AAA: Asynchronous, Adaptive, and Asymmetric Power Management for Mobile Ad Hoc Networks

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***Abstract*—The Quorum-based Power Saving (QPS) protocols have been proposed to increase the energy efficiency of wireless communication. However, it remains challenging to apply existing QPS protocols to the Mobile Ad hoc NETworks (MANETs) as the timers of nodes are usually asynchronous, the incurred delay are expected to be adaptive, and the network topology is asymmetric. In this paper, we propose an Asynchronous, Adaptive, and Asymmetric (AAA) power management protocol that fulfills the unique requirements of MANETs. We present the asymmetric grid quorum system, a generalization of traditional grid-based quorum systems, to ensure the network connectivity. Theoretical analysis is conducted to demonstrate the benefits of AAA over previous arts.**

I. INTRODUCTION

The *Quorum-based Power Saving* (QPS) protocols [3], [4], [8], [13], [14], [15], [17] at MAC layer are widely discussed over the past years to save the energy wasted in idle listening. In a QPS protocol, the time axis on each station is divided evenly into *beacon intervals*. A station may stay either awake or sleep during each beacon interval. Given an integer n, a quorum system defines a *cycle pattern*, which specifies the awake/sleep schedule during n continuous beacon intervals, for each station. We call n the *cycle length* since the pattern repeats every n beacon intervals. The merit of QPS protocols is that a station is required to remain awake only $O(\sqrt{n})$ beacon intervals every cycle, and at least one of these awake beacon intervals is guaranteed to overlap with that of another station. By exchanging awake/sleep schedules during the overlapped beacon interval, neighbor stations can *discover* each other, i.e., to know each other's wake up time, and then begin data communication.

Applying QPS protocols to MANETs is challenging due to the dynamic nature of nodes. Specifically, a QPS protocol is required to operate when:

- Beacon intervals are *asynchronous* in time. Timer synchronization in a MANET is generally costly, or even infeasible due to temporary network partition [8], [17]. A QPS protocol should guaranteed the overlap even when the boundaries of beacon intervals shift between stations;
- Cycle patterns are *adaptive* in their lengths. There is a trade-off when it comes to selecting the cycle length, n—the larger the value of n, the more the power saving; yet the longer the (worst-case) neighbor discovery time since the overlapping is guaranteed once per cycle. Requiring all stations to use the same value of n is problematic as individual stations may have their own delay requirement on data communication or constraint of remaining battery power [3], [15]. A QPS protocol should guaranteed the overlap even when the selected cycle lengths are different between stations;
- The network is *asymmetric* in topology. Notice that the clustering and virtual backbone are commonly used techniques in MANETs to facilitate the reuse of resources (e.g., bandwidth), localization of node dynamics, and coordination [6], [7], [11], [12]. Since each member (i.e., a regular node) in a cluster can simply rely on the clusterhead (or backbone node) to forward data, there is no need for a QPS protocol to insist the overlap between *every pair* of stations. In other words, the overlap guarantee between members is *not* necessary in clustered/backboned environments as it is sufficient to promise the overlap between members and the clusterhead in a cluster, and between clusterheads in a network. A QPS protocol should exploit such an asymmetry to enhance energy efficiency.

While largely discussed, surprisingly, none of the existing QPS protocols can fulfill all the above requirements when applied to MANETs. Studies [8], [13], [17] propose *asynchronous QPS protocols* addressing the issue of timer shift between stations. But the cycle length, n, is assumed to be fixed in a network. Studies [3], [4], [15] propose *adaptive QPS protocols* where stations are allowed to pick different values of n, possibly under certain restrictions (e.g., n is a square or prime), according to their individual needs. Nevertheless, these studies assume a symmetric (or flat) network structure. Study [14] proposes an *asymmetric QPS protocol* that is able to differentiate the quorums between the members and clusterheads and allow further power saving on members as compared to that given by the symmetric QPS protocols. Unfortunately, the study [15] cannot deal with asynchronous environments, and the cycle length must be fixed. The practicability of above studies in MANETs, therefore, is limited. Integrating existing QPS protocols is prohibited by the fact that the quorum systems adopted by these protocols are based on different combinatorics which are not compatible with each other.

