

A Survey on Asynchronous Quorum-Based Power Saving Protocols in Multi-Hop Networks

Mehdi Imani*, Majid Joudaki**, Hamid R. Arabnia***, and Niloofar Mazhari****

Abstract

Quorum-based algorithms are widely used for solving several problems in mobile ad hoc networks (MANET) and wireless sensor networks (WSN). Several quorum-based protocols are proposed for multi-hop ad hoc networks that each one has its pros and cons. Quorum-based protocol (QEC or QPS) is the first study in the asynchronous sleep scheduling protocols. At the time, most of the proposed protocols were non-adaptive ones. But nowadays, adaptive quorum-based protocols have gained increasing attention, because we need protocols which can change their quorum size adaptively with network conditions. In this paper, we first introduce the most popular quorum systems and explain quorum system properties and its performance criteria. Then, we present a comparative and comprehensive survey of the non-adaptive and adaptive quorum-based protocols which are subsequently discussed in depth. We also present the comparison of different quorum systems in terms of the expected quorum overlap size (EQOS) and active ratio. Finally, we summarize the pros and cons of current adaptive and non-adaptive quorum-based protocols.

Keywords

Ad Hoc Networks, Asynchronous Sleep Scheduling Protocols, Power Saving Protocols, Quorum Based Systems

1. Introduction

A quorum system is sets of quorums; which any two quorums at least have an intersection. Quorum-based algorithms are widely used to solve several problems like: replica control [1-4], mutual exclusion [5,6], location management [7-10], information dissemination [11,12] and data aggregation [13] in mobile ad hoc networks (MANETs) or wireless sensor networks (WSNs). In all quorum-based protocols (QBP), time is divided into periods called quorum interval (QI) which each QI contains n equal time units called beacon interval (BI). During each BI, a node can stay awake or switch to sleep mode. A quorum system determines a cyclic pattern, that defines the sleep/wakeup scheduling during n BIs (n is an integer), we call n the system size. The advantage of QBP is that a node just needs to be awake $O(\sqrt{n})$ BIs in every n BIs. In QBP, we can guarantee that every two nodes have intersection at least in one awake BI.

In [14] and [15] some methods have been proposed in which the quorum systems are considered the

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base of all new methods. Due to lack of synchronization mechanism between nodes in multi hop networks, a mechanism is needed so that each node will be able to communicate with adjacent nodes during its sleep/wakeup periods.

Recently Zheng et al. [16] have proposed a systematic approach to design asynchronous sleep/wakeup mechanisms for ad hoc networks which can be used in WSN. They formulated the sleep/wakeup scheduling which is based on asynchronous sleep/wakeup mechanisms [17]. The quorum-based methods introduced in [14] guarantee that any two nodes in the network which are in each other's transmission range can communicate, no synchronization needed.

In all QBPs, each BI is divided into three time slots shown in Fig. 1. There is a beacon window in the beginning of any BI, in which a beacon will be sent. The beacon packet contains simple information like node address and node timestamp. In the following, there is MTIM window in which the node waits for receiving the ATIM packets of other nodes. In the Send/Receive window, nodes can send and receive data packets.

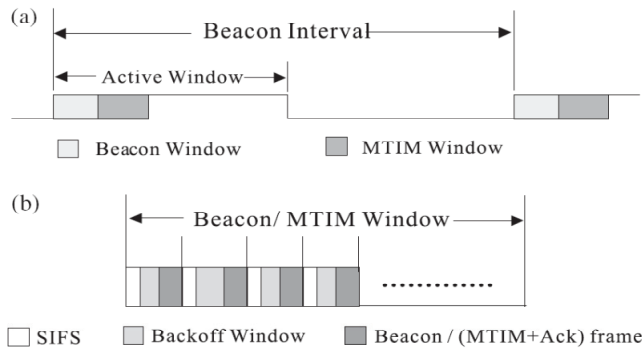


Fig. 1. The structure of BI in QBP [14].

In quorum systems, each BI has beacon window and MTIM window, but only the BIs that are a member of awake periods contain Send/Receive window. A quorum system is shown in Fig. 2. In this system, each node is guaranteed to be sensed by other nodes and is able to send its packets. Node A and node B have independently chosen BIs and there is no synchronization in the beginning of time periods. As we can see in Fig. 2, two nodes (A and B) have some intersections in their awake BIs.



Fig. 2. Sleep/wakeup periods of quorum-based system and nodes overlapping (awake BIs are shown by dark color) [14].

The rest of this paper is organized as follows. In Section 2, we define quorum system properties and in Section 3, we define performance criteria of quorum systems. Section 4 gives preliminaries and review of current quorum-based systems. In Section 5, we define current QBPs including non-adaptive and adaptive protocols. Finally, the paper is concluded in Section 6.

2. Quorum Systems Properties

DEFINITION 1. “Given a universal set $U = \{0, \dots, n-1\}$, a quorum system Q under U is a collection of non-empty subsets of U , each called a quorum (Q_1, Q_2, \dots) , which satisfies the intersection property” [15]:

$$\forall Q_1, Q_2 \in Q : Q_1 \cap Q_2 \neq \emptyset \quad (1)$$

Each one of these non-empty subsets is one quorum. For instant $Q = \{\{1,3\}, \{2,3\}, \{1,2\}\}$ is a quorum system under the universal set of $U = \{1,2,3\}$.

DEFINITION 2. “Given a non-negative integer i and a quorum Q_i in a quorum system Q under $U = \{0, \dots, n-1\}$, we define rotate (Q_i, i) ” [15]:

$$rotate(Q_i, i) = \{(j + i) \bmod n | j \in Q_i\} \quad (2)$$

DEFINITION 3. “A quorum system Q under $U = \{0, \dots, n-1\}$ is said to have the rotational closure property if” [15]:

$$\forall Q_1, Q_2 \in Q, i \in \{0, \dots, n-1\} : Q_1 \cap rotate(Q_2, i) \neq \emptyset \quad (3)$$

THEOREM 1. “If the Q quorum system has rotational closure property, this Q quorum system can be used for solving QPS problem” [15].

DEFINITION 4. In quorum system $Q = \{Q_1, Q_2, Q_3, \dots, Q_n\}$ under $U = \{0, 1, \dots, n-1\}$ the relation size of Q_1 quorum with system size n is known as Q_1 quorum active ratio.

$$Active\ Ratio(Q_i) = \frac{|Q_i|}{n} \quad (4)$$

DEFINITION 5. “For a quorum system Q under $U = \{0, \dots, n-1\}$, the expected quorum overlap size (EQOS) of Q is:

$$\sum_{Q_1, Q_2 \in Q} p(Q_1)p(Q_2)|Q_1 \cap Q_2| \quad (5)$$

where $P(Q_1)$ and $P(Q_2)$ is respectively the probability of accessing quorums Q_1 and Q_2 for a quorum access strategy” [18].

