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Distributed power management protocols for multi-hop mobile ad hoc networks

Shih-Lin Wu [a,*], Pao-Chu Tseng [a], Zi-Tsan Chou [b]

[a] Department of Computer Science and Information Engineering, Chang Gung University, 259 Wen-Hwa 1st Road, Kwei-Shan, Tao-Yuan 333, Taiwan
[b] Department of Computer Science and Information Engineering, National Taiwan University, Taipei 106, Taiwan

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Abstract

The power management scheme in IEEE 802.11 protocol has three severe challenges: beacon contention, timing synchronization, and reliable neighbor maintenance. These challenges are more serious in large and dense multi-hop mobile ad hoc networks (MANETs). To overcome these challenges and improve the energy efficiency as well as network throughput, we propose three new power management protocols. Especially, our solutions offer the network designers full flexibility in trading energy, latency, and neighbor maintenance's accuracy versus each other by appropriately tuning system parameters. Analyses and simulations show that the proposed protocols attain both the better energy efficiency and throughput than existing protocols.

Keywords: Power management; IEEE 802.11; Mobile ad hoc network (MANET); Wireless networks

1. Introduction

Thanks to the advancement in wireless communications and lightweight, small-size, and portable/wearable computing devices have made the dream of "communication anytime and anywhere" possible. A *mobile ad hoc network* (*MANET*) consists of a set of mobile hosts operating without the aid of established infrastructure of centralized administration (e.g. base stations or access points). Communication is done through wireless links among mobile hosts by their antennas. Due to concerns such as radio power limitation and channel utilization, a mobile host may not be able to communicate directly with other hosts in a *single-hop*

* Corresponding author. Tel.: +886 3 2118800x5320; fax: +886 3 2118800.
E-mail addresses: slwu@mail.cgu.edu.tw (S.-L. Wu), zt.chou@msa.hinet.net (Z.-T. Chou).

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fashion. In this case, a *multi-hop* scenario occurs, where the packets sent by the source host must be relayed by several intermediate hosts before reaching the destination host. The applications of the MANET are getting more and more important, especially in the emergency, military, entertainment, and outdoor business environments, in which instant fixed infrastructure or centralized administration is difficult or too expensive to install. However, the finite and non-renewable battery power of mobile stations represents one of the greatest limitations to the utility of MANETs. It is well known that, due to technology limitations, the battery capacity will not be dramatically promoted in the not-so-distant future. Therefore, it is essential to investigate power saving strategies to prolong the lifetime of both individual nodes and the network. One way to reduce energy consumption is simply to use low-power hardware components. Another way is to adopt software-controllable power management protocols that allow transceivers to be used in energy-conserving ways. One of the most common techniques to attain this goal is the *discontinuous reception* [18]; namely, battery power could be greatly saved by periodically turning the radio off when not in use since the network interface may often be idle [6]. However, in such environments, it may take longer time to activate the link between power saving (PS) neighbors. Definitely, a good power management protocol ought to minimize the power consumption without significantly deteriorating the connectivity or capacity of the network.

1.1. Power management protocols with time synchronous

In the literature, several power management protocols for wireless networks have been proposed [3,8,12,16,18–20,22]. The authors in [16] presented TDMA-based birthday protocols for saving energy during the neighbor discovery phase in static wireless sensor networks. The IEEE 802.11 MAC (medium access control) protocol [12] specifies different power saving mechanisms for use within the infrastructure wireless LAN and the independent basic service set (IBSS) respectively. In an IBSS (also known as a single-hop MANET), all stations are within each other's transmission range and time is divided into fixed-sized *beacon intervals*. Clock synchronization by periodic broadcast of a *beacon* frame is required to ensure that all PS stations wake up prior to each *target beacon transmission time* (TBTT). If a sender intends to transmit buffered frames to a destination station that is in a PS mode, the sender should first announce a directed *ad hoc traffic indication message* (ATIM) frame during the *ATIM window*, in which all PS stations are awake. Upon receipt of a directed ATIM frame, the PS station shall acknowledge the ATIM frame and remain in the awake state for the entire beacon interval. The PS station that neither transmitted nor received a directed ATIM frame may return to the *doze* state at the end of the ATIM window. In the doze state, the transceivers are powered down and stations are unable to transmit or receive. Immediately following the ATIM window, the pending buffered frames should be sent using the conventional DCF (distributed coordination function) access procedure. Fig. 1 illustrates an example of power management in an IEEE 802.11 ad hoc network. The more complete and detailed explanation can be found in [12]. The authors in [24] discussed different aspects of power saving addressed in IEEE 802.11 and HYPERLAN standards. They further showed that any fixed size of the ATIM window can not perform very well in all situations. Hence the authors in [8] proposed several energy-conserving optimization techniques, called DPSM, for IEEE 802.11. In DPSM, each station in an IBSS can dynamically tune its ATIM window size according to observed network conditions. Unfortunately, all the above-mentioned protocols [8,12,16,24] are only suitable for synchronous environments.

1.2. Challenges

When designing power management protocols for a large-scale MANET, we will unavoidably encounter three major challenges:

- *Beacon contention*: In IEEE 802.11 [12], every station has to periodically compete with others to broadcast its beacon at around TBTT. Due

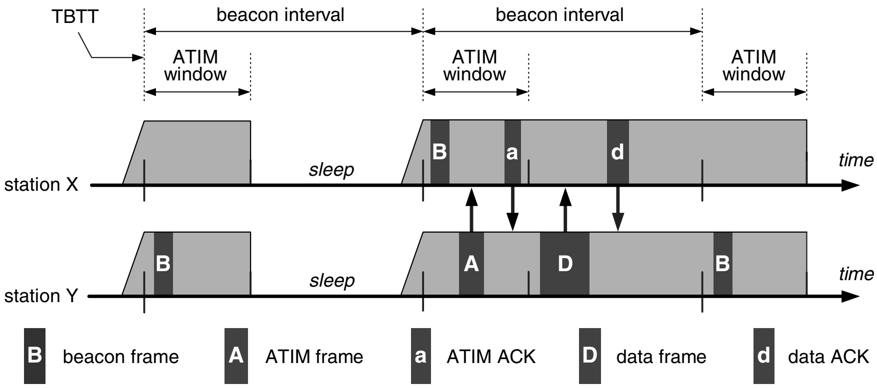

Fig. 1. Power management operation in an IBSS. A beacon frame is broadcasted after each TBTT. All PS stations stay awake for the ATIM window as shown in the first beacon interval, and go to sleep again if no frame is buffered for them. In the second beacon interval, station Y announces a buffered data frame for station X using a directed ATIM frame. X replies by sending an ATIM-ACK, and both X and Y remain active during the entire beacon interval. After the ATIM window, Y sends the data frame, and X acknowledges its receipt.

to the absence of RTS/CTS dialogue, the deficiency of backoff mechanism, and the lack of acknowledgement, the beacon broadcast procedure defined by IEEE 802.11 is highly unreliable. Besides, the higher the node density, the more serious the beacon contention and collisions. As a result, the out of synchronization problem easily arises even in a small IBSS configuration [10].

- *Timing synchronization*: It is extremely difficult (if not impossible) for all nodes to keep synchronized at all times because of severe beacon contention, unpredictable node mobility, and heavy traffic of timing information exchange. Although the Global Positioning System (GPS) can simplify the synchronization problem, it is not necessarily true that all future mobile stations will be equipped with GPS receivers. Once stations get out of synchronization, then IEEE 802.11 power saving operation may completely fail since PS neighbors may forever lose each other's beacons or ATIM frames. See Fig. 2.
- *Neighbor maintenance*: For an active station, it may be unaware of a PS station at its neighborhood since a PS station will reduce its transmitting activity. For a PS station, it may be unaware of a station at its neighborhood since its listening activity is confined to the ATIM window. Besides, without a consistent common reference clock, a PS station may wake up too late to hear neighbors' signals. Such incorrect neighbor information may be an obstacle to many existing protocols, such as zone routing protocol [9] and neighbor coverage-based broadcasting protocol [23], whose success relies

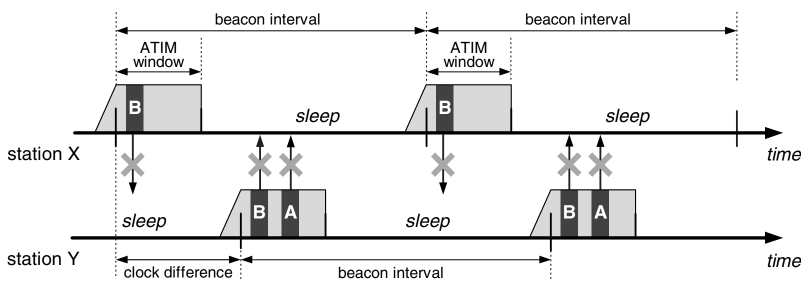

Fig. 2. Because of out of synchronization, PS stations, X and Y, are unable to receive each other's beacons or ATIM frames.

Table 1
Comparison of power management protocols for ad hoc networks

Protocol	Timing synchronization	Special hardware support	Beacon transmission
IEEE 802.11 [12]	Yes	No	Not scalable
Birthday [16]	Yes	No	Scalable
DPSM [8]	Yes	No	Not scalable
PSPA [18]	No	Base station	Not handled
Chiasserini et al. [3]	No	Remote activated switch	Not handled
STEM [19,20]	No	Dual transceivers	Not handled
Tseng et al. [22]	No	No	Not scalable
Ours	No	No	Scalable

on an accurate neighbor table. To make matters worse, since PS stations do not stand much chance of being detected, if some of them constitute a *vertex cutset*, whose removal will disconnect the network, then the *virtual network partition* problem [22] may arise.

Power management protocols (Table 1) introduced in [3,18–20,22] are asynchronous. The authors in [18] proposed the PSPA protocol for reducing the power consumption of portable stations operating in a mobile network with a *base station* support. The base station will keep on sending page messages whenever there are buffered packets. Each mobile station may control its duty cycle relative to its current needs. The authors in [3] assume that a sleeping station can be remotely activated by a wake-up signal using a *remote activated switch* (RAS) receiver. With the aid of RAS, stations can select different sleep patterns to enter various sleep states depending on their battery status and quality of service. The authors in [19,20] presented the STEM protocol that trades power savings for path setup latency in wireless sensor networks, in which all stations are equipped with *dual transceivers*. Unfortunately, these asynchronous protocols [3,18–20] require special hardware support. In addition, they did not take neighbor maintenance into consideration.

1.3. Our contributions

Currently, IEEE 802.11 compliant interface cards are greatly popular. However, three abovementioned challenges pose a strong demand of redesigning IEEE 802.11 power saving mechanism for asynchronous MANETs, in which the clock difference between any pair of stations ranges from zero to any large bounded number. Accordingly, we will make minor modifications to IEEE 802.11 so that our new protocols have the following characteristics. (i) The delivery of a beacon frame is relatively reliable and insensitive to the nodal density, thus alleviating the beacon contention problem substantially. (ii) Our protocols achieve energy conservation and flexible neighbor maintenance in an integrated manner. Precisely, given a predefined number $0 \leqslant \varepsilon \ll 1$, our solutions carefully arrange the awake/sleep patterns such that any two PS neighbors, regardless of their clock difference, are able to discover each other in finite time $\mathscr{T}$ with high probability $1 - \varepsilon$. (iii) The mechanisms for delivering data frames to PS stations can perform high energy efficiency as well as good network throughput and have no need to rely on clock synchronization or any special hardware support. More specifically, in our protocols, each PS station piggybacks its timestamp and awake/sleep pattern with the beacon frame. Once station X received a beacon from PS station Y, X is capable of predicting the timing of the Y's ATIM windows via their clock difference and Y's awake/sleep pattern. By this way, buffered frames destined for PS station Y will be eventually delivered.

