Optimal Asymmetric and Maximized Adaptive Power Management Protocols for Clustered Ad Hoc Wireless Networks

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Abstract—IEEE 802.11 is currently the most popular medium access control (MAC) standard for mobile ad hoc networks (MANETs). On the other hand, clustering in MANETs is a promising technique to ensure the scalability of various communication protocols. Thus, we propose an optimal asymmetric and maximized adaptive power management protocol, called OAMA, for 802.11-based clustered MANETs, which has the following attractive features. 1) Given the length of schedule repetition interval (SRI), the duty cycles of both clusterheads and members reach the theoretical minimum. 2) Under the minimum duty cycle constraints, the numbers of tunable SRIs for clusterheads and members reach the theoretical maximum. 3) By means of factor-correlative coterie-plane product, OAMA guarantees bounded-time neighbor discovery between the clusterhead and its member, and between all clusterheads, regardless of stations' individual SRIs and the schedule offset between neighboring stations. 4) The time complexity of OAMA neighbor maintenance is $O(1)$. 5) OAMA adopts a cross-layer SRI adjustment scheme such that stations can adaptively tune the values of SRI to maximize energy conservation according to flow timeliness requirements. Both theoretical analyses and simulation results show that OAMA substantially outperforms existing power management protocols for clustered MANETs, including AQEC [2] and ACQ [14], in terms of duty cycle, adaptiveness, data delay dropped ratio, network lifetime, and end-to-end energy throughput.

Index Terms—IEEE 802.11, medium access control, clustered ad hoc network, power management, quorum.

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1 INTRODUCTION

A *mobile ad hoc network* (MANET) consists of a set of mobile stations, which are often powered by batteries, without any infrastructure. Due to slow progress in battery technology, the success of MANETs thus relies on energy-efficient communications. The radio of a mobile station can be in one of three *awake* states—transmitting, receiving, and idle listening—or in the *doze* state. Jung and Vaidya [7] indicated that the power consumption in the idle state is only *slightly* lower than that in the transmitting and receiving state. Hence to save power, a mobile station has to put itself into the doze state. However, in this state, it cannot transmit nor receive. Thus, the design of a *power management* protocol, which operates at the *medium access control* (MAC) layer, becomes critical.

1.1 IEEE 802.11 Power Management

IEEE 802.11 [6] is currently the *de facto* MAC standard for MANETs. As shown in Fig. 1, 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 *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 a station H_0 intends to send buffered data frames to the destination H_1 currently operating in the PS mode, H_0 shall first unicast an ATIM frame to H_1 during the ATIM window. Upon reception of that ATIM frame, the PS destination H_1 replies an ATIM-ACK to H_0, and then both H_0 and H_1 stay awake for the entire BI. PS stations which 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 H_0 sends buffered data to H_1, and H_1 then acknowledges its receipts. Note that the transmission and retransmission of ATIM/data frames should follow the *distributed coordination function* (DCF) procedure. For a more detailed description, refer to [6]. For the ease of reading, the supplement, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.92, provides a list of acronyms and abbreviations used in this paper.

1.2 Related Work

From Fig. 1, we can observe that, in 802.11, a PS station should stay awake for the period of ATIM window in *every* BI, which may incur unnecessary awakeness especially for light-load stations. The first solutions to this problem is [12], which allow PS stations to wake up *only* for certain BIs. Then, [8], [16] and our previous paper [15] concurrently and independently proposed the similar *cyclic quorum*-based power management (CQPM for short) protocols to improve the results of [12]. However, [4] indicated that these

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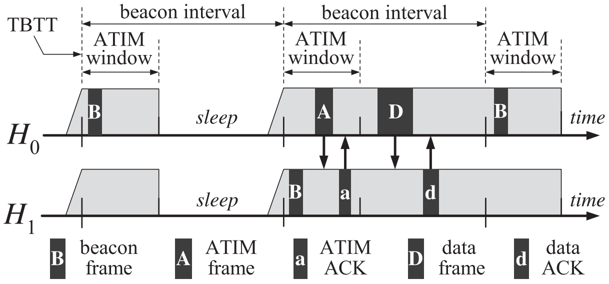

Fig. 1. An example of 802.11 power management operation in MANETs.

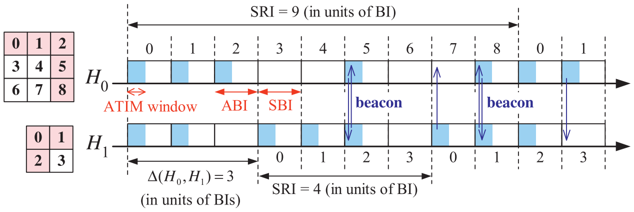

Fig. 2. An example of the neighbor maintenance in AQEC. PS station H_0 chooses SRI $S = 9$ and sets the jth BIs, where $j \in \mathcal{A}(9) = \{0, 1, 2, 5, 8\}$, as its ABIs in an SRI. In AQEC, $\alpha(4) = 3/4$ and $\alpha(9) = 5/9$.

protocols [8], [15], [16] require all PS stations must have the same *duty cycle* (i.e., the fraction of time a station stays awake); otherwise they may completely fail. This implies that they are *nonadaptive*. Thus, [2] proposed an adaptive CQPM protocol, called Adaptive Quorum-Based Energy Conserving (AQEC).[1] Referring to Fig. 2, there are two types of beacon intervals in AQEC; one is the *awake beacon interval* (ABI) and the other is the *sleep beacon interval* (SBI). The ABI starts with the ATIM window, during which a PS station remains awake and broadcasts its beacon frame. On the other hand, a PS station may doze off during the entire SBI. When a station enters the PS mode, the sequence of BIs is divided into groups such that each group consists of S BIs, where $\sqrt{S}$ is an integer. In each group, the S consecutive BIs are arranged as a $\sqrt{S} \times \sqrt{S}$ grid in a row-major fashion. Each PS station can choose one row and one column from a gird of *arbitrary* size $\sqrt{S} \times \sqrt{S}$ as its ABIs; while the residual BIs are SBIs. We call the group size *scheduled repetition interval* (SRI for short) since these S consecutive BIs that constitute the specific ABI/SBI pattern repeat regularly. As shown in Fig. 2, by grid-quorum property [2], AQEC guarantees that any two PS neighbors, H_0 and H_1, are able to hear each other's beacons (and thus *discover* each other) in finite time regardless of their schedule offset[2] $\Delta(H_0, H_1)$ and *individual* SRIs.

