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Unilateral Wakeup for Mobile Ad Hoc Networks

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***Abstract*—Asynchronous wakeup schemes have been proposed for ad hoc networks to increase the energy efficiency of wireless communication. The basic idea is to allow a node to sleep when it is idle, and wakeup periodically to check if there are pending transmissions. In this paper we examine the applicability of asynchronous wakeup schemes to the Mobile Ad Hoc NETworks (MANETs). We discover that, although it is desirable to have nodes with lower mobility to sleep more in reaction to the less-changing link states, in practice this is prohibited due to an unwanted tradeoff between the energy saving and in-time link discovery. All nodes in a network must stay awake frequently based on their highest possible moving speed in order to avoid network partition. To address this problem, we propose a new wakeup scheme, named Unilateral- (Uni-) scheme, for MANETs that allows nodes with slower moving speed to sleep more without losing the network connectivity. Theoretical analysis shows that the Uni-scheme can render up to 24% improvement in energy saving as compared with the previous arts.**

I. Introduction

Mobile Ad Hoc NETworks (MANETs) are self-organizing networks that allow mobile nodes (or stations) to communicate with each other in the situations, such as battlefield commanding, disaster area probing, road traffic monitoring, and wildlife conservation, where centralized control is costly or infeasible. One design goal of MANETs is to ensure the energy efficiency of wireless communication in order to prolong the network lifetime. At PHY layer, when a node is not transmitting, the transceiver persists in idle mode and continuously listens for incoming transmissions. Studies [11], [14] report that the energy consumed by a wireless module in listening to the network is only slightly lower than that of transmitting and receiving data. If there are seldom transmissions destined to the station, *idle listening* would waste significant amount of energy. To address this problem, the concept of *asynchronous wakeup* is introduced at MAC layer, which, instead of idle listening, allows a station to *sleep* (or *doze*)—to suspend the transceiver—when there is no data transmission.

The merit of asynchronous wakeup is that stations can decide when to sleep in a distributed manner while being able to communicate with each other during the awake periods. Specifically, the time axis on each station is divided evenly into *beacon intervals*. A station may stay either awake or sleep during each beacon interval. By adopting a wakeup scheme [7], [13], [16]–[20] and choosing an integer n, the station obtains a *cycle pattern*, which specifies the awake/sleep schedule during n continuous beacon intervals. The station repeats the schedule every n beacon intervals, and n is called the *cycle length*. The wakeup scheme ensures that at least one of the awake beacon intervals on a station must overlap that on another station, even when the stations' clocks (used to divide beacon intervals) are *not* synchronized. By exchanging the 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 begin data communication then.

In this paper, we examine the applicability of asynchronous wakeup to the MANETs. We discover that, while it is desirable to have nodes with lower mobility to sleep more in reaction to the less-changing link states, however, in practice this is prohibited by most existing wakeup schemes [7], [13], [16]–[20] due to an unwanted tradeoff between the energy saving and in-time link discovery. Basically, an asynchronous wakeup scheme requires a station with cycle length n to remain awake at least $O(\sqrt{n})$ beacon intervals per cycle to ensure the overlap [13]. The longer the cycle length, the more the power saving. Nevertheless, two adjacent stations adopting cycle lengths m and n respectively can only discover each other after a delay of $O(\max(m,n))$ beacon intervals. If these two nodes have high relative moving speed, the values of m and n must be *both* small to ensure the in-time neighbor discovery. Since there is no way for a station to measure its relative speed to another before the neighbor discovery (and signal exchange), the $O(\max(m,n))$ delay implies that all nodes in a network must conservatively pick a small cycle length *corresponding to their highest possible relative speed* in order to ensure the network connectivity. Given the $O(\sqrt{b})$ bound, the power saving effect can be severely restricted.

To address this problem, we propose a novel wakeup scheme, named the Unilateral- (Uni-) scheme, for MANETs that allows a node with slower moving speed to save energy by choosing a longer cycle length *unilaterally regardless of its relative speed to the others*. Specifically, the Uni-

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scheme guarantees that two adjacent stations adopting cycle lengths m and n respectively can discover each other within $O(\min(m, n))$ beacon intervals. It is sufficient for *any* of these two nodes to pick a small cycle length to ensure the in-time neighbor discovery. By requiring a faster moving station to have a shorter cycle length and a slower to have a longer, we show that all nodes in a network can obtain cycle lengths *corresponding to their individual speed rather than the highest possible relative one*. As ordinary nodes (e.g., soldiers walking on a battlefield) usually move way slower than the fastest one (e.g., soldiers carried by an armored vehicle), this extends the cycle lengths on the majority of nodes, and saves the overall energy consumption.