In this paper, we propose an *Asynchronous, Adaptive, and*

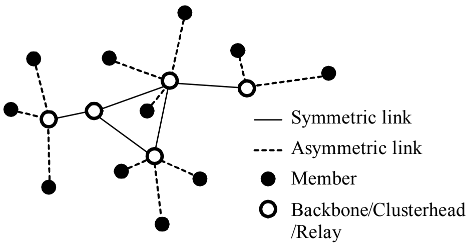

Fig. 1. A MANET with asymmetric topology due to the clustering or virtual backbone.

Asymmetric (AAA) power saving protocol for MANETs. AAA employs an *asymmetric grid quorum system* to ensure the overlap of awake beacon intervals between stations. Although the asymmetric grid quorum system is very simple in terms of combinatorics, it turns out that AAA with this quorum system is the first power management protocol that fulfills all the aforementioned requirements when applied to MANETs. We give detailed explanations for each of these fulfillments and conduct theoretical analysis to justify the benefit of AAA over previous arts. We also design two different types of cycle patterns for a quorum to let AAA protocol deal with both the best-effort and delay-sensitive traffic.

The rest of this paper is organized as follows. In Section II, we review related work. Section III presents the asymmetric grid quorum scheme. In section IV, we elaborate the AAA power management protocol. Section V concludes this paper.

II. RELATED WORK

In this section, we describe our target environments and review existing QPS protocols. Some terminologies and assumptions are specified as well that will be used throughout the text.

A. Target Environments

We focus on the clustered [1], [6], [10], [16] or virtual backboned [9], [12] MANETs. In these environments, certain nodes (such as the clusterheads, relays, backbone nodes, or routing nodes) are delegated to forward data from neighbors across multiple hops, as shown in Figure 1.

B. Quorum-based Power Management

The operation of a Quorum-based Power Saving (QPS) protocol is shown in Figure 2[1]. On each station, the time axis is divided evenly into *beacon intervals*. The station may stay either awake or sleep during each beacon interval. The awake/sleep schedule of each station follows a *cycle pattern* that repeats every n beacon intervals ($n = 9$ in this example). We call n the *cycle length*. At each beacon interval where a station remains awake, a *beacon frame* is broadcasted, which carries the schedule information of the station such as the used cycle pattern and the number of current beacon interval. Beacon frames are required to be sent within the *Announcement Traffic Indication Message* (ATIM) windows; otherwise dropped. It is clear that once their awake beacon intervals overlap, two neighbor stations H_0 and H_1 are able to *discover* each other, i.e., to receive one another's schedule and predict the next awake period at mutual party (Figure 2(1)). Data communication may begin thereafter. Suppose the station H_0 intends to transmit data to H_1 (Figure 2(2)), it first buffers data and waits until arrival of the next awake beacon interval on H_1. The Distributed Coordination Function (DCF) [5] (including RTS, CTS, and random back-off mechanisms, etc.) will then be initiated to transmit the data (Figure 2(3)(4)) while avoiding collisions[2]. We denote the duration of an ATIM window and a beacon interval as $\overline{A}$ and $\overline{B}$ respectively.

As we can see, a QPS protocol functions *as long as the awake beacon intervals overlap between stations*. It is the *quorum system* that ensures the overlap. A quorum system may be constructed using different schemes (e.g., grid/torus [3], [8], [13], finite projective plan [4], or difference set [14], [15], etc.). In the following we briefly summarize the grid/torus schemes as they are relevant to our study. As shown in Figure 2, a grid/torus quorum scheme numbers every n continuous beacon intervals from 0 to $n-1$ and organizes them as an $\sqrt{n} \times \sqrt{n}$ array in a row-major manner. It defines a *quorum* as a set containing all numbers along a column and a number from each of the remaining columns (e.g., $\{0, 1, 2, 3, 6\}$ or $\{1, 2, 3, 4, 7\}$). By definition, we can easily see that any two quorums intersect. Each station obtains its own cycle pattern by remaining awake during the beacon intervals whose numbers are specified in a quorum. As a consequence, the intersection property between quorums implies the overlap between cycle patterns, *if there is no timer shift between stations*. Actually, if the amount of timer shift is a multiple of a beacon interval, the grid/torus scheme can still ensure the overlap. This nice property is due to the fact that the intersections between H_0's and H_1's quorums are *shift-invariant*[3]. For example, as shown in Figure 2 H_1's clock leads H_0's clock by 2 beacon intervals. The quorum adopted by H_1, from H_0's point of view, becomes $\{1-2 (\bmod 9), 2-2 (\bmod 9), 3-2 (\bmod 9), 4-2 (\bmod 9), 7-2 (\bmod 9)\} = \{8, 0, 1, 2, 5\}$. We can easily verify that the rotated schedule of H_1 still overlaps with that of H_0 per cycle. Studies [8], [13], [17] further ensure the overlap when there are arbitrary timer shifts (or specifically, when the *Target Beacon Transmission Time* (TBTT) is not aligned) between stations, as illustrated in Figure 3(a).