Let us define the *ABI-set* $\mathcal{A}(S)$ and *ABI-ratio* $\alpha(S)$ as the set of the positions of ABIs in an SRI S, and the ratio of the cardinality of $\mathcal{A}(S)$ to S, respectively. Intuitively, the larger the ABI-ratio, 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 ABI-ratio, the less frequently the station wakes up, the more battery power the station can save. The apparent advantage of an adaptive CQPM protocol is that each PS station can dynamically adjust the value of SRI (and thus the ABI-ratio) according to its residual battery power or other quality-of-service (QoS) considerations.

Recently, [14] pointed out that, in *clustered* MANETs [3], there is no need for a quorum-based power management to insist on the overlap property between *every pair* of PS stations. Referring to Fig. 3, by only guaranteeing the overlap of ABIs between each cluster member and its clusterhead, and between neighboring clusterheads, the whole MANET can still function well since each member may count on its clusterhead to forward data to the intended destination. On the basis of this principle, Wu et al. [14] proposed the first *asymmetric* power management (APM for short) protocol, called Asymmetric Cyclic Quorum (ACQ), in which the ABI-ratio of the cluster member $\alpha_{\mathrm{M}}(S)$ is *smaller* than that of its clusterhead $\alpha_{\mathrm{H}}(S)$. Since cluster members are the major population in a clustered MANET, this implies that APM may be more energy-efficient than symmetric power management, where both clusterheads and members employ the same ABI-sets construction rules. Specifically, in ACQ, given SRI S and an integer $1 \leq \phi \leq S$, the clusterhead adopts the following rule to build its ABI-set $\mathcal{A}_{\mathrm{H}}(S)$.

$$\mathcal{A}_{\mathrm{H}}(S) = \{0, 1, \ldots, \phi - 1, s_1, s_2, \ldots, s_{q-1}\}, \tag{1}$$

where $q = \lceil (S+1)/2\phi \rceil$, $\phi - 1 < s_1 \leq 2\phi - 1$, $0 < s_i - s_{i-1} \leq \phi$, and $s_{q-1} \geq (S-1)/2$. In contrast, the cluster member in ACQ adopts the following rule to build its ABI-set $\mathcal{A}_{\mathrm{M}}(S)$.

$$\mathcal{A}_{\mathrm{M}}(S) = \{a_0, a_1, \ldots, a_{p-1}\}, \tag{2}$$

where $p = \lceil S/\phi \rceil$, $a_0 = 0$, $0 < a_i - a_{i-1} \leq \phi$, and $0 < S - a_{p-1} \leq \phi$. Remark that although APM poses heavier duty cycle on the clusterhead, this problem can be solved by the periodical clusterhead re-election [3].

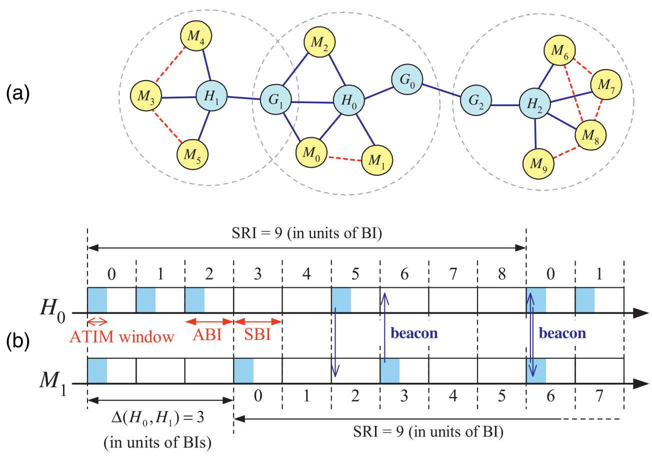

Fig. 3. (a) In clustered MANETs, each station can play one of the following roles: the *clusterhead* (denoted by H_i), *gateway* (denoted by G_i), or *member* (denoted by M_i). The solid blue edge (dotted red edge, respectively) signifies that incident PS stations can (may not, respectively) discover each other in finite time. (b) An example of the neighbor maintenance in ACQ. All PS stations must set the same SRI $S = 9$ and $\phi = 3$. By fixing $s_i - s_{i-1} = a_i - a_{i-1} = \phi$, we have $\mathcal{A}_{\mathrm{H}}(S) = \{0, 1, 2, 5\}$ and $\mathcal{A}_{\mathrm{M}}(S) = \{0, 3, 6\}$.

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[1] Here, we assume that AQEC performs neighbor maintenance since [4] indicated that, without neighbor maintenance, AQEC may waste significant energy on blindly sending the ATIM frames.

[2] With the wide spread of GPS [5] and the availability of industrial-strength clock synchronization mechanisms [17], we assume that the TBTTs of all stations are aligned. After reading Section 2.3, readers can understand that our proposed protocol, called OAMA, can operate in an asynchronous MANET as well. Please notice that the alignment of TBTT does not imply that neighboring stations have no schedule offset.

Thus, compared with AQEC and ACQ, we can make the following observations: 1) From the viewpoint of *adaptiveness*, AQEC outperforms ACQ since, given the maximum SRI $S_{\max}$, both the numbers of tunable SRIs for clusterheads and members in AQEC are $\sqrt{S_{\max}}$, while in ACQ, all PS stations must have the *same* SRI. 2) From the viewpoint of *average power consumption*, ACQ outperforms AQEC since, under the same SRI S, the ABI-ratio of AQEC is about $2/\sqrt{S}$, while, in ACQ, the minimum ABI-ratios of (clusterhead, member) are about $(\sqrt{2/S}, \sqrt{2/S})$ or $(1/2, 2/S)$, both of which are, however, larger than the optimal value.