THEOREM 2. “If Q is a quorum system under $U = \{0, 1, 2, \dots, n-1\}$ and Q has rotational closure property then each Q_i quorum in Q has at least \sqrt{n} size” [15].

In the next section, we will introduce the performance criteria of QBPs and then explain some common quorum-based systems which have rotational closure property.

3. Performance Criteria

Below, we list some metrics for comparing QBPs:

- Duty cycle: ratio of the awake BIs in each QI and the length of the QI is called duty cycle. In fact, the duty cycle is the active ratio of the selected quorum.
- The expected quorum overlap size: this is a metric to evaluate the average neighbor sensibility and means the average number of overlapping BIs between two nodes, which was first introduced in [18].
- Delay: the number of BIs that a node must wait to find an awake BI with its neighbors.

4. Common Quorum-Based Systems

4.1 Grid Quorum System

In this method [14], a complete QI period with n beacon intervals is mapped to a square (\sqrt{n} rows \times \sqrt{n} columns). Each BI is numbered with (i, j) , which i is the row number and j is the column number of that BI. Each node randomly selects one row and one column, and all BIs in that selected row and column will be selected as active periods.

For example, if $n=9$, each node contains 9 BIs and each BI is numbered with a pair of (i, j) numbers between 1 to 3. For example, if a node selects row 1 and column 2, then it will stay active in these BIs: $\{(1,1),(1,2),(1,3),(2,1),(2,2),(2,3)\}$. In this method, two nodes intersect in at least two BIs. Fig. 3 shows a Grid quorum based system with $n=16$.

Regardless of the selected row and column in a grid quorum system, each quorum has $2\sqrt{n} - 1$ members with size of n . Therefore the overlapping value is equal to $\frac{2}{n}$ and active ratio = $\frac{2\sqrt{n}-1}{n}$.

The grid quorum system is very commonly used due to simplicity of implementation; but the size of quorums in this system must be a complete square which causes inflexibility.

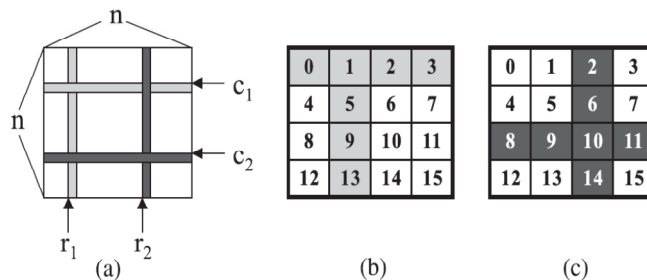


Fig. 3. Mapping a QI with 16 BIs to a square based array on the grid quorum system [14].

4.2 Torus quorum system

At first, this method [15] was implemented in distributed systems for mutual exclusion [19]. In torus, like grid, “the universal set is arranged as a $t \times w$ array where $t \times w = n$. The last column/row in the

array is regarded as wrapping around back to the first column/row. Each node can choose any column c , $0 \leq c \leq w - 1$, plus $\lfloor w/2 \rfloor$ slots, each slots must be in any position of column $c + i$, $c = 1 \dots \lfloor w/2 \rfloor$ [15]. As shown in [19], if $t = \frac{w}{2}$, the quorum size will be equal to $\sqrt{2n}$, that is near optimal. Fig. 4 shows a Torus system. Quorum G and H intersect at element 7.

0	1	2	3	4	5	<div style="display: inline-block; width: 10px; height: 10px; background-color: #cccccc; border: 1px solid black; margin-right: 5px;"></div> Quorum Q_1 <div style="display: inline-block; width: 10px; height: 10px; background-color: #ffffff; border: 1px solid black; margin-right: 5px; margin-top: 5px;"></div> Quorum Q_2 <div style="display: inline-block; width: 10px; height: 10px; background-color: #cccccc; border: 1px solid black; margin-right: 5px; margin-top: 5px; border-style: dashed;"></div> Intersection of Q_1 and Q_2
6	7	8	9	10	11	
12	13	14	15	16	17	

Fig. 4. A Torus quorum system with the size of $t=3$ and $w=6$.

4.3 Cyclic quorum system

The cyclic quorum systems are using the difference sets. A difference set D under Z_n is described as following [20]:

$$D = \{d_1, d_2, \dots, d_k\} | \forall e \neq 0 \Rightarrow \exists d_i, d_j \in D \text{ that } d_i - d_j = e \pmod n, \quad 1 \leq i, j \leq k \quad (6)$$

In order to have a cyclic quorum system with the size of n , if D is a difference set under the Z_n universal set, we define the Q as below [20]:

$$Q = \{G_1, G_2, \dots, G_n\}, \text{ where } G_i = \{d_1 + i, d_2 + i, \dots, d_k + i\} \pmod n, \quad i = 0, \dots, n - 1 \quad (7)$$

“Given any n , a difference set as small as k can be found when $k(k - 1) + 1 = n$ and $k - 1$ is a prime power. Such a difference set is called the Singer difference set” [21]. For example, the set $\{1, 2, 4\}$ and the set $\{1, 2, 4, 9, 13, 19\}$ under Z_7 and Z_{31} , respectively, are Singer difference sets. “Note that in this case the quorum size k meets the lower bound in Theorem 2. So cyclic quorum systems constructed by the Singer difference sets are optimal” [15].

4.4 FPP quorum system

The finite projective plane (FPP) quorum system [22] organizes elements in a hypergraph form, as vertices under the universal set $U = \{0, \dots, n - 1\}$. This hypergraph includes n edges and n vertices. In FPP each edge is connected to k vertices and two edges have intersection just in one vertex. In FPP, we can form a quorum with size of k by the set of all vertices connecting by the edges. Authors in [22] showed that, we can construct a FPP when $k(k - 1) + 1 = n$, and $k - 1$ is a prime power. Authors in [20] proved that the FPP is a special form of the cyclic quorum system when $k(k - 1) + 1 = n$ and $k - 1$ is a prime power.

4.5 S-grid quorum system

In s-grid($t \times w$) ($w = t$ or $w \neq t$) [23] a complete QI period is mapped to an array with n beacon intervals which has t rows and w columns. Each BI is numbered with (i, j) , which i is the row number and j is the column number of that BI.