To the best of our knowledge, the Uni-scheme is the first wakeup scheme that is able to give the $O(\min(m, n))$ neighbor discovery delay and allow a network to save energy by taking advantages of the nodes' diverse mobility. Theoretical analysis is conducted, which shows that the Uni-scheme is able to render 11% to 24% improvement in energy efficiency as compared with the previous arts.

The rest of this paper is organized as follows. In Section II, we review existing wakeup schemes at MAC layer. Section III looks into some practical limitations in MANETs and introduces the Uni-scheme. In section IV, we formally prove the overlap guarantees given by the Uni-scheme. The performance evaluation is conducted in Section V. Finally, Section VI drops the conclusions.

II. Related Work

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

We focus on MANETs where nodes move independently in different directions and speed. We assume that a node is aware of its own moving speed by either a speedometer (ultrasonic-, infrared-, inductive loop-, or vision-based), GPS receiver, or triangulation[1] of the signal strengths from nearby nodes [1], [9], [10].

IEEE 802.11 Power Saving Mode: The operation of IEEE 802.11 Power Saving (PS) mode [8] is shown in Figure 1(a). On each station, the time axis is divided evenly into *beacon intervals*. In every beacon interval, the station is required to remain awake during the entire Announcement Traffic Indication Message (ATIM) window. A *beacon frame* is broadcasted at the Target Beacon Transmission Time (TBTT) to announce the station's existence. If a station, say H_1, intends to transmit data to a destination H_0 (Figure 1(a)(1)), it first unicasts an *ATIM frame* to H_0 during the ATIM window (Figure 1(a)(2)). Remaining awake, H_0 receives the ATIM frame and sends back an acknowledgment.

[1]A simpler two-node model has also been proposed by the PATH [10] at UC Berkeley.

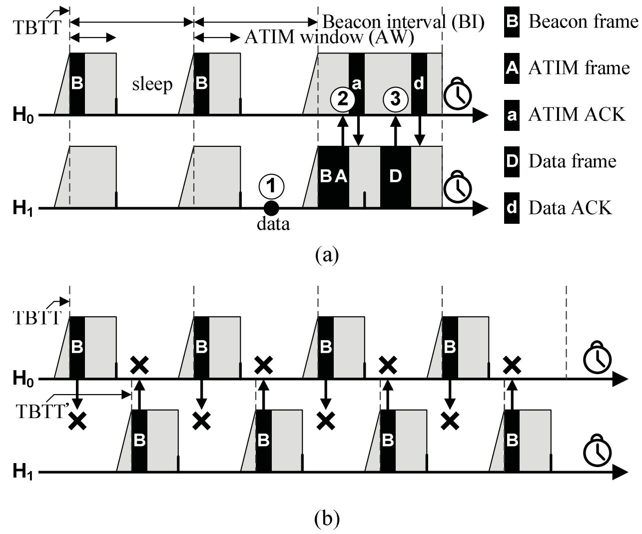

Figure 1. IEEE 802.11 Power Saving (PS) mode. (a) Structures of the awake/sleep beacon intervals. (b) The neighbor discovery problem in asynchronous environments.

Both H_0 and H_1, after this *ATIM notification procedure*, keep awake for the entire beacon interval and start data transmission after the end of ATIM window (Figure 1(a)(3)). To avoid data collisions, the data transmission follows the RTS, CTS, and random back-off procedure specified in the DCF (Distributed Coordination Function)[2]. If there is no ATIM notifications, stations may enter the *doze* mode (that is, to sleep) to save energy after each ATIM window. We denote the duration of a beacon interval and an ATIM window as $\overline{B}$ and $\overline{A}$ respectively.

The IEEE 802.11 PS mode functions only when the timers on stations are *synchronized* (or equivalently, when the TBTT is aligned). Figure 1(b) shows an example where two stations with asynchronous timers fail to discover each other due to the forever lost of beacon frames. As synchronizing the clocks in MANETs is usually costly or even infeasible [3], [12], there is a need for an energy conservation protocol that admits the asynchronous timers between stations.

Asynchronous Wakeup Protocols: Based on the IEEE 802.11 PS mode, the idea of asynchronous wakeup protocols, also known as the Asynchronous Quorum-based Power Saving (AQPS) protocols, is to prolong stations' awake periods at certain beacon intervals to ensure the beacon exchanges. Given a *cycle length* denoted by n, an AQPS protocol numbers n continuous beacon intervals from 0 to $n-1$, and defines a *quorum*, a subset of $\{0, 1, \cdots, n-1\}$, for each station. The set of quorums is named a *quorum system*. During those beacon intervals whose numbers are specified

[2]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 [8].