1.3 Contributions

Given maximum SRI $S_{\max}$, let us denote the numbers of tunable SRIs for clusterheads and members by $\theta_{\mathrm{H}}(S_{\max})$ and $\theta_{\mathrm{M}}(S_{\max})$, respectively. We say that an APM is *optimal* and *maximized adaptive* if it satisfies the following requirements:

R1. For clusterheads, the number of ABIs in an SRI S is no more than $\lceil\sqrt{S}\rceil + 1$. This implies that the ABI-ratio of the clusterhead is $\alpha_{\mathrm{H}}(S) \approx 1/\sqrt{S}$.
R2. For cluster members, the number of ABIs in an SRI S is exactly 1. This implies that the ABI-ratio of the cluster member is $\alpha_{\mathrm{M}}(S) = 1/S$.
R3. $\theta(S_{\max}) = \theta_{\mathrm{H}}(S_{\max}) \times \theta_{\mathrm{M}}(S_{\max}) > \frac{9S_{\max}^2}{16\ln^2 S_{\max}}$.

The reason for **R1** is because [8] proved that, to preserve the overlap property between neighboring PS stations, the number of ABIs in an SRI S can be no less than $\lceil\sqrt{S}\rceil$. The reason for **R2** is because we allow neighboring members can *never* discover each other. The reason for **R3** is that, under the constraints of **R1** and **R2**, $\frac{9S_{\max}^2}{16\ln^2 S_{\max}}$ is currently the best known asymptotic bound of $\theta(S_{\max})$. (See Section 3.)

The major objective of this paper is to design an APM that satisfies **R1**, **R2**, and **R3**. The overall contributions of this paper are as follows:

- In [14], [16], the authors conjectured that the problem of finding an optimal (even nonadaptive) APM schedule for a clustered MANET is NP-complete. We disprove this conjecture by providing a simple yet novel $O(1)$ optimal asymmetric and maximized adaptive power management for the practical value of $S_{\max}$, say 25. We name our protocol as *OAMA*. The technical kernel of OAMA is to devise a topology-independent neighbor maintenance scheme by using the *factor-correlative coterie-plane product*(defined in Section 2.1) to guarantee the bounded-time neighbor discovery between each clusterhead and its members, and between neighboring clusterheads, regardless of stations' individual SRIs and the schedule offset between neighboring stations.
- Since a PS station may often stay in the doze state, we design the ABI/SBI pattern prediction method such that the sending station in OAMA can predict when its PS neighbor will wake up, thus delivering data frames to it at the right time.
- To illuminate the power of adaptiveness, we design a cross-layer SRI adjustment scheme for OAMA such that PS stations can dynamically tune the values of SRI to maximize power conservation according to flow timeliness requirements.

Clusterhead ABI-Set Table

SRI	Positions of ABIs in an SRI						ABI-ratio
1	0						1.000
2	0	1					1.000
4	0	1	3				0.750
5	0	1	3				0.600
7	0	1	3				0.429
10	0	1	3	6			0.400
14	0	1	2	3	7		0.357
19	0	1	2	6	9		0.263
23	0	1	2	3	7	11	0.261

Member SRI-Set Table

SRI	1	2	3	6	11	13	17	22
ABI-ratio	1.000	0.500	0.333	0.167	0.091	0.077	0.059	0.045

Fig. 4. An example of the factor-correlative coterie-plane product stored in a station using table formats. Here, we let $\omega = 2$ and $S_{\max} = 25$.

- We first theoretically prove the optimality of OAMA. Then, by conducting extensive simulations, we demonstrate that OAMA is much more energy-efficient than existing APM protocols [2], [14].

2 THE OAMA PROTOCOL

OAMA contains three components: a *neighbor maintenance procedure*, an *ABI/SBI pattern prediction method*, and a *data frame transfer procedure*.

2.1 Neighbor Maintenance Procedure

Before introducing the OAMA, we need to define the factor-correlative coterie-plane product.

Definition 1. *Given a positive integer* $S_{\max}$*, let both* $\mathcal{S} = \{S_1, S_2, \ldots, S_m\}$ *and* $\mathcal{R} = \{R_1, R_2, \ldots, R_n\}$ *be subsets of* $\{1, 2, \ldots, S_{\max}\}$*. In addition, given* $S_i \in \mathcal{S}$*, let* $\mathcal{A}(S_i) = \{b_1, \ldots, b_h\}$ *be a subset of* $\{0, 1, \ldots, S_i - 1\}$*. The Cartesian product of a collection of ordered pairs* $\{(S_i, \mathcal{A}(S_i))\}$ *and a set* $\mathcal{R}$ *is called a* factor-correlative coterie-plane product *if it satisfies the following properties:* ***P1****) For any integer* t*, we define* $t \oplus \mathcal{A}(S_i) = \{t + b_j \bmod S_i \mid \text{for all } b_j \in \mathcal{A}(S_i)\}$*. Then, for all* $S_i \in \mathcal{S}$*, we require* $\mathcal{A}(S_i) \cap (t \oplus \mathcal{A}(S_i)) \neq \emptyset$*.* ***P2****) Given the integer* S_i*, let* $d_1, \ldots, d_r$ *be the factors (also called divisors) of* S_i*. We require* $\bigcup_{k=1}^{r} \mathcal{A}(d_k) \subseteq \mathcal{A}(S_i)$ *for all* $S_i \in \mathcal{S}$*.* ***P3****) Let* $\omega = \max\{\gcd(S_i, R_j) \mid \text{for all } S_i \in \mathcal{S} \text{ and } R_j \in \mathcal{R}\}$*. Then, for all* $S_i \in \mathcal{S}$*, we require* $\{0 \bmod S_i, 1 \bmod S_i, \ldots, \omega - 1 \bmod S_i\} \subseteq \mathcal{A}(S_i)$*.*

The neighbor maintenance procedure of OAMA operates as follows: Referring to Fig. 4, *every* station stores the *same* two tables: one is the *clusterhead ABI-set table* $\{(S_i, \mathcal{A}(S_i))\}$ and the other is the *member SRI-set table* $\mathcal{R}$, both of which together form the factor-correlative coterie-plane product. As shown in Fig. 5, a PS station in OAMA can adjust the length of SRI only at the *start* of each SRI. Once the value of SRI is determined, the PS station playing the role of clusterhead (or gateway) shall consult the clusterhead ABI-set table to set the positions of ABIs and SBIs in the SRI, while the station playing the role of cluster member sets *only* the *zeroth* BI as its ABI in the SRI. Fig. 5 depicts an example where the cluster member, M_0, and clusterheads, H_0 and H_1, arrange their individual ABI/SBI schedules according to the OAMA protocol. Note that although