Authors in [23] defined s-grid as follows: In s-grid, under a universal set, elements are organized as a $t \times w$ array with the last column/row in the array is regarded as wrapping around back to the first column/row. A quorum of a s-grid($t \times w$) is formed by picking:

- all elements of a row i , $0 \leq i \leq t-1$
- all elements in column 0 starting from the first BI of QI and ending to the first BI of the selected row.
- all elements in column $w - 1$ (last column) starting from the last BI of the selected row and ending to the last BI of QI.

For example, as shown in Fig. 5, BIs are selected in the s-grid(4×4) as follows:

Table 1 shows The EQOS and active ratio of existing quorum-based systems which discussed above. Analyses results in Fig. 6 show that the FPP and ge-torus have better active ratio values than the grid, s-grid($t \times w$), s-grid(n) and torus. In addition, analyses results in Fig. 7 show that the s-grid($t \times w$) and the s-grid(n) have comparably high EQOS values and consequently better neighbor sensibility than the FPP, grid, torus and ge-torus quorum systems, especially for system size >80 .

Table 1. The EQOS and active ratio of existing quorum-based systems

Quorum-based systems	EQOS	Active ratio
Grid [18]	$\frac{(2\sqrt{n} - 1)^2}{n}$	$\frac{2\sqrt{n} - 1}{n}$
Torus [18]	$\frac{\left(t + \frac{\lfloor \frac{w}{2} \rfloor}{t}\right) + 2\left(\frac{\lfloor \frac{w}{2} \rfloor - 1}{t}\right)\left(1 + \frac{\lfloor \frac{w}{2} \rfloor}{2t}\right) + 2}{w} = 2$	$\frac{\sqrt{2tw}}{t \times w}$
Cyclic [18]	$\frac{s \times n + \lambda \times \binom{n}{2}}{\binom{n+1}{2}} = \frac{2s + \lambda \times (n - 1)}{n + 1}$ $s = \text{quorum size.}$	$\frac{1}{\sqrt{n}}$ when $k(k - 1) + 1 = n$ and $k - 1$ is a prime power.
FPP [18]	$\frac{s \times n + \binom{n}{2}}{\binom{n+1}{2}} = \frac{2s + n - 1}{n + 1}$ when $s(s - 1) + 1 = n$, $s = \text{quorum size}$ and $s - 1$ is a prime power	$\frac{1}{\sqrt{n}}$ Authors in [20] proved that the FPP is a special form of the cyclic quorum system when $k(k - 1) + 1 = n$ and $k - 1$ is a prime power.
s-grid($t \times w$)	$\frac{t(t + w - 1) + \sum_{j=3}^t \sum_{i=0}^{j-3} (t - i) + \sum_{j=2}^t \sum_{i=0}^{t-j} (t - i) + \sum_{i=0}^{t-2} (t - i)}{t^2}$	$\frac{t + w - 1}{t \times w}$ if $t = \frac{w}{2}$ then $\frac{3w - 2}{w^2}$
s-grid($\sqrt{n} \times \sqrt{n}$)	$\frac{\sqrt{n}(2\sqrt{n} - 1) + \sum_{j=3}^{\sqrt{n}} \sum_{i=0}^{j-3} (\sqrt{n} - i) + \sum_{j=2}^{\sqrt{n}} \sum_{i=0}^{\sqrt{n}-j} (\sqrt{n} - i) + \sum_{i=0}^{\sqrt{n}-2} (\sqrt{n} - i)}{n}$	$\frac{2\sqrt{n} - 1}{n}$

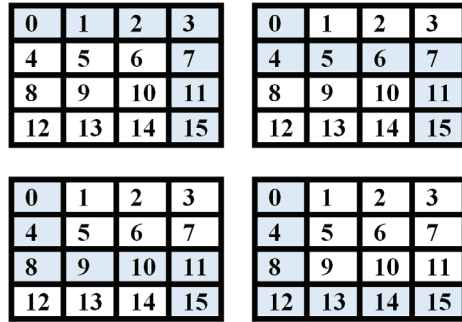


Fig. 5. Arrangement of all 4 possible quorum intervals based on the s-grid(4 × 4).

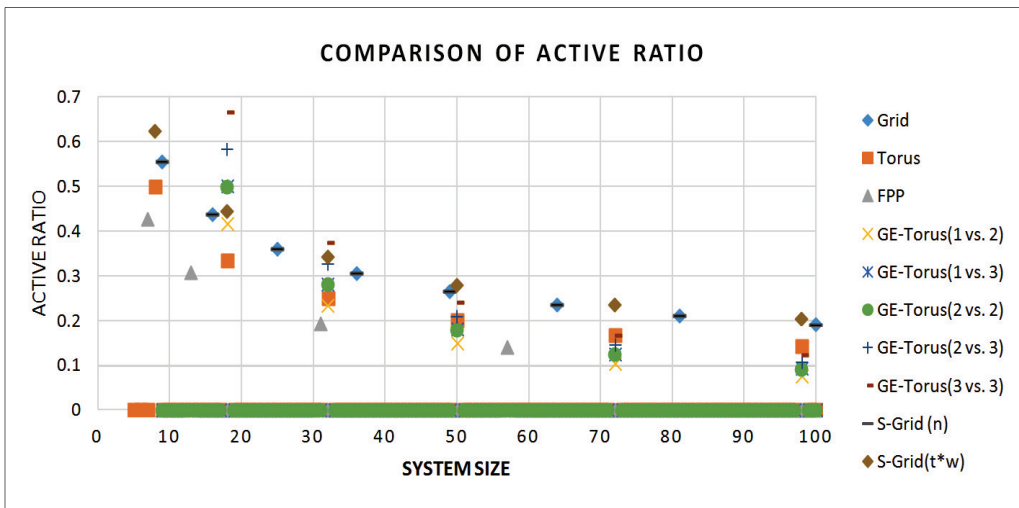


Fig. 6. Comparison of different quorum systems in terms of the active ratio for system size $n = 0, \dots, 100$.