By following the grid/torus scheme, each station is able to obtain its own quorum of *quorum size* (i.e., cardinality) $2\sqrt{n}-1$. Apparently, the larger the cycle length n, the more the power saving. However, the power saving advantage provided

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[1] Since the terminologies used by previous arts are diverse, we follow those employed by the IEEE 802.11 [5] standard to avoid ambiguity.

[2] Note in the situation where data transmission cannot complete within a single beacon interval (due to collisions or large data volume), H_0 can set the `more-data` bit (in data frame header) true telling H_1 to remain awake through the successive beacon interval to continue data transmission [5].

[3] A quorum scheme that guarantees the shift-invariant intersection is called *cyclic*. We will formally define the cyclic property later.

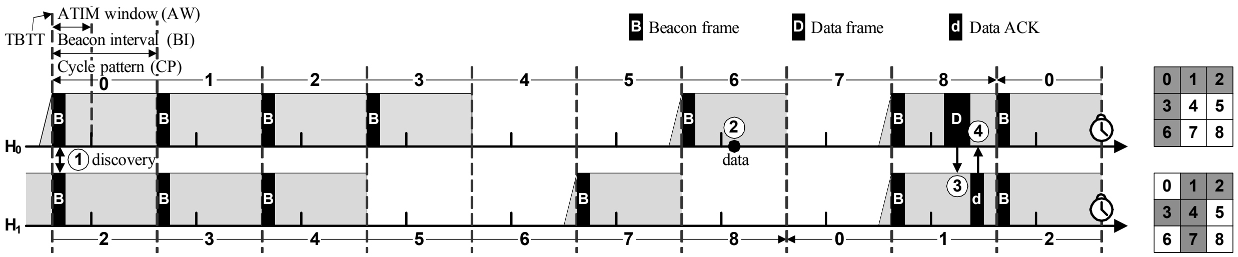

Fig. 2. An example QPS protocol based on the grid/torus quorum scheme. The cycle length, $n = 9$, must be fixed throughout the network.

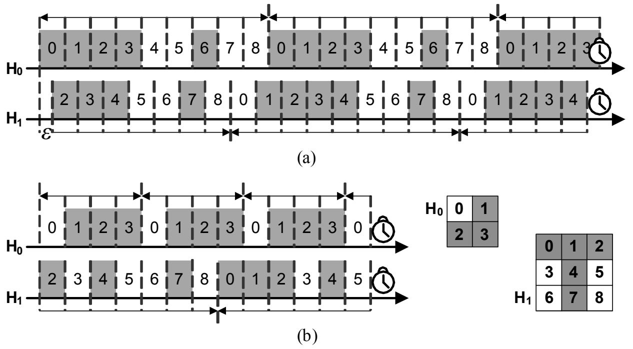

Fig. 3. Challenges encountered when applying the QPS protocols to MANETs. (a) Asynchronous timers ($0 \leq \epsilon \leq \overline{B}$). (b) The adaptive cycle length.

by QPS protocols comes at the price of delay. Such delay includes the *neighbor discovery time*, i.e., the time for a station to discover its new neighbor, and the *data buffering time*, i.e., the duration between a packet arrival (on a sending station) and its start of DCF. As we can see in previous examples, two adjacent stations may not be able to discover each other until a cycle passes by. The delay is therefore $O(n)\overline{B}$ in the worst case. The larger the cycle length n, the longer the delay. This motivates the adaptive QPS protocols [3], [4], [15], where the cycle length can be tailored according to individual station's needs. The studies [3], [15] extends the grid quorum scheme such that quorums of different grid sizes can still intersect, as shown in Figure 3(b). Unfortunately, they apply only to synchronous environments where TBTT between stations is aligned.

