An Adaptive Quorum-Based Energy Conserving Protocol for IEEE 802.11 Ad Hoc Networks

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Abstract—The lifetime of a *mobile ad hoc network* (MANET) depends on the durability of the mobile hosts' battery resources. In the IEEE 802.11 *Power Saving Mode*, a host must wake up at every beacon interval, to check if it should remain awake. Such a scheme fails to adjust a host's sleep duration according to its traffic, thereby reducing its power efficiency. This paper presents new MAC protocols for power saving in a single hop MANET. The essence of these protocols is a *quorum-based* sleep/wake-up mechanism, which conserves energy by allowing the host to sleep for more than one beacon interval, if few transmissions are involved. The proposed protocols are simple and energy-efficiency. Simulation results showed that our protocols conserved more energy and extended the lifetime of a MANET.

Index Terms—Access schemes, data communications, mobile communication systems, wireless communication.

1 Introduction

A *mobile ad hoc network* (MANET) is formed by a cluster of mobile hosts without any predesigned base station infrastructure. A host in a MANET can roam and communicate with other hosts at will. Two hosts may communicate with each other either directly (if they are close enough) or indirectly, through intermediate mobile hosts that relay their packets, because of transmission power limitations. If all hosts are within each other's transmission range, they form a single hop MANET. The protocols proposed in this paper operate in a single hop MANET. One of the main advantages of a MANET is that it can be rapidly deployed since no base station or fixed network infrastructure is required. A MANET can be deployed, even where predeployment of a network infrastructure is difficult or impossible (for example, in open air teaching, festival grounds, and historic sites).

One critical issue for a MANET is *power saving*, as a host is useless without power. The battery of a host can provide only limited energy; thus, the design of an energy-efficient protocol for hosts is important for the operation of a MANET. Many power saving protocols have recently been proposed for wireless networks. According to operation layer, they are classified into *medium access control* (MAC) layer protocols [5], [6], [13], [23], [24], routing layer protocols [7], [8], [26], and transport layer protocols [4], [27]. Most MAC layer power saving protocols focus on improvement of the *ATIM (Ad hoc Traffic Indication Message)* window, either by adjusting the length of the ATIM window [13] or by proposing a new access mechanism [23]. The protocols proposed in this paper are also MAC layer protocols. A more detailed description of previous works can be found in Section 3. Routing layer power saving protocols concentrate on finding the path with minimum power consumption [8], or on maintaining minimum power transmission [26]. Transport layer energy-efficient protocols try to reduce power consumption by reducing retransmitting packets [4].

A wireless interface card can exist in one of three states: *awake*, *doze*, or *off*. In the awake state, a host is fully powered and can be in transmit, receive, or idle modes, each with different degrees of power consumption. In the doze state, a host is in sleep mode, unable to transmit or receive packets, with very low power consumption when compared to an active mode; in the doze state, a host can switch to the awake state within 250 μs (for WaveLan-II PCMCIA card [14]). In the off state, the transceiver of a host is turned off and consumes no power. The power consumption of the Lucent IEEE 802.11 WaveLan card, for Transmit, Receive, Idle, and Sleep modes, is 284, 190, 156, and 10 mA, respectively. It is obvious that when a host is not involved in transmission, it should remain in the sleep mode to conserve energy.

The IEEE 802.11 standard defines two mechanisms to access a channel: Distributed Coordinated Function (DCF) and Point Coordinated Function (PCF). The DCF is a contention-based scheme, which uses CSMA/CA as the access mechanism and is a fully distributed protocol. The PCF is a contention-free scheme, which uses an *access point* (AP) as the coordinator and is a centralized protocol. In this paper, we consider the power saving mechanism of the DCF operation.

In the IEEE 802.11 *Power Saving Mode* (PSM) [12], each host is assumed to be synchronized with the others. Time is divided into a series of *beacon intervals*. At the beginning of each beacon interval, each host must stay awake for a certain period of time, called the ATIM window. The ATIM window is the time period used by hosts to announce to those in the doze state that there are packets pending. A host will listen to these announcements to determine if it needs to remain in the awake state. Such a scheme fails to adjust a host's sleep duration according to its traffic

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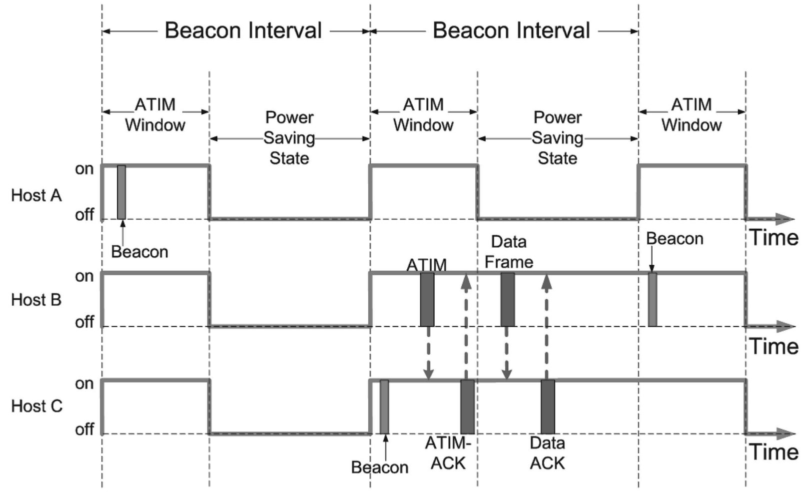


Fig. 1. Power saving mechanism in IEEE 802.11 DCF.

conditions. For example, it is reasonable for a host, with many packets to transmit/receive, wakes up frequently to accomplish data transmissions. On the other hand, when a host has only a few packets to transmit/receive, its sleep duration can be longer, in order to conserve energy. Prolonging sleep duration may reduce energy consumption; however, it can also incur a longer delay. In this paper, we have investigated the possibility of making a tradeoff between the latency and awake time of a host, where the host wakes up less frequently (sleeps during consecutive intervals) with a small increase in latency, in order to conserve energy.

We propose quorum-based protocols that extend the battery lifetime of a host, by allowing the device to sleep during successive beacon intervals. Inheriting the characteristics of a quorum, the hosts are guaranteed to be awake during some concurrent beacon intervals. Our basic idea was to extend the sleep duration of a host, in order to conserve energy, while at the same time increasing the latency. Wake up frequency is usually determined by the traffic load of a host. With a different quorum size, we can balance the power efficiency and increase in latency.

