primary simulation results show that OAPM achieves better energy efficiency than existing CQPM protocols.

I. INTRODUCTION

A mobile ad hoc network (MANET) consists of mobile stations, which are often powered by batteries, without any infrastructure. Due to slow progress in battery technology [8], the design of power management protocol, which operates at the medium access control (MAC) layer, becomes critical.

A. IEEE 802.11 Power Management

IEEE 802.11 [4] is currently the de facto MAC standard for wireless ad hoc networks. 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, for short) mode should wake up prior to each beacon interval (target beacon transmission time) 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 remain awake during the entire ATIM (announcement traffic indication message) window. If a station $Q$ intends to send buffered data frames to the destination $P$ currently operating in the PS mode, $Q$ shall first unicast an ATIM frame to $P$ during the ATIM window (AW for short). Upon reception of that ATIM frame, the PS destination $P$ replies an ATIM-ACK to $Q$, and then both $P$ and $Q$ stay awake for the entire beacon interval. PS stations which neither transmitted nor received an ATIM frame may return to the doze state at the end of the AW. After the AW concludes, station $Q$ uses the DCF (distributed coordination function) procedure to send buffered data to $P$, and $P$ then acknowledges its receipt. For a more detailed presentation, please refer to [4].

B. Challenges

When designing power management protocols for a multi-hop MANET, we inevitably need to face two major challenges: (i) Timing synchronization: It is very difficult or costly for all stations to keep synchronized at all times especially when network topology may frequently change [6]. From Fig. 1(b), we can see that, once PS stations get out of synchronization, then 802.11 power management may completely fail since PS neighbors may forever lose each other’s beacons or ATIM frames. (ii) Neighbor maintenance: An active station may undetect 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
routing protocols, such as ZRP [3], whose success relies on accurate neighbor table. Worse, if some PS stations constitute a vertex cutset, whose removal will disconnect the network, then the PS-induced network partition problem [7] may arise.

C. Previous Work

The authors of [6] proposed the first asynchronous power management protocols that function well without the need of synchronization. Then references [5], [7], and our previous paper [7] concurrently and independently proposed the similar cyclic quorum-based power management (CQPM for short) protocols to improve the results of [6]. In CQPM, there are two types of beacon intervals: one is the fully-awake beacon interval (FBI) and the other is the normal beacon interval (NBI). Referring to Fig. 2(a), the FBI starts with the beacon window (BW) followed by the data window (DW). Every station should broadcast its beacon frame in its BW. After the BW, the PS station keeps awake during the entire DW. Referring to Fig. 2(a), the NBI starts with an AW. After the AW ends, a PS station may doze off during the sleep window (SW). Let BI, BW, AW, DW, and SW denote the lengths of BI, BW, DW, AW, and SW, respectively. CQPM requires BW ≤ AW. Besides, when a station switches to the PS mode, it chooses a quorum $q_i \subseteq \{0, 1, \ldots , S - 1\}$ from the cyclic quorum system $Q = \{ q_i \}_{0\leq i < S}$ as its FBIs in a schedule repetition interval (SRI), while the remaining BIs are NBIs, where SRI = S means that the consecutive S BIs that constitute the specific awake/sleep pattern repeat regularly. Take Fig. 2(a) for example, $S = 7$ and $Q = \{ q_0 = \{0, 1, 3\}, q_1 = \{1, 2, 4\}, q_2 = \{2, 3, 5\}, q_3 = \{3, 4, 6\}, q_4 = \{4, 5, 0\}, q_5 = \{5, 6, 1\}, q_6 = \{6, 0, 2\}\}$, both PS stations $P$ and $Q$ select the $q_0 = \{1, 3\}$-th BIs as their FBIs in every consecutive 7 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, [5], [7], [8] have proven that any two PS neighbors, $P$ and $Q$, are able to hear each other’s beacons (and thus discover each other) in finite time regardless of their clock difference $D(P, Q)$.

Let us define the idle duty cycle as the fraction of time during which the PS station stays awake and there is no data traffic. Intuitively, the larger the duty cycle, the more frequently the station wakes up, the shorter data reception delay and neighbor discovery time the station may perceive. On the other hand, the smaller the duty cycle, the less frequently the station wakes up, the more battery power the station can save. Hence we hope that a PS station can adaptively tune its duty cycle according to its remaining battery power or other QoS considerations. The common drawback of the existing CQPM protocols [5], [7], [8] is that they require all PS stations must have the same SRI. This implies that, from the viewpoint of duty cycle, they are non-adaptive. Fig. 2(b) depicts that, if PS stations have different values of SRI, then these protocols [5], [7], [8] may completely fail. Although the e-torus protocol proposed in [5] can let the PS station dynamically increase its idle duty cycle to shorten the neighbor discovery time, it still requires all PS stations have the same SRI. Besides, in e-torus, the minimum number of BWs in an SRI $S$ is about $\sqrt{2S}$, which is larger than the optimal value.