Observing that there is no need to guarantee the overlap between members in a clustered/backboned environment (as we can see in Figure 1), the study [14] proposes a new type of quorum, called *asymmetric quorums*, for members. The asymmetric quorums are guaranteed to intersect the traditional (symmetric) quorums used by the clusterheads or backbone nodes, *but not themselves*. With this loosened definition, study [14] shows that the size of an asymmetric can be arbitrarily small (i.e., $O(1)$-sized). Since the majority of nodes are members in a typical clustered network, the proposed scheme yields further reduction on average energy consumption. However, this study assumes that the timers of stations are synchronized and the cycle length is fixed throughout the network. It cannot be easily applied to MANETs.

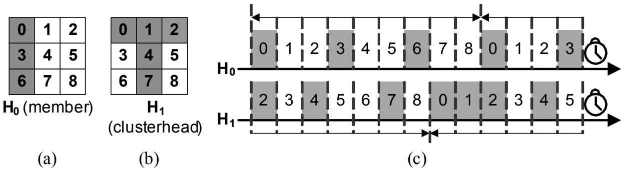

Fig. 4. The asymmetric grid quorum scheme. (a) An a-quorum for members. (b) An s-quorum for clusterheads/relays/backbones. (c) Example schedule.

As the above protocols are proposed based on different assumptions, quorum schemes, and worse—definitions for a quorum system, combining the advantages of existing QPS protocols remains a challenging task.

III. THE ASYMMETRIC GRID QUORUM SCHEME

In this section, we present the asymmetric grid quorum scheme, a generalization of the grid scheme used in [3]. The asymmetric grid quorum scheme has been used for the concurrency control in the database field [2].

Given an $\sqrt{n} \times \sqrt{n}$ grid with row-major beacon numbers starting from 0 to $n - 1$.

Definition 3.1: We define an *a-quorum*, $A(n)$, as a set containing all numbers in the a column ("a" stands for asymmetric).

Definition 3.2: We define an *s-quorum*, $S(n)$, as a set containing all numbers in the a row and a column ("s" stands for symmetric).

Figures 4(a) and (b) respectively show an example a-quorum and an s-quorum given $n = 9$ (note there can be many a- and s-quorums given the same n). Each member node in a cluster can adopt an a-quorum to form its own awake/sleep schedule. On the other hand, the clusterhead/relay/backbone nodes in a network can adopt an s-quorum to form their cycle patterns.

It can be easily seen that the generating sets of a-quorums and s-quorums must intersect, implying the overlap of awake beacon intervals between the members and their clusterhead. Actually, the intersection between $A(n)$ and $S(n)$ holds *even when the clocks shift between stations*:

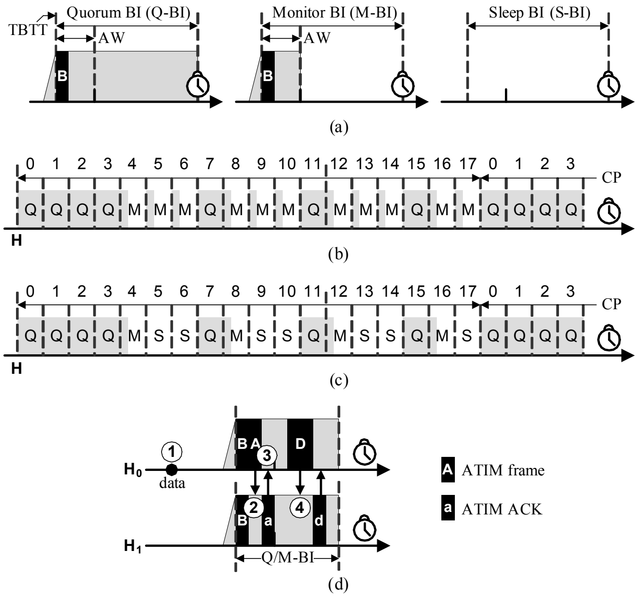

Fig. 5. Protocol design. (a) Structure of beacon intervals. (b) Arrangement of beacon intervals for delay-sentitive traffic given an s-quorum $S(12, 0) = \{0, 1, 2, 3, 7, 11\}$. (c) Arrangement of beacon intervals for best-effort traffic given the same quorum. (d) Data transmission procedure.