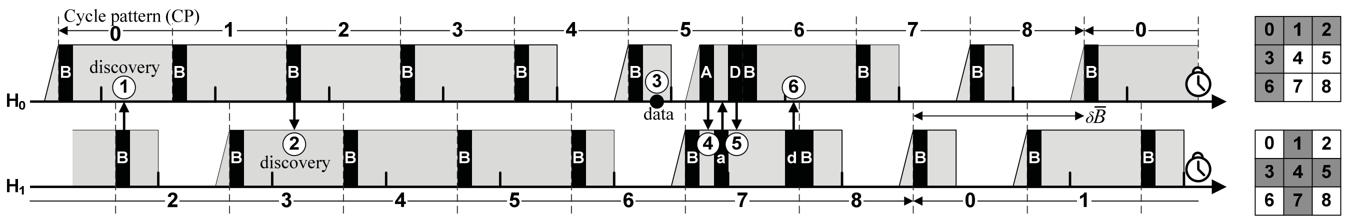

Figure 2. Asynchronous wakeup based on the grid quorum scheme. Stations with arbitrary timer shift $\delta\overline{B}$ are guaranteed to discover each other. In this case, both H_0 and H_1 choose the same cycle length $n = 9$.

in the quorum, a station must remain awake after the ATIM window, even when there is no data transmission. This awake/sleep schedule repeats every n beacon intervals and is called the *cycle pattern*. Figure 2 gives an example where two stations adopt quorums $\{0, 1, 2, 3, 6\}$ and $\{1, 3, 4, 5, 7\}$ respectively to form their cycle patterns. It can be shown [13], [19] that two adjacent stations with arbitrary timer shift $\delta\overline{B}$, $\delta \in \mathbb{R}$, are guaranteed to exchange their beacons within a finite delay *if their quorums intersect*[3]. Note that in an AQPS protocol the beacon frames carry additional information about the awake/sleep schedule of the sending station, such as the selected quorum and the number of current beacon interval, etc. Once receiving a beacon (Figure 2(1)(2)), a station can *discover* the sending party and predict its next awake period. The ATIM notification and data transmission procedures can start thereafter when data arrive (Figure 2(3)-(6)).

A quorum system can be constructed using different quorum schemes (also called the *wakeup schemes*), such as grid/torus [4], [13], [16], [19], finite projective plan [7], or difference set [5], [17], [18]. In the following we briefly summarize the grid/torus scheme as it is relevant to our study. By assuming that n is a square, a grid scheme organizes the numbers 0, 1, $\cdots$, $n-1$ as an $\sqrt{n} \times \sqrt{n}$ array in a row-major manner, as shown in Figure 2. It defines a quorum as a set containing all numbers along a column and a number from each of the remaining columns (e.g., $\{0, 1, 2, 3, 6\}$ and $\{1, 3, 4, 5, 7\}$ adopted by H_0 and H_1 respectively). By definition, we can easily see that any two quorums intersect. This ensures the neighbor discovery between every pair of nodes in a network[4]. Note a quorum defined by the grid-scheme has *quorum size* (i.e., cardinality) $2\sqrt{n} - 1$. Study [13] shows that a quorum applicable to an AQPS protocol can have size no smaller than $\sqrt{n}$. The larger the cycle length n, the more the power saving.

Recently, the grid-scheme is extended [4], [6], [18] to allow the nodes to pick different cycle lengths, as shown in Figure 3, without losing the network connectivity. The motivation is that the delay incurred by an AQPS protocol is proportional to n, so by picking different cycle lengths dynamically, a node can control the trade-off between energy efficiency and delay based on its own current needs (such as the remaining battery life, traffic type, and traffic load, etc).

[3]Not every quorum system is applicable to an AQPS protocol. The quorums system must be *cyclic* to ensure the neighbor discovery when the timers shift between stations. The formal definition of the cyclic property will be given in Section IV.

[4]A quorum system constructed by the grid/torus scheme is cyclic.

III. Unilateral Wakeup for MANETs

While many schemes are proposed, little effort has been made to understand the impact of asynchronous wakeup to the MANETs. In this section, we first look into the delays incurred by existing wakeup schemes. Then we propose the Uni-scheme to address some practical limitations.

A. The Impact of AQPS Protocols

The power saving advantage given by an AQPS protocol comes at the price of delay. This includes the *neighbor discovery delay*, i.e., the time required for a station to discover its new neighbor, and *data buffering delay*, i.e., the duration between a packet arrival (on a sending station) and its start of DCF. Since a receiving station must remain awake during the ATIM window of each beacon interval, the data buffering delay can be no longer than a $\overline{B}$ (usually 100 ms [8]). On the other hand, two adjacent nodes picking the cycle lengths m and n respectively to form their quorums $Q(m)$ and $Q(n)$ following the existing wakeup schemes [4], [5], [18], [19] can only discover each other after a worst-case delay $l_{Q(m),Q(n)} = (\max(m,n) + \min(\sqrt{m}, \sqrt{n}))\,\overline{B} = O(\max(m,n))\overline{B}$. The larger the cycle lengths, the longer

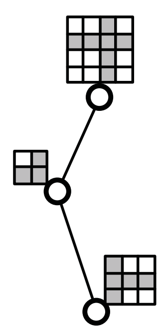

Figure 3. Adaptive wakeup schemes. Nodes choosing different cycle lengths are guaranteed to discover each other.

