Power Saving Protocol based on Rectangular Grid Quorums for IEEE 802.11 Ad Hoc Networks

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Abstract

Energy conservation is one of the most important issues in wireless communication networks. Many power saving methods have been proposed in the literature. Among them, approaches based on the grid quorum systems are common. In a grid quorum based power saving protocol, the grid size is an important factor to the sleep ratio. A larger grid size implies a higher sleep ratio and hence less power consumption, but, on the other hand, it will lead to longer neighbor discovery time. To tackle this dilemma, this study proposed a power saving protocol based on rectangular grid quorums for wireless ad hoc networks. The proposed protocol dynamically adjusts the row sizes of the rectangular grid quorums according to different traffic load conditions so as to effectively conserve power. Simulation results show that the proposed approach can reduce the neighbor discovery time while achieving higher sleep ratio than those of the other existing related approaches.

Key words: Power Saving, Traffic Aware Protocols, Grid Quorums, Ad Hoc Networks

1. Introduction

Portable devices mainly rely on their batteries for power. When the battery is depletion, the portable device cannot provide the service anymore. Thus, extending the battery life of portable device is a very most important issue. IEEE 802.11 wireless local area networks (WLANs) are the most utilized wireless network systems for portable devices. There are two modes in IEEE 802.11 WLANs [1]: the ad hoc mode and the infrastructure mode. In the infrastructure mode, all hosts communicate with the access point and cannot communicate directly. That is, all frames are relayed between hosts by the access point. In the ad hoc mode, the hosts communicate directly with each other via the wireless media in a peer-to-peer manner. IEEE 802.11 standard proposes two power saving protocols for these different modes. This paper focuses on the power saving methods for the ad hoc networks.

In the IEEE 802.11 ad hoc mode, a host will wake up periodically. The short interval in which a host wakes up to transmit/receive Announcement Traffic Indication Message (ATIM) frames to/from the other hosts is called the ATIM window [2]. Many asynchronous power saving methods for wireless ad hoc networks have been proposed in the literature. Among them, the power saving methods based on grid quorum system are common. In such grid quorum power saving protocols, a large grid size leads to power saving with long neighbor discovery time. On the other hand, a great deal of energy would be wasted with a small grid size. In order to balance the tradeoff between energy saving and neighbor discovery time, some researches focus on dynamical adjustment of the grid size. However, the power saving advantage provided by the adaptive grid quorum systems comes at the expense of increased neighbor discovery time. To cope with this problem, this study proposed a traffic aware power saving protocol based on rectangular grid quorums for wireless ad hoc networks. Through dynamically adjusting the row size of the rectangular grid quorums, the proposed protocol not only conserves more energy but also reduces the neighbor discovery time. The details of the protocol will be elaborated in Section 3.

The rest of this paper is organized as follows. Related work is introduced in Section 2. The proposed power saving protocol is described in Section 3. Simulations and performance analyses are presented in Section 4. Finally, conclusions are drawn in Section 5.

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2. Related Work

In IEEE 802.11 ad hoc mode, every host can communicate directly within the same independent basic service set (IBSS). Therefore, when host A intends to transmit a data packet to host B, host A has to ensure that host B keeps awake at the same time. For this purpose, every host has to wake up periodically and remain awake during the ATIM window. In the ATIM window, a host can transmit/receive ATIM frames to/from the other hosts. The ATIM frame is used to notify the other host that the host intends to transmit data. Each host that intends to transmit data will contend to send an ATIM frame in the beginning of each ATIM window. Through a back-off algorithm, the successful host will send an ATIM frame to the receiver. The receiver will reply with an immediate acknowledgement to the sender. After the ATIM window, the sender will try to send the data to the receiver. If there is no pending data to/from the other hosts within the rest of time, the host will go to the power saving (PS) mode [1][2].

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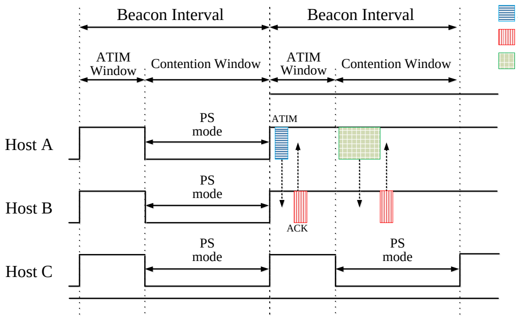

Figure 1. An example of power management in IEEE 802.11 ad hoc networks

The above scheme is for synchronous networks. However, for asynchronous networks, because the start times of the beacon intervals of hosts A and B are asynchronous, B may be in sleep mode during the beacon window of A, and vice versa. That is, A and B will not be aware of each other. To tackle this problem, some asynchronous power saving protocols have been proposed in the literature, which are devised for ensuring the intersection of wakeup periods between two mobile hosts. In [2], Tseng proposed three asynchronous power saving protocols, namely dominating-awake-interval (DA), periodically-fully-awake-interval (PFA), and grid quorum (GQ) protocols. For Brevity's sake, the details of DA and PFA are omitted. Interested readers can refer to [2]. Since this study is based on grid quorum. The GQ protocol is described briefly as follows.