The rest of this paper is organized as follows: Preliminaries are presented in Section 2. Section 3 reviews related works. Section 4 describes the details of the proposed quorum-based power-saving protocols. Simulation results are presented in Section 5. Conclusions are drawn in Section 6.

2 Preliminaries

We made the assumption that all hosts were time synchronized and operated in a fully connected manner, the same as in IEEE 802.11 PSM.

2.1 Power Saving Modes in IEEE 802.11 DCF

As mentioned earlier, time is divided into consecutive beacon intervals. At the beginning of each beacon interval, hosts will contend to send a beacon frame, which is used for clock synchronization. Each host generates a random delay and waits for the duration of that delay. A host will cancel the random delay timer before it has expired, if a beacon is received from another host. Otherwise, it will send a beacon when the random delay timer has expired. A host operating in IEEE 802.11 PSM can either be in the awake mode or the sleep mode. The host is fully powered in the awake mode and, thus, can transmit or receive at any time, whereas when a host is in the sleep mode, it cannot transmit/receive packets. A host must be awake during the ATIM window, which is located at the beginning of every beacon interval, to check if it has any pending packets. If so, the host must remain awake for the remainder of the time. A host with packets pending for another host must first make an announcement during the ATIM window. This announcement is accomplished by sending an ATIM frame. Each host monitors these announcements to decide whether it should stay awake for the remainder of the beacon interval. Upon receiving an ATIM frame, the receiving host must reply with an ATIM-ACK frame. A host who does not receive an ATIM frame can switch to sleep mode at the end of the ATIM window. Actual data transfer is accomplished after the ATIM window. Fig. 1 illustrates this IEEE 802.11 PSM. In the first beacon interval, host A has successfully broadcast a beacon. After the ATIM window, all hosts switched to sleep mode, since no host had to transmit packets. In the second beacon interval, after host C had broadcast a beacon, host B sent an ATIM frame to host C during the ATIM window and received an ATIM-ACK frame from host C as the acknowledgement. Hosts B and C both remained awake for the entire beacon interval. After the ATIM window, host B started its data transmission to host C.

2.2 Problem Statement

A host in the IEEE 802.11 PSM must wake up at every beacon interval and stay awake for the duration of the ATIM window. After this, it can switch to sleep mode if it does not have to transmit/receive. If a host is an infrequent sender/receiver, having no need to participate in transmission for several successive beacon intervals, such frequent doze-to-awake and awake-to-doze switches can induce an excess amount of unnecessary energy consumption. Furthermore, the IEEE 802.11 PSM defines fixed values for the ATIM window (usually one-fifth of the beacon interval) and the beacon interval (usually 0.1 or 0.2 second), meaning that the sleep duration for a host is also fixed and the host cannot adjust its sleep duration according to its traffic condition.[1] To solve the power inefficiency problem of IEEE 802.11 PSM, an intuitive solution would be to allow a host to sleep longer when its traffic load is lighter. However, without proper control of sleep duration, two hosts may not wake up at the same time in order to achieve data communication. That is, a protocol that can not only achieve power saving but also guarantee data transmission must be provided to solve the power inefficiency problem. In addition, hosts running IEEE 802.11 PSM may incur many unsuccessful beacon transmissions, which result from excessive contentions, hence inducing extra power consumption. Increasing a host's sleep duration also helps to reduce the contention probability.

3 Related Works

In DPSM [13], each host chooses its ATIM window size dynamically, based on observed network conditions. A host may use any ATIM window size in a finite set of allowable values, specified in advance. A DPSM defines rules for increasing and decreasing the ATIM window size. Initially, each host will use the smallest ATIM window size. A host will increase this size to the next higher value in the allowable set if any of the increasing rules are satisfied. Similarly, the ATIM window size will be reduced to the next lower value if the decreasing rule is satisfied. Basically, the DPSM is an improvement over the IEEE 802.11 PSM. The dynamic window size can enhance throughput and energy efficiency. However, a host running DPSM must still be awake for every beacon interval, which results in the same unnecessary energy consumption for light-load hosts, as found in the IEEE 802.11 PSM.

Span [8] is another energy saving protocol. In Span, each host switches between assuming a coordinator or noncoordinator, according to a "coordinator eligibility rule." Span coordinators stay awake continuously to perform packet routing while Span noncoordinators follow an IEEE 802.11 PSM type operation: Hosts with buffered packets make ATIM announcement during the ATIM window. In this scheme, hosts still must periodically wake up to check if they have any packets pending.

Several power saving protocols, designed for multihop MANETs, can be found in Tseng et al. [23]. These protocols consider an environment where no clock synchronization mechanism is available. Hosts with unsynchronized ATIM windows may wake up at different times, in which case the IEEE 802.11 standard power saving mechanism may not work well. Much effort has been invested to overcome this asynchronistic problem. The idea of these protocols is to extend a host's active time, in order to provide awake intervals that overlap. However, distributed time synchronization mechanisms exist for single hop MANET [11], [16] and multihop MANETs [20]. Thus, it is not necessary to prolong a host's active period, which consumes extra energy, in order to provide overlapping awake intervals.

The ATSP protocol [11] is proposed to achieve time synchronization in MANETs. The idea behind ATSP comes from the observation that, in the IEEE 802.11, only later (faster) timing synchronizes the others. Thus, ATSP gives the fastest host (the host with the fastest timing) the highest priority to transmit beacons (by increasing its beacon transmission frequency); the slower hosts' beacon transmission frequencies are, thus, reduced. ATSP successfully alleviates the time asynchronism problem, but, in some cases, such as when the fastest host leaves, the clocks of some of the other hosts may differ by hundreds of microseconds. To overcome these problems, a revision of the ATSP, called the TATSP, has been proposed [16]. Both ATSP and TATSP achieve clock synchronization for hosts in a single hop MANET. However, these two algorithms cannot be applied to a multihop MANET. ASP [20] is a solution for the time synchronization problem in a multihop MANET. ASP enables hosts to carry out self-synchronization, if enough timing information has been collected. Two tasks must be carried out to fulfill clock synchronization in such an environment: Successful transmission probability for faster hosts must be increased and faster timing information must be spread throughout the whole network. In ASP, the first task can be accomplished by increasing the beacon transmission priority of a faster host and cutting down the priorities of the others. Then, when some slower hosts have gathered enough information to accomplish synchronization by themselves, their beacon transmission priorities can be increased to carry out the second task.

