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A location-aware power saving mechanism based on quorum systems for multi-hop mobile ad hoc networks

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ABSTRACT

IEEE 802.11 specifies a Power Saving Mode (PSM) in order to save the consumption of energy or power for mobile stations in wireless ad hoc networks. Following the standard of PSM, a number of studies [1–5] further discussed the wake-up/sleep scheduling of beacon intervals based on Quorum systems so that any communication pair of stations has common awake intervals for data exchange. However, most of them did not take into consideration the fact that non-neighbor stations did not require common wake up intervals since they were unable to communicate with each other. Hence, the energy conservation and the transmission delay could not be significantly improved. This paper utilizes the location information and proposes a location-aware power saving mechanism. In the proposed scheme, the network area is partitioned into regular hexagon cells and every station determines the basic quorum intervals based on its cell location information such that only neighboring cells have common beacon intervals for data exchange. In addition, a collision avoidance strategy is proposed to improve the network throughput. Experiment results reveal that the proposed scheme outperforms existing approaches in terms of energy conservation and transmission delay.

1. Introduction

A Mobile Ad-hoc Network (MANET) which comprises mobile stations can construct a low cost wireless network anywhere and anytime without infrastructure. Since the mobile stations are battery powered, how to save their energy is one of the most important issues in the MANETs. A number of studies [1–9, 23–25] have proposed energy conservation mechanisms for mobile stations based on IEEE 802.11 PSM [10]. The concept of IEEE 802.11 PSM [10] is given as follows.

1.1. IEEE 802.11 power saving mode (PSM)

In PSM, each station is assumed to be synchronized with each other. The time is partitioned into beacon intervals. Each beacon interval contains two sub-intervals, called ATIM and Data windows, as shown in Fig. 1.

In the ATIM window, a sender intending to communicate with its neighboring station can send an ATIM packet to ask its neighbor. Upon receiving the ATIM packet, the receiver replies with an ATIM-ACK packet which indicates the agreement of data transmission in the Data window. Then the sender and receiver should keep awake in the Data window and compete for a transmission opportunity based on the DCF (Distributed Coordination Function), as defined in IEEE 802.11 standard. All of the other stations that do not play the roles of sender and receiver can sleep in the Data window for energy conservation.

However, a station in the IEEE 802.11 PSM must wake up at every beacon interval. This causes significant energy consumption, even though the station did not demand to exchange data. On the contrary, when the traffic is heavy, each station stays awake and competes with all the other stations, leading to significant contentions and collisions.

To overcome the energy inefficiency problem of IEEE 802.11 PSM, an intuitive solution is to allow some stations to sleep for a long time when its traffic load is light. However, this might introduce the rendezvous problem where two stations do not have any common awake intervals. To cope with the rendezvous problem, a number of studies [1–5] further discussed the wake-up/sleep scheduling of beacon intervals based on Quorum systems so that any communication pair of stations has common awake intervals for data exchange. The following briefly introduces the concept of the quorum system.

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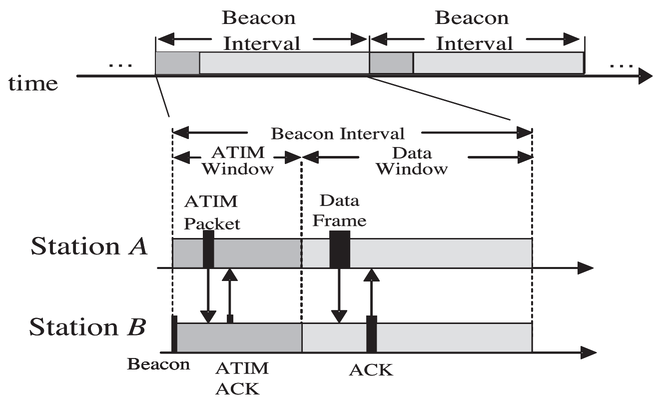


Fig. 1. The illustration of beacon intervals applied in the power saving mode of IEEE 802.11.

1.2. The concept of quorum system

In the quorum system, time is divided into several equal-length beacon intervals. Let n denote a global parameter. Each continuous n^2 beacon intervals are called a quorum array and these n^2 intervals are arranged in a two dimensional array with $n \times n$ entries. Each station can randomly select one row and one column of intervals in the quorum array as its awake intervals. Based on the quorum's properties, each pair of neighboring stations is guaranteed to have the at least two rendezvous opportunities where they can communicate with each other in a distributed manner.

Fig. 2 gives an example of quorum system with $n = 3$. As shown in Fig. 2(a), the quorum arrays of station *A* is arranged in a two dimensional array with 3×3 entries. The number labeled on each entry of quorum array denotes the sequence number of beacon interval. Station *A* selects the 3rd row and the 1st column as its awake intervals. Similarly, station *B* depicted in Fig. 2(b) selects the 3rd row and the 2nd column of the array as its awake intervals. This means that station *A* wakes up in beacon intervals 0, 3, 6, 7, and 8 while station *B* wakes up in beacon intervals 1, 3, 4, 5, and 7. As a result, the common beacon intervals for stations *A* and *B* communicating with each other are beacon intervals 3 and 7, as shown in Fig. 2(c).

Adopting the quorum system in MANET not only simply exploits the rendezvous and communication opportunities for any pair of stations in a distributed manner but also saves the energy consumption. However, the quorum size cannot be dynamically changed according to the traffic loads. Furthermore, they do not take into consideration the fact that non-neighboring stations do not require any common quorum interval since they are unable to communicate with each other. The common quorum intervals assigned for non-neighboring stations will increase the collision rate, increasing energy conservation and transmission delay.

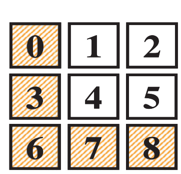
This paper proposes a Location-Aware Power Saving mechanism (LAPS), which adopts a location-aware quorum and takes into account the problem of hidden terminal avoidance within the neighborhood relationships to improve the energy conservation and transmission delay. In the proposed scheme, the network area is partitioned into regular hexagon cells and each station is assumed to be aware of its own location information. Every station determines the basic quorum intervals based on its cell location information such that only neighboring cells have common beacon intervals for data exchange. In addition, a collision avoidance strategy is proposed to improve the network throughput. Performance results reveal that the proposed scheme outperforms the existing approaches in terms of energy conservation, end-to-end delay, and packet loss ratio.

The remainder of this paper is organized as follows. Section 2 discusses the related works. Section 3 specifies the network environment and problem formulation. The detail of the proposed LAPS is presented in Sections 4. Section 5 discusses the quorum system developed by the proposed scheme, while Section 6 investigates the performance study. Section 7 concludes this work.

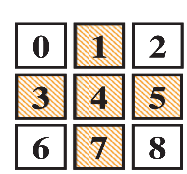
2. Related works

The quorum systems are widely applied to develop mechanism for mutual exclusion, data replication, and power-saving in the distributed systems [3,11]. Previous work proposed by Tseng et al. [1] assumed that each station in MANET is with unsynchronized ATIM windows and wakes up at different times. This protocol intends to increase the active time of stations and hence provides more overlapping awake intervals. However, prolonging the active period of stations, that consumes extra energy, is not necessary since some distributed synchronization mechanisms are provided in [16,17,26,27]. Furthermore, literature [5] identified a rotation closure property for quorum systems to ensure that the quorum system satisfying the property can be translated to the asynchronous power-saving protocol [1] for MANETs. A new e-torus quorum system is also proposed in [5] to demonstrate that a station with higher mobility may have more common beacon intervals with its neighbors so as to be more environment-sensitive. In fact, neighbor discovery with high sensitivity means that much energy will be consumed in the listen intervals.

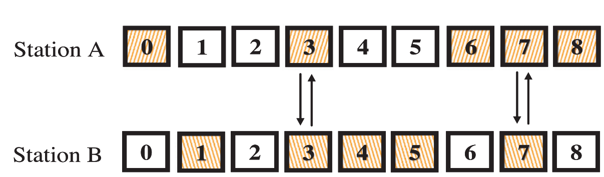
Study [2] proposed a traffic-aware quorum scheme, called Adaptive Quorum-Based Energy Conserving Protocol (AQEC), to adjust the quorum size according to the traffic load. In AQEC, the



(a) The quorum intervals applied in station *A*.



(b) The quorum intervals applied in station *B*.



(c) The illustration of the common beacon intervals by applying the quorum system for stations *A* and *B*.

Fig. 2. An example for illustrating the common beacon intervals of stations *A* and *B* determined by the $\sqrt{9} \times \sqrt{9}$ quorum set.

quorum size will be decreased in order to increase the number of the beacon intervals in the following quorum cycles when the traffic load grows. Similarly, the adaptive traffic-aware power-saving protocols [3,12] dynamically adjust the length of the quorum cycle by considering the network utilization during its previous quorum cycle. OFPM [4] proposed the Factor-hereditary quorum system and the closed-loop listen interval adjustment scheme such that each power-saving station can adaptively adjust its listen interval according to flow timeliness requirements. However, the global quorum size proposed in [2–4,12] will be difficult to control for the local burst traffic. Also, all pairs of stations will have equal opportunities of common quorum intervals which are only required by the neighboring stations.

Clock synchronization is fundamental and important problem in multi-hop mobile ad hoc networks. Unsynchronized stations may wake up at different times, leading to low efficiency of power saving and network throughput. Although the IEEE 802.11 standard provides a clock synchronization protocol, it suffers from the scalability problem due to it provided inefficiency contention mechanism. In literature, several studies have proposed efficient clock synchronization mechanisms [16,26,27]. Study [16] proposed the ATSP protocol, which aims to achieve time synchronization in MANETs. Let term *fastest station* denote the station that has the largest instantaneous clock frequency. The major idea of ATSP is that it assigns the fastest station with the highest priority for transmitting beacons by increasing its beacon transmission frequency. Meanwhile, the transmission frequencies of other stations will be reduced. By applying the ATSP, the problem of asynchronous time can be mitigated. However, the performance highly depends on the factors such as mobility and scalability. In [26], an extension, called TATSP, was further proposed to improve the constraint of ATSP. However, both ATSP and TATSP are developed for single hop MANET, which cannot be efficiently applied in multi-hop MANET.

Study [27] proposed the ASP protocol, aiming to achieve time synchronization for multi-hop MANET. The ASP mainly consists of two tasks. First, successful transmission probability for faster stations must be increased. To achieve this, the ASP increases the beacon transmission priority of a faster station and decreases the priorities of the other stations. Second, the faster timing information must be spread throughout the whole network. When the slower stations collect enough timing information, it executes synchronization by applying the faster time and hence its beacon transmission priorities will be increased. By applying the ASP protocol, the time synchronization problem can be resolved for multi-hop MANET. In addition, the power saving protocols that adopt the semi-asynchronous method are also proposed in [28] for multi-hop MANET. The major idea of [28] comprises two tasks. First, stations are clustered. Inside each cluster, stations adopt a synchronous power saving protocol in order to conserve energy. Then, an asynchronous power saving protocol is executed among clusters. That is, within each cluster, some stations are selected to execute the asynchronous power saving protocol.