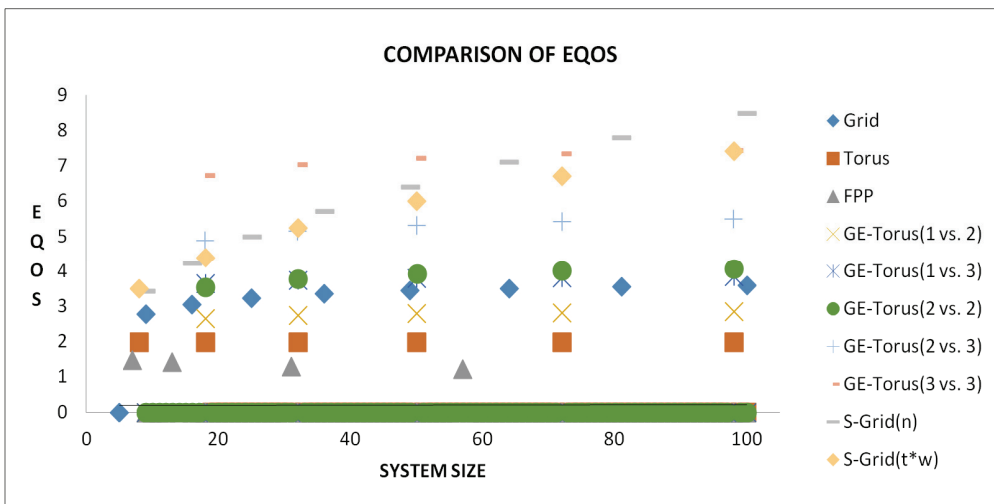


Fig. 7. Comparison of different quorum systems in terms of the EQOS for system size $n = 0, \dots, 100$.

5. Quorum-Based Protocols

Each QBP which uses one of the quorum-based systems and QBPs is divided in two main categories: non-adaptive QBPs and adaptive QBPs. In the next section, we first introduce some common non-adaptive QBPs and then we study some common adaptive QBPs.

5.1 Non-adaptive Quorum-based Protocols

5.1.1 Quorum-based energy conserving (QEC), year 2003

Quorum-based protocol (QEC or QPS) [14] is the first study and the first proposed method in the asynchronous sleep scheduling protocols. QEC guarantees that, in a complete QI period with n slots, two nodes have intersection at least in two active slots (BI) during $(2\sqrt{n} - 1)$ awakening slots. In QEC, each node chooses a row and a column from a $\sqrt{n} \times \sqrt{n}$ array and stays active in chosen slots, as shown in Fig. 3.

5.1.2 Cyclic difference set-based protocol (CDS), years 2003 and 2006

Authors in [16] and [24] proposed some energy efficient sleep/wakeup schedules that are more efficient than QPS. These protocols are constructed by cyclic difference set, which can guarantee to have intersection in at least one active slot between two sets and can reach the optimal active ratio. In addition, authors in [25] proposed a protocol, named CQPM, which is similar to QEC and CDS protocols.

5.1.3 Stepped-grid quorum-based protocol (s-grid), year 2017

The s-grid that proposed in [23] has two different forms: the s-grid($t \times w$) when $t \neq w$ and the s-grid(n) when $t = w = \sqrt{n}$. The s-grid is very easy to implement and despite other QBPs, the s-grid($t \times w$) is very flexible and works with any array size.

The grid works with just $\sqrt{n} \times \sqrt{n}$ arrays, the torus works with just $t \times w$ arrays when $w = 2t$, and the cyclic and the FPP can be only used when $n = k(k - 1) + 1$ and $k - 1$ is a prime power. But the s-grid($t \times w$) is very flexible and works with any array size. The s-grid satisfies rotational closure property and authors in [23] proved it in Theorem 3. They derived EQOS values for the s-grid($t \times w$) and s-grid(n) and compared their results with the EQOS values of all the above-mentioned quorum systems by analysis. Analyses results in [23] show that the s-grid($t \times w$) and the s-grid(n) have comparably high EQOS values than the FPP, grid, cyclic, torus and e-torus quorum systems. The s-grid is quite simple and efficient and can be a suitable alternative for the grid.

5.2 Adaptive Quorum-based Protocols

The main drawback of non-adaptive QBPs is that they do not guarantee overlapping active slots between sets which have different sizes. On the other hand, when sets have different sizes, nodes, probably, do not have any active slot in common. Therefore, they are not good choices for networks with variable conditions, such as traffic load, topology, or node mobility. To overcome this drawback, several adaptive asynchronous sleep scheduling protocols have been proposed. These adaptive protocols guarantee overlapping active slots between sets which have different sizes. Clearly, the more the number of active slots is per set, the more the number of overlapping active slots and the amount of energy

wasting will be. There is a minimum number of slots requirement to guarantee overlapping between two different sets at least in one active slot. Therefore, adaptive protocols designers should consider making a trade-off between the number of active slots in each set and the required minimum number of slots to increase energy efficiency based on the network conditions. In this section we study some common adaptive QBPs.

5.2.1 Extended torus (e-torus), year 2005

The extended torus (e-torus) quorum protocol is an extended version of the torus quorum protocol. Like torus, the universal set $U=\{0, \dots, tw-1\}$ is organized as a $t \times w$ array where $t \times w = n$ [15]. “Given any integer $k \leq t$, a quorum of an e-torus(k) quorum system is formed by picking any position $[r,c]$, where $0 \leq r < t$ and $0 \leq c < w$, such that the quorum contains all elements on column c plus k half diagonals. These k half diagonals alternate between positive and negative ones, and start from the following positions” [15]:

$$\left[r + \left\lfloor i \times \frac{t}{k} \right\rfloor, c \right], i = 0 \dots k - 1 \tag{8}$$

“Each quorum in the e-torus(k) quorum protocol looks like a Christmas tree with a trunk in the middle and k branches, each as a half diagonal, alternating between positive and negative ones” [15]. Fig. 8 shows the structure of an e-torus(4) quorum protocol.

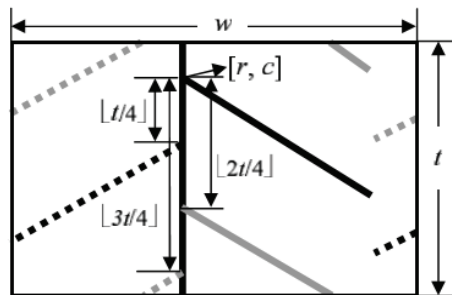


Fig. 8. The “Christmas tree” structure of an e-torus(4) quorum [15].

For example, Fig. 9 shows how an e-torus(2) and an e-torus(3) intersect with each other. This method guarantees that the intersecting elements appear in the trunks of the “Christmas trees”. There is no guarantee that two branches from two e-torus quorums have intersection with each other. In order to guarantee overlapping between $G (e - torus(k_1))$ and $H (e - torus(k_2))$, the below relation must be true [15]:

$$|Rotate(G,i) \cap Rotate(H,j)| \geq \left\lfloor \frac{(k_1+k_2)}{2} \right\rfloor \tag{9}$$

The ge-torus is a more general form of e-torus quorum protocol that is defined in [18]. In this protocol with increasing the amount of k , the neighbor sensitivity is increased and the quorum system size is increased too. Based on the network conditions, such as nodes mobility and QoS, the amount of k can be determined.