Recently, based on IEEE 802.11, three asynchronous power saving protocols for a multi-hop MANET have been proposed in [22], whose work is the most relevant to ours. Compared with their protocols, two major distinctive contributions are described as follows. (i) While the beacon contention problem is completely ignored in [22]; in this paper, we borrow the idea from the design of

HYPERLAN [1] to propose a new backoff mechanism such that the probability of successful *broadcast* of a beacon frame is drastically boosted. While some modified backoff algorithms have been designed for achieving maximum throughput [2] or real-time transmissions [5]; our backoff scheme is specifically geared towards scalable beacon broadcast. While some proposed MAC-level broadcast protocols are based on black burst signals [1,21] or handshaking [4], which are not regular schemes defined in IEEE 802.11; our scalable beacon broadcast protocol is completely compatible with IEEE 802.11. (ii) In this paper, we design three randomized asynchronous power management protocols, called *randomized coterie-based*, *naive cyclic finite projective plane-based* (CFPP-based) and *interleaving CFPP-based* protocols. In contrast with deterministic approaches [22], our randomized schemes achieve additional energy saving gains in neighbor maintenance by also exploiting the *accuracy* dimension. Namely, our protocols may fail to discover a link which joins two PS stations; however, such a neighbor discovery loss can be bounded to any predefined small number ε. Intuitively, the higher the neighbor discovery probability, the more battery power the protocol may consume. In a nutshell, our protocols can offer the network designers full flexibility in trading energy, latency, and accuracy versus each other by appropriately setting ε and $\mathscr{T}$. Especially, the CFPP-based protocol always guarantees a 100% neighbor discovery probability even though it is a randomized algorithm. Above all, we obtain a nearly 75% reduction in *radio active ratio* (which will be defined in Section 2.2) for the CFPP-based protocol as compared with the most energy-conserving protocol in [22].

The remainder of this paper is organized as follows. In Section 2, we present and analyze our power management protocol. In Section 3, simulation experiments are conducted to evaluate the proposed protocols. The final conclusions are drawn in Section 4.

2. Our power management protocols

As mentioned in Section 1.2, three major challenges exist in designing power management protocols for a large-scale MANET. To overcome these challenges and improve the energy efficiency as well as network throughput, three new power management protocols are proposed and each of them is composed of three parts: a *scalable beacon transfer procedure* for the beacon contention and time synchronization challenge, *one of three randomized asynchronous power management schemes* for neighbor maintenance challenges, and a *data frame transfer procedure* provides the high energy efficiency and good throughput transmission procedure.

Fig. 3 shows our two types of beacon intervals: one is *fully-awake* beacon interval and the other is *fully-sleep* beacon interval as shown in Fig. 3(a) and (b), respectively. Each fully-awake beacon interval starts with a beacon window followed by a data window. During the fully-awake interval, a PS station always stays awake. The purposes of the fully-awake beacon interval are (i) for a PS station to discover all its neighbors by extending its listening duration to the maximum in the data window, and (ii) for a PS station to announce its presence by trying to send out its beacon during the beacon window using our beacon transmission procedure. Each fully-sleep beacon interval starts with an ATIM window. After the ATIM window concludes, a PS station may enter the doze state. The purpose of the fully-sleep beacon interval is for a PS station to reduce its energy consumption by condensing its listening activity to the minimum. How a PS station choose one of the two

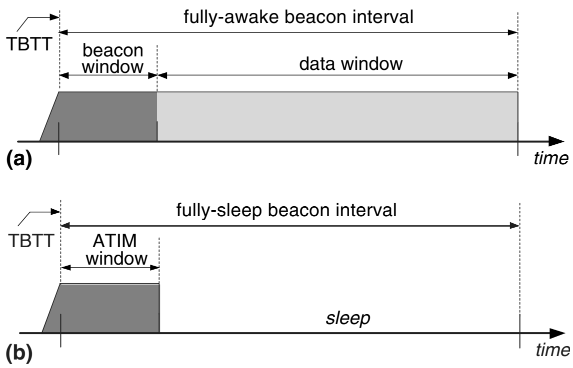

Fig. 3. (a) Fully-awake beacon interval. (b) Fully-sleep beacon interval.

type beacon interval is decided by our randomized asynchronous power management schemes.

The rest of this section is organized as follows. In Section 2.1, we first review some of beacon transmission procedures and then give our scalable beacon transmission procedure. In Section 2.2, we present and analyze our three randomized asynchronous power management schemes. Finally, the data frame transfer procedure is given in Section 2.3.

2.1. Beacon transmission

2.1.1. Review of some beacon transfer procedures

Beacon frames are mainly used for *clock synchronization* in an IEEE 802.11 ad hoc network [12]. Therefore, all PS stations should wake up at the beginning of a beacon interval, i.e., TBTT. When perceiving the medium idle after TBTT, each node contends to send a beacon with each other. To avoid collisions among beacons, each station calculates a random delay uniformly distributed in the range between 0 and *CW* (*contention window*) before sending out its beacon. If a beacon arrives before the random delay timer has expired, the pending beacon transmission should be cancelled. Because of the cancellation of the beacon transmission, the chance for the PS station to announce its existence is significantly reduced. On the other hand, beacon frames play an important role for *neighbor maintenance* in MANETs. Periodically, a station should advertise its presence to its neighbors by broadcasting a beacon frame. Also, a station should maintain its up-to-date neighbor table according to its newly received beacons. Hence the authors in [22] modified the IEEE 802.11 standard so each station shall persist in explicitly sending its beacon during the ATIM window even others' beacons have been heard. Following this principle, we design and show the new structure of a beacon interval in Fig. 3 to allow multiple beacon frames transmissions and explain how it work in the next section.

2.1.2. Scalable beacon transfer procedure

To announce its presence for neighbor maintenance, every station should turn its radio on and broadcast its beacon during the beacon window in each fully-awake beacon interval. In IEEE 802.11 [12], after each TBTT, all stations contending for the beacon transmission *immediately* dive into the random backoff stage when the medium becomes idle. However, in our implementations, as shown in Fig. 4(a), every station should first wait for the duration of T_{IFS} = PIFS (Priority InterFrame Space) before performing the backoff procedure. The design considerations for setting T_{IFS} are described as follows. (i) Claim T_{IFS} < DIFS. Various interframe spaces including SIFS (Short Interframe Space), PIFS, and DIFS (DCF Interframe Space) are defined in IEEE 802.11 to provide different priority levels for different types of frames. Besides, SIFS < PIFS < DIFS. We argue that beacon management frames should take priority over normal data frames. (ii) Claim T_{IFS} > SIFS. Due to a busy medium, the strict start of the beacon window may begin later than the nominal start of the beacon window. Such a phenomenon is called *stretching* and we show the stretching event in Fig. 4(b). After TBTT, if a PS station unaware of the NAV (network allocation vector) set during the previous beacon interval selects the zero backoff time and transmits a beacon frame immediately after the medium becomes idle, then that beacon frame may destroy an on-going stretching directed data frame transmission, which

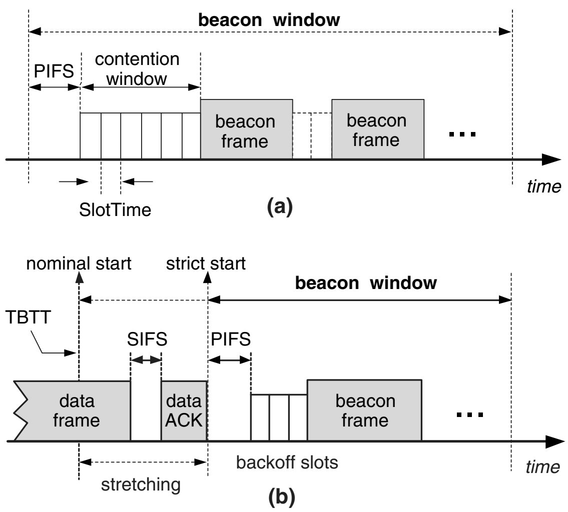

Fig. 4. (a) Beacon transfer procedure. (b) An example of beacon transmission and the stretching event.

includes the associated ACK and the intervening *SIFS*. Therefore, we set T_{IFS} = PIFS to avoid such an undesired event.

After the PIFS medium idle time, the station shall then generate a random backoff period SlotTime $\times B$, $0 \leqslant B \leqslant CW$, for an additional deferral time before transmitting a beacon. Definitely, the station choosing the smallest backoff time among the competitors will seize the medium. If conforming to the IEEE 802.11 conventional approach, B will be a random variable with *discrete uniform* distribution over the set $\{0, 1, 2, \ldots, CW\}$, and we have

$$\Pr[B = b] = \frac{1}{CW + 1}, \quad 0 \leqslant b \leqslant CW. \tag{1}$$

However, in our proposed scheme, $\mathscr{B}$ is a *reverse truncated geometric* random variable with parameter q, $0 < q < 1$. And we assign

$$\Pr[\mathscr{B} = b] = \begin{cases} q^{CW}, & \text{if } b = 0, \\ (1-q)q^{CW-b}, & \text{if } 1 \leqslant b \leqslant CW. \end{cases} \tag{2}$$

2.1.3. Analysis of beacon contention

We follow the analytic model proposed in [1,10] to compare our beacon transfer procedure with the IEEE 802.11 approach on the success probability of a beacon transmission. This metric is our chief concern since there is no MAC-level recovery on beacon frames [12]. For tractability and ease of analysis, we only consider the IBSS configuration with m stations. Moreover, we assume that the channel introduces no errors, so frame collisions are the only source of errors. A beacon transmission is considered successful if it encounters no collision.