Table 1 investigates the characteristics of the proposed scheme compared to the related schemes. The proposed scheme intends to address a novel location-aware quorum system for improving the network performance in terms of energy conservation and transmission delay.

Table 1
The characteristics of the proposed scheme compared to the related studies.

Schemes	Quorum system	Clock	Traffic-aware	Hidden terminal avoidance
PSM [10]	No	Sync.	No	No
PowerMac [1]	Grid-based	Async.	No	No
AQEC [2], [3,12]	Grid-based	Sync.	Adaptive	No
OFPM [4]	Factor-hereditary	Sync.	Adaptive	No
[5]	E-torus	Async.	No	No
LAPS	Location-aware	Sync.	Adaptive	Yes

3. Network model and problem formation

3.1. Network model

Let the service region for MANET N be geographically partitioned into a number of equal-sized hexagon cells. The service region is called Cellular-based Partitioning Network (*CPN*) G. A grouping scheme is applied on the partitioned cells so that each group consists of seven neighboring cells. In each group, the central cell is labeled with cell number 0 and the other cells are labeled with numbers 1 to 6 in a clockwise order. Let G^k and C_i^k denote the group k and the cell i in G^k. That is, the service region is partitioned into the groups $G^1, G^2, \ldots, G^{m-1}$and G^m, where $G^i \cap G^j = \Phi$ for $1 \le i \ne j \le m$ and each group, say G^k, consists of seven cells labeled by $C_0^k, C_1^k, \ldots, C_5^k$and C_6^k, where $1 \le k \le m$. The groups will be indexed in the order left to right and then top to down. Fig. 3(a) shows a *CPN* $G = \{G^1, G^2, \ldots, G^{13}\}$ with 13 disjoint groups while Fig. 3(b) depicts that group G^k, $1 \le k \le m$, consists of the central cell C_0^k and its surrounding cells $C_1^k, \ldots, C_5^k$ and C_6^k. Similar to studies [1–4,12], herein, we assume that the clocks on the stations are well synchronized [13]. In addition, the stations are assumed to be location-aware and know the location of central point of cell C_0^1.

Let r be the communication range of mobile stations. So that any station can communicate with another station located in the same cell or the neighboring cell, the farthest distance from one point of a given cell to another point of the neighboring cell should be smaller than r. Hence the edge length, say e, of each hexagon is $e = r/\sqrt{13}$, as shown in Fig. 4. The total transmission time of the Data Window will be partitioned into T slots with the same interval of time. This means that all stations will compete for transmission opportunities in T slots. The positioning information of each station can be acquired by GPS device, or by applying some GPS-less positioning systems [18–20].

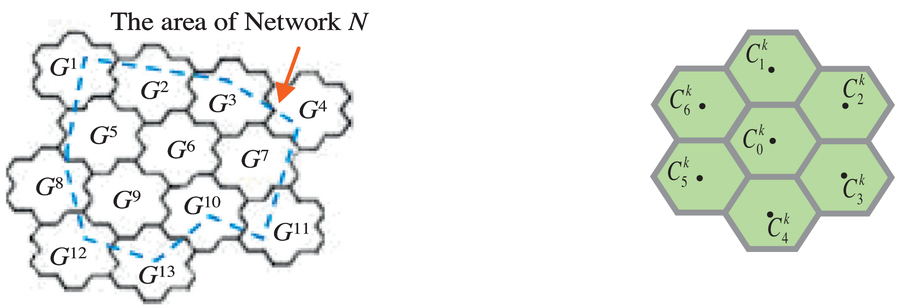
3.2. Problem formulation

Given a *CPN* G and a universal set $U = \{0, 1, \ldots, n\}$, a quorum system over U will be arranged by using an array A. Each group in G applies the same quorum array A. Let Q_i denote the quorum set i whose elements are assigned from the elements of the resultant quorum array. Let C_i^* denote the union set $\bigcup_{t=1}^{m} C_i^t$, where $1 \le k \le m$ and $0 \le i \le 6$. In LAPS, the stations in cells C_i^* will apply the quorum intervals assigned in Q_i. This means that $Q_0, Q_1, \ldots, Q_6$ will be constructed into the quorum system Q in the proposed scheme. Let $N_d(x)$ denote the d-hop neighboring cells of cell x, where $N_0(x)$ specifies the cell x itself. The packets sent by a station in cell x will be forwarded to the station located in the cell $N_d(x)$, $d > 0$, in a manner of cell by cell. Let H_i^k denote the set of stations located in C_i^k. Following defines the *Neighbor Common Intervals (NCI)* and *Hidden Terminal Avoidance (HTA)* requirements before introducing the proposed Location-Aware Quorum System.

Definition. Neighbor Common Intervals (*NCI*) and Hidden Terminal Avoidance (*HTA*) Requirements

To satisfy the *NCI* and *HTA* requirements, the constructed quorum sets have the following constraints.

(1) ***Neighbor Common Intervals*** (*NCI*) constraint: $Q_i \cap Q_j \neq \varphi$, where $0 \le i \ne j \le 6$.



(a) An example of the *CPN* $G = \{G^1, G^2, \ldots, G^{13}\}$.

(b) An example of group G^k combined by C_0^k, C_1^k, …, C_5^k and C_6^k.

Fig. 3. The MANET *N* is assumed to be partitioned into regular hexagon cells and groups.

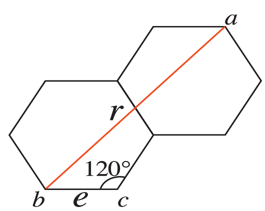


Fig. 4. The length *e* of each cell edge can be evaluated by the communication range *r*, where $e = r/\sqrt{13}$.

(2) ***Hidden Terminal Avoidance*** (*HTA*) constraint: Each station in H_i^k, $0 \le i \le 6$ and $1 \le k \le m$, should avoid the packet collisions due to hidden terminal problem. That is,

$$Q_i \cap Q_j = \phi, \quad \forall C_j^h \in N_2(C_i^k), \quad 1 \le h \ne k \le m, 0 \le j \le 6 \tag{1}$$

The *Location-Aware Quorum System Identification* (***LQSI***) problem refers to the assignment problem that elements in *U* should be assigned to array *A* such that the *NCI* and *HTA* requirements can be satisfied. Furthermore, the quorum array *A* also aims to achieve the minimal transmission delay when the stations in cell C_i^k intend to communicate with their neighbors located in $N_1(C_i^k)$, where $1 \le k \le m$ and $0 \le i \le 6$. In the *CPN G*, the proposed quorum should satisfy the *NCI* and *HTA* requirements. First, the *NCI* requirement refers to the demand that stations in $H_i^k$and stations in $N_1(C_i^k)$ have common quorum intervals for data exchange, where $1 \le k \le m$ and $0 \le i \le 6$. Second, the *HTA* requirement reflects the need that the quorum intervals used by H_i^k have to avoid the hidden terminal problem from the stations located in $N_2(C_i^k)$, where $1 \le k \le m$ and $0 \le i \le 6$. Take Figs. 3(a) and (b) as examples. The sets $N_1(C_0^6)$ and $N_2(C_0^6)$ are $\{C_1^6, C_2^6, C_3^6, C_4^6, C_5^6, C_6^6\}$ and $\{C_4^2, C_3^2, C_5^3, C_4^3, C_6^7, C_5^7, C_1^{10}, C_6^{10}, C_2^9, C_1^9, C_3^5, C_2^5\}$, respectively. If station *x* in C_0^6 and station *y* in $N_2(C_0^6)$ are assigned with the same quorum intervals for $c_{x,y}$, the hidden terminal problem might occur since stations *x* and *y* in the two cells are two hop neighbors. For example, the hidden terminal problem might occur in H_6^6 or H_1^6 when H_0^6 and H_4^2 are assigned to the same quorum intervals.

Definition. *Delay*(Q_i, Q_j)

Let *U* and q_{ij} be a universal set {0, 1, …, *n*} and the *i*th beacon interval assigned in Q_i, respectively. Function *Delay*(Q_i, Q_j) is used to measure the transmission delay time from the sender using Q_i to the receiver using Q_j. Let Q_i and Q_j be $\{q_{i1}, q_{i2}, \ldots, q_{iv}\}$ and $\{q_{j1}, q_{j2}, \ldots, q_{ju}\}$, respectively, where $0 \le q_{i1} < q_{i2} < \ldots < q_{iv} \le n$ and $0 \le q_{j1} < q_{j2} < \ldots < q_{ju} \le n$. When the sender intends to transfer data at q_{it}, where $1 \le t \le v$, the value of *Delay*(Q_i, Q_j) is defined by Eq. (2)

$$Delay(Q_i, Q_j) = \begin{cases} 0, & \text{if } q_{it} = q_{jr}, \text{ where } 1 \le r \le u, \\ n - q_{it} + q_{j1}, & \text{if } q_{it} > q_{ju}, \\ \min\{q_{jr} - q_{it} | q_{jr} > q_{it}, r \le u\}, & \text{if } q_{it} < q_{ju}. \end{cases} \tag{2}$$

This paper aims to cope with the *LQSI* problem. The goal of this work is to minimize the maximal transmission delay *Delay*(Q_i, Q_j) under satisfying the constraints *NCI* and *HTA*. That is

$$Minimize(\max.(Delay(Q_i, Q_j))), 0 \le i \ne j \le 6. \tag{3}$$

The design of quorum system *Q* associated with $U = \{0, 1, \ldots, n\}$ can determine the value of *Delay*(Q_i, Q_j). Let a round represent the period of $n+1$ intervals. A quorum system *Q* with a large value *n* implies a large value of round length, which increases the average transmission delay. Therefore, a large value of *n* is not appreciated since Eq. (3) aims to minimize the maximal transmission delay. However, a small value of *n* might lead to the situation that the numbers assigned to *Q* have several duplicates, resulting in heavy collisions and contentions. This occurs because the stations in cell C_i^k and $N_2(C_i^k)$, $0 \le i \le 6$, and $1 \le k \le m$, might have hidden terminal problem due to several common awake beacon intervals. Therefore, the main challenge for achieving the goal depicted in Eq. (3) is to design an appropriate quorum system *Q* associated with *U*.

4. Location-aware power saving mechanism

The proposed location-aware power saving mechanism consists of the *Interval Scheduling* (or *IS*) phase and the *Cell Identifying* (or *CI*) phase. The *IS* phase introduces the procedure on how to construct the location-aware quorum system which assigns the awake beacon intervals to the cells. All stations in each cell should stay in an active state in the awake beacon intervals assigned to that cell. Then, in the *CI* phase, each station has to identify the IDs of its cell where it locates such that it can apply the assigned awake intervals. The following presents the design of each phase of LAPS.