Theorem 3.1: Given a square n, let $C(X)$ denote the cyclic set of X. The ordered pair $(C(A(n)), C(S(n)))$ forms an asymmetric cyclic quorum system [14].

We omit the proof due to the space limitation. Since the overlap happens at least once every n beacon intervals, the neighbor discovery time between the members and their clusterhead is no more than $n\overline{B}$.

We can also see that two s-quorums $S(n)$ and $S'(n)$ must intersect. It can be shown that the intersection holds *even when the two s-quorums are constructed based on different grid sizes* [3], [15]:

Theorem 3.2: Given two squares n and n', $n < n'$, the set $\{S(n), S(n')\}$ forms an $(n, n', \lfloor\sqrt{n}\rfloor + n' - 1)$-hyper quorum system [15].

We omit the proof due to the space limitation. Note the above theorem indicates that the neighbor discovery time between $S(m)$ and $S(n)$ is no more than $(\lfloor\sqrt{m}\rfloor + n - 1)\overline{B}$.

The above theorems provide a basis for the AAA protocol to ensure the network connectivity.

IV. THE AAA POWER MANAGEMENT

In this section, we propose an AAA protocol for MANETs that fulfills the asynchronous, adaptive, and asymmetric requirements.

Basically, the design of AAA protocol inherits that of a traditional QPS protocol as we have seen in Section II. A station remains awake during the entire beacon intervals whose numbers are specified by a quorum. In addition to the fully awake and asleep beacon intervals (i.e., Q-BIs and S-BIs), AAA defines the *monitor beacon intervals* (M-BIs) where stations are required to remain awake during the ATIM windows, as shown in Figure 5(a). Given a quorum, AAA defines two different types of cycle patterns, the *delay-sensitive* and *best-effort patterns*, for stations. Stations with the delay-sensitive cycle patterns have to remain awake during the ATIM window of every beacon interval, as depicted in Figure 5(b). Stations with the best-effort cycle patterns, on the other hand, only need to remain awake during the first ATIM window of every series of beacon intervals whose numbers are not specified by a quorum, as depicted in Figure 5(c).

Since now stations may awake partially during a beacon interval, data transmissions in AAA is preceded by the *ATIM notification procedure*. If a station H_0 intends to transmit data to a destination H_1 (Figure 5(d)(1)), it first buffers the data and then unicasts an *ATIM frame* during the ATIM window of the next coming Q-BI or M-BI on H_1 (Figure 5(d)(2)). H_1, upon receiving the ATIM frame, will send back an acknowledgement (Figure 5(d)(3)). After this ATIM notification procedure, both H_0 and H_1 will keep awake for the rest of the beacon interval, during which the DCF will be initiated to transmit the data while avoiding collisions (Figure 5(d)(4)). The AAA protocol, by following the above procedure, is compatible with the IEEE 802.11 [5] standard.

As we can see, if a receiving station employs the best-effort cycle patterns, the data buffering delay will be no more than $k - 1$ beacon intervals, where k is the maximal difference between the numbers of two interspaced Q-BIs (e.g., m and $\lfloor\sqrt{n}\rfloor$ respectively given $A(m)$ and $S(n, \delta)$) on that station. Alternatively, stations receiving delay-sensitive data may use the delay-sentitive cycle patterns. In this case, the data buffering delay will be no more than one beacon interval (usually 100 ms [5]). Note this shortened delay comes at the price of extra energy consumption during each ATIM window (Figure 5(b)).