After TBTT and an elapsed PIFS, each station i, $1 \leqslant i \leqslant m$, independently generates a random backoff timer $\mathscr{B}_i$ for beacon transmission, where $\mathscr{B}_i$ follows the reverse truncated geometric distribution. Let $P_{\mathscr{G}}[m]$ be the probability that at least one of the m stations succeeds in beacon transmission by using the scalable beacon transfer procedure. Let $m \geqslant 2$, then the event that there is a successful beacon transmission in the contention window $[0, CW]$ if and only if (i) exactly *one* station transmits in slot j, for some $0 \leqslant j \leqslant CW - 1$, and (ii) all other stations are scheduled to transmit *after* slot j. Thus, we have

$$\begin{aligned} P_{\mathscr{G}}[m] &= \sum_{j=0}^{CW-1} \binom{m}{1} \Pr[\mathscr{B} = j](\Pr[\mathscr{B} > j])^{m-1} \\ &= \binom{m}{1} \times \left\{ \Pr[\mathscr{B} = 0](\Pr[\mathscr{B} > 0])^{m-1} \right. \\ &\quad \left. + \sum_{j=1}^{CW-1} (1-q)q^{CW-j}(1-q^{CW-j})^{m-1} \right\} \\ &= \binom{m}{1} \times \left\{ q^{CW}(1-q^{CW})^{m-1} \right. \\ &\quad \left. + \sum_{j=1}^{CW-1} (1-q)q^{j}(1-q^{j})^{m-1} \right\}. \end{aligned} \tag{3}$$

To compare with the IEEE 802.11 approach, let us consider the case that the backoff timer of each station B_i is independently sampled from a discrete uniform distribution over the set $\{0, 1, \ldots, CW\}$. Under the circumstances, let and $P_{\mathscr{U}}[m]$ denote the probability that one of the m stations succeeds in beacon transmission. By the similar way, we have

$$\begin{aligned} P_{\mathscr{U}}[m] &= \sum_{j=0}^{CW-1} \binom{m}{1} \Pr[B = j](\Pr[B > j])^{m-1} \\ &= \frac{m}{CW+1} \sum_{j=0}^{CW-1} \left(\frac{CW - j}{CW + 1} \right)^{m-1}. \end{aligned} \tag{4}$$

For the standard value of $CW = 31$, the functions $P_{\mathscr{G}}[m]$ and $P_{\mathscr{U}}[m]$ are plotted in Fig. 5 for various values of m. We can see that, when $q = 0.8$, $P_{\mathscr{G}}[m]$ is very close to 0.9 and decreases very slowly with an increasing number of contending stations. On the contrary, $P_{\mathscr{U}}[m]$ drops sharply and rapidly as the number of competing stations increases. The results do confirm that, in contrast with IEEE 802.11, our scheme delivers a more scalable and reliable performance, thus relieving the beacon contention problem remarkably.

2.2. Three randomized power management schemes

In this section, we present three randomized power management schemes, which allow stations

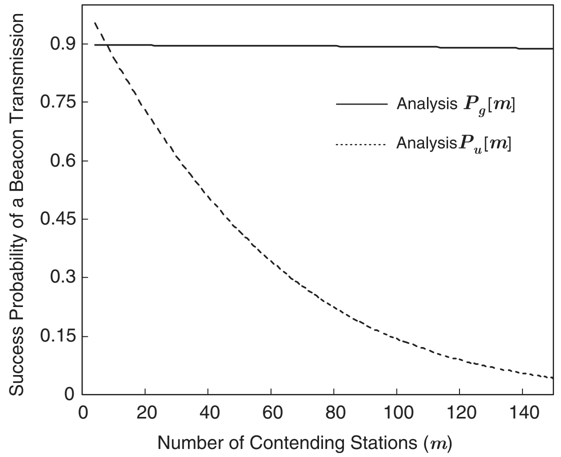

Fig. 5. Success probability of a beacon transmission versus number of contending stations.

operating in a PS mode to save a great deal of energy by periodically entering the doze state, while also allowing PS stations a high probability of discovering their neighbors in an asynchronous MANET. Although, in the beginning of this section, we have introduced two general types of beacon interval, each of these schemes has a slight different awake/sleep pattern for PS stations. In other words, the structure of a beacon interval may vary for different schemes. Note that all stations are assumed to have the same clock rate, although this is not true in the real world. Fortunately, the solution of the problem has been proposed in [10] by adjusting station's clock to the fastest one in all stations at each beacon interval. Besides, in all our settings, the lengths of the beacon window and ATIM window remain constant in every beacon interval. The notations used to facilitate the forthcoming presentation are listed below:

- BI: the length of a beacon interval,
- BW: the length of a beacon window,
- AW: the length of an ATIM window,
- DW: the length of a data window,
- $actW$: the length of an active window.

2.2.1. Randomized coterie-based scheme

We design two types of beacon intervals for this scheme; one is the *fully-awake* beacon interval, and the other is the *fully-sleep* beacon interval, which are same as our previous defined in the beginning of this section. The active window $actW$ is defined as $actW = BW + DW = BI$ in fully-awake beacon interval or $actW = AW$ in fully-awake beacon interval.

Take Fig. 6 for example, for the PS station X, 0th, 1st, 2nd, and 9th beacon intervals are fully-awake while the remaining beacon intervals are fully-sleep. We can find that, for a PS station, the fully-awake beacon intervals take on the burden of announcing its presence and detecting the existence of neighbors. As a result, the chance for two PS neighbors to discover each other relies on the overlaps of their fully-awake beacon intervals. With the intersection property, a *coterie* system [7] is expected to be a powerful tool in developing power management schemes. The definition of a coterie [7] is formally given below.

Definition 1. Let U be the universe set of finite objects. A collection of subsets (*quorums*) $\mathscr{L} = \{L_1, \ldots, L_m\}$, where $L_i \subseteq U$, is called a *coterie* if and only if (i) For any two quorums L_i and L_j in

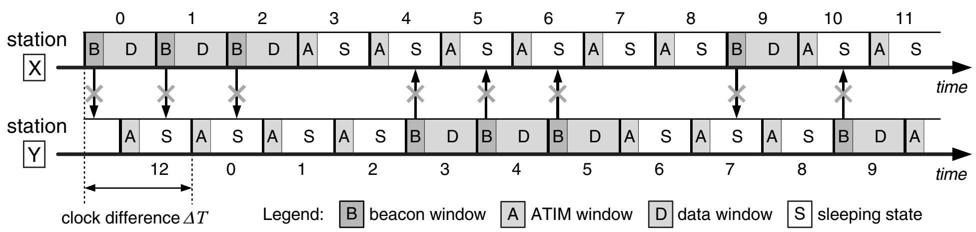

Fig. 6. A snapshot of the worst case scenario for coterie-based scheme.

$\mathscr{L}$, $L_i \cap L_j \neq \emptyset$. (ii) There are no two quorums L_i and L_j in $\mathscr{L}$ such that $L_i \subseteq L_j$.

Example 1. A set of coteries can be obtained by letting $U = \{0,1,\ldots,12\}$ and $\mathscr{L} = \{L_0 = \{0,1,2,9\}, L_1 = \{0,3,6,10\}, L_2 = \{0,4,8,11\}, L_3 = \{0,5,7,12\}, L_4 = \{3,4,5,9\}, L_5 = \{1,4,7,10\}, L_6 = \{1,5,6,11\}, L_7 = \{1,3,8,12\}, L_8 = \{6,7,8,9\}, L_9 = \{2,5,8,10\}, L_{10} = \{2,3,7,11\}, L_{11} = \{2,4,6,12\}, L_{12} = \{9,10,11,12\}\}$. It is easy to verify that $L_i \cap L_j \neq \emptyset$ and $L_i \not\subseteq L_j$ for all $i \neq j$ and $0 \leqslant i, j \leqslant 12$. Although the coterie techniques have been widely used in distributed systems [7,14], such as mutual exclusion and data replication, a coterie without any proper modifications may not be directly applicable to the power management schemes especially in asynchronous environments. For instance, let us consider an coterie-based power management scheme which formally works as follows. When a station decides to switch to the PS mode, it randomly selects a quorum L_i from $\mathscr{L}$ as the set of fully-awake beacon intervals within a pattern repetition interval $\mathscr{R}$, where $\mathscr{R}$ is a global parameter. The remaining beacon intervals are all fully-sleep beacon intervals. The *pattern repetition interval* is defined as the consecutive $\mathscr{R}$ beacon intervals that comprise some different awake/sleep patterns repeat at regular intervals. Fig. 6 shows an example of the coterie-based scheme, in which station X chooses jth beacon intervals, for all $j \in L_0 = \{0,1,2,9\}$, as its fully-awake beacon intervals from a pattern repetition interval $\mathscr{R}$ (13 consecutive beacon intervals); while station Y selects beacon intervals in $L_4 = \{3,4,5,9\}$ as its fully-awake beacon intervals. Obviously, when two PS neighbors, X and Y, are perfectly synchronized, i.e., their clock difference $\Delta T = 0$, they may discover each other in the 9th beacon interval since $L_0 \cap L_4 = \{9\}$. However, as shown in Fig. 6, if X's clock is ahead of Y's clock by $BI + \Delta t$, where $\max\{BW, AW\} < \Delta t < BI - \max\{BW, AW\}$, then they forever lose each other's beacons.

To mitigate the asynchronism problem, we relax the non-empty intersection property and introduce a randomized coterie, in which every two distinct quorums intersect with high probability. The randomized coterie is in essence a special case of the probabilistic quorum systems [14]. The randomized coterie-based power management scheme operates formally as follows. When a station switches to the PS mode, it selects k beacon intervals randomly and uniformly from a pattern repetition interval $\mathscr{R}$ as the set of fully-awake beacon intervals, while the remaining beacon intervals are all fully-sleep beacon intervals. With appropriately setting parameters $\mathscr{R}$ and k, this simple yet novel approach guarantees that, even in an asynchronous environment, the fully-awake beacon intervals of two PS neighbors overlap with high probability. The more precise result is given in the following theorem. Moreover, via Corollary 1, we demonstrate the power of the randomized coterie-based scheme.

Theorem 1. *In the randomized coterie-based scheme, if no collisions in beacon reception, then the probability $P[\mathscr{R},k]$ that any two PS neighbors, regardless of their clock difference, are able to discover each other within a pattern repetition interval is given below*

$$\begin{cases} P[\mathscr{R},k] = 1 \quad \text{if } \lfloor \mathscr{R}/2 \rfloor + 1 \leqslant k \leqslant \mathscr{R}, \\ P[\mathscr{R},k] \geqslant \\ \quad 1 - \dfrac{\binom{\mathscr{R}}{k}\binom{\mathscr{R}-k}{k} + \binom{\mathscr{R}}{1}\binom{\mathscr{R}-2}{k-1}\binom{\mathscr{R}-k-1}{k-1}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k}} \\ \quad \text{if } 1 \leqslant k \leqslant \lfloor \mathscr{R}/2 \rfloor. \end{cases} \tag{5}$$

Proof. In the randomized coterie-based scheme, the chance for two PS neighbors, X and Y, to discover each other relies on the overlaps of their fully-awake beacon intervals. By using the well-known pigeonhole principle, it is easy to verify that $P[\mathscr{R},k] = 1$ when $k \geqslant \lfloor \mathscr{R}/2 \rfloor + 1$.