4 Protocols Description

In this section, we present our *Quorum-Based Energy Conserving (QEC)* and *Adaptive Quorum-Based Energy Conserving (AQEC)* MAC Protocols. Both protocols achieve power conservation and guarantee that any two hosts will wake up concurrently, during the same beacon intervals, through use of a quorum. In the following section, we first introduce the concept of a quorum and then present the details of these two protocols; we also propose a method to reduce latency.

4.1 Quorum Concept

The concept of a quorum, which has been widely used in distributed systems, provides mutual exclusion guarantees, fault tolerance, agreement, and voting [10], [19]. A quorum is a request set [21], to enable some actions, if permission is granted. Typically, there are nonempty intersections between any two quorum sets. There are many kinds of quorum, such as majority-based [22], tree-based [3], grid-based [9], [18], and others [15], [17], [25]. Here, we use quorums to identify the beacon intervals, during which a host must wake up. Based on a quorum's properties, it is guaranteed that any two hosts will meet at some beacon intervals. Without loss of generality, we used a grid-based quorum to implement our protocol. In a grid-based quorum, one row and one column are picked in an $n \times n$ grid; Fig. 2 illustrates this concept. As can be seen, host A picked row R_a and column C_a as its quorum, while host B picked row R_b and column C_b. There are two intersections between hosts A and B, one for R_a and C_b and the other for C_a and R_b.

4.2 Quorum-Based Energy Conserving (QEC) Protocol

In QEC, time is also divided into beacon intervals, the same as in IEEE 802.11 PSM. Each continuous n^2 beacon intervals are

1. A user's sleep pattern should consider both transmission and receiving packets. However, it is difficult and time-consuming to collect receiving traffic information for each user. In this paper, we only considered the packets to be sent and the received ones, when determining the sleep pattern, which can be easily obtained.

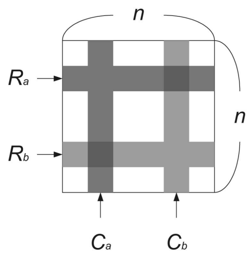


Fig. 2. An example of a grid-based quorum.

0	1	2
3	4	5
6	7	8

Fig. 3. A consecutive nine beacon intervals can be represented by a 3×3 grid.

called a *quorum group* and these n^2 intervals are arranged in an $n \times n$ grid, where n is a global parameter. Every host in the system adopts the same n. The QEC protocol achieves power saving by reducing the amount of awake intervals. For an $n \times n$ grid, each host is awake for $\frac{2n-1}{n^2}$ intervals. Fig. 3 shows an example of nine consecutive beacon intervals represented by a 3×3 grid in a left-to-right and top-to-bottom manner. A host can randomly select one row and one column as its *quorum intervals* within which a host must stay awake for at least as the duration of the ATIM window to handle ATIM announcements (as in IEEE 802.11 PSM). For non-quorum intervals, a host can sleep for the entire beacon interval. Fig. 4 shows an example of quorum interval selections, where host A picked the first row and the first column as its quorum while host B selected the third row and third column. That is, host A will wake up at beacon intervals $0, 1, 2, 3$, and 6 while host B will wake up at beacon intervals 2, $5, 6, 7$, and 8. The intersections occur at beacon intervals 2 and 6, when both host A and B will be awake.

For now, we have assumed that the startpoints of all hosts' quorum groups are also synchronized; later, we will show how to remove this assumption. Under this assumption, it is not difficult to prove the following theorem.

Theorem 1. *If the startpoints of all hosts' quorum groups are synchronized, two hosts running the grid-based QEC protocol have at least two intersections in every n^2 consecutive beacon intervals.*

If a host wants to join the QEC operation, it must first be synchronized with the other hosts. This is done through monitoring the channel for at most n beacon intervals to get a beacon frame. The new host can join the QEC operation at the next beacon interval, after it is synchronized. If the new host does not detect any beacon frame after n beacon intervals, it concludes that there is no host around it and begins its own QEC operation. The operation of a new host, joining the power saving operation, is formally defined below:

- The host will monitor the channel for at most n beacon intervals in order to synchronize with the others.
- If a beacon is received during these n beacon intervals, the host is able to synchronize with existing hosts and begin running the QEC protocol at the next beacon interval.
- If no beacon is detected after n beacon intervals, the host concludes that no host exists and begins running the QEC at the next beacon interval.

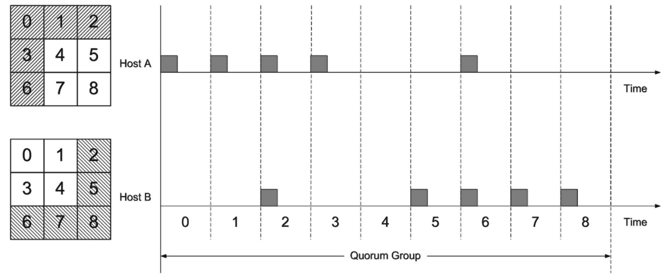


Fig. 4. An example of intersections. Host A and host B meet each other at intervals 2 and 6.

It is of note that the only requirement of a new host for joining the QEC operation is to become synchronized with existing hosts. It need not know other hosts' quorum intervals or the startpoints of the quorum groups. It means that IEEE 802.11 could be easily extended to our QEC protocol. The assumption in Theorem 1, that the hosts' quorum groups must be synchronized, was eliminated. However, in order to maintain the property that any two hosts have at least two intersections in every n^2 beacon intervals, the grid cannot be randomly arranged. Fig. 5a shows an example of an unsatisfactory 4×4 grid. Both hosts selected the first row and the fourth column as their quorum intervals. Host B started its quorum group one beacon interval later than did host A. As shown in Fig. 5b, these two hosts never met.