D. Our Contributions

[5], [8] have shown that, in CQPM, the minimum number of BWs in an SRI $S$ should be no less than $\lceil \sqrt{S} \rceil$. Thus we say that a CQPM protocol is fully-adaptive and optimal if (i) every PS station can adjust the value of SRI; besides, given the maximum value of SRI $S_{\text{max}}$, the number of adjustable SRIs is $S_{\text{max}}$, (ii) given SRI $S$, the number of BWs in an SRI is no more than $\lceil \sqrt{S} \rceil + 1$. The authors of [8] claimed that the problem of finding an adaptive and optimal CQPM schedule is NP-complete. Surprisingly, in this paper, we will propose an $O(1)$ optimal fully adaptive CQPM protocol for the practical value of $S_{\text{max}}$, say 22. We name the resulting protocol OAPM (optimal asynchronous power management). The technical kernel of OAPM include (i) the new structures of BIs and the interleaving of forward and backward SRIs, (ii) a topology-independent neighbor maintenance scheme by using the factor-hereditary quorum space (defined in Section II-B) such that any two PS neighbors can discover each other in finite time regardless of their clock difference as well as their individual SRIs. Since a PS station may often remain in the doze state, OAPM 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. Finally, to illuminate the power of OAPM, we propose a cross-layer SRI adjustment scheme, which instructs a PS station how to set its SRI according to flow delay requirements. Simulation results show that OAPM is much more energy-efficient than existing CQPM protocols.
The OAPM protocol contains four parts: (i) new structures of beacon intervals, (ii) a neighbor maintenance procedure, (iii) a awake/sleep pattern prediction method, and (iv) a data transfer procedure.

### A. New Structures of Beacon Intervals

As shown in Fig. 3(a) and Fig. 3(b), we design three types of BIs for OAPM: the forward half-awake BI, the backward half-awake BI, and the sleep BI (SBI). The first two kinds of BIs are collectively called the half-awake BIs (HBIs). The structures of these BIs are defined as follows.

1) **The forward HBI** (refer to Fig. 3(a)) starts with a beacon window followed by the data window. After the ATIM window ends, a PS station may enter the doze state. Let $actW$ denote the length of active window, during which a PS station stays awake. Importantly, OAPM requires $actW = BW + DW + AW \geq BW + BI/2$.

2) **The backward HBI** (refer to Fig. 3(b)) starts with the data window, but the active window is terminated by the beacon window. After the active window finishes, a PS station may enter the doze state. Importantly, OAPM requires $actW = DW + AW + BW \geq BI/2 + BW$.

3) **During the SBI** (refer to Fig. 3(a)), a PS station dozes off during the entire BI.

One of the design purposes of HBIs is for a PS station to save more energy than the FBI shown in Fig. 2(a). The other design purpose of (two kinds of) HBIs is for two PS neighbors to discover each other in finite time by means of the yet-to-be-presented interleaving technique.

### B. Neighbor Maintenance Procedure

Before introducing the OAPM, we need to define the factor-hereditary quorum space.

**Definition 1.** Let $S_1 \geq 1$ be a positive integer and $B(S_1) = \{b_1, \ldots, b_k\}$ be a subset of $\{0, 1, \ldots, S_1 - 1\}$. A collection of pairs $C = \{(S_i, B(S_i))\}_{1 \leq i \leq n}$ is called a factor-hereditary quorum space if it satisfies the following properties: P1)

**Theorem 1.** The OAPM guarantees that any two PS neighbors, $P$ and $Q$, are able to discover each other in finite time regardless of their clock difference $D(P, Q)$ as well as their respective SRIs, $S_P$ and $S_Q$.

**Proof.** Without loss of generality, we assume that $P$‘s clock leads $Q$‘s clock by $D(P, Q) = h \cdot BI + \Delta t$, where $h \geq 0$ is an integer and $0 \leq \Delta t < BI$. In addition, $P$ and $Q$ select $(S_P, B(S_P))$ and $(S_Q, B(S_Q))$ as their respective (SRI, HBI-set), where the HBI-set denotes the positions of HBIs in an SRI. In what follows, we prove this theorem by showing that, in finite time, at least one of $Q$‘s entire BWs is fully covered by one of $P$‘s active windows, and vice versa. Before giving the proof, we need Lemma 1.

**Lemma 1.** Let $S_1 \geq 1$ be a positive integer and $B(S_1) = \{b_1, \ldots, b_k\}$ be a subset of $\{0, 1, \ldots, S_1 - 1\}$. If a collection of
pairs $C = \{ (S_i, B(S_i)) \}_{1 \leq i \leq n}$ is a factor-hereditary quorum space, then given two integers $h$ and $S_i$, there must exist two integers $\beta_1$ and $\beta_2$ in $S_i$ such that $\beta_1 - \beta_2 = h \pmod{S_i}$.