Now, let us consider the case that $k \leqslant \lfloor \mathscr{R}/2 \rfloor$. Without loss of generality, we can assume that the worst case scenario (refer to Fig. 6) occurs when X's clock is faster than Y's clock by $\Delta T = h \times BI + \Delta t$, where $\max\{BW, AW\} < \Delta t < BI - \max\{BW, AW\}$ and $h \geqslant 0$ is an integer. In the following derivation, we use X's clock as a reference clock to derive Y's clock. Note that other cases can be derived via the similar way. We define $i \ominus h \equiv i - h \bmod \mathscr{R}$. Thus X can receive Y's beacons within a pattern repetition interval if and only if both $\langle i \rangle_X$ and $\langle i \ominus h \rangle_Y$ are fully-awake beacon intervals, for some $0 \leqslant i \leqslant \mathscr{R} - 1$, where $\langle i \rangle_X$ denotes the ith beacon interval in X's pattern repetition interval. Let us denote by $X \leftarrow Y$ the event that X hears the beacons issued from Y within a pattern repetition interval. And we have

$$\Pr[X \leftarrow Y] = 1 - \frac{\binom{\mathscr{R}}{k}\binom{\mathscr{R}-k}{k}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k}}. \tag{6}$$

On the other hand, X's beacons can be received by station Y during a pattern repetition interval if and only if both $\langle j \rangle_X$ and $\langle j \ominus (h+1) \rangle_Y$ are fully-awake beacon intervals for some $0 \leqslant j \leqslant \mathscr{R} - 1$. Let us denote by $X \rightarrow Y$ ($X \nrightarrow Y$) the event that Y can (cannot) receive X's beacons during a pattern repetition interval. By exploiting conditional probabilities, $P[\mathscr{R}, k]$ can be expressed as

$$\begin{aligned} P[\mathscr{R}, k] &= \Pr[(X \rightarrow Y) \cap (X \leftarrow Y)] \\ &= \Pr[X \rightarrow Y \mid X \leftarrow Y] \times \Pr[X \leftarrow Y] \\ &= (1 - \Pr[X \nrightarrow Y \mid X \leftarrow Y]) \times \Pr[X \leftarrow Y]. \end{aligned} \tag{7}$$

In what follows, we derive the probability $\Pr[X \nrightarrow Y | X \leftarrow Y]$. The event $X \leftarrow Y$ can occur in any of

$$\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k} - \binom{\mathscr{R}}{k}\binom{\mathscr{R}-k}{k}$$

possible ways. Given that the event $X \leftarrow Y$ has occurred, we want to determine the number of possible outcomes in which the event $X \nrightarrow Y$ also happens. First, there are $\binom{\mathscr{R}}{1}$ ways for station X to arbitrarily select a fully-awake beacon interval, say $\langle i \rangle_X$. In order to guarantee that X can hear Y's beacons, Y must choose $\langle i \ominus h \rangle_Y$ as its fully-awake beacon interval. At this moment, X cannot select $\langle i+1 \rangle_X$ as the fully-awake beacon interval, otherwise the event $X \rightarrow Y$ will take place. Then station X has $\binom{\mathscr{R}-2}{k-1}$ ways to choose its remaining $k-1$ fully-awake beacon intervals from a pattern repetition interval, excluding $\langle i \rangle_X$ and $\langle i+1 \rangle_X$. We label these $k-1$ beacon intervals $\langle \ell_1 \rangle_X, \langle \ell_2 \rangle_X, \ldots, \langle \ell_{k-1} \rangle_X$ respectively, as illustrated in Fig. 7. To avoid the event $X \rightarrow Y$, station Y is forbidden to choose $\langle \ell_1 \ominus (h+1) \rangle_Y, \langle \ell_2 \ominus (h+1) \rangle_Y, \ldots, \langle \ell_{k-1} \ominus (h+1) \rangle_Y$. As a result, Y has only $\binom{\mathscr{R}-k-1}{k-1}$ ways to select its remaining $k-1$ fully-awake beacon intervals. However, we may not obviate the possibility of counting the redundant outcomes. Thus, we have

$$\Pr[X \nrightarrow Y \mid X \leftarrow Y] \leqslant \frac{\binom{\mathscr{R}}{1}\binom{\mathscr{R}-2}{k-1}\binom{\mathscr{R}-k-1}{k-1}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k} - \binom{\mathscr{R}}{k}\binom{\mathscr{R}-k}{k}}. \tag{8}$$

By substituting (6) and (8) in (7), we can derive the inequality (5). □

Corollary 1. *In the randomized coterie-based scheme, if every PS station randomly selects $\beta\sqrt{\mathscr{R}}$ fully-awake beacon intervals from a pattern repetition interval $\mathscr{R}$, where $1 \leqslant \beta \leqslant \sqrt{\mathscr{R}}/2$, then we have*

$$P[\mathscr{R}, \beta\sqrt{\mathscr{R}}] \geqslant 1 - (1+\beta^2)e^{-\beta^2}. \tag{9}$$

For example, $P[\mathscr{R}, \sqrt{3\mathscr{R}}] \geqslant 0.801$, $P[\mathscr{R}, 2\sqrt{\mathscr{R}}] \geqslant 0.908$, *and* $P[\mathscr{R}, 3\sqrt{\mathscr{R}}] \geqslant 0.999$.

Proof. See Appendix A. □

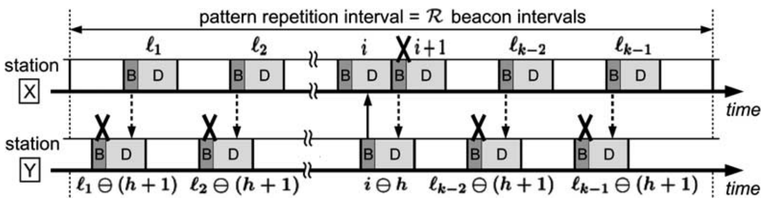

Fig. 7. The event that, during a pattern repetition interval, X can receive Y's beacons, while Y cannot receive X's beacons.

Remark 1. The choice of $\mathscr{R}$ and k demands the tradeoff among power consumption, neighbor discovery probability, and neighbor discovery time. For instance, by Corollary 1, we can obtain $P[10000, 300] \geqslant 0.999$. This means that each PS station can be awake only about 3% of the time, yet it can discover neighbors with probability at least 99.9%. However, if we require that neighbor discovery probability must be 100%, then, by Theorem 1, each PS station should stay awake at least 50% of the time. This implies that, in the randomized coterie-based scheme, if we can tolerate a little more neighbor discovery loss, then we can earn a significant energy saving. We defer the power consumption analysis until Section 2.2.3. If the designer demands the probability that a PS neighbor can be discovered within the duration $\mathscr{T} \geqslant \mathscr{R}$ shall be at least $1 - \varepsilon$, then the value of $P[\mathscr{R}, k]$ must satisfy the following inequality:

$$1 - (1 - P[\mathscr{R}, k])^{\lfloor \frac{\mathscr{T}}{\mathscr{R}} \rfloor} \geqslant 1 - \varepsilon.$$

Remark 2. To simplify our theoretical analysis and presentation, the assumption of collision-free beacon reception is made only in this section. Obviously, collision is inevitable in any random-access networks. However, when $0 \leqslant \Delta t \leqslant BW$, a high success probability of a beacon delivery is guaranteed via scalable beacon transfer procedure; when $BW < \Delta t < BI - BW$, the asynchronism is also of help in relieving the beacon contention. In our simulations, we will remove this assumption.

2.2.2. Cyclic finite projective plane-based schemes

Although the randomized coterie-based scheme is simple, flexible, and easy implementable, it does not always guarantee a 100% neighbor discovery probability (especially when $k \approx \sqrt{\mathscr{R}}$). In this section, on the basis of the *cyclic finite projective plane*, we propose new randomized power saving schemes, in which a PS station is able to discover its neighbors with probability 1, while it sends beacon frames only $\lceil \sqrt{\mathscr{R}} \rceil$ times in a pattern repetition interval $\mathscr{R}$. The finite projective plane (FPP) [15] is formally defined as follows.

Definition 2. Let U be a finite set, and let $\mathscr{L}$ be a system of subsets of U. The pair $(U, \mathscr{L})$ is called a *finite projective plane* if it satisfies the following properties. (i) There exists a 4-element set $F \subseteq U$ such that $|L_i \cap F| \leqslant 2$ holds for each set $L_i \in \mathscr{L}$. (ii) Any two distinct sets $L_i, L_j \in \mathscr{L}$ intersect in exactly one element; i.e., $|L_i \cap L_j| = 1$. (iii) For any two distinct elements $u_i, u_j \in U$, there exists exactly one set $L_k \in \mathscr{L}$ such that $u_i \in L_k$ and $u_j \in L_k$.

An example of an FPP can be found in Example 1. The FPP is a finite analogy of the so-called real projective plane (an extension of Euclidean plane and all elements are real numbers) studied in geometry. Therefore, if $(U, \mathscr{L})$ is an FPP, we call the elements of U *points* and the sets of $\mathscr{L}$ *lines*. The following two theorems [15] are useful in the presentation of our algorithms.

Theorem 2. *Let $(U, \mathscr{L})$ be an FPP. Then all its lines have the same number of points; i.e., $|L_i| = |L_j|$ for any two lines $L_i, L_j \in \mathscr{L}$.*

Accordingly, we can define the *order* of the FPP as the number *one* less than the number of points on each line; i.e., $|L_i| - 1$, where $L_i \in \mathscr{L}$.

Theorem 3. *Let $(U, \mathscr{L})$ be an FPP of order $n \geqslant 2$. Then the following statements are equivalent.* (i) *Every line contains $n + 1$ points.* (ii) *Every point is on exactly $n + 1$ lines.* (iii) *There are exactly $n^2 + n + 1$ points in U.* (iv) *There are exactly $n^2 + n + 1$ lines in $\mathscr{L}$.*

However, as illustrated in Example 1, the FPP-based power management scheme may fail when operating over asynchronous environments. Thus we call for the cyclic FPP (CFPP).

Definition 3. Let $\mathscr{R} = n^2 + n + 1$ and $U = \{0, 1, \ldots, \mathscr{R} - 1\}$. An FPP $(U, \mathscr{L})$ of order n is called a *cyclic FPP* of order n if and only if, for any line $L_i = \{\ell_0, \ell_1, \ldots, \ell_n\} \in \mathscr{L}$ and an integer h, the coset $h \oplus L_i = \{h + \ell_j \bmod \mathscr{R} \mid \text{for all } \ell_j \in L_i\}$ is also a line in $\mathscr{L}$.

An example of the CFPP of order 2 can be obtained by letting $U = \{0, 1, \ldots, 6\}$ and $\mathscr{L} = \{L_0 = \{0, 1, 3\}, L_1 = \{1, 2, 4\}, L_2 = \{2, 3, 5\}, L_3 = \{3, 4, 6\}, L_4 = \{4, 5, 0\}, L_5 = \{5, 6, 1\}, L_6 = \{6, 0, 2\}\}$. $3 \oplus L_0 = \{3, 4, 6\} = L_3 \in \mathscr{L}$ and $-3 \oplus L_0 = \{4, 5, 0\} = L_4 \in \mathscr{L}$. The CFPP is in essence a special case of Abelian difference sets [11]. By Singer's theorem

[11], we can conclude that if $n \geqslant 2$ is a power of a prime, then there exists a CFPP of order n. By Theorem 3 and Definition 3, we can obtain the following important corollary.

Corollary 2. *Let* $(U, \mathscr{L})$ *be a CFPP of order n and* $\mathscr{R} = n^2 + n + 1$. *Then for any two lines* $L_i, L_j \in \mathscr{L}$, (i) $|L_i| \leqslant \lceil\sqrt{\mathscr{R}}\rceil$ *and* (ii) $(h_1 \oplus L_i) \cap (h_2 \oplus L_j) \neq \emptyset$, *for any two integers* h_1 *and* h_2.

The naive CFPP-based randomized power management scheme operates formally as follows. When a station switches to the PS mode, it selects a line L_i randomly from $\mathscr{L}$ as the set of fully-awake beacon intervals within a pattern repetition interval $\mathscr{R}$, where the parameter $(U, \mathscr{L})$ is globally maintained. The remaining beacon intervals are all fully-sleep beacon intervals. The following theorem is used to guarantee that any two stations can meet each other in every pattern repetition interval.