To guarantee at least two intersections between any two hosts, the following grid allocation rules must be followed when arranging n^2 beacon intervals into an $n \times n$ grid g:

- **Grid Allocation Rule 1.** Each row of g consists of n consecutive ($mod\ n^2$) beacon intervals.
- **Grid Allocation Rule 2.** $\forall m \in [1, 2, \ldots, n^2]$, any n continuous beacon intervals,

$$\{[m, m+1, \ldots, m+n-1](mod\ n^2)\},$$

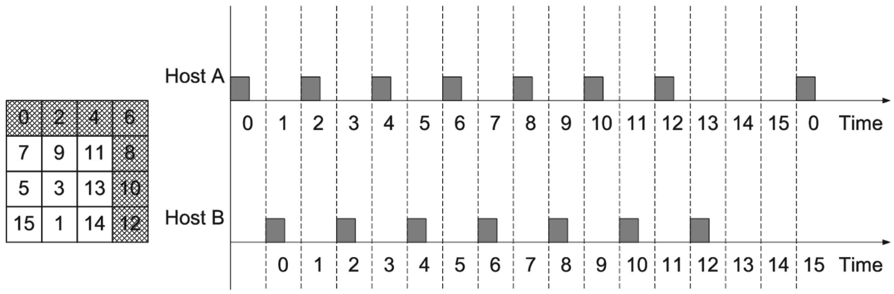
are distributed in n different columns.

A grid constructed according to the grid allocation rules is called a legal grid. Note that the roles of rows and columns can be exchanged.

Fig. 6 illustrates some legal grids. Fig. 6a shows the basic grid sequence. All the other grids' modifications have been applied to this basic grid. Fig. 6b has exchanged the first and third columns. Fig. 6c has exchanged the first and third rows. Fig. 6d has exchanged the roles of rows and columns. Fig. 6e has inverted the grid sequence. Fig. 6f has shifted one beacon interval backwards.

Following the grid allocation rules, we have the following theorem (the proof is shown in Appendix A):

Theorem 2. *Following the grid allocation rules, two hosts that run grid-based QEC protocol have at least two intersections in every n^2 consecutive beacon intervals.*



(a) (b)

Fig. 5. An example of an unsatisfactory grid sequence that makes no intersection for two hosts.

4.3 Adaptive Quorum-Based Energy Conserving (AQEC) Protocol

In the QEC protocol, all hosts share the same grid size of $n \times n$; the selection of this grid size is important. A large grid size implies extensive power saving with longer delays. On the other hand, the amount of conserved energy can be reduced with a small grid size. In extreme cases, for instance, when the grid size is reduced to 1×1, the QEC protocol is equal to the IEEE 802.11 PSM. In order to achieve better performance, it is necessary to dynamically adjust the grid size for each individual host since they have different traffic loads and different performance requirements. In order to do this, we have proposed the *Adaptive Quorum-Based Energy Conserving (AQEC) Protocol*. The idea behind AQEC is to increase a host's grid size, in order to prolong its sleep duration when its traffic is light, and to decrease its grid size, making it wake up more frequently, when its traffic load is heavier.

In AQEC, user i selects its grid size according to its traffic load, LD_i. In this paper, to facilitate implementation, we defined three traffic thresholds, *Threshold_1*, *Threshold_2*, and *Threshold_3*, meaning four grid sizes can be selected by user i in the AQEC protocol:

1×1 ($LD_i \geq$ Threshold_1),
2×2 (Threshold_1 $> LD_i \geq$ Threshold_2),
3×3 (Threshold_2 $> LD_i \geq$ Threshold_3), and
4×4 (Threshold_3 $> LD_i$).

(a)

0	1	2
3	4	5
6	7	8

(b)

2	1	0
5	4	3
8	7	6

(c)

6	7	8
3	4	5
0	1	2

(d)

0	3	6
1	4	7
2	5	8

(e)

8	7	6
5	4	3
2	1	0

(f)

8	0	1
2	3	4
5	6	7

Fig. 6. Some legal grids.

According to our simulation of IEEE 802.11 PSM, channel was capacity 2 Mbps (where the number of hosts ranged from 30 to 150 and the packet size from 128 to 1,024 bytes). The latency increased dramatically when every host's packet arrival rate exceeded 12 Kbps. We considered the network environment to be overloaded when each host's traffic load was more than 12 Kbps; thus, we set grid size to 1×1 when its traffic load exceeded 12Kbps. That is, we set Threshold_1 to be 12 Kbps. Note that this definition of Threshold_1 is according to our simulation scenarios. The number of thresholds and their values can be adjusted according to different environments.

When the traffic load decreases, a host's wake up frequency should also be reduced, accordingly. Threshold_2 and Threshold_3 are defined as being proportional to the wake up frequency, when compared to a 1×1 grid. In an $n \times n$ grid, we picked $2n-1$ among n^2 beacon intervals as the quorum intervals. That is, a host with a grid size of $n \times n$ woke up at the fraction of $\frac{2n-1}{n^2}$, compared to a host with a grid size of one. When a host's packet arrival rate is reduced to $\frac{2n-1}{n^2}$, when compared to being overloaded, we should also increase its grid size to $n \times n$; this implies

$$\text{Threshold\_2} = 12 \times \frac{2 \times 2 - 1}{2^2} = 12 \times \frac{3}{4} = 9 \text{ Kbps}$$

and

$$\text{Threshold\_3} = 12 \times \frac{2 \times 3 - 1}{3^2} = 12 \times \frac{5}{9} = 6.67 \text{ Kbps}.$$

With these settings, a host can select the best grid size, according to its traffic load, in order to achieve energy conservation.

The grid allocation rules must still be followed and, with legal grids, two hosts with different grid size will intersect with each other. For example, in Fig. 7, host A has a 2×2 grid and its quorum intervals are 0, 1, and 2. Host B has a 3×3 grid and its quorum intervals are 2, 5, 6, 7, and 8. Host A wakes up more frequently than host B, but they have intersections during host B's quorum group. Proof of the following theorem can be found in Appendix B.

Theorem 3. *Following the grid allocation rules, two hosts running the AQEC protocol, with grid sizes $m \times m$ and $n \times n$, respectively, intersect with each other even if the startpoints of their quorum groups are not synchronized.*[2]

2. Extension to any $n \times m$ grid is available in Appendix C.

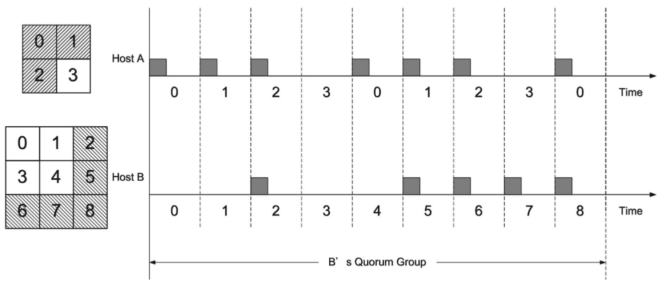


Fig. 7. A 2×2 grid intersects with a 3×3 grid.