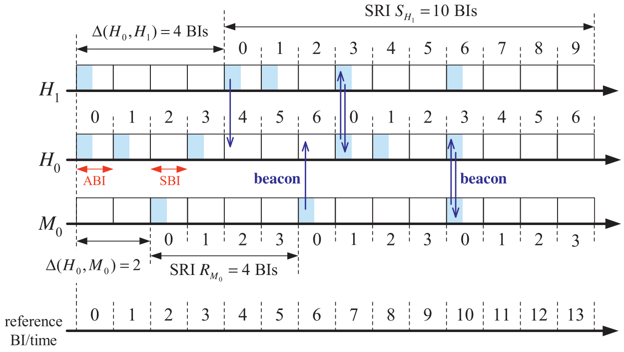


Fig. 5. An example of the neighbor maintenance in OAMA. Here, we assume the schedule offset $\Delta(H_0, M_0)$ between H_0 and M_0 is 2 (in units of BI). According to Fig. 4, PS station H_1 selects the $\{0, 1, 3, 6\}$th BIs as its ABIs within every consecutive 10 BIs. Since the factors of 10 include 1, 2, and 5, OAMA requires $\mathcal{A}(1) \subseteq \mathcal{A}(10)$, $\mathcal{A}(2) \subseteq \mathcal{A}(10)$, and $\mathcal{A}(5) \subseteq \mathcal{A}(10)$.

deriving the optimal tables for $\{(S_i, \mathcal{A}(S_i))\}$ and $\mathcal{R}$ may need exhaustive search, the time complexity of OAMA neighbor maintenance is $O(1)$ since it involves only table lookup operations and the table size is constant. Above all, we have the following results. Note that due to space limitations, all the proofs of theorems in the rest of this paper can be found in the supplement, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.92.

Theorem 1. *Given bounded* $S_{\max}$*, OAMA guarantees that two neighboring clusterheads,* H_0 *and* H_1*, can discover each other in bounded time regardless of their schedule offset* $\Delta(H_0, H_1)$ *as well as their respective SRIs,* S_{H_0} *and* S_{H_1}*.*

Theorem 2. *Given bounded* $S_{\max}$*, OAMA guarantees that each cluster member* M_0 *and its clusterhead* H_0 *can discover each other in bounded time regardless of their schedule offset* $\Delta(H_0, M_0)$ *as well as their respective SRIs,* R_{M_0} *and* S_{H_0}*.*

2.2 Data Frame Transfer Procedure

Since a PS station is not always awake, the sending station must predict when its PS neighbor will wake up. To achieve 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 a *role-indication bit*, besides other 802.11 management parameters. Upon receiving a beacon frame, a station inserts or refreshes the record about this neighbor in its *cached neighbor table*. Referring to Fig. 6, let CRT_{H_0} be the cached record about the TBTT of the BI, during which station M_0 received the beacon frame from its neighbor H_0. Moreover, let I_{H_0} denote the position of the BI in H_0's SRI S_{H_0} in that record. Then at time t_1, the current position of BI δ_{H_0} in H_0's SRI S_{H_0} can be derived via the following formula:

$$\delta_{H_0} = \left\lfloor \frac{(t_1 - CRT_{H_0} + I_{H_0} \cdot BI) \bmod (S_{H_0} \cdot BI)}{BI} \right\rfloor, \qquad (3)$$

where $a \bmod b = a - b\lfloor a/b \rfloor$, if both a and $b \neq 0$ are any *real* numbers. By using the role-indication bit and comparing (δ_{H_0}, S_{H_0}) with the tables of factor-correlative coterie-plane product, M_0 can infer whether H_0 is currently in ABI or SBI.

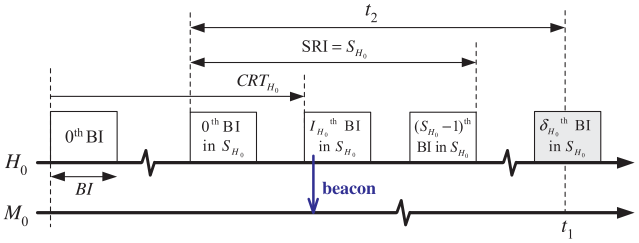


Fig. 6. An example of the ABI/SBI pattern prediction method. We can find that $t_2 = t_1 - CRT_{H_0} + BI \dots I_{H_0}$, where BI denotes the length of a BI.

Once station M_0 intends to transmit data frames to its PS neighbor H_0, M_0 should first employ the abovementioned ABI/SBI pattern prediction method to judge whether H_0 is currently in ABI or SBI. If H_0 is currently in SBI, M_0 should buffer data frames and wait for the coming of H_0's ABI. In H_0's ABI, M_0 sends an ATIM frame to H_0 during the ATIM window. Upon receipt of M_0's ATIM frame, H_0 replies an ATIM-ACK to M_0, and both M_0 and H_0 remain awake after the close of the ATIM window. Then, M_0 begins to send data frames to H_0. When sending data frames to H_0, if the data queue for H_0 is not empty, M_0 will set the *more data* bit to 1 in the *frame control* filed [6]. After H_0 receives the last data frames (with more data bit set to 0) from all stations that sent ATIM frames, it immediately returns to the doze state. On the other hand, if M_0's data transmissions for H_0 cannot be completed within a single BI due to congestion or large amount of buffered data, both M_0 and H_0 will remain awake across multiple BIs (some of which may be originally SBIs) until communication is not needed.