4.1. Interval scheduling phase

Since the *CPN G* has been regularly partitioned into several groups, the sleep/awake scheduling rule applied on each group will be identical. Thus we will focus on how to schedule the awake beacon intervals for each cell in a group G^k. Recall that each group consists of seven cells, as shown in Fig. 2(b). The main concept is that two neighboring cells should be assigned with one common beacon interval for satisfying the *NCI* requirement while two-hop neighboring cells should be assigned with different beacon intervals for satisfying the *HTA* requirement. In general, a smaller size

C_0^k	C_1^k	C_2^k	C_3^k	C_4^k	C_5^k	C_6^k
0	1	2	3	4	5	x
6	7	8	9	10	11	x
12	13	14	15	16	17	x
18	19	20	21	22	23	x
24	25	26	27	28	29	x
30	31	32	33	34	35	x

Fig. 5. The initial grid-based quorum over U will be arranged by applying the proposed scheme.

Q_0	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
0	1	2	3	4	5	x
6	7	8	9	10	11	x
12	13	14	15	16	17	x
18	19	20	21	22	23	x
24	25	26	27	28	29	x
30	31	32	33	34	35	x

Fig. 6. . The initial awake beacon intervals assigned for C_0^k, $1 \le k \le m$.

of U applied in the quorum system can achieve better performance in terms of transmission delay. However, a small size of U also increases the opportunities of packet collision among the stations in the neighboring cells. The minimal size of U is discussed in the next section.

The following discusses the proper size of quorum array A. According to an intuitive observation, each group G^k consists of seven cells C_i^k, $1 \le k \le m$ and $0 \le i \le 6$. Take C_0^k as an example. Cells C_1^k and C_4^k are neighboring cells of C_0^k. In cases where C_1^k and C_4^k are assigned with the same awake interval to communicate with the stations in C_0^k, a hidden terminal problem will occur since C_1^k and C_4^k are two-hop neighboring with each other. Therefore, stations in C_0^k should use different beacon intervals to communicate with each of its neighboring cells. From this observation, we conclude that each quorum set will include at least six awake beacon intervals. Given a group G^k, $1 \le k \le m$, stations in C_i^k will apply Q_i to communicate with the stations in $N_1(C_i^k)$, where $0 \le i \le 6$. Since there are exactly seven cells in each group, the proposed quorum system requires at least seven quorum sets, where there are six beacon intervals assigned for the neighboring cells existing in each set. Consequently, the following uses $A_{6\times 7}$ as an initial quorum array design.

Next, we discuss how to construct the quorum array $A_{6\times 7}$. Initially, let $U = \{0, 1, \ldots, 35\}$. The elements of U will be assigned to the first six columns of Q in a row-major order, as shown in Fig. 5. The last column will be reserved without any assignment since the proposed *LAPS* aims to minimize the value of n. The proposed *LAPS* applies Eq. (4) to assign the beacon interval t in the first six columns to element $A[p, i]$, where $0 \le p \le 5$ and $0 \le i \le 5$. For example, the initial awake beacon intervals assigned for C_0^k, $1 \le k \le m$, are 0, 6, 12, 18, 24, and 30, which are the numbers assigned in the 0th column of array A as shown in Fig. 6 .

$$A[p, i] = A\left[\left\lfloor \frac{t}{6} \right\rfloor, (t \bmod 6)\right] = t, \text{ for each } t \in U. \tag{4}$$

The *Interval Scheduling Phase* mainly consists of intra-group and inter-group scheduling procedures. The intra-group scheduling procedure aims to replace the beacon intervals for satisfying the *NCI* constraint. The assignment of common beacon intervals for two cells that neighbor with each other but belong to different groups is achieved in the inter-group scheduling procedure. The following presents each procedure in detail.

4.1.1. Intra-group scheduling procedure

This procedure is designed to replace the intervals given in Fig. 6 for satisfying the *NCI* constraint. The Intra-group Scheduling Procedure mainly consists of two steps. For each group G^k, $1 \le k \le m$, the first step assigns one common awake interval for C_0^k to communicate with each of cells $N_1(C_0^k)$, as shown in Fig. 7(a). As shown in Fig. 7(a), step 1 aims to achieve the goal that two cells pointed by an arrow should have one common awake interval. Let $u(i)$ be the function for $C_i^k \in N_1(C_0^k)$to map the common awake intervals with $C_{u(i)}^k \in N_1(C_0^k)$. The value of $u(i)$ will be $i+1$, where $1 \le i \le 5$. If i is equal to 6, $u(i)$ will be one. In the second step, C_i^k and $C_{u(i)}^k$, $1 \le i \le 6$, are considered to have one common awake since they are also neighboring to each other in group G^k. Fig. 7(b) depicts awake interval adjustment operated in step 2. As shown in Fig. 7(b), step 2 focuses at achieving the goal that C_i^k and $C_{u(i)}^k$ should have one common awake interval for each i, where $1 \le i \le 6$.

To satisfy the *NCI* constraint, C_0^k and C_i^k, $1 \le i \le 6$, should have one common interval. To achieve this, the element $A[p\text{-}1, p]$ is replaced by $A[p\text{-}1, 0]$, for each p, where $1 \le p \le 6$. Since the replacement operation will cause replaced number $A[p-1, p]$ to disappear, which causes these beacon intervals to be idle without any data exchange, the original value of $A[p-1, p]$ will be moved to $A[p-1, 6]$ before they are replaced. In addition, the element $A[5, 6]$ is replaced by $A[5, 0]$. Fig. 8(a) and (b) show the steps of intra-group scheduling. In each group, say G^k, since cell C_0^k neighbors to cell C_1^k, the element $A[0, 1]$ will be replaced by the element $A[0, 0] = 0$, resulting in a common beacon interval between cells C_0^k and C_1^k. Thus H_0^k and H_1^k have opportunities for communicating with each other since they are awake at the beacon interval 0. Before the replacement, a shift operation that moves the element $A[0, 1]$ to $A[0, 6]$ should be executed because the element $A[0, 1]$ will not be used by cell C_1^k. The similar replacement operations will be applied by considering C_0^k and each C_i^k, $2 \le i \le 6$. Fig. 8(a) depicts the resultant replacement after the step.

In the second step, the proposed LAPS further considers C_i^k and $C_{u(i)}^k$, $1 \le k \le m$ and $1 \le i \le 6$, since cells C_i^k and $C_{u(i)}^k$ are neighboring cells in group G^k. That is, C_i^k and $C_{u(i)}^k$ should also have one common interval. Let $v(x)$ be the cell indexing function to assign the common awake intervals for $C_{v(x)}^k$ in the row x of array A. If x is equal to zero or one, $v(x)$ is set to $x+5$. The value of $v(x)$ is $(x-1)$, where $2 \le x \le 5$. To achieve this, the element $A[i, v(i)]$ is set to $A[i, u(v(i))]$ for each i, $0 \le i \le 5$. As a result, the elements $A[0, 5]$, $A[1, 6]$, $A[2, 1]$, $A[3, 2]$, $A[4, 3]$, and $A[5, 4]$ are set to $A[0, 6]$, $A[1, 1]$, $A[2, 2]$, $A[3, 3]$, $A[4, 4]$, and $A[5, 5]$, respectively. Fig. 8(b) shows the affected elements of array A in this procedure. Herein, each cell has at least one awake beacon interval to communicate with its neighboring cells in the group. The remainder elements of array A, as shown in Fig. 8(c), will be assigned for inter-group scheduling.

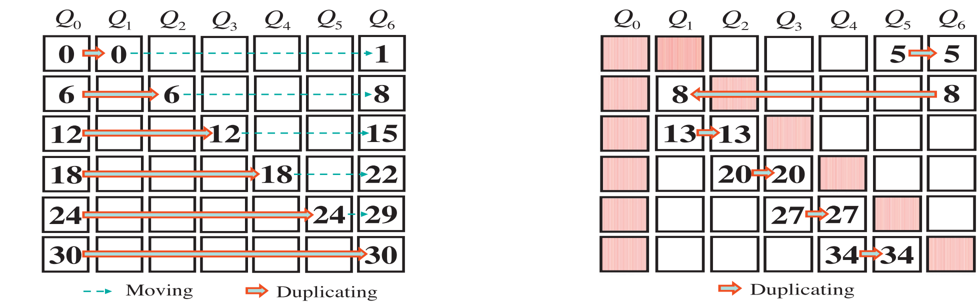
4.1.2. Inter-group scheduling procedure

The *Inter-group Scheduling Procedure* further considers the common awake beacon intervals between those cells that belong to neighboring groups. The following introduces the dual properties of *CPN* which will be applied in the procedure.

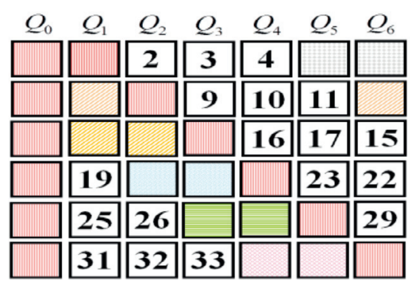
Recall that a group in a *CPN* has at most six neighboring groups. Consider a certain group G^k, $1 \le k \le m$, as shown in Fig. 9(a). In Fig. 9(a), assume that six groups are neighboring with G^k, say G^a, G^{a+1}, $G^{k\text{-}1}$, G^{k+1}, G^b and G^{b+1}, where the cells in a group are marked with the same color. As shown in Fig. 9(b), 18 arrows,

(a) Scheduling goal of step 1.   (b) Scheduling goal of step 2.

Fig. 7. An example to illustrate the neighboring cells for the interval replacements in the intra-group scheduling procedure.



(a) Step 1 of the intra-group scheduling.   (b) Step 2 of the intra-group scheduling.



(c) The remainder elements after executing the intra-group scheduling.

Fig. 8. The procedure of assigning awake beacon intervals achieves the neighboring cells of C_i^k, $1 \le i \le 6$, having a common awake beacon interval with C_0^k for any group k.

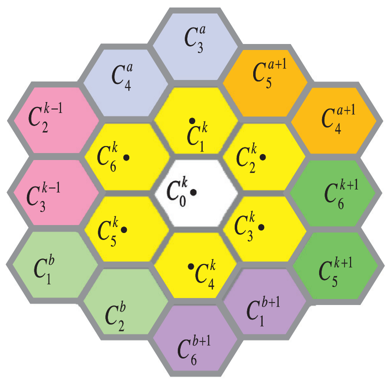
each representing an awake interval assigned by the two neighboring cells, will be needed for the inter-group scheduling procedure. Since the stations in cells C_i^* will apply the quorum intervals assigned in Q_i, some awake intervals needed in Fig. 9(b) will be duplicated. For example, the awake intervals assigned for C_3^a and C_1^k, C_4^a and C_1^k, C_5^{a+1} and C_1^k will also be used for C_3^k and C_1^{b+1},C_4^k and C_1^{b+1}, C_5^k and C_1^b, respectively, as shown in Fig. 9(c). As a result, there are at most nine awake intervals needed for the inter-group scheduling procedure, as shown in Fig. 9(d). The following property aims to be applied for reducing the number of interval replacements in the procedure. The property is described below.