Theorem 4. *The naive CFPP-based scheme guarantees that, assume no collisions in beacon reception, any two PS neighbors, regardless of their clock difference, are able to discover each other in every pattern repetition interval.*

Proof. We prove this theorem by showing that, given any two PS neighbors X and Y, at least one X's entire beacon window is fully covered by Y's active windows during a pattern repetition interval, and vice versa. We assume that X and Y randomly select the lines L_x and L_y respectively from the same CFPP $(U, \mathscr{L})$ as the set of their fully-awake beacon intervals within a pattern repetition interval, and $\mathscr{R} = n^2 + n + 1$. Without loss of generality, we can assume that X's clock is faster than Y's clock by $\Delta T = h \times BI + \Delta t$, where $0 \leqslant \Delta t < BI$ and $h \geqslant 0$ is an integer. In the following derivation, we use X's clock as a reference clock to derive Y's clock. Note that other cases can be derived by the similar way.

As illustrated in Fig. 8, X can receive Y's beacons within a pattern repetition interval if and only if both $\langle i\rangle_X$ and $\langle i \ominus h\rangle_Y$ are fully-awake beacon intervals, for some $0 \leqslant i \leqslant \mathscr{R} - 1$. Since $L_x \cap \{-h \oplus L_y\} \neq \emptyset$ (by Corollary 2), there must exist an element i such that $i \in L_x$ and

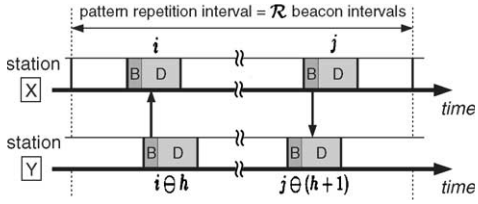

Fig. 8. The event that stations X and Y are able to discover each other within a pattern repetition interval.

$i \in \{-h \oplus L_y\}$. This implies that both $\langle i\rangle_X$ and $\langle i \ominus h\rangle_Y$ are fully-awake beacon intervals. On the other hand, X's beacons can be received by Y if and only if both $\langle j\rangle_X$ and $\langle j \ominus (h+1)\rangle_Y$ are fully-awake beacon intervals, for some $0 \leqslant j \leqslant \mathscr{R} - 1$. Since $L_x \cap \{-(h+1) \oplus L_y\} \neq \emptyset$ (by Corollary 2), there must exist an element j such that $j \in L_x$ and $j \in \{-(h+1) \oplus L_y\}$. This implies that both $\langle j\rangle_X$ and $\langle j \ominus (h+1)\rangle_Y$ are fully-awake beacon intervals. □

In what follows, we employ the *interleaving* technique such that the power consumption of the CFPP-based scheme can be further reduced. We design three types of beacon intervals: the *forward half-awake* beacon interval, the *backward half-awake* beacon interval, and the fully-sleep beacon interval. The structures of the half-awake beacon intervals are defined as follows:

- Each forward half-awake beacon interval starts with a beacon window followed by an ATIM window. After the ATIM window finishes, a PS station may enter the doze state. Importantly, we set $actW = BW + AW + DW \geqslant BW + BI/2$.
- Each backward half-awake beacon interval starts with an ATIM window, but the active window is terminated by a beacon window. After the active window ends, a PS station may enter the doze state. Importantly, we set $actW = AW + DW + BW \geqslant BW + BI/2$.

The interleaving CFPP-based randomized power management scheme operates formally as follows. When a station switches to the PS mode, it selects a line L_i randomly from $\mathscr{L}$ as the set of half-awake beacon intervals within a pattern repetition interval $\mathscr{R}$, where the CFPP $(U, \mathscr{L})$ is a global parameter. The remaining beacon intervals are all fully-sleep beacon intervals. It is worth noticing that the sequences of pattern repetition intervals are alternatively labelled as *forward* and *backward* pattern repetition intervals, as illustrated in Fig. 9(c). During the forward (backward) pattern repetition interval, all half-awake beacon intervals should be forward (backward) half-awake beacon intervals. Fig. 9(a) and (b) depict an example where PS station X schedules its awake/sleep patterns according to the interleaving CFPP-based scheme. Via the interleaving approach, we obtain a nearly 50% reduction in the radio active ratio (which will be defined in the next section) as compared with the naive CFPP-based scheme. The correctness of the interleaving CFPP-based scheme is given below.

Theorem 5. *The interleaving CFPP-based scheme guarantees that, if no collisions occur when receiving beacons, then any two PS neighbors, regardless of their clock difference, are able to discover each other in every other pattern repetition interval.*

Proof. See Appendix B. □

2.2.3. Power consumption analysis

Three yardsticks (beacon transmission ratio, radio active ratio, and neighbor discovery time) have been proposed in [22] to judge the goodness of the power management schemes for ad hoc networks. *Beacon transmission ratio* indicates the average number of beacons that a station needs to transmit in a beacon interval. *Radio active ratio* is defined as the ratio of the total time that a PS station turns its radio on in a pattern repetition interval to the length of the pattern repetition interval. Namely, radio active ratio denotes the proportion of time in a beacon interval that a station needs to stay awake when operating in the PS mode. *Neighbor discovery time* signifies the average time duration that a PS station takes to detect a neighboring station. Table 2 summarizes the characteristics of our proposed power management schemes and compares them to IEEE 802.11 and the most power-conserving scheme (grid quorum-based protocol) in [22]. The beacon transmission ratio of IEEE 802.11, $p(m)$, is equal to the probability that a station sends out its beacon frame in a beacon interval, where m is the number of contending stations in a single-hop cluster. The approximate value of $p(m)$ can be calculated as follows:

$$p(m) = \sum_{j=0}^{CW-1} \Pr[B = j](\Pr[B \geqslant j])^{m-1}$$
$$= \sum_{j=0}^{CW-1} \left(\frac{1}{CW+1}\right)\left(\frac{CW-j+1}{CW+1}\right)^{m-1}.$$

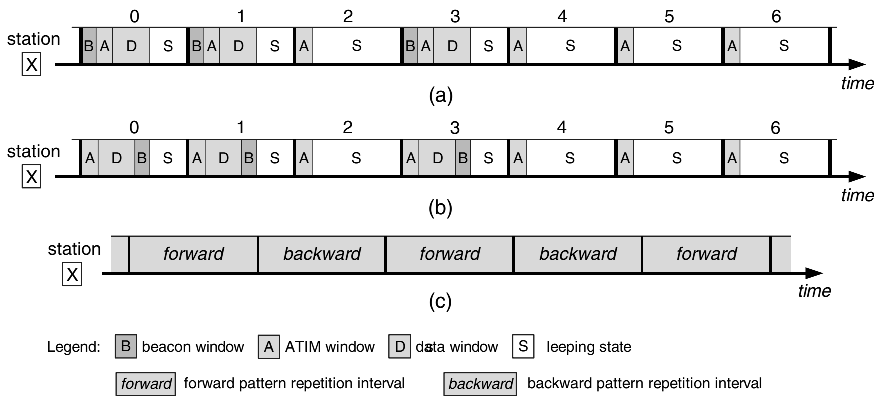

Fig. 9. With the PS mode enabled, station X chooses the line $L_0 = \{0, 1, 3\}$ from the CFPP of order 2 as the set of its half-awake beacon intervals. (a) The awake/sleep pattern in a forward pattern repetition interval. (b) The awake/sleep pattern in a backward pattern repetition interval. (c) The sequence of pattern repetition intervals.

Table 2
Comparison of power management schemes for an asynchronous MANET

Scheme	Beacon transmission ratio	Radio active ratio	Neighbor discovery time
IEEE 802.11 [12]	$p(m)$	$\frac{AW}{BI}$	∞
Grid quorum-based [22]	$\frac{2\sqrt{\mathscr{R}}-1}{\mathscr{R}}$	$\frac{2\sqrt{\mathscr{R}}-1}{\mathscr{R}}+\left(1-\frac{1}{\sqrt{\mathscr{R}}}\right)^2\left(\frac{AW}{BI}\right)$	$\frac{\mathscr{R}\times BI}{4}$
Randomized coterie-based	$\frac{k}{\mathscr{R}}$	$\frac{k}{\mathscr{R}}+\frac{\mathscr{R}-k}{\mathscr{R}}\left(\frac{AW}{BI}\right)$	$\frac{\mathscr{R}\times BI}{2\times P[\mathscr{R},k]}$
Naive CFPP-based	$\frac{1}{\sqrt{\mathscr{R}}}$	$\frac{1}{\sqrt{\mathscr{R}}}+\frac{\mathscr{R}-\sqrt{\mathscr{R}}}{\mathscr{R}}\left(\frac{AW}{BI}\right)$	$\frac{\mathscr{R}\times BI}{2}$
Interleaving CFPP-based	$\frac{1}{\sqrt{\mathscr{R}}}$	$\frac{1}{2\sqrt{\mathscr{R}}}+\frac{1}{\sqrt{\mathscr{R}}}\left(\frac{BW}{BI}\right)+\frac{\mathscr{R}-\sqrt{\mathscr{R}}}{\mathscr{R}}\left(\frac{AW}{BI}\right)$	$\mathscr{R}\times BI$

The neighbor sensitivity of IEEE 802.11 is infinitely large since any two PS neighbors never discover each other when their clock difference ΔT satisfies the inequality that $h\times BI+AW<\ \Delta T<(h+1)\times BI-AW$, where $h\geqslant 0$ is an integer.

Through the formulas we derived in Table 2, the settings $(\mathscr{R},k)$ of our schemes can be flexibly tuned at design time, positioning the network at the predictably desired operating point in the energy–delay-accuracy design space. Moreover, Table 2 reveals that decreased radio active ratio generally comes with a penalty of increased neighbor sensitivity. The authors in [13] argue that a good power management protocol ought to minimize *energy* $\times$ *delay* metric. We further argue that, under about the same bounded energy–delay product, a power management protocol with a smaller ratio active ratio is more suitable for energy-limited applications, in which the stations are subject to hard constraints on available battery energy. Clearly, IEEE 802.11 performs poorly in an asynchronous MANET because of its intolerably large neighbor sensitivity. Compared with the most energy-conserving scheme (grid quorum-based protocol) in [22], the interleaving CFPP-based scheme achieves a nearly 75% reduction in radio active ratio while keeping about the same *radio active ratio* $\times$ *neighbor discovery time*.

2.3. Data frame transfer procedure

This section presents how a station sends a directed data frame to a PS neighbor. Since the PS station is not always active, the sending station has to predict when the PS destination will wake up; i.e., the timings of the receiver's data windows or ATIM windows. To attain this goal, each beacon frame should contain a MAC address, a *timestamp*, *awake/sleep pattern number*, and other management parameters. The timestamp records the current time of the sending station and is used by a neighboring station to calculate their clock difference. We know that each station has its own line L_i. Thus, only i is sufficient for the PS station to convey its awake/sleep pattern. Only the interleaving CFPP-based scheme needs one more bit for judging whether the current pattern repetition interval is forward or backward. Table 3 summarizes the timings of data windows and ATIM windows in the proposed power management schemes, where a, b are integers and $a\geqslant 0$, $1\leqslant b\leqslant \mathscr{R}-1$. We assume that the PS station selects the set $\{\ell_1,\ldots,\ell_k\}$ ($\{\bar{\ell}_1,\ldots,\bar{\ell}_{\mathscr{R}-k}\}$) as its awake (sleep) beacon intervals in a pattern repetition interval.