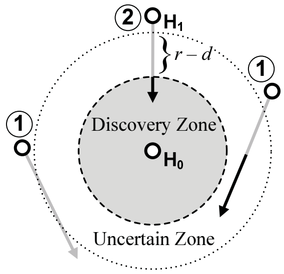

Figure 4. The asynchronous wakeup divides the coverage of a node into the zones of discovery and uncertainty. The node H_0 moves upwards and the relative moving trajectories of its neighbors are depicted as solid lines. A trajectory becomes black if the neighbor is discovered.

the neighbor discovery delay. Note we have $l_{Q(m),Q(n)} \leq \max\left(l_{Q(m),Q(m)}, l_{Q(n),Q(n)}\right)$.

The impact of asynchronous wakeup to a mobile node H_0 can be characterized as a *zone of uncertainty*, as shown in Figure 4. In this area, neighbors of H_0 may not be discovered (Figure 4(1)) unless they move into the *discovery zone*, where the neighbor discovery is guaranteed. Denote r and d the radiuses of node coverage and discovery zone respectively. To make the impact transparent to the upper layers (e.g., routing protocols), one may regard the discovery zone as the effective node coverage. Like r, the proper value of d depends on the application needs. Given r and d, the node H_0 must ensure that, for each neighbor H_1,

$$(s_0 + s_1) \cdot l_{Q(n_0),Q(n_1)} \leq r - d,$$

where s_i and n_i denote the moving speed and cycle length of H_i respectively, and $s_0 + s_1$ is the highest (face to face) relative speed between H_0 and H_1, as shown in Figure 4(2). The picked n_0 and n_1 must satisfy

$$l_{Q(n_0),Q(n_1)} \leq \frac{r-d}{s_0+s_1}. \tag{1}$$

However, n_1 and s_1 are unknown to H_0 (so are n_0 and s_0 to H_1). To discover each other in-time, *both* of the two nodes must pick a conservative n_i such that

$$l_{Q(n_i),Q(n_i)} \leq \frac{r-d}{s_i+s_{high}}, \tag{2}$$

where s_{high} is the highest possible moving speed of a node, as

$$\begin{aligned} l_{Q(n_0),Q(n_1)} &\leq \max\left(l_{Q(n_0),Q(n_0)}, l_{Q(n_1),Q(n_1)}\right) \\ &\leq \frac{r-d}{\min(s_0,s_1)+s_{high}} \leq \frac{r-d}{s_0+s_1}. \end{aligned}$$

This implies that *all* nodes in a network must fit their cycle lengths to Eq. (2) in order to ensure the all-pair neighbor discovery. Observe that s_{high} may be way higher than the ordinary speed of nodes. For example, in the battlefields an armored vehicle can move much faster than the soldiers. The fitted cycle lengths will be dominated by s_{high} and become very short. This limits the effect of power saving in practice.

B. The Uni-Scheme

Given a positive integer z, for each cycle length n, $n \geq z$, chosen by a station, we define a quorum $S(n,z)$, a subset of $\{0, 1, \cdots, n-1\}$, as

$$S(n,z) = \{0, 1, \cdots, \lfloor\sqrt{n}\rfloor - 1, e_1, \cdots, e_{p-1}\}, \tag{3}$$

where $\lfloor\sqrt{n}\rfloor - 1 < e_1 \leq \lfloor\sqrt{n}\rfloor + \lfloor\sqrt{z}\rfloor - 1$, $0 < e_i - e_{i-1} \leq \lfloor\sqrt{z}\rfloor$ for all $2 \leq i \leq p-1$, $p = \lfloor(n - \lfloor\sqrt{n}\rfloor) / \lfloor\sqrt{z}\rfloor\rfloor$. Basically, $S(n,z)$ contains $\lfloor\sqrt{n}\rfloor$ continuous elements starting from 0, followed by $p-1$ interspaced elements with mutual distances less than or equal to $\lfloor\sqrt{z}\rfloor$. $S(n,z)$ is not unique with the above definition. We call Eq. (3) the *Unilateral- (Uni-) scheme*. Based on Eq. (3), each node obtains its cycle pattern by following the AQPS protocol described in Section II.