Property 1. ***Dual neighboring relationship among inter-group cells***

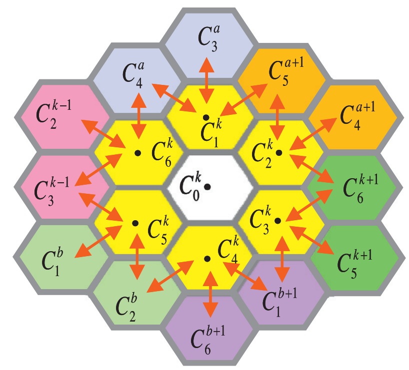
Recall that the *CPN G* are regularly partitioned into the groups. The fact that cell C_i^*, where $1 \le i \le 6$, neighbors with C_j^*, $1 \le j \le 6$, between groups means that, for a group G^k, $1 \le k \le m$, if cell C_i^k neighbors with C_j^x, where $1 \le x \ne k \le m$, there exists a group G^y neighboring with G^k, where $1 \le y \ne k \le m$ and $1 \le y \ne x \le m$, which implies the fact that cell C_j^k neighbors with C_i^y.

Fig. 10(a) shows a part of the remaining intervals depicted in Fig. 8(c) which are available to be assigned for the inter-group neighboring cells for communication. The unassigned intervals in Q_1, Q_3, Q_4, and Q_5 can be further assigned to inter-group cells C_1^k and C_3^a, C_1^k and C_4^a, C_1^k, andC_5^{a+1}, giving them rendezvous opportunities for data exchanges. Consider the interval replacement in Q_1 and Q_3. In order to minimize the waiting time between columns, the element $A[j, 3]$ will be replaced by $A[i, 1]$ such that $|A[i, 1] - A[j, 3]|$ is minimal, where $3 \le i \le 5$ and $j \in \{0, 1, 5\}$. Thus, elements $A[1, 3]$ will be replaced by $A[3, 1]$. Similarly, element $A[2, 4]$ will be replaced by $A[4, 1]$ for Q_1 and Q_4 while element $A[3, 5]$ will be replaced by $A[5, 1]$ for Q_1 and Q_5. The results of the interval replacements for C_1^k are shown in Fig. 10(b). Similarly, the interval replacement for cells C_2^k, C_3^k, and C_6^k in the inter-group scheduling procedure can be determined like that for C_1^k. After the execution of replacement operation, the constructed location-aware quorum sets are presented in Fig. 11(a). As shown in Fig. 11(a), the quorum intervals Q_0, Q_1, ..., and Q_6which will be used for C_0^*, C_1^*, ..., and C_6^*, respectively, defines a collection of quorum sets that the intersection of any two sets is always non-empty.

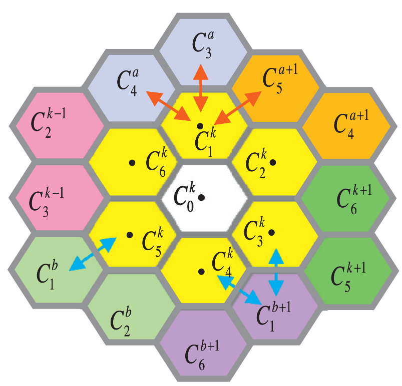
When this phase is complete, the minimal set of U can be determined by the quorum size subtracting the number of the unused beacon intervals shown in Fig. 11(a). As a result, the value of $|U| = 21$ can be applied to develop the proposed quorum system for satisfying both of the *NCI* and *HTA* requirements. Therefore, the resultant quorum system adopts $U = \{0, 1, ..., 20\}$ by reordering the intervals in array A, as shown in Fig. 11(b). For example, the interval 2 assigned for Q_2 and Q_4 in Fig. 11(a) will be changed to 1



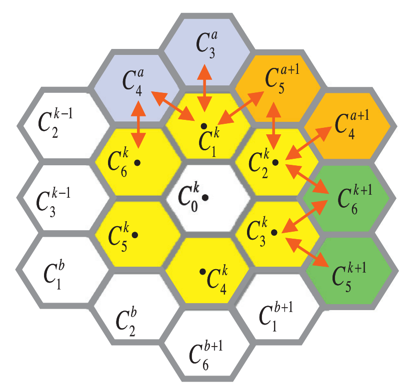
(a) The cells in G^k, $1 \le k \le m$ and their neighboring cells.



(b) The assignments of common awake intervals needed for the inter-group scheduling procedure.

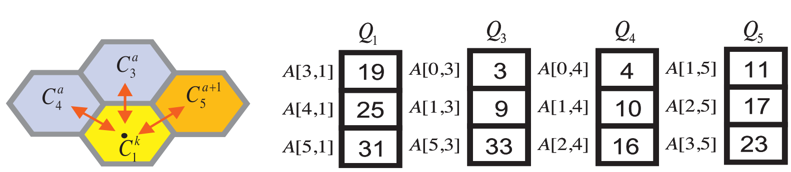


(c) An example of the interval replacements with the dual relationship among inter-group cells.

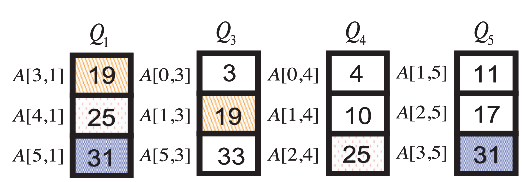


(d) The total number of interval replacements needed in the inter-group scheduling procedure.

Fig. 9. An example to illustrate the neighboring cells for the interval replacements in the inter-group scheduling procedure.



(a) The remaining intervals are available to be assigned to the inter-group neighboring cells for communication.



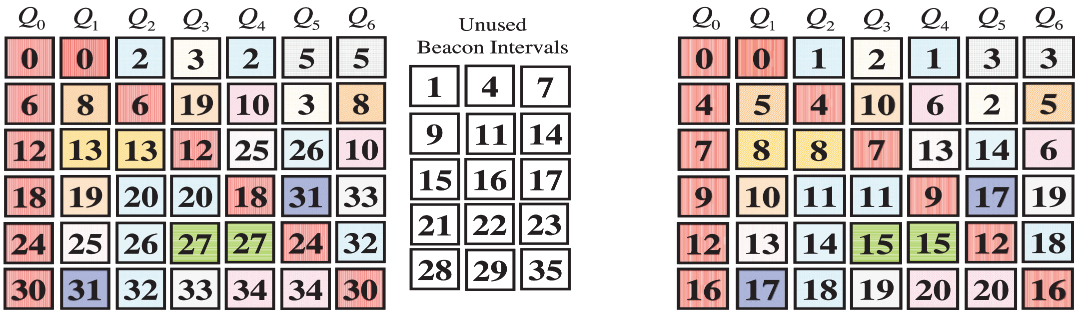
(b) The results of the interval replacements for C_1^k.

Fig. 10. The example to illustrate the interval replacement for C_1^k, $1 \le k \le m$, in the inter-group scheduling procedure.

after removing the unused interval 1 from U then reassigning the interval order such that the original interval 2 becomes interval 1, as shown in Fig. 11(b).

The algorithm of the Interval Scheduling scheme depicts the procedure to construct the location-aware quorum system which assigns the awake beacon intervals to the neighboring cells.

Algorithm*: *Intra-group Scheduling Procedure
// Given a *CPN* $G = \{G^1, G^2, \ldots, G^m\}$
// Let the universal be $U = \{0, 1, \ldots, 35\}$.
Input: The quorum array $A_{6\times 7}$, where $A[i, j] \in U$, $0 \le i \le 5$, $0 \le j \le 6$.
Mark array $M_{6\times 7}$, where $M[i, j] \in \{0, 1\}$, $0 \le i \le 5$, $0 \le j \le 6$.
Output: Assign the common intervals between C_i^k and C_j^k for each group k, $0 \le i \ne j \le 6$ and $1 \le k \le m$.
1. $A[p, i] = A[\lfloor \frac{t}{6} \rfloor, (t \bmod 6)] = t$, foreach$t \in U$; // Initial assignment
2. $M[i, j] = 0$, for all i and j, $0 \le i \le 5$, $0 \le j \le 6$.



(a) The quorum intervals Q_0, Q_1, ..., and Q_6 will be used for C_0^*, C_1^*, ..., and C_6^*, respectively.

(b) After removing the unused beacon intervals depicted in (a) and reordering the other used intervals, the proposed quorum intervals are obtained.

Fig. 11. The resultant quorum intervals for the proposed scheme.

3. for $i = 1$ to 6 {// The common intervals are assigned for C_0^k and C_i^k, $1 \le i \le 6$.
4. $A[i\text{-}1, 6] = A[i\text{-}1, i]$;
5. $A[i\text{-}1, i] = A[i\text{-}1, 0]$;
6. $M[i\text{-}1, i] = 1$; $M[i\text{-}1, 0] = 1$;
7. }
8. for $i = 0$ to 5 {// The common intervals are assigned for cells in $C_i^k \in N_1(C_0^k)$, $0 \le i \le 5$.
9. $A[i, v(i)] = A[i, u(v(i))]$;
10. $M[i, v(i)] = 1$; $M[i, u(v(i))] = 1$;
11. }

Function *v*(*x*)

// Compute the cell ID $v(x)$, $0 \le x \le 5$, that will be assigned the common intervals in the row x of A;
1. If $(x = 0)$ or $(x = 1)$
2. return $(x + 5)$;
3. else
4. return $(x - 1)$;

Function *u*(*x*)

// Compute the cell ID $u(x)$, $1 \le x \le 6$, that will be assigned for the common intervals between C_x^k and $C_{u(x)}^k$, where $C_x^k, C_{u(x)}^k \in N_1(C_0^k)$;
1. If $(1 \le x)$ and $(x \le 5)$
2. return $(x + 1)$;
3. else
4. return 1;

Algorithm*: *Inter-group Scheduling Procedure

// Given a *CPN* $G = \{G^1, G^2, ..., G^m\}$. Let the universal be $U = \{0, 1, ..., 35\}$.
Input: The quorum array $A_{6 \times 7}$, where $A[i, j] \in U$, $0 \le i \le 5$, $0 \le j \le 6$.
Mark array $M_{6 \times 7}$, where $M[i, j] \in \{0, 1\}$, $0 \le i \le 5$, $0 \le j \le 6$.
Output: Assign the common intervals between C_i^k and $C_j^h \in N_1(C_i^k)$, $1 \le h \ne k \le m$, $1 \le i \ne j \le 6$.
1. *Replacement*(1, 3, 5); // assign the common intervals between Q_1 and Q_i, $3 \le i \le 5$.
2. *Replacement*(2, 4, 6); // assign the common intervals between Q_2 and Q_i, $4 \le i \le 6$.
3. *Replacement*(3, 5, 6); // assign the common intervals between Q_3 and Q_i, $5 \le i \le 6$.
4. *Replacement*(6, 4, 4); // assign the common intervals between Q_6 and Q_4.