AAA is asymmetric. The asymmetric grid quorum scheme does not guarantee the intersection between a-quoums. Taking advantage of this loosened requirement, members are allowed to remain awake only nearly half of their clusterhead does. For example, given $n = 9$. Suppose $A(9) = \{0, 3, 6\}$ and $S(9) = \{0, 1, 2, 4, 7\}$ as shown in Figures 4(a) and (b). A member need to remain in Q-BI only 3 every 9 beacon intervals, which is 40% lesser than that (5 every 9) required on a clusterhead. Since members are usually the majority of nodes, we are able to reduce the average energy consumption in a network. Note if a traditional symmetric grid quorum (that is, $S(n)$) is used by the member, the value of n must be larger than or equal to 36 to achieve the same power saving effect (11 every 36), which is generally infeasible since n should usually be less than 25 [3] to ensure in-time neighbor discovery during the short lifetime of a link.

AAA is adaptive. With Theorem 3.2, the AAA protocol allow nodes in different clusters to use different cycle lengths based on their own needs without losing the network con-

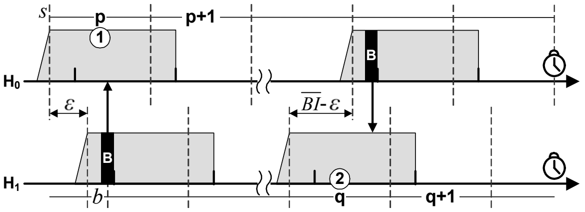

Fig. 6. AAA guarantees neighbor discovery in asynchronous environments.

nectivity. Nodes in the same cluster are able to *adapt* their cycle lengths together to balance the trade-off between energy saving and delay according to either the current traffic load or remaining battery power. One easy way to adaptation is to let the clusterhead monitor the current traffic load. When the load goes over a predefined threshold, the clusterhead can inform all members to shrink the grid size one level (e.g., from 5×5 to 4×4) to shorten the buffering delay.

AAA is asynchronous. By far, we assume that the TBTT is aligned between stations. The AAA protocol, actually, can cope with the asynchronous environments:

Theorem 4.1: Any two stations H_0 and H_1 adopting either the delay-sensitive or best-effort cycle patterns based on $S(n)$ and $S(n')$, $n \leq n'$, respectively are able to discover each other in $\lfloor\sqrt{n}\rfloor + n'$ beacon intervals without the need for TBTT alignment.

Proof: Since the awake periods of a delay-sentitive cycle pattern cover those of a best-effort cycle pattern, it is sufficient to prove the case with the best-effort cycle patterns. Denote ϵ, $0 \leq \epsilon \leq \overline{B}$, the TBTT shift between H_0 and H_1, as illustrated in Figure 6. We first show that H_0 is able to receive H_1's beacons within $\lfloor\sqrt{n}\rfloor + n'$ beacon intervals. If $\epsilon = 0$, from Theorem 4.1 we know there must exist a Q-BI, named p, on H_0 that intersects with some Q-BI on H_1 (Figure 6(1)), and H_0 is able to receive H_1's beacon during the ATIM window of p within $\lfloor\sqrt{n}\rfloor + n' - 1$ beacon intervals. If $\epsilon > 0$, let s denote the starting time of p, and let b denote the elapsed time between $s+\epsilon$ and beacon reception, $0 \leq b \leq \overline{A}$. As we can see, H_1's beacon arrives at time $s+\epsilon+b$. Since $\epsilon \leq \overline{B}$, the arrival must fall within the time range $(s+b, s+b+\overline{B}]$. Notice that in a best-effort cycle pattern, each Q-BI can only be followed by either a Q-BI or an M-BI, H_0 must remain active during the time range $[s, s+\overline{B}+\overline{A}]$. Since $(s+b, s+b+\overline{B}] \subset [s, s+\overline{B}+\overline{A}]$, H_0 is able to receive H_1's beacon within 1 beacon interval more than that when $\epsilon = 0$, that is, within $\lfloor\sqrt{n}\rfloor + n'$ beacon intervals. Now we show that H_1 is able to receive H_0's beacon. Let $\epsilon' = \overline{B} - \epsilon$. Since $0 \leq \epsilon \leq \overline{B}$, we have $0 \leq \epsilon' \leq \overline{B}$. Suppose $\epsilon' = 0$, again, from Theorem 4.1 we know there must exist a Q-BI, named q, on H_1 that intersects with some Q-BI on H_0 (Figure 6(2)). Following the above discussion with ϵ substituted by ϵ', we obtain the proof. ■

Theorem 4.2: Any two stations H_0 and H_1 adopting either the delay-sensitive or best-effort cycle patterns based on $A(n)$ and $S(n)$ respectively are able to discover each other in $n+1$ beacon intervals without the need for TBTT alignment.