A careless glance may suggest that the Uni-scheme is very similar to the schemes proposed in studies [15], [17], [18], therefore incremental. It is true that all these schemes are based on similar combinatorics called *difference sets*[5]. However, the changes we have made in Eq. (3) render a fundamental improvement in practice:

Theorem III.1. *Given integers z, m, and n, where $m, n \geq z$. Without the clock synchronization, two adjacent stations adopting quorums $S(m,z)$ and $S(n,z)$ respectively are able to discover each other within a worst-case delay $l_{S(m,z),S(n,z)} = (\min(m,n) + \lfloor\sqrt{z}\rfloor)\overline{B} = O(\min(m,n))\overline{B}$.*

We will formally prove this theorem in Section IV. Note $l_{S(m,z),S(n,z)} = \min\left(l_{S(m,z),S(m,z)}, l_{S(n,z),S(n,z)}\right)$. Now, consider the case shown in Figure 4 where H_0 and H_1 need to decide their respective n_0 and n_1 such that Eq. (1) holds. Theorem III.1 indicates that it is sufficient for any of these two nodes to reduce $l_{S(m,z),S(n,z)}$ by picking a small cycle length. The delay can be controlled *unilaterally*. With this observation, H_0 and H_1 can simply have their n_i such that

$$l_{S(n_i,z),S(n_i,z)} \leq \frac{r-d}{2s_i} \tag{4}$$

to ensure the in-time neighbor discovery[6], as

$$\begin{aligned} l_{S(n_0,z),S(n_1,z)} &= \min\left(l_{S(n_0,z),S(n_0,z)}, l_{S(n_1,z),S(n_1,z)}\right) \\ &\leq \frac{r-d}{2\max(s_0,s_1)} \leq \frac{r-d}{s_0+s_1}. \end{aligned}$$

Eq. (4) implies that all nodes in a network can choose the cycle lengths *based on their individual speed rather then the*

[5]We omit the discussion about difference sets due to the space limitation. Interested readers may refer to [2], [15] for more details.

[6]The value of z can be set by $l_{S(z,z),S(z,z)} \leq \frac{r-d}{2s_{high}}$ to ensure that it is smaller than any picked n. We will study the effect of z in Section V.

highest possible one. Most nodes will obtain longer cycle lengths. The overall energy efficiency can be improved.

Let's look at a concrete example on the battlefield. Suppose the soldiers (i.e., nodes) have mobility ranging from 5 m/s (when walking/running) to 30 m/s (when carried by vehicles), $s_{high} = 30$ m/s, $r = 100$ m, $d = 60$ m, $\overline{B} = 100$ ms, and $\overline{A} = 25$ ms [8]. Adopting the grid-scheme, a node H with speed 5 m/s needs to fit its cycle length n such that $l_{Q(n),Q(n)} = (n + \sqrt{n})\overline{B} \le \frac{100-60}{5+30} = 1.14$ s. We have $n = 4$, as only a 2×2 grid is feasible. Following the AQPS protocol, the *duty cycle*, i.e., the minimum portion of time a station must remain awake, of H is $\frac{3 \cdot \overline{B} + 1 \cdot \overline{A}}{4 \cdot \overline{B}} = 0.81$. On the other hand, the Uni-scheme has $z = 4$ by $l_{S(z,z),S(z,z)} = (z + \lfloor\sqrt{z}\rfloor)\overline{B} \le \frac{100-60}{2 \cdot 30} = 0.67$ s. The cycle length of H must satisfy $l_{S(n,4),S(n,4)} = (n+2)\overline{B} \le \frac{100-60}{2 \cdot 5} = 4$ s. We have $n = 38$, and the duty cycle of H becomes 0.68, yielding 16% improvement in energy efficiency.

It is also interesting to note that the Uni-scheme is a generalization of the traditional grid-scheme [4], [13], [16], [19]. The Uni-scheme degenerates when n is a square, $n = z$, and $e_i - e_{i-1} = \lfloor\sqrt{z}\rfloor$. For example, let $z = n = 9$ and $e_i - e_{i-1} = 3$, we have $S(9,9) = \{0,1,2,5,8\}$ containing a column and a row in a 3×3 grid shown in Figure (2). Unlike the grid-scheme, however, the Uni-scheme is defined over arbitrary values of n (as long as $n \ge z$) rather than squares only. This provides a finer granularity for each node in selecting a proper cycle length to strike the balance between the energy efficiency and incurred neighbor discovery delay.

IV. Theoretical Foundations

In this section, we give rigorous proof of the theorems described in Section III and explain their rationales. Note the definitions given in Section IV-A are largely based on the previous arts [2], [15], [18], and are included for self-containment. Our contributions lay in Section IV-B.

A. Definitions

Consider the sets containing the numbers of beacon intervals. We have :

Definition IV.1 (n-coterie)**.** Given an integer n and a universal set $U = \{0, 1, \cdots, n-1\}$ over the modulo-n plane. Let X be a set of nonempty subsets of U. We call X an *n-coterie* if and only if $\forall Q, Q' \in X$, $Q \cap Q' \neq \varnothing$.

For example, the set $\{\{0,1,2,3,6\},\{1,3,4,5,7\}\}$ given in Figure 2 is a 9-coterie. Conventionally, a coterie X is termed a *quorum system*, and the elements of X (i.e., Q) are called the *quorums*.