Procedure *Replacement*(*col, s_row, e_row*)

// Assign the common intervals between Q_{col} and Q_i, $s\_row \le i \le e\_row$;
1. for $i = s\_row$ to e_row {
2. if $(M[i, col] = 0)$ {
3. $d = \min.\{|A[i, col] - A[i, j]| \mid M[i, j] = 0$ and $0 \le j \le 5\}$;
4. for $j = 0$ to 5 {
5. if $(|A[i, col] - A[i, j]|)$ and $(M[i, j] = 0)$ {
6. $A[i, j] = A[i, col]$;
7. $M[i, i] = 1$; $M[i, col] = 1$;
8. }
9. }
10. }
11.}

4.2. Cell identifying phase

In the previous phase, the LAPS assigns awake intervals to each cell such that the *NCI* and *HTA* constraints can be satisfied. In this phase, each station has to identify the cell where it locates such that it can apply the assigned awake intervals. The identification of cell ID relies on some information, including the location of central point of cell C_0^1, the area of the given network N, and the station's location information. Recall that the *CPN G* is partitioned by the groups, say $G^1, G^2, ..., G^{m-1}$ and G^m, and indexed in an order from left to right and then top to down. The center of group G^k is set at the center point of cell C_0^k. Let the center point of C_0^1 locate at (x_1, y_1). Let L_1 and L_2 denote the set of lines that pass through the central point of each group, as shown in Fig. 12(a) and (b), respectively. Fig. 12(a) and (b) show the slopes of lines L_1 and L_2 are $\frac{2\sqrt{3}}{3}$ and $-\frac{5\sqrt{3}}{3}$, respectively. Fig. 13 shows the fact that the horizontal distances between two neighboring lines are equal to $4.5e$, where $e = r/\sqrt{13}$. As a result, the line sets L_1 and L_2 can be derived by Eqs. (5) and (6), respectively. Take Fig. 13 as an example. As shown in Fig. 13, the line of L_1 and the line of L_2 will pass the central location of G^1, or (x_0^1, y_0^1), when the value of α and β are set to zero. Similarly, line L_1 will pass the central locations of G^2, G^5, and G^8 when the value of α is one.

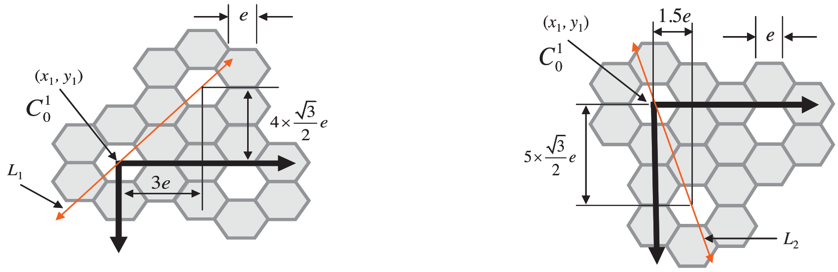
$$L_1 : (y - y_0^1) = \frac{2\sqrt{3}}{3}(x - x_0^1) + 4.5e\alpha, \alpha \in Z \quad (5)$$

$$L_2 : (y - y_0^1) = \frac{-5\sqrt{3}}{3}(x - x_0^1) + 4.5e\beta, \beta \in Z \quad (6)$$

The following discusses how to determine the cell where station v locates. There are two steps to calculate the location of the cell where the station locates. Let (x_i^k, y_i^k) be the central location of cell C_i^k where station v locates, where $1 \le k \le m$. The central location of G^k, or the central location of cell C_0^k, is (x_0^k, y_0^k). According to Eqs. (5) and (6), the central location of cell C_0^k can be determined by calculating the intersection of L_1 and L_2 and selecting the proper integers α and β which can identify the specific lines crossing (x_0^k, y_0^k). As a result, the central location of cell C_0^k can be measured by Eq. (7).

$$(x_0^k, y_0^k) = \left(\frac{9\sqrt{3}}{14}e(\beta - \alpha) + x_0^1, \frac{9e}{14}(2\beta + 5\alpha) + y_0^1\right) \quad (7)$$

Herein, Eqs. (8) and (9) determine the values of α and β to satisfy the shortest distance from (x_v, y_v) to the specific line in L_1



(a) The slope of line set L_1. (b) The slope of line set L_2.

Fig. 12. The slope calculation of line sets L_1 and L_2.

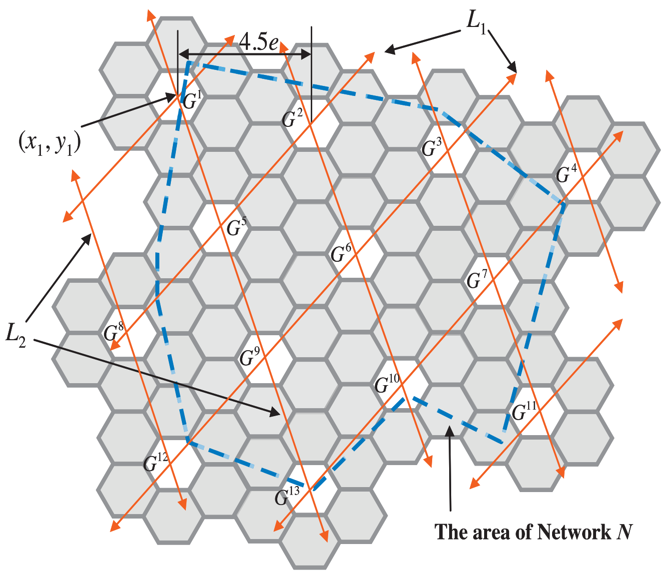


Fig. 13. An example of determining the indexes of the groups and the group where the station located by applying the line sets L_1 and L_2.

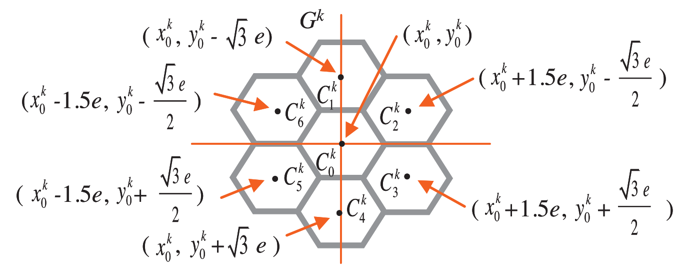


Fig. 14. An example to illustrate how to determine the cell where the station locates.

and L_2, respectively.

$$\alpha = \left\lfloor \frac{2\sqrt{3}(x_0^1 - x_v) + 3(y_v - y_0^1)}{13.5e} \right\rfloor \text{or} \left\lceil \frac{2\sqrt{3}(x_0^1 - x_v) + 3(y_v - y_0^1)}{13.5e} \right\rceil \quad (8)$$

$$\beta = \left\lfloor \frac{5\sqrt{3}(x_v - x_0^1) + 3(y_v - y_0^1)}{13.5e} \right\rfloor \text{or} \left\lceil \frac{5\sqrt{3}(x_v - x_0^1) + 3(y_v - y_0^1)}{13.5e} \right\rceil \quad (9)$$

This means that there are four candidate locations (x_0^k, y_0^k) obtained from Eq. (7) since both α and β have two possible values. Let the location (x_v, y_v) fall in the cell with location (x_0^k, y_0^k). The distance between (x_0^k, y_0^k) and (x_v, y_v) should be smaller than $\frac{3\sqrt{3}}{2}e$. The stations that satisfies constraint (10) fall in C_0^k.

$$\sqrt{(x_0^k - x_v)^2 + (y_0^k - y_v)^2} \le \frac{3\sqrt{3}}{2}e \quad (10)$$

After obtaining the central location of G^k where the station locates, the following illustrates how to determine the central locations of C_1^k, C_2^k, C_3^k, C_4^k, C_5^k, and C_6^k depending on the location of C_0^k. Fig. 14 shows the location relationship between C_i^k, $1 \le i \le 6$, and C_0^k. Let (x_i^k, y_i^k) denote central location of C_i^k. Let notation *dist* denote the distance between (x_i^k, y_i^k) and (x_v, y_v). The station with location (x_v, y_v) satisfies constraint (11) and can identify that it falls in cell C_i^k.

$$dist = \sqrt{(x_i^k - x_v)^2 + (y_i^k - y_v)^2} \le e \quad (11)$$

For example, if the center point of C_0^1, (x_0^1, y_0^1) is $(-150, 170)$ and the communication range is 100, the length $e = 27.74$ of each cell can be estimated. Then, according to Eq. (7), the location of C_0^k, or (x_0^k, y_0^k), can be calculated by

$$(x_0^k, y_0^k) = (30.88 \times (\beta - \alpha) - 150, 17.83 \times (2\beta + 5\alpha) + 170)$$

Assume that the station is at $(x_v, y_v) = (160, -30)$. The central location of the closest group can be calculated by selecting two available values of α and β from Eqs. (8) and (9) so that the distance constraint between (x_0^k, y_0^k) and $(160, -30)$ satisfies

$$\sqrt{(x_0^k - 160)^2 + (y_0^k - (-30))^2} \le \frac{3\sqrt{3}}{2}e$$

As a result, the location $(128, -8)$ can be set for (x_0^k, y_0^k), where α and β are set to -4 and 6, respectively. The station can identify that it locates in the group G^6. Then, by checking constraint (11), the central location of cell C_3^6, or $(x_3^6, y_3^6) = (170, -54)$, can be determined, which is the closest central location of C_i^6, $0 \le i \le 6$, to the station.

The algorithm of the cell identifying scheme depicts the operations that the stations should execute to identify the group and the cell where it locates in the network *N*.

Algorithm: Cell Identifying Scheme
// Let l_v and L_0^1 denote the location of station *v* and the center point location of C_0^1.
// Let the communication range and the edge length of the cell denote by *r* and *e*, respectively.
// Let $\Delta x_i = x_i^1 - x_0^1$ and $\Delta y_i = y_i^1 - y_0^1$, where $0 \le i \le 6$.