Grid Quorum Power Saving Protocol: The concept of quorums is typically defined as the minimum number of members of a deliberative assembly necessary to conduct the business of that group. The concept has been widely used in distributed systems (e.g., fault-tolerant [3], mutual exclusion [4], and data replication [5]). D. Peleg and A. Wool introduced the quorum system in [6]. A quorum can be classified into several categories, including majority-based quorums, tree-based quorums, and grid-based quorums, and so on [7][8][9]. In this paper, we focus on the grid-based quorums.

The grid quorum system consists of continuous $n \times n$ beacon intervals. These continuous $n \times n$ beacon intervals are called a quorum cycle. A quorum cycle is considered an $n \times n$ matrix in a row major manner, and n is the grid size. Beacon intervals are classified into quorum intervals and non-quorum intervals. Every host can select an arbitrary row and an arbitrary column at the beginning of a quorum cycle. These $2n$-1 selected beacon intervals are called quorum intervals. The remaining n^2-$2n$+1 beacon intervals are called non-quorum intervals.

The structure of quorum intervals and non-quorums interval are defined below [10]:

Quorum interval: A quorum interval is divided into three parts: a beacon window, an MTIM window, and a contention window. The quorum interval begins with a beacon window and is followed by an MTIM window. In the beacon window, the host will contend to send a beacon frame. In the MTIM window, the host will send a traffic announcement if it has data to be transmitted. After the MTIM window, the host will remain awake in monitor mode for the rest of time.

Non-quorum interval: The non-quorum interval starts with an MTIM window. After the MTIM window, the host can go into PS mode for the rest of time.

An example is shown in Figure 2. Assume that the grid size is 3. Host A selects row 2 and column 3 as quorum intervals. Host B selects row 1 and column 2 as quorum intervals. Thus, quorum intervals 2 and 4 overlap with each other.

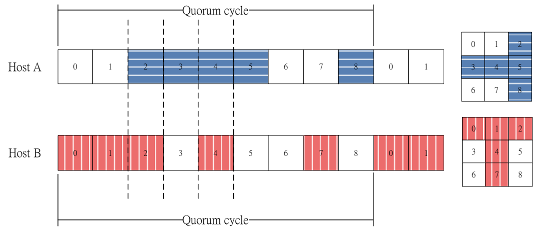

Figure 2. Intersection of quorum intervals of two hosts

3. The Proposed Protocol

3.1 Problem Statement

Grid quorum power saving protocols have been proposed in many studies [2][11][12]. Most of them are based on square grid quorum systems. In such power saving protocols, large grid sizes will save more energy at the expense of increased neighbor discovery time; whereas, small grid sizes will waste energy but can reduce neighbor discovery time. To balance the tradeoff between energy consumption and neighbor discovery time, some studies investigate schemes with different grid size or dynamic adjustment of the grid size [11][12].

Consider a square-grid-quorum based power saving system, in which hosts choose different grids size according to their traffic conditions. Assume that host A has quorum cycle QC_1, and host B has quorum cycle QC_2. The square grid quorum system can guarantee that two hosts can hear from each other at least once within QC_2. That is, the neighbor discovery time is approximately equal to QC_2. This is formally described as follows.

Theorem 1: In a square grid quorum system, for two hosts A and B whose grid cycles are $m \times m$ and $n \times n$, respectively ($m \geq n$), A and B must be able to hear from each other at least once in every $m \times m$ continuous beacon intervals.

Chao *et al*. had proven this fact in [12].

Example 1: As shown in Figure 3, in a square grid quorum system, suppose that hosts A and B have grid sizes of 2×2 and 8×8, respectively. Host A selects row 2 and column 2 as the quorum intervals, and host B selects row 5 and column 8 as the quorum intervals. From Figure 3(c), one can see that the first intersection of A's quorum intervals and B's quorum intervals appears at the beacon interval of number 57, which is less than 64(=8×8). Note that in this example it is assumed that the beacon intervals of A and B are synchronized. In case that they are not synchronized, the first intersection of

A's quorum intervals and B's quorum intervals will still be less than 64 [11].