Not every quorum system is applicable to the AQPS protocols [13]. In an AQPS protocol, two quorums must intersect even when one "shifts." This leads to the following definitions:

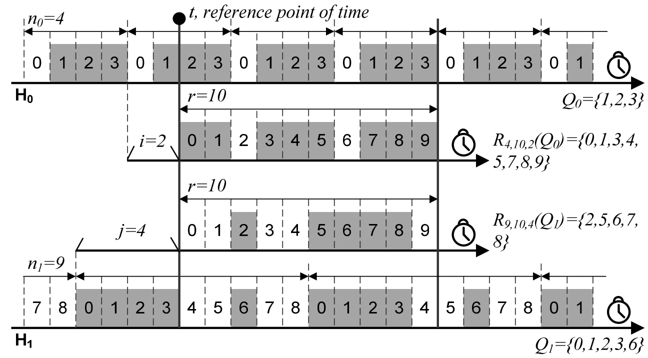

Figure 5. The Hyper Quorum System (HQS) guarantees the intersection between *projections* of quorums over a modulo-r plane.

Definition IV.2 ((n,i)-cyclic set)**.** Given integers n and i, $0 \le i \le n-1$. Let Q be a subset of U, $U = \{0, 1, \cdots, n-1\}$. We call $C_{n,i}(Q)$ an (n,i)-*cyclic set* of Q if and only if $C_{n,i}(Q) = \{(q+i) \bmod n : \forall q \in Q\}$.

For brevity, we denote a group of cyclic sets as $C_n(Q) = \{C_{n,i}(Q) : \forall i\}$.

Definition IV.3 (n-cyclic quorum system)**.** Given an integer n and a universal set $U = \{0, 1, \cdots, n-1\}$. Let X be a set of nonempty subsets of U. We call X an *n-cyclic quorum system* if and only if $\bigcup_{Q \in X} C_n(Q)$ forms an n-coterie.

For example, the set $\{\{0,1,2,3,6\},\{1,3,4,5,7\}\}$ also forms a 9-cyclic quorum system because each pair of elements in

$$\{\{0,1,2,3,6\},\{1,2,3,4,7\},\cdots,\{8,0,1,2,5\}\} \cup \{\{1,3,4,5,7\},\{2,4,5,6,8\},\cdots,\{0,2,3,4,6\}\}$$

intersects. The cyclic property ensures the *shift-invariant* intersection. Suppose H_1's clock leads H_0's clock by 2 beacon intervals in Figure 2 (that is, $\delta = 2$), from H_0's point of view, the quorum of H_1 becomes $C_{9,-2}(\{1,3,4,5,7\}) = \{8,1,2,3,5\}$ which, by definition, still belongs to $C_9(\{1,3,4,5,7\})$. We will discuss the case when $\delta \in \mathbb{R}$ later.

To allow different nodes to adopt quorums defined based on different universal sets (and therefore different power saving effect and neighbor discovery delay), the above definitions can be generalized as follows:

Definition IV.4 ((n,r,i)-revolving set)**.** Given integers n, r, and i, where $0 \le i \le n-1$. Let Q be a subset of U, $U = \{0, 1, \cdots, n-1\}$. We call $R_{n,r,i}(Q)$ an (n,r,i)-*revolving set* of Q if and only if $R_{n,r,i}(Q) = \{(q+kn)-i : 0 \le (q+kn)-i \le r-1, \forall q \in Q, k \in \mathbb{Z}\}$.

Intuitively, $R_{n,r,i}(Q)$ is a "projection" of Q from a modulo-n plane onto a modulo-r plane with an index shift i. For example, consider a quorum $Q = \{0, 1, 2, 3, 6\}$ shown in Figure 5, which is a subset of the universal set $U = \{0, 1, \cdots, 8\}$. Given a shift index $i = 4$, we may project Q from the modulo-9 plane onto the modulo-10 plane by $R_{9,10,4}(Q) = \{2, 5, 6, 7, 8\}$, a subset of another universal set $U' = \{0, 1, \cdots, 9\}$. A revolving set $R_{n,r,i}(Q)$ degenerates into a cyclic set $C_{n,(-i \bmod n)}(Q)$ when $r = n$. For brevity, we denote a group of revolving sets as $R_{n,m}(Q) = \{R_{n,m,i}(Q) : \forall i\}$.

Definition IV.5 ($(n_0, n_1, \cdots, n_{d-1}; r)$-hyper quorum system)**.** Given integers n_0, n_1, $\cdots$, n_{d-1} and r, where $d \in \mathbb{Z}$. Let $Y = \{Q_0, Q_1, \cdots, Q_{d-1}\}$ in which Q_i, $0 \le i \le d-1$, is a nonempty subset of the universal set $U_i = \{0, 1, \cdots, n_i - 1\}$ over the modulo-n_i plane. We call Y an $(n_0, n_1, \cdots, n_{d-1}; r)$-*Hyper Quorum System* (HQS) if and only if the set $\bigcup_{Q_i \in Y} R_{n_i,r}(Q_i)$ forms an r-coterie.