2.3 Synchronization Issue

The existing CQPM protocols can be classified into two categories: In *synchronous* mode, CQPM (e.g., [14]) must rely on clock synchronization to guarantee the alignment of TBTT. In *asynchronous* mode, CQPM (e.g., [16]) requires PS stations to stay awake during the *whole* period of every ABI, instead of *only* ATIM window in the ABI, to overcome the alignment problem. Clearly, achieving global synchronization is costly especially in a multihop MANET [12]. Fortunately, OAMA does not require global synchronization. In OAMA, each station tries to synchronize with its neighbors via beacon exchange. Since synchronization in a cluster is easy, OAMA can correctly operate as long as any two neighboring clusterheads can receive each other's beacons. Before looking at how OAMA attains this goal, we need the following theorem:

Theorem 3. *Let* $\{(S_i, \mathcal{A}(S_i))\}$ *be the clusterhead ABI-set table in OAMA, where* $\mathcal{A}(S_i) = \{ b_1, \dots, b_h \mid b_j < b_{j+1}$ *for all* $1 \le j \le h-1\}$*. Let* $\gamma(S_i) = \max\{ b_{j+1} - b_j$ *and* $(b_1 - b_h) \bmod S_i \mid 1 \le j \le h-1\}$*. Then, we have* $\gamma(S_i) \le \lceil S_i/2 \rceil$ *for all* $S_i \in \mathcal{S}$*.*

In OAMA, when a PS station becomes a clusterhead, it *temporarily* remains awake for L consecutive BIs until it determines the operating (i.e., synchronous or asynchronous) mode. During this period, if that newborn clusterhead received (did not receive, respectively) beacons from its adjacent clusterheads after the close of ATIM windows, it thereafter operates in asynchronous (synchronous, respectively) mode. From Theorem 3, we know that two adjacent ABIs are interspaced by at most $(\lceil S/2 \rceil - 1)$ consecutive SBIs, where S is the SRI of a clusterhead. Hence, $L \le \lceil S_{\max}/2 \rceil$. Clearly, when a clusterhead operating in asynchronous mode can synchronize with all of its adjacent clusterheads, it can then switch to the synchronous mode.

3 OPTIMALITY OF OAMA

From the viewpoint of MAC layer, the ABI-ratio, adaptiveness, and average neighbor discovery time are used to judge the goodness of a power management protocol [2], [8], [15]. In this section, we provide performance comparisons among AQEC, ACQ, and OAMA in regard to these metrics.

Theorem 4. *Let* $\{(S_i, \mathcal{A}(S_i))\}$ *be the clusterhead ABI-set table in OAMA. We have* $|\mathcal{A}(S_i)| \leq \lceil\sqrt{S_i}\rceil + 1$. *This implies that the ABI-ratio of the clusterhead is* $\alpha_{\mathrm{H}}(S_i) \approx 1/\sqrt{S_i}$.

Theorem 5. *Let* $\{(S_i, \mathcal{A}(S_i))\}$ *be the clusterhead ABI-set table and* $\mathcal{R}$ *be the member SRI-set table in OAMA. Moreover, we denote by* $\theta_{\mathrm{H}}(S_{\max})$ *and* $\theta_{\mathrm{M}}(S_{\max})$ *the numbers of tunable SRIs for clusterheads and members, respectively. For* $S_{\max} \geq 7$, *the adaptiveness of OAMA is* $\theta(S_{\max}) = \theta_{\mathrm{H}}(S_{\max}) \times \theta_{\mathrm{M}}(S_{\max}) > \frac{9S^2_{\max}}{16\ln^2 S_{\max}}$.

Combining Theorems 4 and 5 leads to the following result.

Theorem 6. *The OAMA is optimal and maximized adaptive.*

Then, we investigate the average neighbor discovery time. We define the *common awake BIs* (CABIs) between stations H_0 and H_1 as the reference BIs when both H_0 and H_1 are in ABIs. Take Fig. 5 for example, the seventh reference BI is the CABI between H_0 and H_1. Assume that H_0 and H_1 select S_{H_0} and S_{H_1} as their SRIs, respectively. The average neighbor discovery time $\tau(S_{H_0}, S_{H_1})$ between H_0 and H_1 is formally defined as follows:

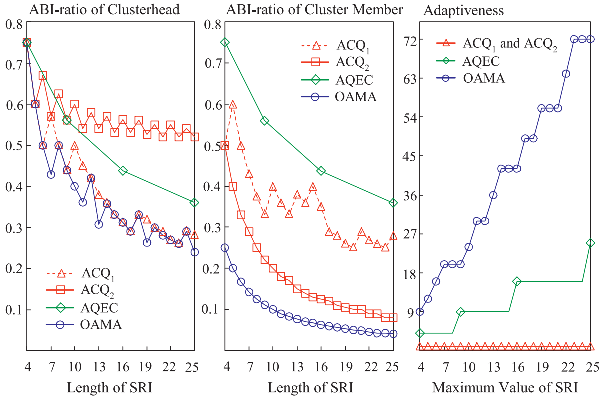
$$\tau(S_{H_0}, S_{H_1}) = \lim_{\Delta t \to \infty} \frac{\Delta t}{\text{number of CABIs in } [t, t+\Delta t)}.$$

Theorem 7. *Let* $\{(S_i, \mathcal{A}(S_i))\}$ *be the clusterhead ABI-set table in OAMA. Then, the average neighbor discovery time between neighboring clusterheads* H_0 *and* H_1 *is*

$$\tau(S_{H_0}, S_{H_1}) = \frac{S_{H_0} \times S_{H_1}}{|\mathcal{A}(S_{H_0})| \times |\mathcal{A}(S_{H_1})|} \approx \sqrt{S_{H_0} \times S_{H_1}} \leq S_{\max}.$$

Theorem 8. *Let* $\{(S_i, \mathcal{A}(S_i))\}$ *be the clusterhead ABI-set table and* $\mathcal{R}$ *the member SRI-set table in OAMA. Assume that the clusterhead* H_0 *and its member* M_0 *select* S_{H_0} *and* R_{M_0} *as their SRIs, respectively. Then, the average neighbor discovery time between* H_0 *and* M_0 *is*

$$\tau(S_{H_0}, R_{M_0}) = \frac{S_{H_0} \times R_{M_0}}{|\mathcal{A}(S_{H_0})|} \approx \sqrt{S_{H_0}} \times R_{M_0} \leq S^{3/2}_{\max}.$$



(a) (b) (c)

Fig. 7. The length of SRI versus the ABI-ratio for the (a) clusterhead and (b) member. Part (c) shows the adaptivenesses of various APM protocols.