**Proof.** By P1, $B(S_i) \cap (h \oplus B(S_i)) \neq \emptyset$. So we assume $\beta \in \{ B(S_i) \cap (-h \oplus B(S_i)) \}$. This implies that there must exist an element $\beta' \in B(S_i)$ so that $\beta = -h + \beta' \pmod{S_i}$. Let $\beta_1 = \beta'$ and $\beta_2 = \beta$. This lemma thus follows.

The proof of Theorem 1 can be divided into two cases.

**Case 1** $\Delta t = 0$. Referring to Fig. 5, we can find that the chance for PS neighbors to discover each other relies on the encounter of their HBIs. Therefore, if $P$ and $Q$ can discover each other, there must exist some $b_p \in B(S_p)$ and $b_q \in B(S_q)$ such that the following linear equation has positive integer solutions $(x, y)$.

$$S_p \cdot x + b_p = h + S_q \cdot y + b_q. \quad (1)$$

Take Fig. 5 for example, $P$’s 2nd BI and $Q$’s 1st BI can meet each other at the 10th reference BI since $8 \cdot 1 + 2 = 10 = 3 + 6 \cdot 1 + 1$.

Let $g = \gcd(S_p, S_q)$. By performing the $(\mod g)$ operation on both sides of (1), we can obtain the following equations.

$$(S_p \cdot x + b_p) \mod g = (h + S_q \cdot y + b_q) \mod g.$$  

$$\Leftrightarrow (S_p \cdot x - S_q \cdot y) \mod g = (h + b_q - b_p) \mod g. \quad (2)$$

According to Bezout’s lemma [1], equation (2) has infinitely many positive-integer solutions only when $\gcd(S_p, S_q)$ is a divisor of $h + b_q - b_p$. Since every integer divides 0, if the right hand side of (2) equals 0 ($\mod g$), then (2) has infinitely many positive-integer solutions.

By Lemma 1, we know that, for any integer $-h$, there must exist two integers $\beta_1$ and $\beta_2$ in $B(g)$ such that $\beta_1 - \beta_2 = h \pmod{g}$. Since $g = \gcd(S_p, S_q)$, by P2, we have $B(g) \subseteq B(S_p)$ and $B(g) \subseteq B(S_q)$. The proof of Case 1 thus follows by letting $b_q = \beta_1 \in B(S_q)$ and $b_p = \beta_2 \in B(S_p)$.

**Case 2** $0 < \Delta t < B I$. Due to space limitations, the proof is omitted. Interested readers please refer to [2].

Referring to Fig. 4, it is easy to verify that, in OAPM, the number of BWs in an SRI, $|B(S_i)|$, is no more than $\lceil \sqrt{S_i} \rceil + 1$ for all $1 \leq S_i \leq 22$. Especially, when $S_i$ is a prime and of the form $\alpha^2 + \alpha + 1$, where $\alpha$ is a prime power, the BW-set $B(S_i)$ (or, equivalently, the positions of HBIs in an SRI) in fact forms a line in the cyclic finite projective plane [7]. In this case, $|B(S_i)| = \alpha + 1 = \lceil \sqrt{\alpha^2 + \alpha + 1} \rceil = \lceil \sqrt{S_i} \rceil$. This concludes that OAPM is optimal and fully adaptive.

**C. Data Frame Transfer Procedure**

This subsection presents how a station sends data frames to its PS neighbor. Since the PS station is not always awake, the sending station must predict when the PS station will wake up. To attain this goal, each beacon frame shall contain a MAC address, a timestamp, the TBTT of the current BI, the value of SRI, the position of the current BI in the SRI, and the forward/backward pattern bit, besides other 802.11 management parameters. The forward/backward pattern bit is used for a PS station to convey that its current SRI is forward or backward. Referring to Fig. 6, once $Q$ has a cached record about its PS neighbor $P$, $Q$ can use the timestamp record to deduce their clock difference $D(P, Q)$, and $P$’s current time $t_p = t_q + D(P, Q)$ if $Q$ finds that $P$’s clock leads its clock. Referring to Fig. 6, let $\text{CRT}_p$ be the cached record about the TBTT of the BI, during which $Q$ received the beacon from $P$. Moreover, let $t_P$ denote the position of the BI in $P$’s SRI $S_p$ in that record. If $Q$ intends to send data frames to $P$ at time $t_Q$, it first computes the value of $\delta_P$ as follows.