Both the QEC and AQEC protocols allow a host to sleep longer than one beacon interval; thus, the latency produced by these two protocols is greater than with the IEEE 802.11 PSM. Here, we have proposed a simple way to reduce latency. To distinguish these from the original protocols, we have attached a plus sign at the end of the protocols (that is, *QEC+* and *AQEC+*) to represent this modification.

In the QEC+ and AQEC+ operations, when a host has packets to send, it will stay awake during every beacon interval, until the packets have been sent. In other words, the host must wake up at every beacon interval, instead of only during its quorum intervals, when there is a packet pending.

Take Fig. 8 as an example, host A's quorum intervals are 0, 1, 2, 3, and 6, while host B's quorum intervals are 2, 5, 6, 7, and 8. Hosts A and B only have intersections at intervals 2 and 6. In QEC+/AQEC+, assuming that host A has packets for host B at interval 3, host A will wake up at every beacon interval after interval 3, until the packet has been delivered.

5 Simulation Results

The proposed QEC/QEC+ and AQEC/AQEC+ protocols were evaluated by the *ns-2* [1] simulator (CMU wireless and mobile extensions, version ns-allinone-2.1b9a [2]). The contention resolution protocol is CSMA/CA. Default radio propagation model of the simulator is used in our simulations (path loss exponent is set to 4, antenna gain is set to 12 dB, and so forth). The DPSM and IEEE 802.11 were also implemented for comparison purposes. The hosts were randomly placed within an area of $200\ \text{meters} \times 200\ \text{meters}$. There were 50 hosts in the area; one half being sources and the other half being destinations. Source-destination pairs were randomly chosen. The transmission range for each host was 300 meters, with the channel capacity being 2 Mbps. The hosts were assumed to have no mobility and beacon intervals were set to 200 ms. The ATIM values for DPSM varied between 2 ms and 100 ms, while it was set to 40 ms for the other protocols. Packet size was set to 128 bytes and hosts were supplied with different constant bit rate traffic, between 1 and 24 packets per second, to simulate light-loads and heavy-loads. The energy consumption model, described in Chen et al. [8], was employed; this model uses measurements taken by the *Cabletron Roamabout 802.11 DS High Rate network interface card* that operates at 2 Mbps. Power consumption for transmit, receive, idle, and sleep modes was 1,400, 1,000, 830, and 130 mW, respectively. The initial energy was set to 500 Joules for each host. A spot in the following figures shows the average of 10 simulations, each simulating 300 second constant bit rate connections. The standard deviations or confidence intervals were also reported except Fig. 9, Fig. 10, Fig. 11a, and Fig. 12a since they were packed. The maximum standard deviation was about 4 percent for these figures. The confidence level shown in the other figures was at 95 percent with the confidence interval of ($\bar{X} - 1.96\sigma/3.16$, $\bar{X} + 1.96\sigma/3.16$), where $\bar{X}$ is the mean and σ is the standard deviation of the samples.

Below, we have made observations from three different aspects. Notations QECn and QECn+ stand for QEC and QEC+ with a grid size of $n \times n$, respectively.

5.1 Effect of Different MAC Protocols

In this experiment, we fist investigated the performance of the proposed protocols. The criterion used here was the fraction of alive hosts. Our simulation was carried out for

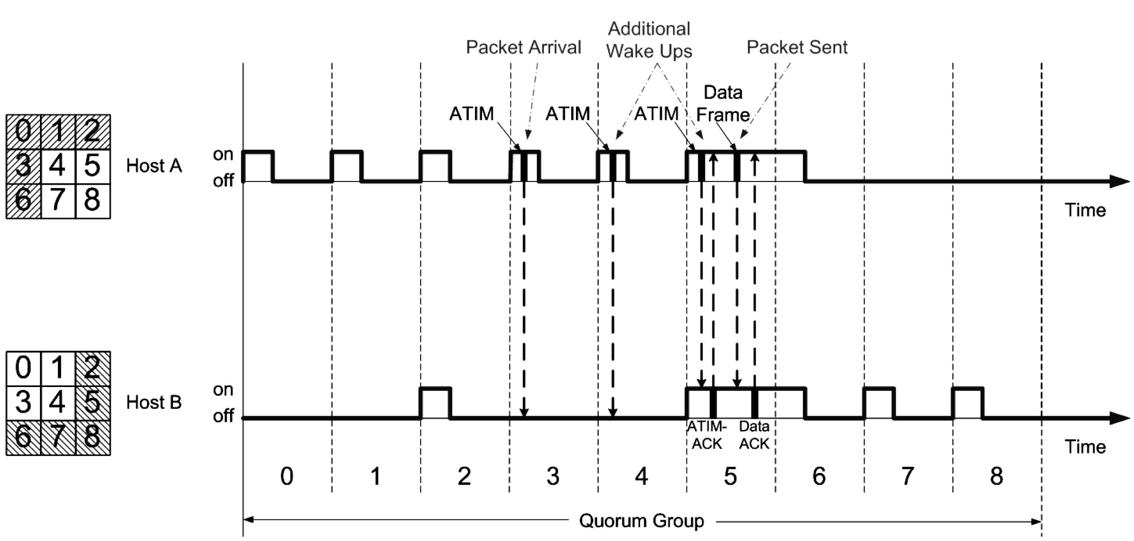


Fig. 8. Host A with pending packets wakes up more when running the QEC+/AQEC+ protocol.

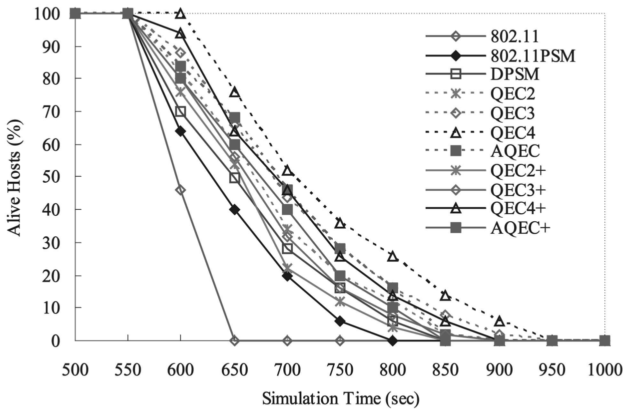


Fig. 9. The effect of different MAC protocols on the fraction of alive hosts with zero workload.