Input: $l_v = (x_v, y_v)$ and $L_0^1 = (x_0^1, y_0^1)$;
Output: The cell ID where station v locates
1. $\alpha_1 = \lfloor \frac{2\sqrt{3}(x_0^1 - x_v) + 3(y_v - y_0^1)}{13.5e} \rfloor, \alpha_2 = \lceil \frac{2\sqrt{3}(x_0^1 - x_v) + 3(y_v - y_0^1)}{13.5e} \rceil$;
2. $\beta_1 = \lfloor \frac{5\sqrt{3}(x_v - x_0^1) + 3(y_v - y_0^1)}{13.5e} \rfloor, \beta_2 = \lceil \frac{5\sqrt{3}(x_v - x_0^1) + 3(y_v - y_0^1)}{13.5e} \rceil$;
3.
$Z = \{(g_x, g_y) | g_x = \frac{9\sqrt{3}}{14} e(\beta - \alpha) + x_0^1, g_y = \frac{9e}{14}(2\beta + 5\alpha) + y_0^1, \alpha \in \{\alpha_1, \alpha_2\}, \beta \in \{\beta_1, \beta_2\}\}$;
4. Select the only one $(g_x, g_y) \in Z$ that satisfies
$\sqrt{(g_x - x_v)^2 + (g_y - y_v)^2} \leq \frac{3\sqrt{3}}{2} e$;
5. for $i = 0$ to 6 {
6. $c_x = g_x + \Delta x_i$ and $c_y = g_y + \Delta y_i$;
7. $dist = \sqrt{(c_x - x_v)^2 + (c_y - y_v)^2}$;
8. if ($dist \leqq e$) {
9. Station v locates in cell C_i^* and the central point of the cell is (c_x, c_y);
10. return i;
11. }
12.}

The algorithm of the cell identifying scheme depicts the operations that the stations should execute to identify the group and the cell where it locates in the network N.

The following describes how the proposed LAPS maintains the cellular-based partitioning network in MANETs. In LAPS, each station will maintain its current location periodically. Then each station applies the *Cell Identifying Algorithm* to identify which cell it is located in. In *Cell Identifying Algorithm*, since each station is assumed to know the location of center point of C_0^1 and the size of regular hexagon cells, it can determine which the center point of group it is located. After determining the located group, each station then determine which cell it is located in by calculating the vertical and horizontal distances between its location and the center point of the located group. As a result, each station can determine its located cell by itself without exchanging messages with its neighbors in order to maintain the cellular-based partitioning network. On the other hand, when a station joins in the MANET or moves from one cell to another one, it will broadcast a HELLO message in the well scheduled awake beacon intervals. In addition, when a station joins in the MANET or moves from one cell to another one, it will also listen to the information of neighbors. Therefore, each station knows the numbers of stations in its current cell and its neighboring cells and hence it can exchange message with its neighbors.

4.3. The extensions of LAPS

4.3.1. Borrowing interval strategy

To handle the problems that some cells are overcrowded and some others are empty. A station in the overcrowded-cell might loss the data exchange opportunities because that there are high traffic demands in this cell. This station might intend to exchange data in the awake beacon interval that is not assigned to that cell. We called this station as overcrowded station. The new algorithm allows the overcrowded station to use the interval which is assigned to the neighboring sparse cell that has low traffics in the past cycle of quorum intervals. This newly designed strategy is called *borrowing interval strategy*. To achieve this, each station should maintain two predefined thresholds, called *high-traffic* and *low-traffic thresholds*. When a station joins in the MANET or changes cell, it will broadcast the HELLO message in the awake beacon intervals of that cell and collect the neighboring information. Therefore, each station is able to obtain the number of stations in its own cell and its neighboring cells. The number of stations in a cell will be used to simply evaluate the traffic load of that cell. A station can *borrow* the awake beacon intervals of the neighboring sparse cell when its traffic load grows up above the *high-traffic threshold*. Besides, the awake beacon intervals of a neighboring cell can be *borrowed* if its traffic load is below the *low-traffic threshold*. Each awake beacon interval is associated with a priority, which is decreased with the number of stations stayed in that cell. The overcrowded station will select the awake beacon interval with highest priority and will try to use that beacon interval.

Based on the *borrowing interval strategy*, the number of beacon intervals that can be used by a cell can be dynamically changed. Although this way can reduce the end-to-end delays for those overcrowded cells, it might introduce collisions. A retransmission threshold for controlling the collisions should be predefined. Each station in the overcrowded-cell will count the total number of retransmissions and the *borrowing interval strategy* can be applied only when the total number of retransmissions is lower than the predefined retransmission threshold.

4.3.2. LAPS+

The proposed LAPS scheme can be extended such that it can be applied to the stations without location information. In the considered scenario, how to determine the quorum intervals for the stations without location information from the information of their neighbors is very important. To achieve that, the extension of the LAPS, called LAPS+, will collect the central locations of the neighboring cells where the neighboring stations locate.

In LAPS+, the central location of the cell where the station locates will be included in the IEEE 802.11 beacon payloads. When the station is not aware its location, it stays in listen state during all of beacon intervals and collects the central locations of the cells where the neighboring station locate. The station will estimate its location by averaging the collected locations. Let $S_v = \{(x_i, y_i) \mid 1 \leq i \leq h\}$ be the set including the central locations of the cells neighboring to station v. The location of station v, say (x', y'), can be estimated by

$$(x', y') = \left(\sum_{i=1}^{h} \frac{x_i}{h}, \sum_{i=1}^{h} \frac{y_i}{h} \right) \tag{12}$$

Then, station v uses the location (x', y') to determine the cell where it locates by executing the cell identifying phase of LAPS. As shown in Fig. 15(a), stations s_1, s_2, and s_3 with location information are located in C_6^k, C_1^k, and C_2^k, while station a is located in C_0^k. Assume that station a is not aware of its location. The central locations of the cell where stations s_1, s_2, and s_3 are located are (x_6^k, y_6^k), (x_1^k, y_1^k), and (x_2^k, y_2^k), respectively. When station a has collected the central locations, the location of station a can be estimated by

$$(x', y') = \left(\frac{x_6^k + x_1^k + x_2^k}{3}, \frac{y_6^k + y_1^k + y_2^k}{3} \right)$$

Station a will estimate that it locates in C_1^k as shown in Fig. 15(a). In Fig. 15(b), when a new-moving station, say s_4, operates in C_5^k whose central location is located at (x_5^k, y_5^k), station a will collect the central location of the cell where station s_4 locates and modify the cell estimation by calculating

$$(x', y') = \left(\frac{x_6^k + x_1^k + x_2^k + x_5^k}{4}, \frac{y_6^k + y_1^k + y_2^k + y_5^k}{4} \right)$$

Then, station a will estimate that it is located at cell C_0^k, as shown in Fig. 15(b).

5. Discussion of the proposed quorum system

In this section, the validation of the resultant quorum system constructed in the *IS* phase will be verified. Firstly, the satisfaction of the *NCI* and *HTA* constraints to the quorum sets constructed by LAPS will be discussed. Then, the validation of the proposed quorum system is proved in Theorem 1. A smaller size of U applied

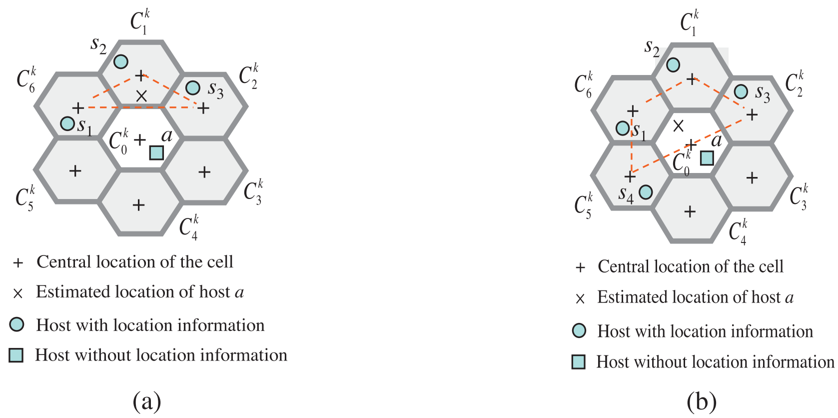


Fig. 15. An example for illustrating the cell where it is located by the cell identifying phase of LAPS+.

in the quorum system can achieve better performance in terms of transmission delay. However, a small size of U also increases the opportunities of packet collision among the stations in the neighboring cells. Herein, the minimal size of U will be discussed for the proposed quorum system. Finally, the minimal size of U for the proposed quorum system is presented in Theorem 2.

Lemma 1. *The quorum sets constructed by LAPS satisfies the NCI constraint.*

Proof. The given *CPNs* are partitioned into disjointed groups where each group consists of seven neighboring cells. There are 21 different relationships between neighboring cells, as the arrows showed in Fig. 7(a), (b), and 9(d). The *IS* phase of LAPS assigns different common awake beacon intervals for each relationship by applying the intra-group or inter-group scheduling procedures. Therefore, the intersection of any two quorum sets is non-empty, as shown in Fig. 11(b). This means that the quorum sets satisfy the *NCI* constraint:

$$Q_i \cap Q_j \neq \phi, \quad \text{where} \quad 0 \leq i \neq j \leq 6$$

Lemma 2. *The quorum sets constructed by LAPS satisfy the HTA constraint.*

Proof. The given *CPNs* are regularly partitioned into disjointed groups where each group consists of seven neighboring cells, as shown in Fig. 3(a) and (b). The quorum sets, Q_0 to Q_6, are constructed by LAPS, as shown in Fig. 11(b). Recall that quorum set Q_i represents the quorum intervals applied for the stations located in C_i^*. In Fig. 3(a), there exists $C_i^w \in N_2(C_i^k)$, where G^w is neighbor to G^k and $0 \leq i \leq 6$. This means that station x in C_i^w and station y in C_i^k will use the same quorum set Q_i but they can avoid the collisions due to the hidden terminal problem. As a result, the quorum sets constructed by LAPS satisfy the *HTA* constraint. □

Theorem 1. *The proposed quorum sets*, Q_0, Q_1, ..., Q_5, *and* Q_6, *shown in Fig. 11(b) organize a valid quorum system.*

Proof. A valid quorum system has to satisfy three constraints, including (1) No quorum set is empty, (2) Any set cannot be included in the other sets, and (3) the intersection of any two sets is always non-empty. The proposed quorum sets over {0, 1, ..., 20} include $Q_0 = \{0, 4, 7, 9, 12, 16\}$, $Q_1 = \{0, 5, 8, 10, 13, 17\}$, $Q_2 = \{1, 4, 8, 11, 14, 18\}$, $Q_3 = \{2, 7, 10, 11, 15, 19\}$, $Q_4 = \{1, 6, 9, 13, 15, 20\}$, $Q_5 = \{2, 3, 12, 14, 17, 20\}$, and $Q_6 = \{3, 5, 6, 16, 18, 19\}$. Since any quorum set obviously is not empty and cannot be included by the others, the constraints (1) and (2) hold. In addition, the *IS* phase of LAPS assigns the awake beacon intervals between the quorum sets by applying the intra-group and inter-group scheduling procedures. Therefore, the intersection of any two quorum sets Q_0 to Q_6 is non-empty. □

Theorem 2. *The set of U with* $|U| = 21$ *shown in Fig. 11(b) is the minimal set of the proposed quorum system for the CPNs.*

Proof. For each *CPN*, there are 21 neighboring relationships needed to be assigned with common awake beacon intervals for communicating between cells, as the arrows showed in Fig. 7(a), (b), and 9(d). Consider the cells in Fig. 9(a). Let $I_{i,j}$ be the common awake beacon interval between the neighboring cells C_i^k and C_j^h. Assume that there exists two neighboring cells C_a^k and C_b^x that can be assigned with the same common awake beacon interval, say $I_{i,j} = I_{a,b}$, in the *CPN*. There exist three conditions considered below.