$$\delta_P = \left[ \frac{(t_P - \text{CRT}_p + P \cdot B I)}{B I} \right], \quad (3)$$

where $a \mod b = a - b \lfloor a/b \rfloor$, if both $a$ and $b \neq 0$ are any real numbers. If $0 \leq \delta_P \leq S_p - 1$, then station $P$ is currently in the forward SRI; if $S_p \leq \delta_P \leq 2 \cdot S_p - 1$, then station $P$ is currently in the backward SRI. Then station $Q$ employs the following formula to derive the current position of BI $\theta_P$ in $P$’s SRI $S_p$.

$$\theta_P = \delta_P \mod S_p. \quad (4)$$

By comparing $\theta_P$ and $S_p$ with the HBI/SBI schedule table (e.g. Fig. 4), $Q$ can infer whether $P$ is currently in HBI or SBI. For example, $\delta_P = 5$ and $S_p = 11$, we can derive that $P$ is currently in forward HBI and $P$’s next BI is SBI.

Once $Q$ intends to send data frames to its PS neighbor $P$, $Q$ should first use the above-mentioned procedure to predict whether $P$ is currently in HBI or SBI. If $P$ is currently in SBI, $Q$ shall buffer data frames and wait for the coming of $P$’s next BI.
III. ADAPTIVE SRI CONTROL AND SIMULATION RESULTS

Before presenting simulation results, we first explore how a PS station adjusts its SRI according to traffic timeliness requirements. Specifically, we integrate OAPM with a geographic routing protocol. We assume that each station piggybacks its residual energy and location information on the beacon frame. In OAPM, every station by default sets its SRI \( S_{\text{max}} \). When the source station intends to transmit a data flow to the destination whose location is known in advanced, it forwards the RREQ (route request) packet which specifies the tolerable delay \( L \) and attaches the hop-count field \( C \) to the neighbor whose remaining energy is highest and whose location is closer to the destination. Referring to Fig. 4, we can see that if two PS neighbors have the same SRI \( S \), the maximum data transfer delay between them is no more than \( (S/2) \) (in units of BI). Hence upon receipt of the RREQ, the destination replies the RREP (route reply) packet which fills out the SRI field \( S^* = \min \{S_{\text{max}}, \max \{2L/(C \cdot BI)\}, 1\} \) back to the source in the reverse direction. All PS stations along this path change their current SRI values \( S \) to \( S^* \) if \( S > S^* \), or remain their SRI values unchanged if \( S \leq S^* \). On the contrary, in CQPM, every station initially sets its SRI \( S_{\text{max}} \). Once a flow path is set up, all PS stations along that path can switch only to the active mode \( S_{\text{max}} \), and keep all BIs awake until the end of the data flow transmission.

Now, we compare the performance of OAPM and CQPM. We assume that, in a multi-hop MANET, (i) channel rate is 11 Mbps, (ii) beacon frame length is 65 bytes, and (iii) all stations have the same transmission range and initial battery energy \( E = 300 \) J. We use 1.4 W, 0.95 W, 0.805 W, and 0.06 W as the values of power consumed by network interface card [5] in transmit, receive, listen, and doze states, respectively. The transition between doze state and awake state consumes 0.575 mJ. The lengths of BW, AW, DW, and BI are fixed at 10 ms, 20 ms, 30 ms, and 100 ms, respectively. Fig. 7(a) shows the considered MANET configuration. We assume that the tolerable delays of flow_1 and flow_2 are 2.6 s and 1.4 s respectively. Simulation results are displayed in Fig. 7(b) and 7(c). We can see that OAPM not only satisfies the end-to-end delay constraints, but also reaches a 68.3% reduction in total energy consumption as compared with CQPM.

IV. CONCLUSION

IEEE 802.11 has become the de facto MAC standard for multi-hop MANETs. However, Fig. 1(b) shows that once PS stations get out of synchronization, then 802.11 power management may completely fail. Thus [5]–[8] proposed various CQPM protocols to overcome this problem. However, they require that all PS stations must have same SRI. This implies that, from the viewpoint of duty cycle, they are nonadaptive. In this paper, we proposed the OAPM protocol, which adopts the new structures of BIs, the interleaving technique, and the novel factor-hereditary quorum space to ensure that two PS neighbors can discover each other in finite time regardless of their clock difference and individual SRIs. The time complexity of OAPM neighbor maintenance is \( O(1) \). Importantly, OAPM achieves maximum adaptiveness and minimum idle duty cycle for IEEE 802.11-based multi-hop MANETS.

To show the power of OAPM, we proposed a cross-layer SRI adjustment scheme such that PS stations can adaptively set the values of SRI to maximize power conservation while satisfying flow delay requirements. Due to space limitations, extensive simulation results are left to the journal version paper. Primary numerical results reveal that OAPM achieves better energy-efficiency than existing CQPM protocols.

REFERENCES