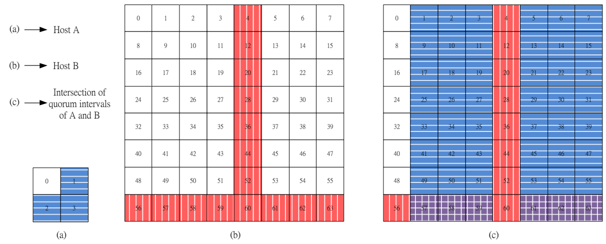

Figure 3. Intersection of two quorum interval sets with different grid sizes

In light of the above observation, a new scheme to provide a remedy to the long neighbor discovery time problem is proposed in this study. The details are elaborated as follows.

3.2 Rectangular Grid Quorum

The proposed protocol is based on the rectangular grid quorum. The rectangular grid quorum consists of continuous $m \times n$ intervals and adopts an array structure. These continuous $m \times n$ intervals are called quorum cycle. In the rectangular grid quorum system, the row size m is unfixed, depending on the network utilization; whereas, the column size n is fixed. Every host in the system can select an arbitrary row and an arbitrary column in the array structure. These $m+n$-1 selected intervals are the quorum intervals and the remaining $m \times n-(m+n-1)$ intervals are the non-quorum intervals.

Theorem 2: In a rectangular grid quorum system, for two hosts A and B whose grid cycle are $m_1 \times n$ and $m_2 \times n$, respectively ($m_1 \leq m_2$), A and B must be able to hear from each other at least once in every $m_1 \times n$ continuous intervals. (Note that A and B are of the same column size n.)

Proof: Let Q_{RA} Rand Q_{CA} be the set of quorum intervals that host A selects from row R_A and column C_A of the rectangular grid quorum, respectively. Similarly, let Q_{RB} and Q_{CB} be the set of quorum intervals that host B selects from row R_B and column C_B of the rectangular grid quorum, respectively. Clearly, the n quorum intervals in Q_{RA} are consecutive; and the quorum intervals in Q_{CB} appear periodically in every n intervals. (An example of n=3 is shown in Figure 4) Thus, it is easy to see that Q_{RA} and Q_{CB} must overlap with each other. Note that this fact holds no matter how much time differences between hosts A and B. (That is, A and B are asynchronous.) In the same reasoning, one can verify that Q_{RB} and Q_{CA} must overlap with each other even when A and B are asynchronous. ■

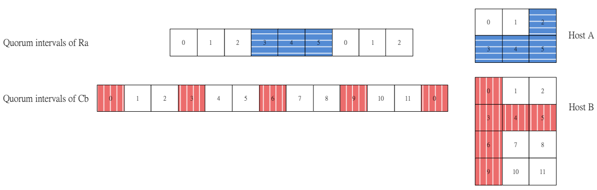

Figure 4. Overlapping of quorum intervals from row R_A and column C_B

Compared with the square grid quorum system, in the proposed rectangular grid quorum system, the neighbor discovery time between two neighboring nodes will be significantly reduced.

Example 2: The matrix in Figure 5 shows an example of the rectangular grid quorum consisting of a 2×6 matrix and a 6×6 matrix. Host A selects intervals on row 2 and column 2 as quorum intervals, and host B selects intervals on row 4 and column 6. On the bottom, the figure shows a case in which host A and host B are asynchronous in clocks. In this example, hosts can find each other at least once within a quorum cycle of A.

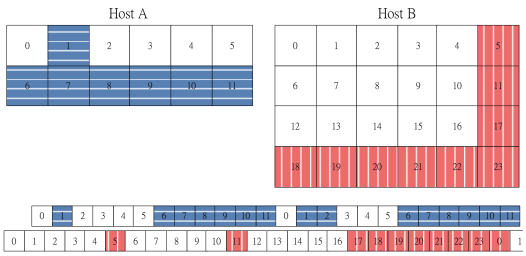

Figure 5. Intersection of quorum intervals of hosts A and B with n=6

3.3 Grid Size Adjustment

In a rectangular grid quorum system, a host has to keep awake in quorum intervals and go into PS mode in a non-quorum interval if it does not have data waiting to be transmitted or received during the interval. This implies that, under a light traffic load condition, all hosts have to wake up in the quorum interval even if they have no data to be transmitted. The effects on power saving with different row size are described as follows.