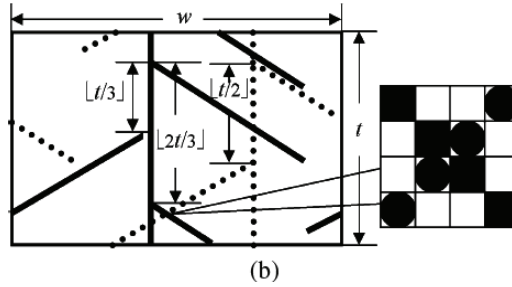


Fig. 9. The intersection between e-torus(2) and e-torus(3) [15].

5.2.2 Adaptive quorum-based energy conserving (AQEC), year 2006

In the QEC protocol, all nodes are using the same grid size of $\sqrt{n} \times \sqrt{n}$; the process of selecting this grid size is important. A large grid size results in saving more power but also longer delays in the network. On the other hand, the small grid size results in more energy consumption. In order to achieve better performance, it is necessary that each individual node can change its grid size based on different traffic loads and different performance requirements.

In order to do this, authors in [26] proposed the adaptive quorum-based energy conserving (AQEC) Protocol. “The idea behind AQEC is to increase a node’s grid size, in order to prolong its sleep duration when its traffic is light, and to decrease its grid size, making it wake up more frequently, when its traffic load is heavier. In AQEC, user i selects its grid size according to its traffic load, LD_i ” [26]. In [26], to make implementation easier, authors determined three traffic thresholds: $Th1$ for heavy traffic, $Th2$ for medium traffic, and $Th3$ for light traffic. Each user (i) in the AQEC protocol can change its grid size among these four grid sizes [26]:

$$\text{System Size} = \begin{cases} 1 \times 1, & LD_i \geq Th1 \\ 2 \times 2, & Th2 \leq LD_i < Th1 \\ 3 \times 3, & Th3 \leq LD_i < Th2 \\ 4 \times 4, & LD_i < Th3 \end{cases} \quad (10)$$

5.2.3 AQEC+ protocol, year 2006

QEC and AQEC protocols allow a node to sleep longer than one BI; thus, the latency time produced by these two protocols is greater than the latency time produced by the IEEE 802.11 PSM. Authors in [26] have proposed a method to reduce this latency time and call them QEC+ and AQEC+ to denote this modification. In the QEC+ and AQEC+, when a node needs to send packets, it will stay awake during every BI, until the completion of sending packets entirely. However, in this protocol the amount of conserved energy is increasing, but it causes a shorter delay in sending packets.

5.2.4 Fuzzy control quorum-based energy conserving protocol (FQEC), year 2007

FQEC [27] uses fuzzy control to change the quorum size in order to have a better energy conserving. In FQEC, each node i has two input variables. The first input variable is the average transmission delay of the packets received by node i during the last n BIs that is called history data. The second input

variable is the queuing delay of the packets waiting in node i 's buffer that is called future data. Each node should select its quorum size based on these two inputs. A node can be a receiver or a sender. If a node is a receiver node, it should consider the first input variable. A receiver can reduce its quorum size to reduce the transmission delay. And if a node is a sender node, it should consider the second input variable and change its quorum size based on its outgoing queuing delay. When a packet waits for a noticeable amount of time in the outgoing queue, it means the node should reduce its quorum size. In this protocol, each node has its own output variable. So each node can select its optimal quorum size based on its condition independently.

5.2.5 Adaptive MAC (AMAC) protocol, year 2007

Authors in [28] proposed an asynchronous MAC (AMAC) protocol, based on the concept of pattern-MAC. In the AMAC, the length of sleeping time is changed based on network conditions. "In the AMAC, they retained the original rules for the generation of sleeping schedule and replace the original scheduled wake time (character 1) with a string of wake time (word string 11...1), and replace the original sleep time (character 0) with the first wakeup time plus a string of sleep time (word string 10...0)" [28]. The idea is that each node generates a sleep schedule plan based on its own traffic conditions.

In the AMAC protocol [28], the form of array does not have to be in a square form, but choosing too large or too small numbers of rows and columns has a bad influence on network's stability. In this protocol, if the number of columns (n) is a lot greater than the number of rows (m), the switch time for node between sleep and wake up mode will be longer, and results in poor adaptation to the environmental changes; if n is too smaller than m , then the nodes switch frequently, causing extra energy consumption. As we know, switching the node from the sleeping mode to the active mode is one of the several ways that leads to energy consumption [28].

In this protocol, if the traffic of network is light and the size of array becomes larger, the number of active slots is then relatively less than the number of sleep slots. Fig. 10 shows sleep schedules with different number of sleep slots generated by different patterns. Regardless of clock drift, the active slots in these different schedules have some slots in common.

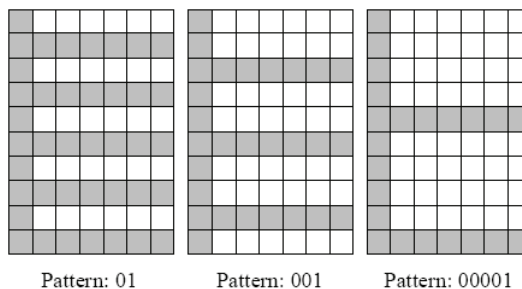


Fig. 10. Different sleep schedules generated by different pattern [28].

5.2.6 Adaptive asynchronous power management protocol (AAPM), year 2007

Authors in [29] proposed the AAPM (adaptive asynchronous power management) protocol. The

AAPM ensures that any two asynchronous power saving nodes can meet each other even if they have different quorum sizes [29]. The AAPM protocol is based on CQPM protocol [15,24,25] and is just used for *prime system size* ≤ 47 .

“The AAPM protocol divided into three parts: 1) a neighbor maintenance procedure, 2) a pattern prediction method based on the ratio of active/sleep slots, and 3) a data frame transfer procedure” [29]. Since a power saving node may often be in sleep mode, the AAPM protocol uses a pattern prediction method which power saving source can predict when the power saving destination will wake up in order to deliver data frames to it.

In the AAPM protocol some energy thresholds are defined and for each threshold there is an equivalent system size. Therefore, nodes can change its system size and its active ratio based on its remaining energy adaptively. The less the remaining energy is, the more the system size will be and therefore, the nodes’ active ratio will be decreased. This protocol has two main drawbacks: 1) the system size must be a prime number lower than 47 and 2) this protocol cannot reduce transmission delay impressively.