An HQS guarantees the intersection between "projections" of quorums over a modulo plane that may be different from where the quorums reside originally. Following the example shown in Figure 5 where $Q_0 = \{1, 2, 3\}$ and $Q_1 = \{0, 1, 2, 5, 8\}$ are adopted by H_0 and H_1 respectively. Given an arbitrary reference point of time, denoted by t. Suppose at t, H_0 and H_1 are in their beacon intervals 2 and 4 respectively. Then H_0 and H_1 are guaranteed to overlap in at least one awake beacon interval within the 10 beacon intervals after t, since $R_{4,10,2}(Q_0) \cap R_{9,10,4}(Q_1) \neq \varnothing$. Actually, we may easily verify that given any reference point of time where H_0 and H_1 are in their beacon intervals i and j respectively, H_0 and H_1 are guaranteed to overlap within 10 beacon intervals. Therefore, the set $\{\{1, 2, 3\}, \{0, 1, 2, 5, 8\}\}$ is a $(4, 9; 10)$-HQS. Nodes with an HQS can obtain cycle patterns of different lengths without losing the network connectivity.

B. Proof of Theorem III.1

Define the *heads* of a revolving set $R_{n,r,i}(Q)$ as those elements projected from the smallest element in Q. For example, in Figure 5 the elements 3 and 7 are heads of $R_{4,10,2}(\{1, 2, 3\})$. There could be none, or more than one head.

Lemma IV.6. *Given positive integers m, n, and z, where $m, n \ge z$. The set $\{S(m, z), S(n, z)\}$ based on Eq.* (3) *forms an $(m, n; \min(m, n) + \lfloor\sqrt{z}\rfloor - 1)$-hyper quorum system.*

Proof: Without loss of generality, let $m \le n$, and $r = m + \lfloor\sqrt{z}\rfloor - 1$. We show that $\forall i, j$, $0 \le i \le m$ and $0 \le j \le n$, $R_{m,r,i}(S(m, z)) \cap R_{n,r,j}(S(n, z)) \neq \varnothing$. Denote h the first head in $R_{m,r,i}(S(m, z))$. Since $r \ge m$, h exists and $h \le m - 1$. If h is included in $R_{n,r,j}(S(n, z))$, we finish the proof. Otherwise, consider two elements s and t in $R_{n,r,j}(S(n, z))$ such that $s < h < t$. By definition of $S(n, z)$, any two interspaced elements in $R_{n,r,j}(S(n, z))$ must have mutual distance less than or equal to $\lfloor\sqrt{z}\rfloor$. We have $t \le s + \lfloor\sqrt{z}\rfloor$, leading to $t \le h + \lfloor\sqrt{z}\rfloor - 1 \le (m-1) + \lfloor\sqrt{z}\rfloor - 1 = r - 1$. The element t exists. On the other hand, by definition of $S(m, z)$, h is a head of $R_{m,r,i}(S(m, z))$ implies that there exist $\lfloor\sqrt{m}\rfloor - 1$ continuous elements after h in $R_{m,r,i}(S(m, z))$. Since $t \le h + \lfloor\sqrt{z}\rfloor - 1 \le h + \lfloor\sqrt{m}\rfloor - 1$, the element t must also be included in $R_{m,r,i}(S(m, z))$. We have $R_{m,r,i}(S(m, z)) \cap R_{n,r,j}(S(n, z)) \neq \varnothing$. ■

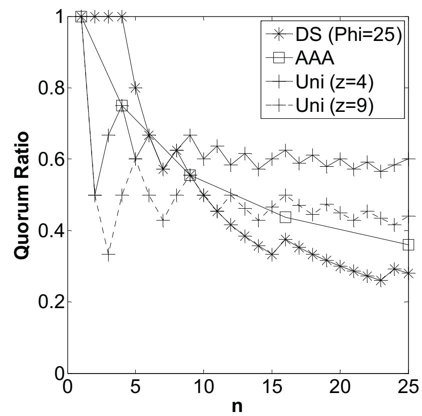

Figure 6. Quorum ratios given different cycle lengths.

The above lemma indicates that under the situation where there is no clock shift between stations *or the clock shifts are multiples of a $\overline{B}$*, two adjacent nodes adopting quorums $S(m, z)$ and $S(n, z)$ respectively are guaranteed to discover each other within $\min(m, n) + \lfloor\sqrt{z}\rfloor - 1$ beacon intervals. Study [13] has further pointed out that:

Lemma IV.7. *Two stations having an arbitrary clock shift $\delta\overline{B}$, $\delta \in \mathbb{R}$, and remaining awake/sleep based on the AQPS protocol described in Section II are guaranteed to discover each other within $l\overline{B}$ if given any clock shift $i\overline{B}$, $i \in \mathbb{Z}$, the two stations can discover each other within $(l-1)\overline{B}$.*

Theorem III.1 is a direct consequence of Lemmas IV.6 and IV.7.