Definition: The ratio of non-quorum intervals to quorum size is called the sleep ratio of the quorum. The sleep ratio is defined as the following.

$$sleep\ ratio = \frac{Total\ sleep\ time}{Total\ time} = \frac{m \times n - (m + n - 1)}{m \times n}$$

For instance, assume that the row size is 2 and the column size is 6. The host can go into PS mode in the 5 non-quorum intervals in a quorum cycle. Thus, the sleep ratio is 5/12=41.7%. If the row size is 8 and the column size is 6, the mobile host has to sleep for 35 intervals in a quorum cycle. The sleep ratio is 35/48=72.9%. Therefore, the sleep ratio will be increased when the row size is increased.

Table 1. Sleep ratios of different row sizes

	Sleep ratio (Column size = 6)				
nth changes	Row size	Quorum cycle	Awake times	Sleep times	Sleep ratio
base	1	6	6	0	0.0%
1	2	12	7	5	41.7%
2	4	24	9	15	62.5%
3	8	48	13	35	72.9%
4	16	96	21	75	78.1%
5	32	192	37	155	80.7%
6	64	384	69	315	82.0%

As mentioned above, large grid sizes will save more energy at the expense of increased neighbor discovery time; whereas, small grid sizes will waste energy but have the merits of reducing neighbor discovery time. With different row sizes, the power efficiency and neighbor discovery time can be balanced.

This paper proposes a traffic aware power saving protocol based on rectangular grid quorums, which can dynamically adjust the row size according to different traffic conditions. To determine the traffic conditions, the following formulation is defined.

$$Network\ utilization = \frac{Transmission\ intervals}{Quorum\ cycle}$$

The network utilization is used to represent the ratio of the time spent on sending or receiving data to the time of a quorum cycle. When the network utilization is high, the host should sleep less, and hence the row size should be decreased (according to Table 1). Conversely, if the network utilization is low, the host can sleep more to save more energy and the row size should be increased. Thus, in our proposed scheme, the row size is adjusted according to the network utilization, which is classified into three levels: light level, medium level, and heavy level.

(1) Light level: When the network utilization of a host is less than 33%, the utilization status is classified as light. The wake up frequency should be reduced, and the row size should be increased.

(2) Medium level: When the network utilization is between 34% - 66%, utilization status is classified as medium. In this level, the row size would not be changed in the next quorum cycle.

(3) Heavy level: When the network utilization is more than 67%, the network environment is considered overloaded and utilization status is considered as heavy. Thus, the row size should be decreased. (Note that if the row size is decreased to the base row size, it won't be decreased anymore.)

4. Performance Analysis

4.1 Simulation Environment

In our simulation, it was assumed that the hosts were randomly placed within an area of $1000\times1000m^2$. There were 20 hosts in the area. In the beginning, half of the hosts were active, and the remaining hosts became active within the latter 30 seconds (in a random manner). The transmission range between hosts was 250 meters with a wireless channel rate of 11Mbps. The battery power of each mobile host was 100J. The duration of the simulation is 100 seconds. The power consumption rates of the wireless modules were set 1346, 900, 739 and 47mW in the transmit, receive, idle and sleep modes, respectively [13]. The data sizes and traffic patterns were random. All hosts were asynchronous in their clocks. The proposed protocol (denoted as RGQ), using column sizes= 4, 6, 8, and 10, is compared against the adaptive traffic aware power saving protocol (ATA) [12], grid quorum power saving protocol (GQ, fixed grid size=3), dominating-awake-interval protocol (DA), and periodically-fully-awake-interval protocol (PFA, p=4) [2].

4.2 Simulation Results

Our simulation analyzed three traffic load conditions: light, medium, and heavy. Sleep ratio and neighbor discovery time are considered as performance metrics and were measured in our simulations.

Sleep Ratio

The sleep ratio is the total sleep time divided by the simulation time. The simulation results are displayed in Figure 6. Under light traffic load conditions, the proposed protocol, ATA protocol and PFA protocol can achieve high sleep ratios. In addition, the sleep ratio of the ATA protocol is little higher than that of the proposed protocol. This is because that since the network utilization is low, the row size of the rectangular grid quorum in the proposed protocol will increase over time, and so will the grid size of the ATA protocol. In the ATA protocol, the row size and column size of the square grid quorum are increased exponentially. In contrast, in the proposed protocol, only the row size is increased but the column size is fixed.

Under the medium traffic load conditions, the row size will be increased until the traffic load and the network utilization are balanced. The sleep ratios of different protocols under the medium traffic load conditions are in the same order as those observed under the light traffic load conditions. Moreover, due to higher traffic loads, the sleep ratios under the medium traffic load conditions are generally smaller than those observed under the light traffic load conditions. Again, the sleep ratio of the proposed protocol is higher than that of the other protocols except for the ATA protocol.