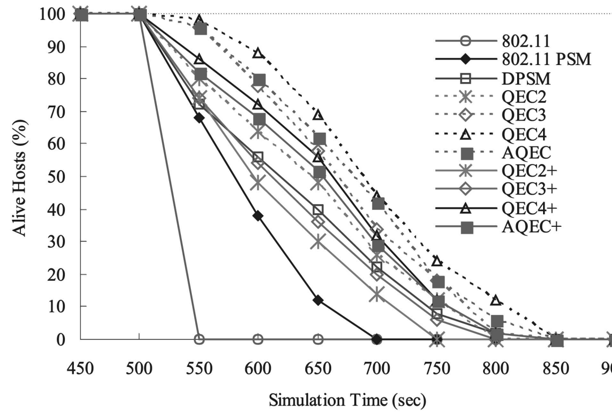
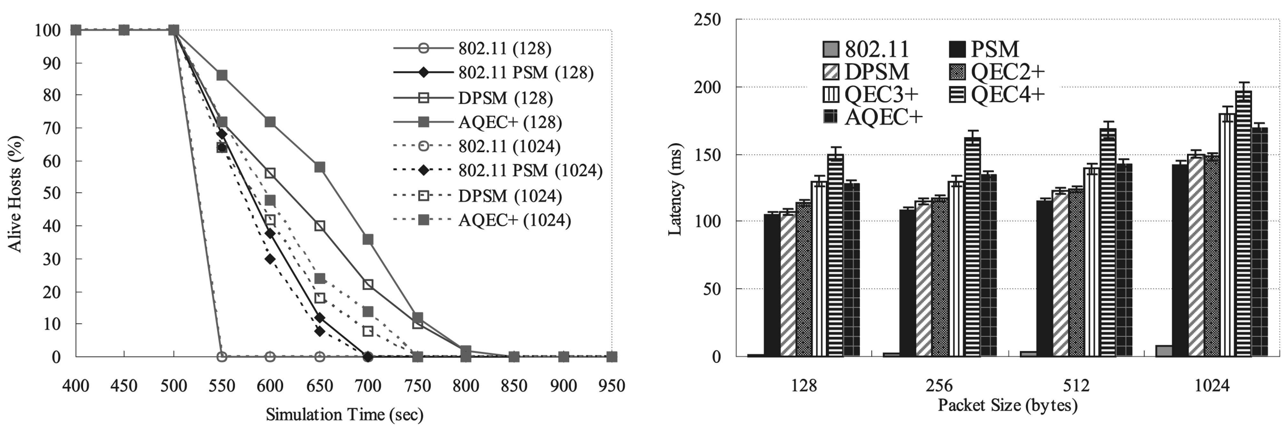


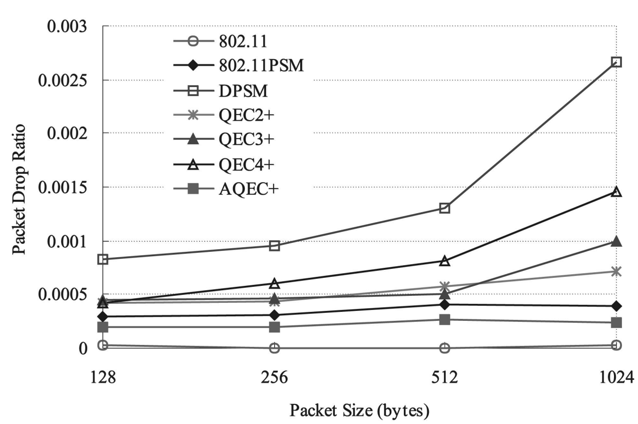
Fig. 10. The effect of different MAC protocols on the fraction of alive hosts with packet size 128 bytes.

1,000 seconds and the number of living hosts was recorded every 50 seconds. We first experimented with a zero workload, to explore the best results that each power saving protocol could achieve. As can be seen in Fig. 9, the DPSM and our proposed protocols could increase the potential network lifetime, when compared to the IEEE 802.11 and 802.11 PSM. Moreover, most of our protocols conserved more energy than the DPSM.

Next, we show the results obtained with a packet size equal to 128 bytes. As shown in Fig. 10, hosts running IEEE 802.11 ran out of energy after 550 seconds. After a simulation time of 700 seconds, all hosts running IEEE 802.11 PSM had exhausted their energy, while hosts running QEC still had 28, 34, and 44 percent hosts surviving for grid sizes 2×2, 3×3, and 4×4, respectively. For those hosts running the QEC+protocol, there were still 14, 20, and



(a) (b)



(c)

Fig. 11. The effect of packet size on (a) the fraction of alive hosts, (b) latency, and (c) the packet drop ratio.