V. Performance Evaluation

In this section, we analyze the performance of Uni-scheme by comparing it with the other existing schemes that allow nodes to pick different cycle lengths to control the neighbor discovery delay, including the DS- [18] and AAA-schemes [19]. Note the AAA-scheme is a generalization of various grid-/torus-schemes [4], [13], [16] so we effectively compare the Uni-scheme with all these studies.

To see the power saving effect given purely by a wakeup scheme without the involvement of protocol design, we define a theoretical metrics, the *quorum ratio*, that denotes the proportion of beacon intervals in a cycle where a station is required to awake. Specifically, it is defined as $|Q|/n$, where $|Q|$ is the quorum size and n is the cycle length. The smaller the quorum ratio, the more the power saving achievable by an AQPS protocol.

Figure 6 shows the quorum ratios given by the schemes taking different cycle lengths as the input. Basically, the longer the cycle length, the lower the quorum ratio. In particular, the DS-scheme is able to yield the lowest quorum ratios given a cycle length picked on a station. Note AAA is able to provide different types of quorums to different nodes in a clustered network. Figure 6 also shows the quorum ratios of the clusterheads/relays in this network to ensuring all-pair neighbor discovery.

A higer quorum ratio does not imply higher energy consumption. It is important to note that in MANETs, a scheme giving smaller quorum ratios over cycle lengths does *not* necessarily result in better energy efficiency. Given the cycle lengths m and n on two stations, the DS-, AAA- and Uni-schemes result in the worst-case neighbor discovery delay $(\max(m,n)+\lfloor(\min(m,n)-1)/2\rfloor+\phi)\overline{B}$, $(\max(m,n)+\min(\sqrt{m},\sqrt{n}))\overline{B}$, and $(\min(m,n)+\lfloor\sqrt{z}\rfloor)\overline{B}$ respectively, where ϕ and z are constants. Figure 7 exhibits the lowest quorum ratios given by these schemes that satisfy the delay requirements under different moving speed, s, of nodes. In a clustered environment, Figure 7 also shows the quorum ratios of clusterheads/relays. Due to the assumption that n is a square, in AAA only the 2×2 grid is feasible to Eq. (2) for all s, and the quorum ratios remain 0.75. By taking arbitrary cycle lengths, both the DS- and Uni-scheme fit n to a particular s with better granularity, thereby improving the ratios. Notice that the DS-scheme does not outperform Uni with its superior quorum ratios over cycle lengths. This is because that the Uni-scheme shortens the neighbor discovery delay from $O(\max(m,n))$ to $O(\min(m,n))$, so given any s it is able to fit a longer cycle length using Eq. (4) rather than Eq. (2) as DS does. Uni-scheme allows nodes with slower moving speed to save more energy. Another advantage of the Uni-scheme is that it avoids a common drawback of most existing schemes—the quorum ratio fluctuates sharply when n is small (especially when $n<10$). As we can see, the Uni-scheme render more stable quorum ratios than DS, and consistently improves the ratios of AAA (from 11% up to 24%) across all speed.

VI. Conclusions

In this paper, we investigated the impact of node mobility to the asynchronous wakeup protocols. We identified several shortcomings of existing quorum schemes if to be applied to the MANETs, and proposed the Uni-scheme. The concept of unilateral wakeup is introduced that allows nodes with slower moving speed to save more energy. The Uni-scheme shortens the neighbor discovery delay from $O(\max(m,n))$ to $O(\min(m,n))$ so each node can select the cycle length based on its own speed rather than the highest possible one in the network. Theoretical analysis shows that the Uni-scheme is able to improve the energy efficiency while guaranteeing the network connectivity.

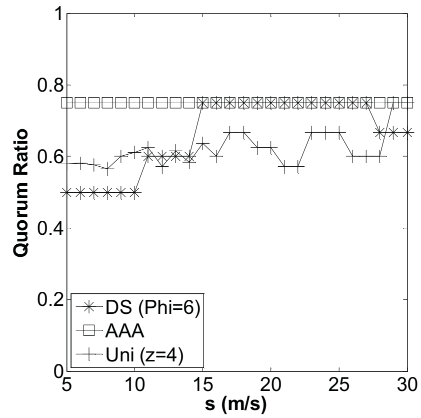

Figure 7. Quorum ratios given different moving speed of nodes.

As the future work, we will study how the Uni-scheme can be applied to MANETs with group mobility. We also plan to implement the wakeup protocols based on the Uni-scheme both in simulators and on real sensors.

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