5.2.7 Fraction torus (f-torus) protocol, year 2008

Authors in [18] proposed a new protocol called f-torus which is based on torus. “By many possible values of the integer k and the fraction f , the f-torus($k + f$) quorum protocol provides much flexibility to design adaptive quorum-based asynchronous power saving protocols. The protocols can now rank a node’s mobility into a higher level and thus are more adaptive to mobility changes than those using e-torus quorum protocols” [18]. One drawback of e-torus is that e-torus can choose the integer values for k and when the mobility level of a node is between k and $k + 1$ (k is an integer value), we have to choose $k + 1$ and this is not an optimal mobility level value. Thus, the authors in [18], account this problem and use float value for k and reduce energy conserving in this protocol.

Fig. 11 shows two f-torus quorums Q_1 and Q_2 under $U = \{0, \dots, 17\}$ with $t=3$ and $w=6$. Q_1 is belonging to a f-torus($\frac{2}{3}$) and is constructed by choosing all slots in the second column plus two more slots ($= \frac{2}{3} \times \lfloor \frac{6}{2} \rfloor$), one slot from the third column and one slot from the fifth column. Q_2 is belonging to a f-torus($1\frac{1}{2}$) and is constructed by choosing all slots in the sixth column plus three more slots (one slot from the first column, one slot from the second column, and one slot from the third column, respectively), plus one more slot ($= \frac{1}{2(\lfloor \frac{6}{2} \rfloor - 1)}$) from the fifth column. As you can see, Q_1 and Q_2 intersect at slot 7.

In general, with increasing in the value of $t \times w$, the active ratio is decreased. “In addition, for $k \geq 1$ and $f = 0$, the f-torus($k + f$) is the same as ge-torus(k)” [18]. For example, f-torus(1) and f-torus(2) is the same as ge-torus(1) and ge-torus(2) quorum-based power saving protocols.

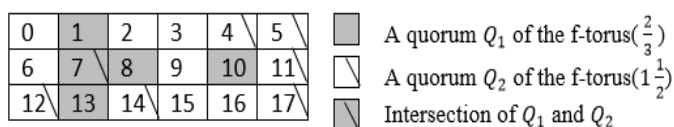


Fig. 11. The intersection of Q_1 and Q_2 at slot 7 in a f-torus quorum system.

5.2.8 Adaptive quorum protocol, year 2008

The major drawback of cyclic protocol (like grid) is that cyclic protocol does not have any information about traffic conditions which can result in having more delay time in packet forwarding. Authors in [30] try to utilize quorum protocols that are more adaptive with network's traffic conditions. They proposed an adaptive protocol [30] which changes its quorum size according to traffic buffered in its queue. They use five different values for quorum sizes. Difference sets for different quorum sizes are shown in Table 2.

Table 2. Quorum sizes and equivalent different sets [30]

N	Difference set
1	{1}
5	{1,2,3}
10	{1,2,3,6}
20	{1,2,3,4,7,11}
80	{1,2,3,4,5,6,11,24,41,57,72}

In this protocol, according to traffic buffered in node's queue, every node can choose one of these sizes and switch to it. When traffic is low, node can choose quorum with maximum size. When the traffic which is passing the node increases, node will increase its throughput by choosing the smaller quorum size. And, when network needs full capacity to pass the traffic, then quorum size is set to 1 and nodes operate like IEEE 802.11 "always on" state.

5.2.9 Cyclic quorum system pair (CQS-Pair), year 2008

Authors in [31] proposed the cyclic quorum system pair (CQS-Pair) that guarantees two nodes with different cyclic quorum systems can at least meet each other in one slot. Authors in [31] also proposed a scheme to construct a CQS-Pair, which relies on the Multiplier Theorem and the (N,k,M,l) -difference pair. They showed that by the help of CQS-Pair, two heterogeneous nodes can have different power saving proportions during their connectivity.

As we know, when the sending node wants to transmit a multicast or broadcast message, the quorum-based asynchronous protocols can only guarantee that one receiver, and not more than one, is awake. There are several methods to send multicast and broadcast messages. One method is to choose prime frequencies between all nodes to wake up. "In this method, synchronization between senders and receivers is not required, and the sender will only need to notify m receivers to wake up via the pairwise relative primes p_1, p_2, \dots, p_m , respectively. Then each one of the receivers, by getting the received frequency, can generate its own new wakeup frequency" [31].

The sending node can then transmit a multicast or a broadcast message at its wakeup frequency. Another way to send multicast or broadcast messages is a synchronization method with the help of Lamport's clock synchronization algorithm [32] that is beyond the scope of our study. The advantage of the first mechanism is that no synchronization is required between sender and receivers. The disadvantage though, is that it cannot put a limit on the average delay. The second mechanism can put a limit on the average delay but synchronization is needed.

5.2.10 Asynchronous, adaptive, and asymmetric (AAA) power management protocol, year 2009

The AAA protocol [33] is designed based on the grid quorum system to guarantee the intersection between nodes at least in one active slot. AAA is an asymmetric and asynchronous adaptive protocol based on clustering. In this protocol, two different quorums are defined for cluster members and cluster-heads. The a-quorum is for cluster members and s-quorum is for cluster-heads. In a-quorum, one of columns in grid quorum system is selected randomly for awake slots. In s-quorum, one of rows in grid quorum system is selected randomly for awake slots. In AAA, the quorum of cluster members is asymmetric and the quorum of cluster-heads is symmetric.

AAA is using HQS [34] for cluster-heads and for communicating between cluster-heads and cluster members, which cluster members are using cyclic quorum system. The system size for each clusters can be different and cluster-heads can change the system size based on cluster conditions. Each node in a cluster can choose an a-quorum different from other nodes to generate its own pattern for sleep and wake up. On the other hand, the cluster-heads can choose a s-quorum to generate their own cycle patterns [33].

5.2.11 Asymmetric cyclic quorum (ACQ) protocol, year 2007 and year 2010

The ACQ [35,36] is a quorum-based protocol that is suitable for clustered networks. Authors of the ACQ proposed two types of quorums: the symmetric quorums (s-quorums) and the asymmetric quorums (a-quorums). The s-quorum can be used by cluster-heads to setup symmetric links between themselves. The a-quorums can be used by cluster members to setup asymmetric links to contact their cluster-heads. The ACQ guarantees that any cluster members have intersection with its cluster-head at least once in bounded time intervals. In addition, the ACQ guarantees that cluster-heads have an intersection of ATIM window per cycle. But the ACQ does not guarantee overlapping between cluster members (a-quorums). Since the size of an a-quorum can be small, energy efficiency is expected to be improved [35].