Under the heavy traffic load conditions, the average sleep ratios are smaller than those observed under light and medium traffic load conditions. This occurs because the network utilization is high and hence the quorum cycle is small. Besides, for the PFA protocol, in which the hosts wake up in every 4 beacon intervals, the hosts will have more collisions due to heavy traffic loads, and hence they go to PS mode more frequently. Thus, the average sleep ratio of the PFA protocol is higher than those of the other protocols.

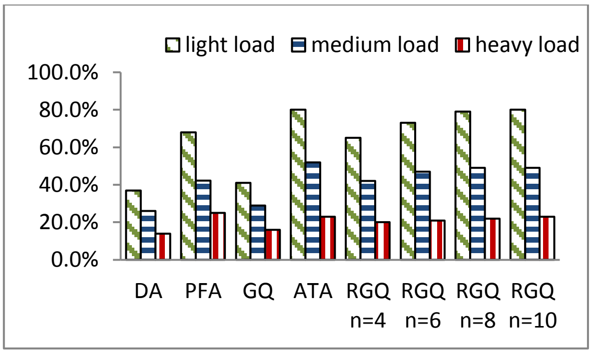

Figure 6. Average sleep ratio

Neighbor Discovery Time

The neighbor discovery time is the average time for all hosts to discover their neighbors. Figure 7 shows the simulation results. Under light traffic loads, the DA protocol always has the shortest neighbor discovery time because the DA protocol guarantees that any host is able to receive its neighbors' beacon frames in every two beacon intervals. Besides, under the light traffic load conditions, the average neighbor discovery times of the ATA protocol and the proposed protocol are higher than those of the other protocols. Because the network utilization is low, the grid size of the ATA protocol and the row size of the proposed protocol will increase over time. Thus, the quorum cycle becomes larger, which leads to increased neighbor discovery time. Due to the fact that the proposed protocol guarantees that two hosts can hear from each other at least once within the smaller quorum cycle of these two hosts, the neighbor discovery time of the proposed protocol is shorter than that of the ATA protocol. Compared with the ATA protocol, the neighbor discovery time can be reduced by approximately 45% with the proposed RGQ protocol (column size = 6).

Compared with the light traffic load conditions, the neighbor discovery times of different protocols under the medium traffic load conditions are in the same order as those observed under the light traffic load conditions. Moreover, because of increased traffic loads, the neighbor discovery times are generally smaller. Besides, compared with the ATA protocol, the neighbor discovery time can be reduced by approximately 40% with the proposed RGQ protocol (column size = 6). Under heavy traffic loads, since high network utilization leads to low sleep ratio, the neighbor discovery times of all protocols are low.

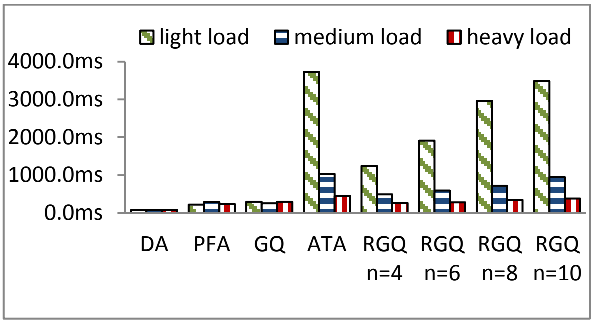

Figure 7. Average neighbor discovery time

5. Conclusions

In this paper, a traffic aware power saving protocol based on rectangular grid quorums was proposed for extending the battery life of portable devices. The adaptive traffic aware power saving protocol [13] guarantees that two hosts can hear from each other at least once within the hosts' larger quorum cycle; whereas, the proposed RGQ protocol guarantees that two hosts can hear from each other at least once within the hosts' smaller quorum cycle. Thus, the neighbor discovery time will be significantly reduced. The simulation results show that the sleep ratio of the proposed protocol is slightly lower than that of the ATA protocol; however, the neighbor discovery time can be reduced by approximately 45% under the light traffic load conditions and approximately 40% under the medium traffic load conditions, with the RGQ protocol (column size = 6). Note that, under the heavy traffic load conditions, because hosts seldom sleep, most protocols have short neighbor discovery times. Overall, in comparison with other related protocols, simulation results show that the proposed approach can reduce the neighbor discovery time while achieving higher sleep ratio so as to conserve more energy.

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