(1) If C_i^k is equal to C_a^k, the assumption will obviously conflict with the *NCI* requirement at $I_{i,j}$ since $C_a^k \in N_1(C_i^k)$ and $C_b^x \in N_1(C_i^k)$.
(2) If C_j^h is equal to C_b^x, the assumption will also obviously conflict with the *NCI* requirement at $I_{i,j}$ since $C_i^k \in N_1(C_j^h)$ and $C_a^k \in N_1(C_j^h)$.
(3) If neither $C_i^k = C_a^k$ nor $C_j^h = C_b^x$, there exists two sub-conditions in the case. First, when $i = 0$ or $a = 0$ is held, the assumption will conflict with the *HTA* requirement at $I_{i,j}$ since $C_a^k \in N_1(C_0^k)$ or $C_i^k \in N_1(C_0^k)$ such that $C_a^k \in N_2(C_j^h)$ or $C_i^k \in N_2(C_b^x)$. Second, when both of $i \neq 0$ and $a \neq 0$ are held, the assumption will conflict with the *HTA* requirement at $I_{i,j}$ since $C_a^k \in N_2(C_i^k)$.

The conditions above will conflict with *NCI* or *HTA* requirements of the proposed quorum system. Therefore, the assumption does not hold. As a result, the case $C_i^k = C_a^k$ and $C_j^h = C_b^x$ will be held. This means that no common awake beacon interval can be replaced for the cells in *CPN*. The set of U with $|U| = 21$ is the minimal set of the proposed quorum system for the *CPNs*. □

6. Performance study

This section investigates the performance improvement of the proposed scheme against the 802.11 PSM, PowerMac [1], and AQEC [2] by using the simulator ns-2 [14]. In the experiments, the MANET region is set to the area of 1200 m × 1200 m and a number of stations, ranging from 300 to 1500, are randomly deployed

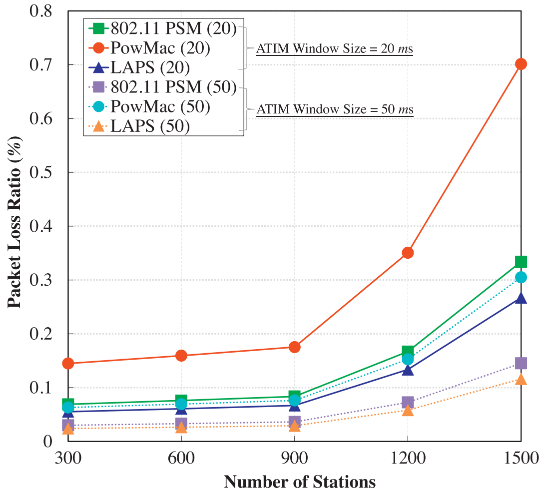


Fig. 16. The performance improvement of the proposed algorithm in terms of the packet loss rate.

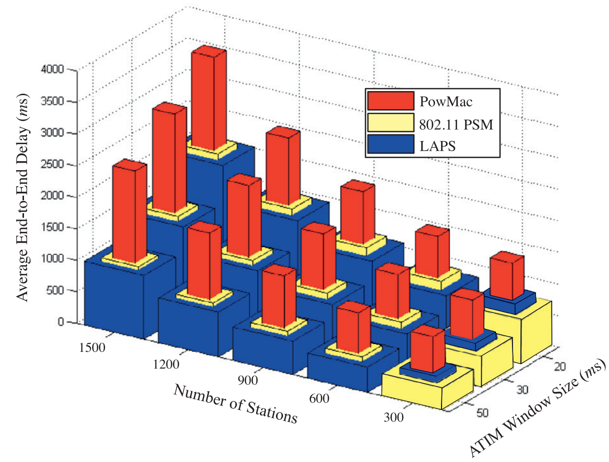


Fig. 17. The performance comparison of the compared three algorithms in terms of average end-to-end delay by varying the number of stations.

in the network. The communication range is 250 m. The Variable Bit Rate (VBR) from 0 to 40 kbps is considered as the traffic model when comparing LAPS with the other schemes. The energy consumption for transmitting, receiving, idling, and sleeping are set to 1400 mW, 1000 mW, 830 mW, and 130 mW, respectively. The communication bandwidth is set to 11 Mbps. There are 10 routes evaluated in 120 seconds of simulation time. The DSDV (Destination-Sequenced Distance-Vector) routing [15] is applied to construct the route with a length of 4 or 5 hops. The mobility of the stations is set from 0 to 20 m/s. The beacon interval is set to 100 ms and the 700 ATIM window size is ranged from 20 ms to 50 ms [2,10,22]. The efficiency of energy consumption is used to evaluate the network performance in the metric of the energy consumption per each success of a byte transmission.

In IEEE 802.11 PSM, a large number of stations exchange ATIM packets in ATIM Window for contending the transmission probabilities. This results in a large number of collisions and hence significantly increases the number of ATIM packets retransmissions, especially when the traffic is heavy. In addition, the IEEE 802.11 PSM did not handle the Hidden Terminal Problem, which leads to more retransmissions. Therefore, the packet loss rate and end-to-end delay are increased. Compare with 802.11 PSM, the proposed LAPS adopts the well-scheduled quorum system to arrange each station in specific awake beacon intervals for transmissions, which significantly reduces the numbers of contentions and collisions. Besides, two restrictions, including the *NCI* (*Neighbor Common Intervals*) and *HTA* (*Hidden Terminal Avoidance*), are further satisfied. This ensures that each pair of neighboring stations not only has communication probabilities, but also overcomes the Hidden Terminal Problem. In addition, we have additionally added the *borrowing interval strategy*, aiming to reduce the end-to-end delay. A performance comparison has been further given to show the improved performance of the proposed LAPS in terms of end-to-end delay.

The packet loss rate is an important indicator of the degree of traffic bottleneck of a given network. Fig. 16 investigates the performance improvement of the proposed LAPS against the 802.11 PSM and PowMac in terms of packet loss ratio. As shown in Fig. 16, the LAPS outperforms both the 802.11 PSM and PowMac. This occurs because that the LAPS arranges disjoint sets of awake beacon intervals for every two hop cells and thus prevents the occurrence of hidden terminal problem. Besides, the *borrowing interval strategy* is further presented to increase the opportunities of communications for the traffic unbalance environment. Therefore, the burden of queue of each station can be mitigated and hence the packet loss ratio can be efficiently reduced. Compared with LAPS, both the 802.11 PSM and PowMac did not handle the hidden terminal problem, which leads to a large number of collisions. In addition, they did not adaptively change the sleep/awaken ratio according to the traffic load. Based on these two issues mentioned above, they raise the problem that the collided packets accumulated in the queue will be dropped when the buffer overflows. Thus the packet loss rates of PowMac and 802.11 PSM will be significantly increased.

Another important metric that determines the network throughput is the end-to-end transmission delay. A packet transmission with smaller end-to-end delay indicates that it consumes smaller energy. The network throughput will be decreased with the end-to-end delay. As shown in Fig. 17, the proposed LAPS outperforms both the 802.11 PSM and PowMac in terms of average end-to-end delay when the number of stations is larger and equal to 600. This occurs because that the proposed LAPS adopts the *borrowing interval strategy* which increases the opportunities of communications when the traffic load of some cell is increased. By applying the *borrowing interval strategy*, the stations in the overcrowded-cells can extra *borrow* the awake beacon intervals of neighboring cells. It is worth to note that the 802.11 PSM slightly outperforms the LAPS when the number of stations is 300. This occurs because that both the contention and collision are happened rarely when the service region has low density of stations. However, with the increasing number of stations and moving speed, the impacts on the proposed LAPS are not significant.

Fig. 18 compares the average energy consumption of the proposed mechanism against the 802.11 PSM and PowMac mechanisms. The proposed mechanism outperforms the IEEE 802.11 PSM and the PowMac mechanisms in terms of average energy consumption. The IEEE 802.11 PSM has a poor performance because all stations stay awake in each ATIM window regardless of whether or not they attempt to transmit data. The proposed mechanism schedules common awake beacon intervals for the neighboring cells and hence stations can sleep in more beacon intervals as compared to the PowMac mechanism.

Fig. 19 further investigates the energy efficiency which is measured by the energy consumption for each byte successful transmission. In general, all three compared mechanisms result in the fact that the energy efficiency is decreased with the number of stations. This is because the network traffic increases with the number of stations and hence the energy consumption required for successfully transmitting each byte is also increased accordingly. The proposed mechanism outperforms the other compared mech-

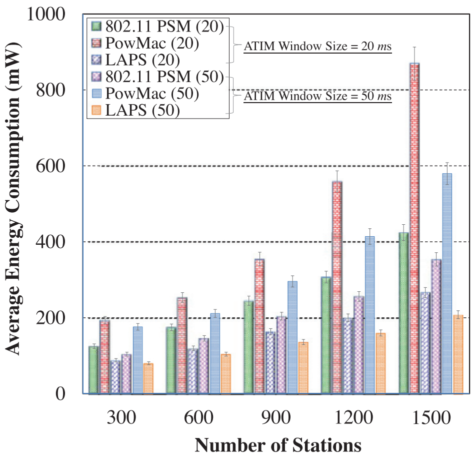


Fig. 18. The comparison of average energy consumption.

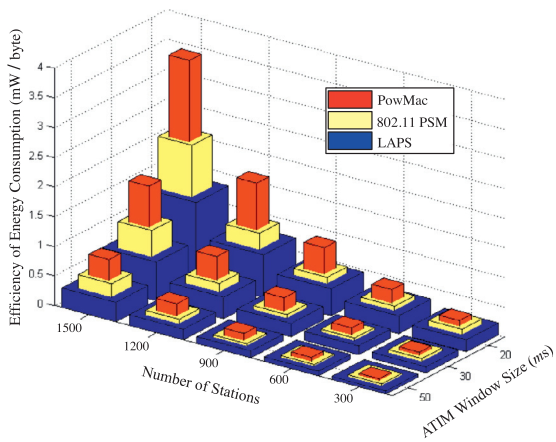


Fig. 19. The comparison of three mechanisms in terms of energy efficiency.

anisms in terms of energy efficiency. The PowMac mechanism has higher packet loss rate and thus has lower energy efficiency.

The following experiments further compare the proposed mechanism with the AQEC mechanism in the traffic model of variable bit rate. The AQEC mechanism proposes a formula to adaptively change the awake beacon intervals according to the network traffic. The threshold for changing the awake beacon intervals proposed in AQEC is given by

$$Threshold_n = 12 \times \left(\frac{2n-1}{n^2}\right) \tag{13}$$

where n denotes the size of a two dimensional array. The proposed mechanism is compared with the AQEC in the traffic model of variable bit rate. The traffic variance is designed according to the threshold values designed in Eq. (13). With the substitution of $n = 1$, 2, 3, and 4 in Eq. (13), four traffics are obtained as shown in Fig. 20.