Fig. 7 depicts theoretical performance comparisons among AQEC, ACQ, and OAMA. Referring (1) and (2), the minimum ABI-ratio of ACQ sensitively depends on the parameter ϕ. [14] indicated that, given SRI S, ACQ has minimum ABI-ratio when $\phi = \lceil\sqrt{(S+1)/2}\rceil$ or $\lceil(S+1)/2\rceil$. Hence, we denote by ACQ$_1$ and ACQ$_2$ when ACQ adopts $\phi = \lceil\sqrt{(S+1)/2}\rceil$ or $\lceil(S+1)/2\rceil$, respectively. Since ACQ requires all stations, including clusterheads and members, use the same SRI, its adaptiveness is always 1. On the other hand, due to the fluctuation of parameters $0 < s_i - s_{i-1} \leq \phi$ and $0 < a_i - a_{i-1} \leq \phi$ in (1) and (2), the neighbor discovery time in ACQ is unpredictable.

4 CROSS-LAYER SRI ADJUSTMENT PROCEDURE

Before seeing the SRI adjustment procedure of OAMA, we need to derive the maximum *one-hop* data transfer delay.

Theorem 9. *Assume that in a noncongested cluster, a data frame sent from a station to its neighbor can be completed in a single BI, when they are simultaneously awake. Then, in a noncongested cluster, the maximum data frame transfer delay* $\xi(S_{H_1})$ *from station* H_0 *to its* discovered *neighboring clusterhead* H_1 *that selects* $S_{H_1} \in \mathcal{S}$ *as its SRI is no more than* $(\lceil S_{H_1}/2\rceil + 1)BI - AW$, *where BI and AW are the lengths of BI and ATIM window, respectively.*

Theorem 10. *In a noncongested cluster, the maximum data frame transfer delay* $\xi(R_{M_0})$ *from the clusterhead* H_0 *to its* discovered *member* M_0 *that selects* $R_{M_0} \in \mathcal{R}$ *as its SRI is* $(R_{M_0} + 1)BI - AW$, *where BI and AW are the lengths of BI and ATIM window, respectively.*

Now, we show how to integrate OAMA with a geographic routing protocol, called Greedy-Face-Greedy (GFG) routing [1], so that PS stations along the routing path can adjust the values of SRI in response to the flow timeliness requirement. Theoretically, OAMA, which operates at MAC layer, can integrate with any ad hoc routing protocols. The choice of GFG is mainly because of its simplicity and the freedom of *dead-end* problem[3] [1]. We assume that each station piggybacks the residual energy and location information on the beacon frame. In OAMA, the clusterheads and members by default set the SRI values to $\max\{S \mid S \in \mathcal{S}\}$ and $\max\{S \mid S \in \mathcal{R}\}$, respectively. When a clusterhead is aware that the members of its neighboring clusterheads have changed, that clusterhead instantly performs the planarization procedure to ensure the correctness of GFG. When the source station X intends to transmit a

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[3] The dead-end problem here arises when greedy forwarding fails at a clusterhead that is closer to the destination than all its neighboring clusterheads.

data flow to the destination Y, whose location is known in advanced, it forwards the *route request* (RREQ) packet specifying its tolerable delay T_{delay} to the neighboring clusterhead whose residual energy is highest and whose location is *closer* to the destination. If no such clusterhead can be found, X then enters the *perimeter-mode* and forwards that RREQ packet to the appropriate clusterhead using the *planar face traversal* techniques [1].

Upon receipt of the RREQ packet, if the receiving station is not the destination, it appends its address to the RREQ and then propagates that RREQ towards the destination. Assume that RREQ travels from the source X, through clusterheads $H_{k_1}, H_{k_2}, \ldots, H_{k_n}$, and finally to the destination Y. Y first performs *admission control* checking whether the following inequality can be satisfied.

$$\Upsilon = (n+1)(2BI - AW) \leq T_{delay}. \tag{4}$$

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

If so, Y should determine the values of $S_{H_{k_1}}, \ldots, S_{H_{k_n}}$, and S_Y such that the following inequality can be satisfied:

$$\xi(S_{H_{k_1}}) + \cdots + \xi(S_{H_{k_n}}) + \xi(S_Y) \leq T_{delay}. \tag{5}$$

It has been proven in [11], [13] that the problem of finding minimum energy routes in a multihop MANET without violating delay constraints is NP-complete. Hence, we design a simple heuristic method to quickly determine the feasible solutions of $S_{H_{k_1}}, \ldots, S_{H_{k_n}}$, and S_Y. To balance the power consumption, we hope that all stations along the path use roughly the same SRI. If $S_{H_{k_i}} = S_Y = S^*$ for all $1 \leq i \leq n$, inequality (5) can be reworded as follows:

$$\begin{cases} (n+1)\left[\left(\lceil \frac{S^*}{2} \rceil + 1\right)BI - AW\right] \leq T_{delay}, \\ \hfill \text{if } Y \text{ is a clusterhead,} \\ n\left[\left(\lceil \frac{S^*}{2} \rceil + 1\right)BI - AW\right] + (S^*+1)BI - AW \leq T_{delay}, \\ \hfill \text{if } Y \text{ is a clusterhead member.} \end{cases}$$

To maximize S^* (and thus, minimize the ABI-ratio), we let

$$S^* = \begin{cases} 2\left\lfloor \frac{T_{delay} - (n+1)(BI - AW)}{(n+1)BI} \right\rfloor, & \text{if } Y \text{ is a clusterhead,} \\ 2\left\lfloor \frac{T_{delay} - (n+1)(BI - AW)}{(n+2)BI} \right\rfloor, & \text{if } Y \text{ is a member.} \end{cases}$$

However, the value of S^* may not satisfy Definition 1. Let $S_{\mathrm{H}} = \max_{S \in \mathcal{S}}\{S \mid S \leq S^*\}$ and $S_{\mathrm{M}} = \max_{S \in \mathcal{R}}\{S \mid S \leq S^*\}$. If Y is a clusterhead, it sets $S_Y = S_{\mathrm{H}}$ if its current SRI is greater than S_{H}. If Y is a cluster member, it sets $S_Y = S_{\mathrm{M}}$ if its current SRI is greater than S_{M}. Besides, Y replies the *route reply* (RREP) packet attaching S_{H} back to the source station in the reverse direction. Every clusterhead along this path changes the SRI value to S_{H} only when its current SRI is larger than S_{H}. Once the source station received the RREP, it can commence the data flow transmission.