5.2.12 Exponential/multiplicative adaptive cyclic difference set protocols (EACDS and MACDS), year 2011

In well-connected ad hoc networks, it is better to have relatively small round sizes to reach short end-to-end delays [34]. But, in delay tolerant networks (DTN) with low network connectivity, it is better to have large round sizes. Since nodes with small round sizes only waste their energy without sensing many neighbors [37,38]. Authors in [39], proposed Adaptive Cyclic Difference Set protocol with two different types of sleep schedule mechanisms that are suitable for DTN: exponential ACDS (EACDS) and Multiplicative ACDS (MACDS). ACDS with multiple power saving levels, is an energy efficient protocol for large round sizes.

“The basic strategy of EACDS is to use hierarchical arrangements of sets. As shown in Fig. 12(a), the EACDS uses an exponential set ($E = (v_E, k_E, \lambda_E)$) for scaling a difference set called an initial set at power saving level 1 ($P_1 = I = (v_I, k_I, \lambda_I)$), to create a hierarchical set with power saving level 2 (P_2). By scaling again with E, a higher level hierarchical set P_3 is obtained, which has higher energy efficiency than P_2 . The Kronecker product is used for scaling as defined in” [39].

“The basic strategy of MACDS is the same as EACDS, but a multiplier set (M_1) is used for scaling the initial set ($P_1 = I$), to create a hierarchical set ($P_2 = M_1 \otimes I$) and scaled by M_2 to create another hierarchical set ($P_3 = M_2 \otimes I$), as shown in Fig. 12(b). M_1 and M_2 are in the same hierarchical level but have different neighbor sensitivity” [39].

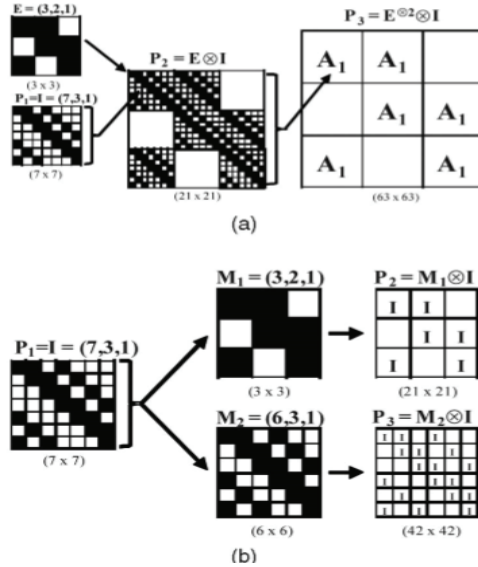


Fig. 12. Construction of adaptive cyclic difference set system (ACDS). (a) Exponential adaptive CDS. (b) Multiplicative adaptive CDS [27].

Theoretical analysis and simulation results of active ratio and neighbor sensitivity in [39] showed high performance of their proposed protocols, especially for DTN with large sleep schedules, and significant energy consumption in the listening mode.

5.2.13 Optimal fully adaptive and asynchronous (OFAA) power management protocol, year 2013

In [40], authors proposed the optimal fully adaptive and asynchronous (OFAA) power management protocol for a multi-hop MANET, which guarantees that any node can discover its neighboring node in bounded time, even when nodes have clock difference and individual SRIs. “The OFAA protocol contains four parts: 1) new structures of BIs; 2) a neighbor maintenance procedure; 3) an awake/sleep pattern prediction method; and 4) a data frame transfer procedure” [40].

Authors in [40] designed two types of BIs for the OFAA protocol, which are called half-awake BI (HBI) and SBI. The structures of these BIs are defined in [40]. Since the node is not always awake, the sender must predict when the destination node will wake up [40]. To achieve this, authors in [40] designed a beacon frame that contains a MAC address, a sequence number, a timestamp, the TBTT of the current BI, the value of the SRI, and the position of the current BI in the SRI, in addition to other 802.11 management parameters.

“When station Q intends to transmit data frames to its PS neighbor P, Q should first employ the aforementioned HBI/SBI pattern prediction method to judge whether P is currently in the HBI or the

SBI, see Fig. 13. If P is currently in the HBI, Q can directly send data frames to P in P’s data window. If P is currently in the SBI, Q should buffer data frames and wait for the coming of P’s data window. If Q’s data transmissions for P cannot be completed within a data window due to congestion or large amount of buffered data, both P and Q will remain awake across multiple BIs until data transmissions is completed” [40].

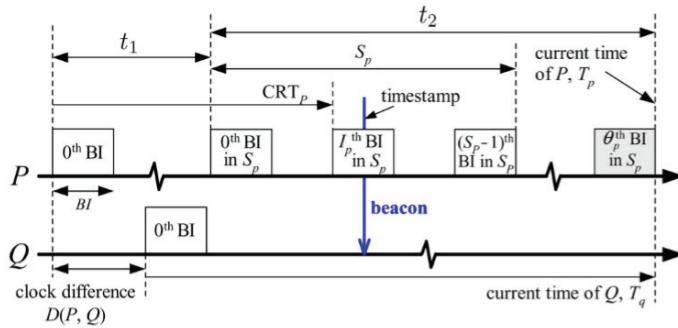


Fig. 13. Example of the HBI/SBI pattern prediction method [40].

Authors in [40] claimed that the OFAA protocol achieves minimum duty cycle and maximum adaptation for IEEE 802.11-based multi-hop MANETs. Both theoretical analysis and simulation results in [40] showed that the energy efficiency in OFAA protocol is better than the energy efficiency of AQEC and HQS protocols.

5.2.14 Hyper quorum system (HQS), year 2008 and year 2014

HQS [34,41] is based on traditional quorum systems, which any node can choose different cycle patterns based on its own conditions. The first advantage of HQS is that it allows better energy conservation, especially for nodes with critical battery power or light traffic load. The second advantage of HQS is that, it provides controllable delay that is a necessary requirement for some applications. Clearly, the second advantage is useful only when all nodes in a network have different requirements of energy consumption and delay [34].

Basically, a hyper quorum system guarantees the intersection between the projections of quorums over a plane. For example, Fig. 14 shows two quorum systems with different start frame time ($L_0=2, L_1=1$) where $Q_0 = \{1,2,3\}$ under the universal set $U_0= \{0,1,2,3\}$ and $Q_1 = \{0,3,6,7,8\}$ under the universal set $U_1= \{0,1,2,3,4,5,6,7,8\}$. If we consider these two quorum systems in a new quorum system with size of 10, the quorum systems Q_0 and Q_1 converted to $R_{4,10,2}(Q_0) = \{0,1,3,4,5,7,8,9\}$ and $R_{9,10,1}(Q_1) = \{2,5,6,7,8\}$ respectively. “Suppose at time t (reference point of time) the nodes H_0 and H_1 are in their 2nd and 1st beacon interval respectively. Then H_0 and H_1 are guaranteed to overlap in at least one awake beacon interval within the 10 beacon intervals after t , since $R_{4,10,2}(Q_0) \cap R_{9,10,1}(Q_1) \neq \emptyset$. Formally, we have $R_{4,10,l_0}(Q_0) \cap R_{9,10,l_1}(Q_1) \neq \emptyset$ for all l_0 and $l_1, 0 \leq l_0 \leq 3$ and $0 \leq l_1 \leq 8$. Therefore, the set $\{\{1,2,3\}, \{0,3,6,7,8\}\}$ is a (4,9;10)-hyper quorum system” [34]. Authors of HQS claimed that HQS has better power saving than AQEC [26] and AAPM [29] up to 41% reduction in the amount of energy consumption [41].