Our directed data frame transfer procedure is similar to [12,22] and operates as follows. Assume that station X is intending to send a data frame to the PS neighbor Y. Once X has already received a beacon from Y, X can correctly predict Y's awake/sleep pattern according to Y's awake/sleep pattern bits and their clock difference. If Y's current data window does not expire, X can directly transmit a data frame to Y since Y is known in active state. Otherwise, X should buffer the data frame and wait for Y's data or ATIM window of the next beacon interval. During Y's data window, X can send a directed data frame to Y immediately. During Y's ATIM window, X sends a unicast ATIM frame to Y. Upon reception of X's ATIM frame, Y shall reply an ATIM-ACK and remain active for the entire beacon interval. After Y's ATIM window concludes, X begins to transmit the buffered data frame and Y has to acknowledge its re-

Table 3
Timing of data/ATIM windows of the proposed power management schemes

Scheme	Data windows's timing
Randomized coterie-based	$[(a\mathscr{R}+\ell_i)BI+BW,(a\mathscr{R}+\ell_i+1)BI]$
Naive CFPP-based	$[(a\mathscr{R}+\ell_i)BI+BW,(a\mathscr{R}+\ell_i+1)BI]$
Interleaving CFPP-based	
Forward awake interval	$[(a\mathscr{R}+\ell_i)BI+BW+AW,(a\mathscr{R}+\ell_i)BI+actW]$
Backward awake interval	$[(a\mathscr{R}+\ell_i)BI+AW,(a\mathscr{R}+\ell_i)BI+AW+DW]$
Scheme	**ATIM windows's timing**
Randomized coterie-based	$[(a\mathscr{R}+\bar{\ell}_i)BI,(a\mathscr{R}+\bar{\ell}_i)BI+AW]$
Naive CFPP-based	$[(a\mathscr{R}+\bar{\ell}_i)BI,(a\mathscr{R}+\bar{\ell}_i)BI+AW]$
Interleaving CFPP-based	
Forward awake interval	$[(a\mathscr{R}+\ell_i)BI+BW,(a\mathscr{R}+\ell_i)BI+BW+AW]$
Backward awake interval	$[(a\mathscr{R}+\ell_i)BI,(a\mathscr{R}+\ell_i)BI+AW]$
Fully-sleep interval	$[(a\mathscr{R}+\bar{\ell}_i)BI,(a\mathscr{R}+\bar{\ell}_i)BI+AW]$

ceipt. A PS station that neither transmits nor receives an ATIM frame during the ATIM window may enter the doze state after the end of the active window. Note that transmission of these frames except beacons shall be done using the normal DCF access procedure. Recall that beacon frames are delivered by our scalable beacon transfer procedure.

3. Performance evaluation

3.1. Simulation setup

We have developed an event-driven simulator to evaluate the performance of the proposed power management protocols and compare our results to the grid quorum-based protocol. The notation $(\mathscr{R},k)$ used in the simulation means that a station selects k fully-awake and $\mathscr{R}-k$ fully-sleep beacon intervals from a pattern repetition interval $\mathscr{R}$. In order to compare with the grid quorum-based protocol with $(\mathscr{R},k)=(16,7)$ in [22], we also set randomized coterie-based scheme with $(\mathscr{R},k)=(16,7)$; for the CFPP-based schemes, due to the constraint of Definition 3, we cannot choose $(\mathscr{R},k)=(16,7)$, so let $(\mathscr{R},k)=(13,4)$ which has the most closed ratio $k/\mathscr{R}=7/16$ of the grid quorum-based protocol. Each simulation run is executed for a duration of 30×10^7 µs in a single-hop ad hoc network with 30 (70 for Fig. 12) mobile stations and each receiver of each frame is randomly selected from the sender's discovery neighbors. Note that, in such a dense network, the out of synchronization phenomenon easily arises [10]. Hence we assume that the clock difference between any two stations ranges from 0 to 1000 µs. Initially, all stations are in the PS mode. However, once a PS station has a data frame to transmit, that station will switch to the active mode and remains awake until it successfully sends out the pending frame or until it drops that frame when the DCF retry limit is reached. We assume that the arrival of data frames from higher-layer to MAC sublayer at each PS station follows the Poisson distribution with mean rate λ between 0.1 and 10 frames/sec/station. The energy consumption model shown in Table 4 adopts the specifications suggested in [6], which are obtained by real experiments on Lucent WaveLAN IEEE 802.11 cards. Notice that, when sending a frame

Table 4
Energy consumption parameters used in the simulations

Parameter	Value
Unicast send	$420+1.9\times$ bytes (µJ)
Unicast receive	$330+0.42\times$ bytes (µJ)
Broadcast send	$250+1.9\times$ bytes (µJ)
Broadcast receive	$56+0.5\times$ bytes (µJ)
Idle	808 mW
Doze	27 mW

Table 5
System parameters used in the simulations

Parameter	Value
Channel bit rate	2 Mbps
Beacon window	10 ms
ATIM window	20 ms
DIFS	50 μs
PIFS	30 μs
SIFS	10 μs
Slot time	20 μs
Data frame size	2048 bytes
Beacon frame size	61 bytes
ATIM frame size	28 bytes
Data/ATIM-ACK frame size	14 bytes

of the same size, unicast consumes more energy than broadcast since it requires extra cost to handle RTS, CTS, and ACK frames. The system parameter values are summarized in Table 5.

3.2. Beacon energy consumption

From Table 4, we notice that the energy cost of beacon broadcast is relatively expensive since its fixed cost (send: 250 μJ. receive: 56 μJ.) is much greater than the incremental cost of sending or receiving (send: 1.9×61 μJ. receive: 0.5×61 μJ.) In addition, the total cost of receiving beacon is much greater than the cost of sending beacon since the simulated network is dense. Hence we first evaluate the average beacon energy consumption in a beacon interval during the entire simulation time when using different power management protocols. Since we focus on beacon energy consumption, the arrival rate λ is set to 0.1 (frames/sec/station) the lowest data traffic in our simulations. Fig. 10 presents the average beacon energy consumption in a beacon interval. The results show that, in each protocol, the average beacon energy consumption is almost the same no matter how BI is varied. The reason is that only the beacon transfer procedure and the number of stations in a beacon can affect the average beacon energy consumption. We further observe that, under the same BI, the average beacon energy consumption of the four protocols is interleaving CFPP-based ≅ naive CFPP-based < randomized coterie-based < grid quorum-based. There are two factors which may cause the above consequence: one is radio active ratio, the other is beacon transfer procedure. Because of using our scalable beacon transfer procedure, all of our protocols with different schemes are less than grid quorum-based. Although our three schemes have the same beacon transfer procedure, the interleaving CFPP-based and naive CFPP-based scheme have the lower radio active ratio than the randomized coterie-based scheme so the interleaving CFPP-based ≅ naive CFPP-based < randomized coterie-based.

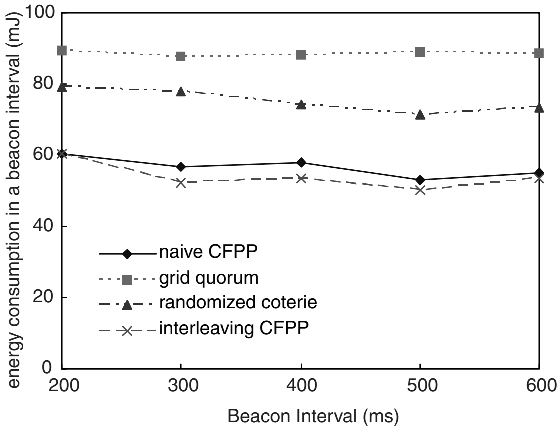

Fig. 10. Average beacon energy consumption in a beacon interval versus different beacon interval length ($\lambda = 0.1$ frames/sec/station).

3.3. Neighbor discovery time

Fig. 11 reports the neighbor discovery time versus the beacon interval length when data traffic load is fixed at $\lambda = 0.1$ frames/sec/station. As expected, the neighbor discovery time increases as the beacon interval enlarges. However, the grid quorum-based protocol has smoother curves than CFPP-based protocols. Specifically, we find that the neighbor discovery time of CFPP-based protocols grow more suddenly and rapidly. The reasons are as follows. In an asynchronous MANET, a PS station may not hear neighbors' beacons because (i) beacon collisions occur, or (ii) that PS station is sleeping when the beacon frame is being broadcast. However, such events occur less frequently in the grid quorum-based protocols. This may be

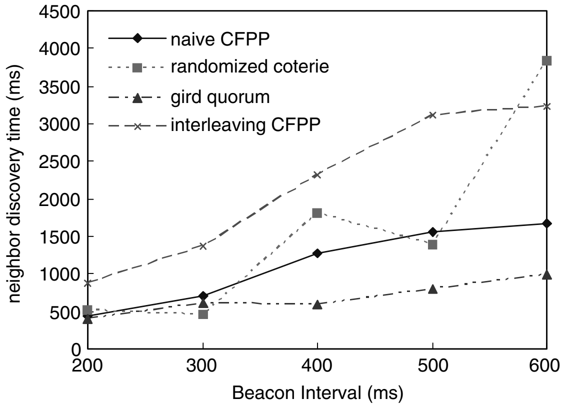

Fig. 11. Neighbor discovery time versus different beacon interval (total 30 mobile stations and $\lambda = 0.1$ frames/sec/station).

because it has double radio active ratio and its fully-awake beacon intervals spread more uniformly in a pattern repetition interval. Furthermore, because of the nature of random in random-coterie scheme, we do not guarantee that any two stations have an meet in a given time period. Therefore, the line in random-coterie protocol presents an unpredictable trend.

In order to see that if the traffic load will affect neighbor discovery time, we increase total mobile station number to 70 and Fig. 12 illustrates the result. We have two observations as follows. First, more stations cause more beacon frame collisions so that all presented protocols need more time to discover all neighbors in the MANET. Second, the grid quorum-based still has better performance because, comparing with CFPP-based protocols, nodes have more fully-awake time and two times to meet other nodes' beacon frames in a pattern repetition interval $\mathcal{R}$. According to Figs. 10–12, they tell us that there is tradeoff between power saving and neighbor discovery time in designing an energy efficient protocol.

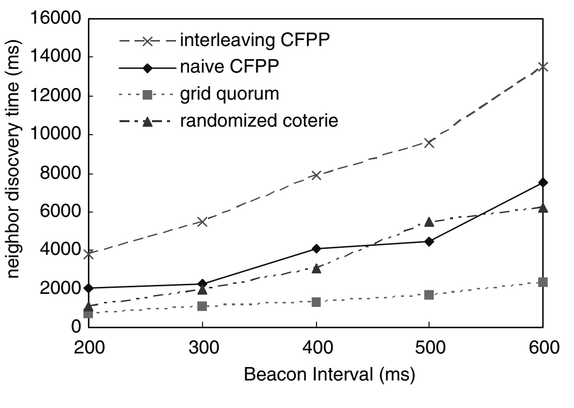

Fig. 12. Neighbor discovery time versus different beacon interval (total 70 mobile stations and $\lambda = 0.1$ frames/sec/station).