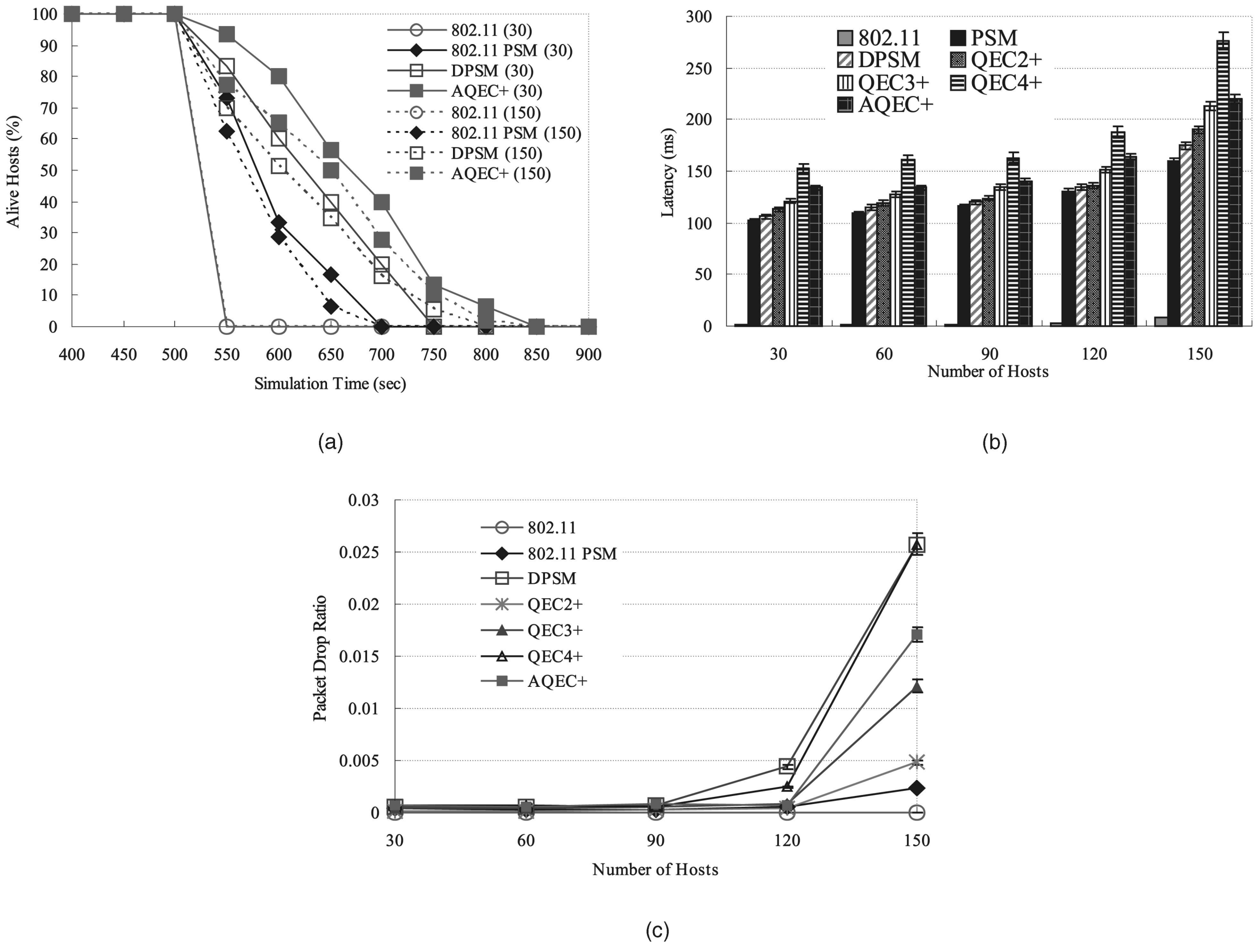


Fig. 12. The effect of number of hosts on (a) the fraction of alive hosts, (b) latency, and (c) the packet drop ratio.

29 percent hosts surviving at a time of 700 seconds for grid sizes 2×2, 3×3, and 4×4, respectively. The lifetime of AQEC(AQEC+) roughly lay between QEC(QEC+), with grid sizes of 3×3 and 4×4. The DPSM performed better than the IEEE 802.11 PSM, but worse than most of our protocols.

One-hop latency, for different MAC protocols, is listed in Table 1. All power saving protocols, including 802.11 PSM and DPSM, as well as our protocols, produced obvious delays over 802.11. The DPSM had a slightly longer latency than the 802.11 PSM, which generated the least delay among all the power saving protocols. Our AQEC and AQEC+ increased latency over the 802.11 PSM, by 30 and 24 ms, respectively.

Since QEC+/AQEC+ performed better as far as latency was concerned, we adopted QEC+/AQEC+ for further experimental demonstrations.

5.2 Effect of Packet Size

In this experiment, we varied the packet size to observe the effect. The results for 128 bytes and 1,024 bytes are shown in Fig. 11a. We can see that the AQEC+ achieved the greatest power conservation. When the packet size was 128 bytes, hosts running IEEE 802.11 ran out of energy after 550 seconds. After a simulation time of 700 seconds, all hosts running IEEE 802.11 PSM had exhausted their energy, while 36 percent and 22 percent of hosts, running the AQEC+ and DPSM, respectively, still survived. When the packet size was 1,024 bytes, hosts running IEEE 802.11 and IEEE 802.11 PSM exhausted their energy after 550 and 700 seconds, respectively. For hosts running AQEC+ and DPSM, 15 percent and 8 percent still survived, respectively, at a simulation time of 700 seconds. Note that large packets increased the traffic load and consumed more energy. The benefit of AQEC+ with smaller packet sizes is obvious

TABLE 1
The Effect of Different MAC Protocols on Latency

Protocol	802.11	802.11 PSM	DPSM	QEC2	QEC3	QEC4
Latency	1.6(0.2)	105.0(0.6)	107.3(1.5)	114.8(2.7)	138.2(3.1)	163.7(3.7)
Protocol		AQEC	AQEC+	QEC2+	QEC3+	QEC4+
Latency		135.4(2.3)	128.8(2.6)	113.9(2.6)	129.5(2.7)	150.2(1.4)

The standard deviations are in the parentheses.

because the hosts running AQEC+ have a greater chance for longer period of sleep when the network has a light load.

The incurred latency for different packet sizes is shown in Fig. 11b. The IEEE 802.11 PSM had the least delay among all of the power saving protocols. Higher delays were realized as packet size increased. This is reasonable since large packets will increase system traffic load, causing the hosts to frequently contend for access privilege. The DPSM produced a 2 to 8 ms higher delay than 802.11 PSM, while our AQEC+produced a 20 to 22 ms higher delay than the DPSM.

The packet drop ratios of all protocols are shown in Fig. 11c. In general, the packet drop ratio increased as packet size increased. This make sense since a large packet size increases system load. The IEEE 802.11 performed the best, followed by the AQEC+ and 802.11 PSM, in sequence. Surprisingly, the DPSM produced the largest packet drop ratio. We feel that this was caused by the improper settings of the ATIM window size. The DPSM started off with the minimum ATIM window size (2 ms), making it unable to quickly handle a heavier traffic load. In our QEC+ protocols, those with a smaller grid size performed better. As the grid size increased, hosts were awake less frequently. This means that more hosts have to contend for packet transmission in the intersection beacon intervals, which results in more collisions and higher drop rates.

5.3 Effect of Number of Hosts

In our earlier experiments, the number of hosts was fixed at 50. More hosts generate higher traffic load. Here, we investigated the effect of different numbers of hosts. In Fig. 12 a, it can be seen that while the number of hosts was 30, those hosts running IEEE 802.11 and IEEE 802.11 PSM ran out of energy after 550 and 700 seconds, respectively. At a simulation time of 700 seconds, those hosts running AQEC+ and DPSM were still 40 percent and 20 percent alive, respectively. When the number of hosts was 150, hosts running AQEC+ and DPSM had a longer life than those running of IEEE 802.11 and IEEE 802.11 PSM. At 700 seconds, 28 percent and 16 percent of hosts running AQEC+ and DPSM, respectively, still survived.