5 PERFORMANCE EVALUATION

5.1 Simulation Model

We follow the event-driven approach [9] to build a simulator whose architecture is specified in the supplement, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.92. The simulation area is $700 \times 700\ \mathrm{m}^2$. We assume that each station is equipped with a GPS receiver [5], which provides reliable positioning. In a clustered MANET, we adopt GRID [10] as the underlying cluster management scheme. Specifically, the geographic area of the MANET is partitioned into 2D logical grids. Each grid (cluster) is a square area of size $d \times d$, where $d = 100$ m. The transmission radius of a station is $r = \sqrt{5}d \approx 223.6$ m. This ensures that the clusterheads of two adjacent grids are in the transmission range of each other. We assume that only clusterheads can forward packets and clusterheads are reelected every 60 s. With the aid of GPS, we assume that the TBTTs of all stations are aligned. When a station powers on or roams into a new grid, it temporarily sets the SRI value to 1 until it determines its role (clusterhead or member). If that station cannot find a clusterhead within $\lceil S_{\max}/2 \rceil$ consecutive BIs, it then declares itself (via the role-indication bit in the beacon frame) as a clusterhead. To eliminate the possibility of having multiple clusterheads in a grid, when a station assuming itself as the clusterhead finds another clusterhead having higher residual energy, it silently turns itself as a cluster member. When a clusterhead has aged for 60 s or leaves its current grid, it appoints the cluster member with the highest residual energy as the new clusterhead and hands over flow-related data to it.

A total of k data flows are established between randomly selected source-destination pairs, where $6 \leq k \leq 12$. Each sender is an ON-OFF Poisson traffic source with interleaved ON and OFF periods of length 10 s and 15 s, respectively. During the ON period, the average data arrival rate is λ Kbps, where $6 \leq \lambda \leq 12$, and the data packet size is 512 bytes. During the OFF period, no traffic is generated. We assume that the channel bit rate is 2 Mbps. The lengths of ATIM window and BI are fixed at 25 and 100 ms, respectively. We use 1.65 W, 1.4 W, 1.15 W, and 0.045 W as values of power, consumed by the network interface in transmit, receive, idle, and doze state, respectively [7]. The transition between doze state and awake state consumes 0.575 mJ [7].

In AQEC, each PS station dynamically tunes the value of SRI according to its observed traffic load [2]. Specifically, the SRI adaptation rules of AQEC for both clusterheads and members are as follows:

$$S = \begin{cases} 1, & \text{if traffic } \geq \alpha(1) \cdot \lambda_{\max}, \\ S_i, & \text{if } \alpha(S_{i+1}) \cdot \lambda_{\max} \leq \text{traffic} < \alpha(S_i) \cdot \lambda_{\max}, \\ S_{\max}, & \text{if traffic } < \alpha(S_{\max}) \cdot \lambda_{\max}, \end{cases}$$

where $\lambda_{\max} = 12$ Kbps, $S_i = i^2$ for all $i \in \{1, 2, 3, 4, 5\}$, $S_{\max} = S_5 = 25$, and $\alpha(S_i) = (2\sqrt{S_i} - 1)/S_i$. In ACQ, all stations must use the same SRI and we assume that the value of SRI is 10. Furthermore, in ACQ_1, the ABI-sets of the clusterhead and the member are $\{0, 1, 2, 5, 9\}$ and $\{0, 3, 6, 9\}$, respectively. In ACQ_2, the ABI-sets of the clusterhead and the member are $\{0, 1, 2, 3, 4, 5\}$ and $\{0, 6\}$, respectively.

All simulation runs are carried out for a duration of $1.5 \times 10^9\ \mu\mathrm{s}$ and each simulation result is obtained from the average of 10 runs. The confidence level shown in the following figures (except Figs. 9 and 10) is at 95 percent with the confidence interval of $(\overline{U} - 1.96\hat{s}/3.16, \overline{U} + 1.96\hat{s}/3.16)$, where $\overline{U}$ is the mean and $\hat{s}$ is the standard deviation of the samples. Note that due to space limitations, the supplement,

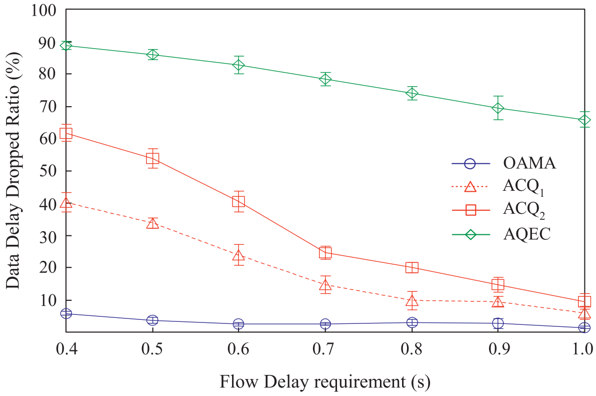

Fig. 8. DDDR versus flow delay requirements. (The total number of stations is 200 and the whole MANET is static. The total number of flows is 9 and $\lambda = 9$ Kbps.)

which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.92, provides additional simulation results about the effects of data traffic load, routing protocol, mobility model, station density, etc.

5.2 Data Delay Dropped Ratio

The data delay dropped ratio (DDDR for short) is defined as the fraction of dropped data packets caused by violating the end-to-end delay constraints. Fig. 8 shows that when the clustered MANET is static, the DDDR of OAMA can be no more than 6 percent regardless of flow delay requirements. This result justifies the superiority of our adaptive SRI adjustment scheme. The reason for having nonzero DDDR in OAMA is that when a clusterhead, say H_1, on a routing path needs to reduce the SRI due to the timeliness requirement of another flow, its upstream clusterhead, say H_0, cannot know the up-to-date ABI/SBI schedule of H_1 until H_0 receives a new beacon from H_1. This will increase the data buffering time at H_0. Fortunately, Theorem 7 shows that the average neighbor discovery time between neighboring clusterheads is only sublinearly proportional to the SRI. Moreover, Fig. 9b depicts that the SRI change rate of a station in OAMA is relatively low. Hence, the DDDR of OAMA is expectably small. The DDDRs of AQEC and ACQ steeply increase as the flow delay requirement decreases. This is mainly because AQEC and ACQ do not perform admission control. However, the DDDR of AQEC is much larger than that of ACQ. The reasons are as follows: In AQEC, stations tune the SRI values according to *observed* traffic load. Since PS stations do not wake up very often, they can hardly derive the *actual* arrival rates of the flows. Fig. 9a shows that during the ON periods of a flow, the SRI value of a station oscillates rapidly and sharply. This easily leads to the situation that the upstream clusterhead *frequently* predicts the wrong ABI/SBI schedule of the downstream clusterhead, causing the huge DDDR.