3.4. Throughput

Since the data frame length is fixed, the throughput could be defined as the average number of data frames successfully sent by all stations per second. Definitely, a good power management protocol ought to minimize the power consumption while not remarkably degrading the throughput. Fig. 13 compares the throughput performances of different power management protocols under various data load when beacon interval = 300 ms. Generally, all of these protocols are the same trend that, as the data load increases, the throughput generally increases monotonically and is finally saturated at a certain point. Compared with the grid quorum-based

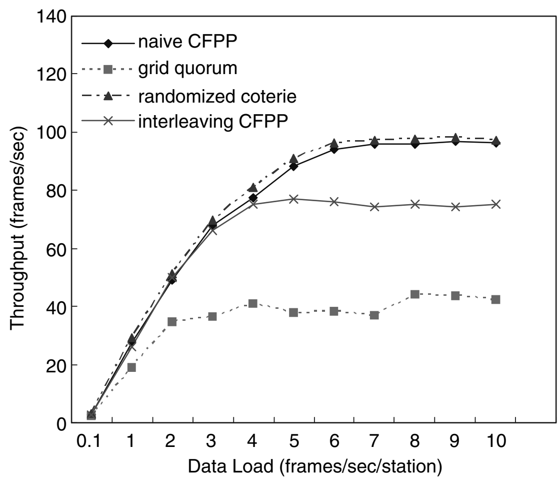

Fig. 13. Throughput versus data load (beacon interval = 300 ms).

protocol, which saturates at about $\lambda = 4$ frames/sec/station, the naive CFPP-based protocol saturates at about $\lambda = 6$ frames/sec/station. Also, the naive CFPP-based protocol can deliver a throughput almost 2.5 times than the grid quorum-based protocol when $6 \leqslant \lambda \leqslant 10$. Although the grid quorum-based and randomized coterie-based protocol have the same beacon transmission ratio and radio active ratio, the gap between their throughput performances is quite large. This is mainly because, in the grid quorum-based protocol, transmitting a data frame to a PS station requires a prior ATIM/ATIM-ACK frame exchange; however, in the randomized coterie-based protocol, if source station perceives that the PS destination is currently in the fully-awake beacon interval, then it will directly issue the data frame via DCF without first performing an ATIM/ATIM-ACK frame exchange. By this way, we can reduce a significant control frame overheads especially when data load is heavy.

In addition, we also notice that the throughput of randomized coterie-based is little better than naive CFPP-based. It is because although randomized coterie-based protocol has to send more beacons than CFPP-based protocols, the more fully-awake periods also let nodes don't need to send/receive ATIM frames before sending/receiving data frames. Therefore, they have almost the same performance. When $\lambda > 4$, interleaving CFPP-based protocol obviously performs worse than the randomized coterie-based and naive CFPP-based protocol since the former consumes some overhead in ATIM/ATIM-ACK transmissions.

3.5. Energy-based throughput

The energy-based throughput is defined as the amount of successful data delivered per Joule of energy. It is obtained by dividing the total number of data frames successfully sent by total energy consumption over all stations during the entire simulation time. Using the energy-based throughput to judge the goodness of a power management protocol is much fairer than using the total energy consumption since some power management protocols may consume very little energy, but also achieve very little throughput. Fig. 14 shows the energy-based throughput performances of different power management protocols under various data load when beacon interval = 300 ms. The figure shows that all of our protocols have the better performance and especially when the traffic load λ is higher than 6 frames/sec/station, the randomized coterie-based can outperform the grid quorum-based about three times. This is because our protocols possess the superior throughput and the less power consumption overhead in ATIM/ATIM-ACK traffic. We also notice that, when $\lambda \leqslant 4$, the interleaving CFPP-based protocol outperforms the naive CFPP-based protocol. This is because when data load is slight, almost all generated data frames can be successfully delivered both in naive and interleaving CFPP-based protocols. However, in this case, the radio active ratio of the interleaving CFPP-based protocol is only about half that of the naive CFPP-based protocol.

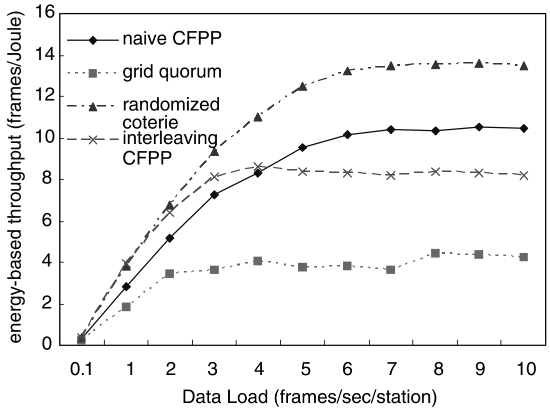

Fig. 14. Energy-based throughput versus data load (beacon interval = 300 ms).

4. Conclusions

Currently, IEEE 802.11 wireless LAN cards are greatly popular on the market. However, when IEEE 802.11 power management protocol operates in a large-scale ad hoc wireless network, it will face three severe challenges: beacon contention, clock synchronization, and reliable neighbor maintenance. To conquer all these challenges, we propose the novel asynchronous power management protocols, which consist of three key components: the scalable beacon transfer procedure, the energy-conserving neighbor maintenance schemes, and the energy-efficient data frame transfer procedure. The scalable beacon transfer procedure offer a high success probability of a beacon broadcast, regardless of the number of contending stations, thus alleviating the beacon contention problem significantly. The energy-conserving neighbor maintenance schemes ensure that any two PS neighbors are able to discover each other (via beacon frames) in finite time with high probability, no matter how much time their clocks drift away. The energy-efficient data frame transfer procedure provides the high energy efficiency as well as good network throughput.

Attractively, our power management protocols offer the network designers full flexibility in trading energy, latency, and neighbor maintenance's accuracy versus each other by appropriately tuning system parameters. In comparison with the grid quorum-based protocol, our cyclic finite projective plane-based protocol also guarantees a 100% neighbor discovery probability while achieving a nearly 75% reduction in radio active ratio under about the same energy–delay product. Accordingly, the CFPP-based protocols are very suitable for energy-limited applications. Extensive simulation results do confirm that our protocols much outperform the grid quorum-based protocol especially in terms of time-based throughput and energy-based throughput.

Acknowledgment

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Appendix A. Proof of Corollary 1

To prove Corollary 1, we claim that, when $k = \beta\sqrt{\mathscr{R}}$ and $\beta \geqslant 1$, the following inequality holds:

$$\frac{\binom{\mathscr{R}}{k}\binom{\mathscr{R}-k}{k} + \binom{\mathscr{R}}{1}\binom{\mathscr{R}-2}{k-1}\binom{\mathscr{R}-k-1}{k-1}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k}} \leqslant (1+\beta^2)\mathrm{e}^{-\beta^2}. \tag{A.1}$$

For the proof, we take advantage of the following well-known results [14,17].

Lemma A.1. *For integers n, c, and i,*

$$\frac{\binom{n-c}{c-i}}{\binom{n}{c}} \leqslant \left(\frac{c}{n}\right)^{i}\left(\frac{n-c}{n-i}\right)^{c-i}.$$

Lemma A.2. *For every positive constant c $(0 < c < n)$, the sequence $(1 - c/n)^n)$ is monotonically increasing and*

$$\lim_{n\to\infty}\left(1-\frac{c}{n}\right)^{n} = \frac{1}{\mathrm{e}^{c}}.$$

Applying Lemmas A.1 and A.2 to the first term in the left hand side of (A.1), we have

$$\begin{aligned}\frac{\binom{\mathscr{R}-k}{k}\binom{\mathscr{R}}{k}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k}} &\leqslant \left(\frac{\mathscr{R}-k}{\mathscr{R}}\right)^{k} \\ &= \left(1-\frac{\beta\sqrt{\mathscr{R}}}{\mathscr{R}}\right)^{\beta\sqrt{\mathscr{R}}} \leqslant \mathrm{e}^{-\beta\sqrt{\mathscr{R}}\times\left(\beta\sqrt{\mathscr{R}}/\mathscr{R}\right)} \\ &= \mathrm{e}^{-\beta^2}.\end{aligned} \tag{A.2}$$

On the other hand,

$$\begin{aligned}\frac{\binom{\mathscr{R}-k-1}{k-1}}{\binom{\mathscr{R}}{k}} &= \frac{\binom{\mathscr{R}-k}{k-1}}{\binom{\mathscr{R}}{k}} \times \left(\frac{\mathscr{R}-2k+1}{\mathscr{R}-k}\right) \\ &\leqslant \left(\frac{k}{\mathscr{R}}\right)\left(\frac{\mathscr{R}-k}{\mathscr{R}-1}\right)^{k-1}\left(\frac{\mathscr{R}-2k+1}{\mathscr{R}-k}\right) \\ &\leqslant \left(\frac{k}{\mathscr{R}}\right)\left(\frac{\mathscr{R}-k}{\mathscr{R}-1}\right)^{k}.\end{aligned} \tag{A.3}$$

The first inequality in (A.3) follows from Lemma A.1; the second inequality in (A.3) is due to

$$\frac{\mathscr{R}-2k+1}{\mathscr{R}-k} \leqslant \frac{\mathscr{R}-2k+1+(k-1)}{\mathscr{R}-k+(k-1)} = \frac{\mathscr{R}-k}{\mathscr{R}-1}.$$

Combining (A.3), Lemma A.2, and the fact that

$$\frac{\binom{\mathscr{R}-2}{k-1}}{\binom{\mathscr{R}}{k}} = \frac{k(\mathscr{R}-k)}{\mathscr{R}(\mathscr{R}-1)},$$

we have

$$\begin{aligned}
&\frac{\binom{\mathscr{R}}{1}\binom{\mathscr{R}-2}{k-1}\binom{\mathscr{R}-k-1}{k-1}}{\binom{\mathscr{R}}{k}\binom{\mathscr{R}}{k}} \\
&\quad \leqslant \frac{k^2}{\mathscr{R}} \times \left(\frac{\mathscr{R}-k}{\mathscr{R}-1}\right)^{k+1} \\
&\quad \leqslant \frac{k^2}{\mathscr{R}} \times \left(\mathrm{e}^{k-1}\right)^{((k+1)/(\mathscr{R}-1))} \\
&\quad \leqslant \beta^2 \mathrm{e}^{-\left((\beta^2\mathscr{R}-\beta^2)/(\mathscr{R}-1)\right)} \\
&\quad = \beta^2 \mathrm{e}^{-\beta^2}. \qquad \text{(A.4)}
\end{aligned}$$

Consequently, (A.2) and (A.4) combined lead to the inequality (A.1).

Appendix B. Correctness of the interleaving CFPP-based protocol

We prove the correctness of the Interleaving CFPP-based protocol by showing that any two PS neighbors, X and Y, are able to discover each other, regardless of their clock difference. We assume that X and Y randomly choose two lines L_x and L_y respectively from the same CFPP $(U, \mathscr{L})$ as the set of their half-awake beacon intervals in a pattern repetition interval, and $\mathscr{R} = n^2 + n + 1$. Let $actW = BI/2 + BW$. Without loss of generality, we can assume that X's clock is faster than Y's clock by $\Delta T = h \times BI + \Delta t$, where $0 \leqslant \Delta t < BI$ and $h \geqslant 0$ is an integer. In the following derivation, we use X's clock as a reference clock to derive Y's clock. We claim that at least one X's entire beacon window is fully covered by one Y's active window within two consecutive pattern repetition intervals, and vice versa. Note that other cases can be derived via the similar way. The analysis is divided into two cases.