Latency resulting from different numbers of hosts is reported in Fig. 12b. Higher values were obtained as the number of hosts increased. Similar performance trends can be found among the other protocols: IEEE 802.11 PSM performed the best, followed by DPSM and then our protocols. The difference between DPSM and our AQEC+ was between 19 and 45 ms.

In Fig. 12c, the packet drop ratio is illustrated. The probability of collision increased in proportion to the number of hosts. Therefore, a higher packet drop ratio resulted from more hosts. When the number of host was 120 or below, the packet drop ratios for all protocols were low (below 0.005). That is, all of these protocols had a high reliability, when the system had a light load. The DPSM still had the highest packet drop ratio. All of the power saving protocols produced higher packet drop ratios when the number of hosts was increased to 150, in which case we believe the system is heavy-loaded.

It is of note that a network with many hosts did not save more power than one with fewer hosts, when the grid size was increased (the results are not reported due to space limitations). As grid size increased, hosts were awake less frequently. This meant that more hosts contended for packet transmission during the intersection beacon intervals, which resulted in more collisions and higher energy consumption.

6 Conclusions

Energy conservation is a critical issue in wireless networks. In this paper, we have proposed new energy conserving MAC protocols: QEC and AQEC. These proposed protocols, built onto the IEEE 802.11 PSM, are able to conserve energy by allowing hosts to sleep continuously for a longer period of time. Utilizing the quorum property that states there must be intersections, these protocols can achieve energy saving and guarantee that hosts can communicate with each other. We use a grid-based quorum to implement our protocols. A large grid size could produce a large amount of energy conservation; latency was also increased, however. The AQEC protocol was able to dynamically adapt grid size, according to the hosts' traffic conditions, obtaining the best performance. We also proposed the schemes QEC+/AQEC+ to reduce the latency produced by longer sleep durations. Simulation results showed that our quorum-based protocols do, indeed, extend network lifetime and also keep packet drop ratios to a minimum. This indicates that we have achieved power efficiency, in conjunction with high reliability. Simulation results also revealed that our protocols are most profitable when the network load is light. In conclusion, the proposed protocols are simple, power-efficient, and highly reliable, which makes them promising MAC protocols in a wireless environment.

In the future work, we will try to extend our protocols to be used in a multihop MANET while keeping the end-to-end delay tolerable. In a multihop MANET, routing issues, such as rerouting when hosts die or move away, and multihop time synchronization must be considered. In addition, routing decisions influence the criteria of choosing quorum size in such an environment. To keep our protocols work, there must be a cross-layer, time synchronized, and distributed mechanism for each host to pick a proper quorum size. All of the mentioned works are big challenges in multihop MANETs.

Appendix A

Proof of Theorem 2

Proof. We prove this theorem via the following two aspects:

- **Case 1.** All hosts' quorum groups are synchronized.

  This is trivial.
- **Case 2.** The hosts' quorum groups are not synchronized.

  Without loss of generality, we assume that host A led x beacon intervals over host B. We also assumed that host A picked row R_a and column C_a and host B picked row R_b and column C_b from a legal grid g. C_b, which consists of n consecutive beacon intervals with an equal difference n, must intersect with R_a which comprises n consecutive beacon intervals, with any value of x. Similarly, with any value of x, R_b, which consists of n consecutive beacon intervals, must intersect with C_a which comprises n consecutive beacon intervals with an equal difference n. That is, with any value of x, hosts A and B have at least two intersections, which proves the theorem. □

APPENDIX B
PROOF OF THEOREM 3

Proof. We assume that host A and host B use grids with size $m \times m$ and $n \times n$, respectively. Without loss of generality, we also assume $m > n$.

Assuming that host A picked row R_a and column C_a and host B picked row R_b and column C_b from legal grids, respectively. C_b, which consists of n consecutive beacon intervals with an equal difference n, must intersect with R_a, which comprises m consecutive beacon intervals, since $m > n$. □

APPENDIX C
EXTENSION TO $n \times m$ GRIDS

Our algorithms can be applied to $n \times m$ ($n \neq m$) grids with some modifications. The grid allocation rules for an $n \times m$ grid g are as follows:

- **Grid Allocation Rule 1′.** Each row of g consists of m consecutive ($mod\ n \times m$) beacon intervals.
- **Grid Allocation Rule 2′.** $\forall w \in [1, 2, \ldots, n \times m]$, any m continuous beacon intervals,

$$\{[w, w+1, \ldots, w+m-1](mod\ n \times m)\},$$

are distributed in m different columns. □

Theorems 2 and 3 have also been changed:

Theorem 2′. *Following the grid allocation rules, two hosts that run the grid-based QEC protocol have at least two intersections in every $n \times m$ consecutive beacon intervals.*

Proof. The proof is similar to that of Theorem 2. The differences occur in Case 2.

- **Case 2.** The hosts' quorum groups are not synchronized.

  Without loss of generality, we assume host A led x beacon intervals over host B. Also assuming that host A picked row R_a and column C_a and host B picked row R_b and column C_b from legal grids, respectively. C_b, which consists of n consecutive beacon intervals with an equal difference m, must intersect with R_a which comprises m consecutive beacon intervals, with any value of x. Similarly, with any value of x, R_b, which consists of m consecutive beacon intervals, must intersect with C_a which comprises n consecutive beacon intervals with an equal difference m. That is, with any value of x, hosts A and B have at least two intersections, which proves the theorem. □

Theorem 3′. *Following the grid allocation rules, two hosts running the AQEC protocol, with grid sizes $n \times m$ and $p \times q$, respectively, intersect with each other, even if the startpoints of their quorum group are not synchronized.*

Proof. We assume that hosts A and B use grids with size $n \times m$ and $p \times q$, respectively. Without loss of generality, we assumed $m \geq q$.

Assuming that host A picked row R_a and column C_a and host B picked row R_b and column C_b, respectively, then C_b, which consists of p consecutive beacon intervals with an equal difference q, must intersect with R_a, which comprises m consecutive beacon intervals, since $m \geq q$.□

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