The proof of Theorem 4.2 is similar to that of Theorem 4.1, therefore omitted. Note the delay-sensitive patterns and best-effort patterns are interoperatable. Stations may freely switch between either ones based on their current traffic type without losing the network connectivity.

V. CONCLUSIONS

In this paper, we proposed an Asynchronous, Adaptive, and Asymmetric (AAA) power saving protocol that fulfill the unique requirements of MANETs. AAA employs an asymmetric grid quorum system to ensure the overlap of awake beacon intervals between stations. We also presented two different types of cycle patterns for a quorum to let AAA protocol deal with both the best-effort and delay-sensitive traffic. We plan to explore how clustering algorithms may effect the performance of AAA in our future study.

REFERENCES

[1] A.D. Amis and R. Prakash. Load-balancing clusters in wireless ad hoc networks. In *Proc. of ASSET*, pages 25–32, 2000.

[2] P.A. Bernstein, V. Hadzilacos, and N. Goodman. *Concurrency Control and Recovery in Database Systems*. Addison-Wesley, 1987.

[3] C.M. Chao, J.P. Sheu, and I.C. Chou. An adaptive quorum-based energy conserving protocol for ieee 802.11 ad hoc netowrks. *IEEE Transactions on Mobile Computing*, 5(5):560–570, 2006.

[4] Z.T. Chou. Optimal adaptive power management protocols for asynchronous wireless ad hoc networks. In *Proc. of WCNC*, pages 61–65, 2007.

[5] IEEE 802 LAN/MAN Standards Committee. *Wireless LAN Medium Access Control and Physical Layer Specifications*, 1999.

[6] T.C. Hou and T.J. Tsai. An access-based clustering protocol for multihop wireless ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 19(7):1201–1210, 2001.

[7] A. Iwata, C.C. Chiang, G. Pei, M. Gerla, and T.W. Chen. Scalable routing strategies for ad hoc wireless networks. *IEEE Journal on Selected Areas in Communications*, 17(8):1369–1379, 1999.

[8] J.R. Jiang, Y.C. Tseng, C.S. Hsu, and T.H. Lai. Quorum-based asynchronous power-saving protocols for ieee 802.11 ad hoc networks. *Mobile Networks and Applications*, 10(1-2):169–181, 2005.

[9] U.C. Kozat, G. Kondylis, B. Ryu, and M.K. Marina. Virtual dynamic backbone for mobile ad hoc networks. In *Proc. of ICC*, pages 250–255, 2001.

[10] C.R. Lin and M. Gerla. Adaptive clustering for mobile wireless networks. *IEEE Journal on Selected Areas in Communications*, 15(7):1265–1275, 1997.

[11] Rajmohan Rajaraman. Topology control and routing in ad hoc networks: A survey. *ACM SIGACT News*, 33(2):66–73, 2002.

[12] P. Sinha, R. Sivakumar, and V. Bharghavan. Enhancing ad hoc routing with dynamic virtual infrastructures. In *Proc. of INFOCOM*, pages 1763–1772, 2001.

[13] Y.C. Tseng, C.S. Hsu, and T.Y. Hsieh. Power-saving protocols for ieee 802.11-based multi-hop ad hoc networks. In *Proc. of INFOCOM*, pages 200–209, 2002.

[14] S.H. Wu, C.M. Chen, and M.S. Chen. An asymmetric quorum-based power saving protocol for clustered ad hoc networks. In *Proc. of ICDCS*, page 18, 2007.

[15] S.H. Wu, C.M. Chen, and M.S. Chen. Fully adaptive power saving protocols for ad hoc networks using the hyper quorum system. In *Proc. of ICDCS*, 2008.

[16] O. Younis and S. Fahmy. Heed: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing*, 3(4):366–379, 2004.

[17] R. Zheng, J.C. Hou, and L. Sha. Optimal block design for asynchronous wake-up schedules and its applications in multihop wireless networks. *IEEE Transactions on Mobile Computing*, 5(9):1228–1241, 2006.