Case 1: $0 \leqslant \Delta t < BI/2$. As illustrated in Fig. 15(a), X can receive Y's beacons in Y's forward pattern repetition interval if and only if (i) both $\langle i \rangle_X$ and $\langle i \ominus h \rangle_Y$ are half-awake beacon intervals, for some $0 \leqslant i \leqslant \mathscr{R}-1$, and (ii) the beacon window in $\langle i \ominus h \rangle_Y$ begins later than the start of the active window in $\langle i \rangle_X$, and terminates earlier than the end of the active window in $\langle i \rangle_X$. In other words, $t_1 \leqslant t_2$ and $t_3 \leqslant t_4$. Since $L_x \cap \{-h \oplus L_y\} \neq \emptyset$, there must exist an element i such that $i \in L_x$ and $i \in \{-h \oplus L_y\}$. This implies that both $\langle i \rangle_X$ and $\langle i \ominus h \rangle_Y$ are half-awake beacon intervals. Without loss of generality, we can assume that $t_1 = a\mathscr{R} \times BI + (i-1) \times BI$, where $a \geqslant 0$ is an integer. Hence, $t_1 \leqslant t_1 + \Delta t = a\mathscr{R} \times BI + (i-1) \times BI +$

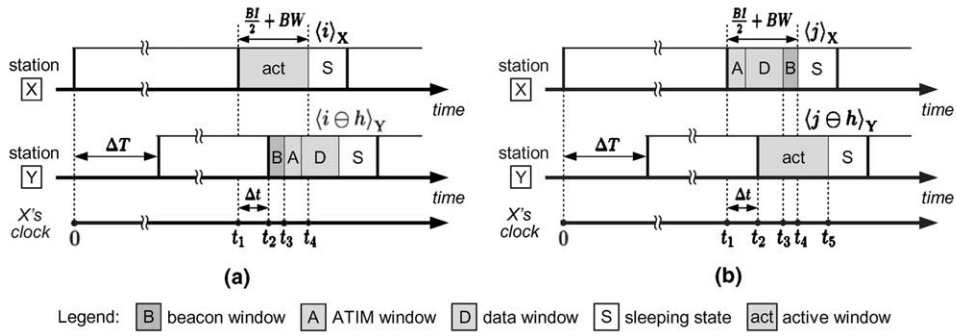

Fig. 15. The case that $0 \leqslant \Delta t < BI/2$. (a) For PS station Y, one of its beacon windows in a forward pattern repetition is fully covered by the X's active window. (b) For PS station X, one of its beacon windows in a backward pattern repetition is fully covered by the Y's active window.

$\Delta t = a\mathscr{R} \times BI + (i-h-1) \times BI + h \times BI + \Delta t = a\mathscr{R} \times BI + (i-h-1) \times BI + \Delta T = t_2$. In addition, $t_3 = t_2 + BW = a\mathscr{R} \times BI + (i-h-1) \times BI + \Delta T + BW = a\mathscr{R} \times BI + (i-h-1) \times BI + h \times BI + \Delta t + BW < a\mathscr{R} \times BI + (i-1) \times BI + (BI/2 + BW) = t_4$.

On the other hand, as depicted in Fig. 15(b), X's beacons can be received by Y in X's backward pattern repetition interval if and only if (i) both $\langle j \rangle_X$ and $\langle j \ominus h \rangle_Y$ are half-awake beacon intervals, for some $0 \leqslant j \leqslant \mathscr{R} - 1$, and (ii) the beacon window in $\langle j \rangle_X$ begins later than the start of the active window in $\langle j \ominus h \rangle_Y$, and terminates earlier than the end of the active window in $\langle j \ominus h \rangle_Y$. That is, $t_2 \leqslant t_3$ and $t_4 \leqslant t_5$. Since $L_x \cap \{-h \oplus L_y\} \neq \emptyset$, there must exist an element j such that $j \in L_x$ and $j \in \{-h \oplus L_y\}$. This implies that both $\langle j \rangle_X$ and $\langle j \ominus h \rangle_Y$ are half-awake beacon intervals. Besides, $t_1 = b\mathscr{R} \times BI + (j-1) \times BI$, where $b \in \{a-1, a, a+1\}$. Hence, $t_2 = b\mathscr{R} \times BI + (j-h-1) \times BI + \Delta T = b\mathscr{R} \times BI + (j-h-1) \times BI + h \times BI + \Delta t < b\mathscr{R} \times BI + (j-1) \times BI + BI/2 = t_3$. $t_4 = t_1 + BI/2 + BW \leqslant t_1 + BI/2 + BW + \Delta t = b\mathscr{R} \times BI + (j-1) \times BI + BI/2 + BW + \Delta t = b\mathscr{R} \times BI + (j-h-1) \times BI + BI/2 + BW + (h \times BI + \Delta t) = b\mathscr{R} \times BI + (j-h-1) \times BI + BI/2 + BW + \Delta T = t_5$.

Case 2: $BI/2 \leqslant \Delta t < BI$. Let $\Delta t = BI/2 + \Delta d$ and $0 \leqslant \Delta d < BI/2$. As illustrated in Fig. 16(a), X can receive Y's beacons in Y's backward pattern repetition interval if and only if (i) both $\langle i' \rangle_X$ and $\langle i' \ominus (h+1) \rangle_Y$ are half-awake beacon intervals, for some $0 \leqslant i' \leqslant \mathscr{R} - 1$, and (ii) the beacon window in $\langle i' \ominus (h+1) \rangle_Y$ begins later than the start of the active window in $\langle i' \rangle_X$, and terminates earlier than the end of the active window in $\langle i' \rangle_X$. In other words, $t_3 \leqslant t_4$ and $t_5 \leqslant t_6$. Since $L_x \cap \{-(h+1) \oplus L_y\} \neq \emptyset$, there must exist an element i' such that $i' \in L_x$ and $i' \in \{-(h+1) \oplus L_y\}$. This implies that both $\langle i' \rangle_X$ and $\langle i' \ominus (h+1) \rangle_Y$ are half-awake beacon intervals. Besides, $t_1 = c\mathscr{R} \times BI + (i'-1) \times BI$, where $c \in \{a-1, a+1\}$. Hence, $t_3 = c\mathscr{R} \times BI + (i'-1) \times BI \leqslant c\mathscr{R} \times BI + (i'-1) \times BI + \Delta d = c\mathscr{R} \times BI + (i'-h-2) \times BI + (h \times BI + BI/2 + \Delta d) + BI/2 = c\mathscr{R} \times BI + (i'-1) \times BI + \Delta T + BI/2 = t_4$. $t_5 = c\mathscr{R} \times BI + (i'-h-2) \times BI + BI/2 + BW + \Delta T = c\mathscr{R} \times BI + (i'-h-2) \times BI + BI/2 + BW + (h \times BI + BI/2 + \Delta d) < c\mathscr{R} \times BI + (i'-1) \times BI + BI/2 + BW = t_6$.

On the other hand, as depicted in Fig. 16(b), X's beacons can be received by Y in X's forward pattern repetition interval if and only if (i) both $\langle j' \rangle_X$ and $\langle j' \ominus (h+1) \rangle_Y$ are half-awake beacon intervals, for some $0 \leqslant j' \leqslant \mathscr{R} - 1$, and (ii) the beacon window in $\langle j' \rangle_X$ begins later than the start of the active window in $\langle j' \ominus (h+1) \rangle_Y$, and concludes earlier than the end of the active window in $\langle j' \ominus (h+1) \rangle_Y$. That is, $t_2 \leqslant t_3$ and $t_4 \leqslant t_5$. Since $L_x \cap \{-(h+1) \oplus L_y\} \neq \emptyset$, there must exist an element j' such that $j' \in L_x$ and $j' \in \{-(h+1) \oplus L_y\}$. This implies that both $\langle j' \rangle_X$ and $\langle j' \ominus (h+1) \rangle_Y$ are half-awake beacon intervals. Besides, $t_1 = d\mathscr{R} \times BI + (j'-1) \times BI$, where $d \in \{a-1, a, a+1\}$. Thus, $t_2 = d\mathscr{R} \times BI + (j'-h-2) \times BI + \Delta T = d\mathscr{R} \times BI + (j'-h-2) \times BI + (h \times BI + \Delta t) < d\mathscr{R} \times BI + (j'-h-2) \times BI + h \times BI + BI = d\mathscr{R} \times BI + (j'-1) \times BI = t_3$. $t_4 = t_3 + BW \leqslant t_3 + BW + \Delta d = d\mathscr{R} \times BI + (j'-1) \times BI + BW + \Delta d = d\mathscr{R} \times$

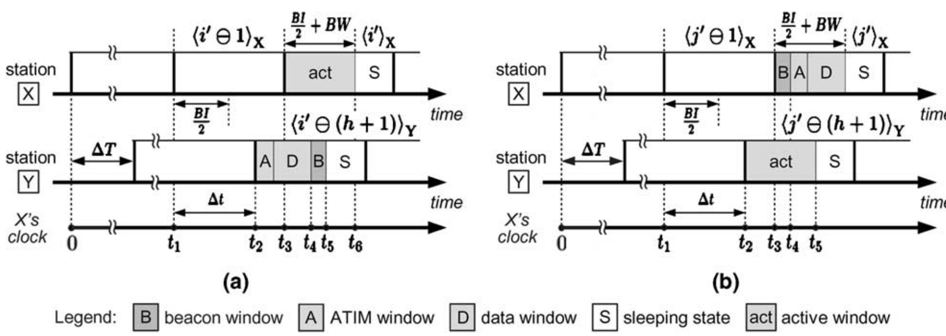

Fig. 16. The case that $BI/2 \leqslant \Delta t < BI$. (a) For PS station Y, one of its beacon windows in a backward pattern repetition is fully covered by the X's active window. (b) For PS station X, one of its beacon windows in a forward pattern repetition is fully covered by the Y's active window.

$BI + (j' - h - 2) \times BI + BI/2 + BW + (h \times BI + BI/2 + \Delta d) = d\mathscr{R} \times BI + (j' - h - 2) \times BI + BI/2 + BW + \Delta T = t_5$.

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Shih-Lin Wu received the BS degree in Computer Science from Tamkang University, Taiwan, in June 1987 and the PhD degree in Computer Science and Information Engineering from National Central University, Taiwan, in May 2001. From August 2001 to July 2003, he was the faculty of the Department of Electrical Engineering, Chang Gung University, Taiwan, as an Assistant Professor. Since August 2003, he has been with the department of Computer Science and Information Engineering, Chang Gung University. His current research interests include mobile computing, wireless networks, distributed robotics, and network security. He is a member of the IEEE Communication Society and the Phi Tau Phi Society.

Pao-Chu Tseng received the BS degree in electronic engineering, from Chung Yuan Christian University, Taiwan, Republic of China, in 1998, and the MS degree in Chang Gung University, Taiwan, Republic of China, in 2004. When she was in graduate school, her research focuses on power saving and reliable broadcast in wireless environment.

Zi-Tsan Chou earned the BS degree in Applied Mathematics from National Cheng-Chi University in 1993, the MBA degree in Information Management from National Taiwan University of Science and Technology in 1995, and the PhD degree in Computer Science and Information Engineering from National Taiwan University in 2003. He is currently a senior engineer and section manager of Network and Multimedia Institute at Institute for Information Industry in Taiwan. His research interests include MAC protocols, mobility management, and multimedia applications for wireless Internet. He received the Innovative and Prospective Technology Award of III in 2004. He is a member of IEEE Communication Society.