As shown in Fig. 20, the traffic is increased with the simulation time and the maximal traffic is reached at the 60th second. The peak traffics are 5.25 Kbps at the 15th second, the 6.67 Kbps at the 30th second, and the 9 Kbps at the 45th second and the 12 Kbps at the 60th second.

Fig. 21 compares the 802.11 PSM, AQEC, and the proposed LAPS in terms of packet loss rate under the VBR traffic model. The AQEC reduce the Quorum size to increase the transmission opportunities when the network traffic increases. The AQEC will degrade to the IEEE 802.11 PSM that all stations awake in each beacon interval when the network traffic is extremely large. However, the accumulated packets compete with the current traffic and hence

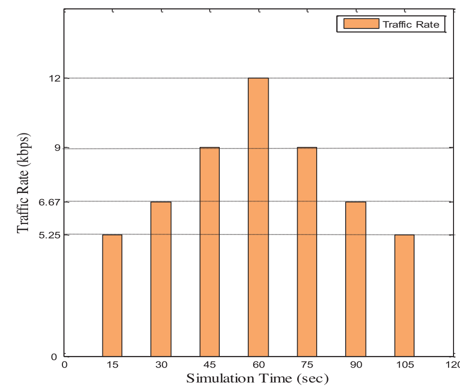


Fig. 20. The variation of Traffic Rate designed according to Eq. (13).

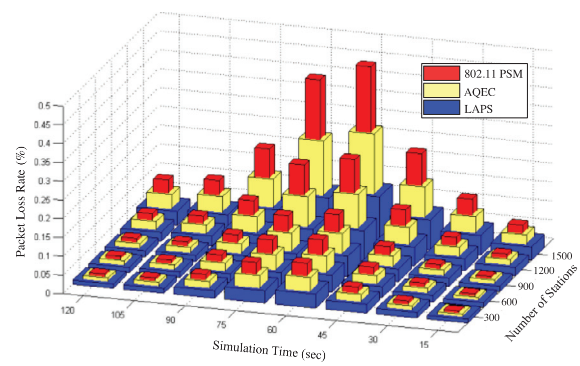


Fig. 21. Packet loss rate of the compared mechanisms in the traffic model of variable bit rate.

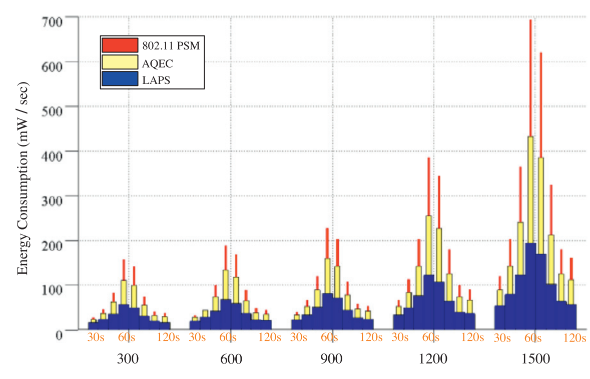


Fig. 22. Energy consumption of the compared mechanisms in the traffic model of variable bit rate.

the overall performance of AQEC is worse than IEEE 802.11 PSM in terms of packet loss rate. The proposed mechanism not only avoids the packet collision problem but also utilizes the *borrowing strategy* to increase the opportunities of communications. Therefore, the burden of queue of each station can be mitigated and hence the packet loss ratio can be efficiently reduced. As a result, the proposed LAPS outperforms all the other compared mechanisms in terms of packet loss rate.

Fig. 22 further compares the performance of the proposed mechanism with the 802.11 PSM and AQEC mechanisms in terms of energy consumption. The VBR traffic model is applied in the simulation. The AQEC has higher energy consumption than 802.11 PSM because the accumulated packets compete for transmission opportunities with the normal packets, increasing the number of packet collisions. In general, the proposed mechanism outperforms the compared mechanisms in terms of energy consumption.

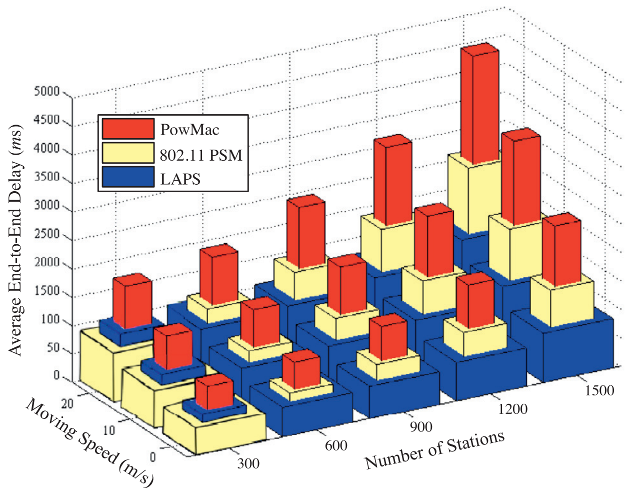


Fig. 23. The performance comparison of the three compared algorithms in terms of average end-to-end delay.

[Fig. 23](#) investigates the average end-to-end delay by varying both the moving speed of station and the number of stations. The moving speed and the number of stations are ranging from 0 m/sec to 20 m/sec and 300 to 1500, respectively. A random mobility model is adopted by all stations. As shown in Fig. 23, the end-to-end delays of the three compared algorithms increase slowly with the mobility. In LAPS, a station with high moving speed will increase the chances of crossing cell and the frequency of changing its awaken-sleeping pattern. As a result, the end-to-end delay would be increased. It is worth to note that the 802.11 PSM slightly outperforms the LAPS when the number of stations is 300. This occurs because that both the contention and collision are happened rarely when the service region has low density of stations. However, with the increasing number of stations and moving speed, the impacts on the proposed LAPS are not significant. Each station can maintain the correct cell ID while the contention and collision can be efficiently avoided. Therefore, the proposed sleep/wake scheduling can be executed as expected. In general, the proposed LAPS outperforms the other two algorithms in terms of average end-to-end delay.

Furthermore, the following further discusses the real case, where the communication range is not a perfect disc [21]. ased on the setting of simulation environment in [21], we set up our experiment. Let R_{max} and $r_{stable} = 0.8R_{max}$ denote the maximum communication range and the stable radio range of each station, respectively. Let notation r denote the communication range of each station. With the consideration of irregularity of communication range, we assume that the r is in the range of $0.8R_{max} \leqq r \leqq R_{max}$. As shown in Fig. 24, the shadow region depicts the actual transmission range of station s_i. Let πr_{stable}^2 denote the *reliable communication zone* of each station. Let $\pi(R_{\max}^2 - r_{stable}^2)$ denote the *unreliable communication zone* of each station. As shown in Fig. 24, the red region represents the *reliable communication zone*, while the shadow region represents the *unreliable communication zone*.

Two stations with distance d_r, where $0.8R_{max} \leqq d_r \leqq R_{max}$, may or may not be able to communicate with each other directly. There are two possible impacts when the radio irregularity is taking into consideration. First, when the communication range $0.8R_{max}$ is used to partition the hexagon cells in LAPS, the collision and hidden terminal interference will be slightly increased. This occurs because that the radio signals fall in the *unreliable communication zone* may impact the communications of the neighboring cells. In this case, the smaller size of the cells will increase the hop count number of each routing path. Second, when the communication range R_{max} is used to partition the hexagon cells applied in LAPS, the stations with a distance ranging from $0.8R_{max}$ to R_{max} may not be able to communicate with each other directly. The communication will be relayed by the other stations, which leads to a large hop count number of each routing path.

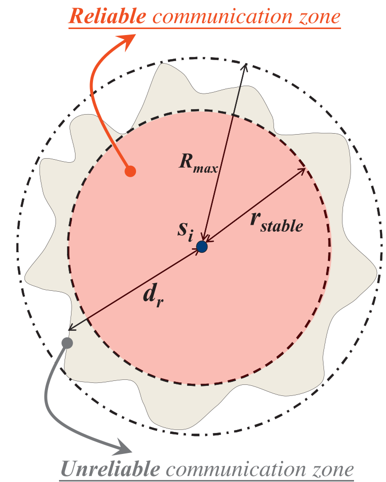


Fig. 24. The transmission range of station s_i varies ranging from $0.8R_{max}$ to R_{max}.

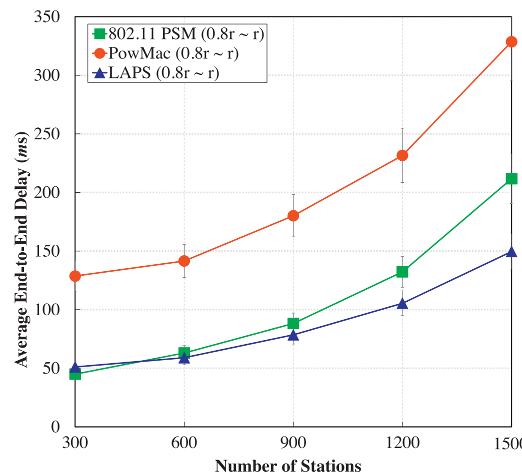


Fig. 25. The performance comparison of the compared three algorithms in terms of average end-to-end delay by considering the irregularity of communication range.

Fig. 25 investigates the performance of LAPS in terms of the average end-to-end delay by considering the irregularity of communication range. The similar performance trends can be found in Figs. 17 and 23, which apply the regular radio model. In comparison, all curves drop about 6% when the irregular radio range is applied. The major reason is that the *reliable communication zone* in an irregular radio range is smaller than that of in a regular radio range. This results in fewer neighbors that can directly communicate with. Thus the number of average hop count of routing path is increased, which leads to long end-to-end delay. However, the proposed LAPS outperforms the other algorithms in terms of average end-to-end delay, as shown in Fig. 25.

7. Conclusions

A number of power saving mechanisms have been developed by applying the quorum system based on the IEEE 802.11 PSM. However, they did not take into account the fact that non-neighbor stations did not did not need to have the common awake intervals since they are unable to communicate with each other. In addition, none of them utilize the location information in the design of the quorum system. This paper proposes a location-aware power saving protocol to schedule the sleep/awake beacon intervals for saving energy and reducing packet collisions due to hidden terminal problem. In addition, the proposed quorum system provides flat opportunities of data exchange for the stations between the neighboring cells, reducing the transmission delay. Performance study reveals that the proposed mechanism improves the performance of existing approaches in terms of energy consumption and transmission delay.

Acknowledgments

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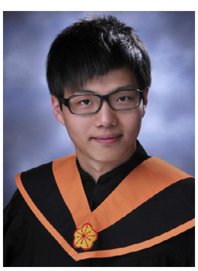

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