5.3 Survival Ratio

The survival ratio is defined as the number of surviving stations (with nonzero energy) over the total number of stations. We assume that the initial energy of every station is 100 Joule. From Fig. 10, we can see that since, in OAMA, the ABI-ratios of both clusterheads and cluster members reach the theoretical minimum, the network lifetime of OAMA can be 243, 169, and 225 percent times that of ACQ_1, ACQ_2, and AQEC, respectively. Fig. 10 also shows that ACQ_2 has a longer network lifetime than AQEC. This is because ACQ_2 has an apparent asymmetric advantage over AQEC (i.e., in ACQ_2, a cluster member has a much smaller ABI-ratio than a clusterhead). On the other hand, when the traffic load is light (especially, during the OFF periods), stations in AQEC tend to use the large values of SRI. Besides, a station with maximum SRI in AQEC has a smaller ABI-ratio than a cluster member in ACQ_1. Hence, the network lifetime of AQEC can be longer than that of ACQ_1.

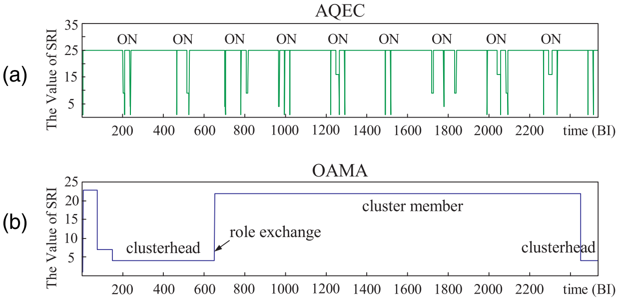

Fig. 9. A snapshot of the evolution of SRI of a station in (a) AQEC and (b) OAMA. (The whole MANET is static and $\lambda = 9$ Kbps. The delay requirement of each flow is 1.0 s.)

5.4 End-to-End Energy Throughput

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. The authors of [7] pointed out that using energy throughput to judge the goodness of a power management protocol is fairer than using total power consumption since some power management protocols may consume very little energy, but also attain very little throughput. Fig. 11 depicts that the end-to-end energy throughputs of ACQ and AQEC decline with the decrease of the flow delay requirement. This is mainly because both the DDDRs of ACQ and AQEC become large as the flow delay requirement becomes small. On the other hand, thanks to the adaptive SRI adjustment procedure, the end-to-end energy throughput of OAMA can be around 1.6 Kbits/J regardless of flow delay requirements.

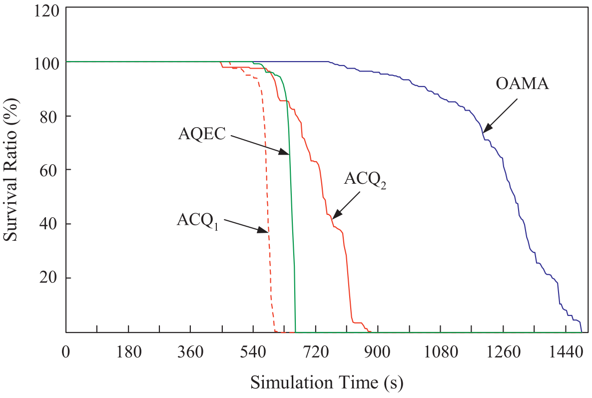

Fig. 10. Survival ratio. (The total number of stations is 300 and the whole MANET is static. The total number of flows is 6 and $\lambda = 9$ Kbps. The delay requirement of each flow is 1.4 s.)

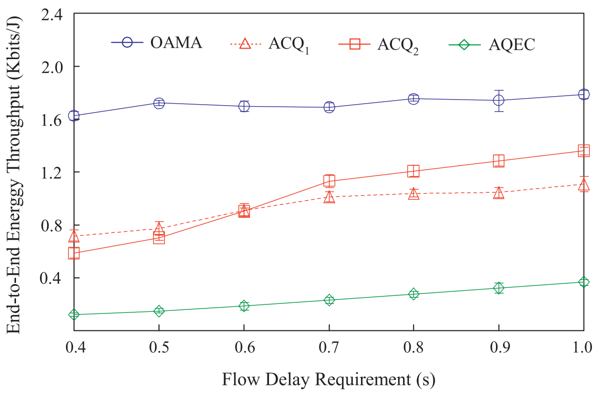

Fig. 11. End-to-end energy throughput versus flow delay requirements. (The total number of stations is 200 and the whole MANET is static. The total number of flows is 9 and $\lambda = 9$ Kbps.)

6 CONCLUSION

IEEE 802.11 has become the *de facto* MAC standard for a multihop MANET. However, in 802.11, all PS stations should stay awake for the period of ATIM window in *every* BI. Hence, Chao et al. [2] proposed AQEC, in which each PS station can adaptively tune its SRI according to traffic load. On the other hand, ACQ [14] adopts different ABI-set construction rules for clusterheads and members to earn an asymmetric advantage over AQEC in a clustered MANET. However, in terms of duty cycle and adaptiveness, the performances of AQEC and ACQ are far from optimal. This motivates us to design the OAMA protocol. By means of the factor-corrective coterie-plane product, OAMA ensures the bounded neighbor discovery time. Importantly, OAMA achieves minimum ABI-ratio and maximized adaptiveness for IEEE 802.11-based clustered MANETs. Finally, we have proposed a cross-layer SRI adjustment scheme such that PS stations can dynamically adjust the SRI values to maximize energy conservation based on flow delay requirements. Both theoretical analyses and extensive simulations indeed confirm that OAMA significantly outperforms AQEC and ACQ.

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