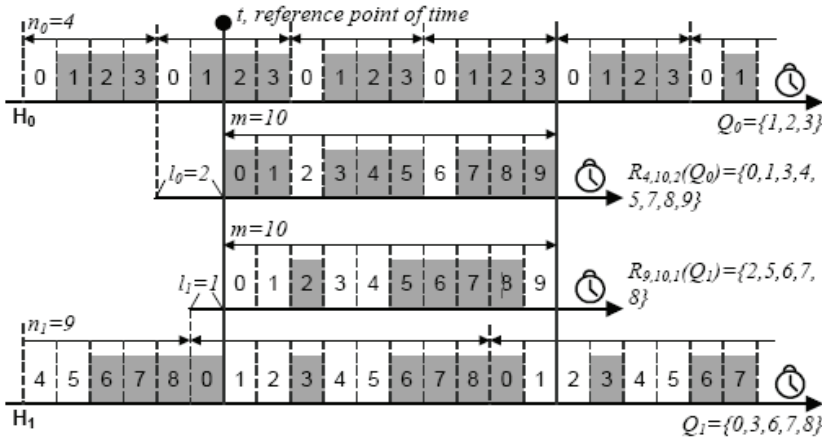


Fig. 14. An example of HQS that shows the intersection between two quorum systems with different sizes [34].

5.2.15 Adaptive stepped-grid quorum-based protocol (AS-GRID), year 2017

The AS-Grid($t \times w$) (for $t \neq w$ or $t = w$) that was proposed in [42], is an adaptive version of s-grid [23] with some modifications. In AS-Grid($t \times w$) a complete QI period is mapped to an array with n beacon intervals, which has t rows and w columns. Each BI is numbered with (i, j) , which i is the row number and j is the column number of that BI. But BIs in the AS-Grid($t \times w$) is numbered in a column-major manner, as shown in Fig. 15.

0	3	6	9
1	4	7	10
2	5	8	11

0	3	6	9
1	4	7	10
2	5	8	11

0	3	6	9
1	4	7	10
2	5	8	11

Fig. 15. Arrangement of all 3 possible quorum intervals based on the AS-Grid(3×4).

In AS-Grid($t \times w$), as it was in s-grid($t \times w$), elements are organized as a $t \times w$ array, with the last column/row in the array regarded as wrapping around back to the first column/row. A quorum of a AS-Grid($t \times w$) quorum system is formed like s-grid($t \times w$). The main difference of AS-Grid($t \times w$), comparing to s-grid($t \times w$) is that, all nodes in a same network should choose a same t value. The idea behind that rule is to satisfy rotational closure property. Using the same t value for all nodes can guarantee to have intersection in at least one active slot between two sets with different sizes.

In AS-Grid($t \times w$) each node in the same network, can choose different w values, but the t values should be the same. Therefore, nodes can change their system size and active ratio based on their remaining energy adaptively. The less the remaining energy is, the more the system size will be and therefore, the nodes' active ratio will be decreased. The EQOS and active ratio of AS-Grid($t \times w$) are equal to EQOS and active ratio of s-grid($t \times w$). The AS-Grid($t \times w$) is quite simple, easy to implement and efficient.

Table 3. The pros and cons of discussed protocols

Quorum-based protocols	Pros	Cons
QEC	Easy to implement. More energy efficient when transmission cost is high.	Non-adaptive. High delay. All nodes use the same grid size. Works with just $\sqrt{n} \times \sqrt{n}$ array sizes. Unawareness of traffic conditions. Nodes learn its vicinity very slow.
CDS	Can reach to the theoretically minimum active ratio.	Non-adaptive. Can be constructed when $k(k-1)+1=n$ and $k-1$ is a prime power. Unawareness of traffic conditions.
S-GRID	Easy to implement. More energy efficient when transmission cost is high. Works with any array sizes. Higher neighbor sensibility than QEC.	Non-adaptive. High delay. All nodes use the same grid size. Unawareness of traffic conditions.
e-torus	Adaptive. Sensitive to the network conditions such as nodes mobility and QoS.	Works with just $t \times w$ array sizes when $w = 2t$. Can choose only the integer values for k . No guarantee that two branches from two e-torus quorums have intersection with each other.
AQEC	Adaptive. Using different system sizes based on network conditions. Low energy conserving.	High delay. Using just three fixed thresholds for different traffic levels. Assuming a symmetric or flat network structure.
AQEC+	Adaptive. Low delay.	High energy wasting. Using just three fixed thresholds for different traffic levels. Assuming a symmetric or flat network structure.
FQEC	Adaptive. Using different thresholds for different traffic levels. Can change its quorum size according to both incoming and outgoing traffic.	Needs time synchronization.
AMAC	Adaptive. Each node can change its system size based on network conditions adaptively.	Works with just rectangular arrays. Choosing too large or too small numbers of rows and columns has a bad influence on network's stability.
AAPM	Adaptive. Nodes can change its system size and its active ratio based on its remaining energy.	The system size must be a prime number lower than 47. Cannot reduce transmission delay impressively. Assuming a symmetric or flat network structure.
f-torus	Adaptive. More adaptive to mobility changes than those using e-torus quorum protocols.	Works with just $t \times w$ array sizes when $w = 2t$. No guarantee that two branches from two f-torus quorums have intersection with each other.
Adaptive quorum protocol	Adaptive. Changes its quorum size according to traffic buffered in its queue. QoS support.	Using five fixed thresholds for different traffic levels.
CQS-Pair	Adaptive. Two heterogeneous nodes can achieve different power saving ratios during their connectivity. First mechanism: no synchronization is needed between sender and receivers. Second mechanism: can put a limit on the average delay.	First mechanism: cannot put a limit on the average delay. Second mechanism: needs bookkeeping and synchronization.

Quorum-based protocols	Pros	Cons
AAA	Adaptive. Deal with the best-effort and delay-sensitive traffic.	Does not guarantee the intersection between cluster members.
ACQ	Adaptive. For small size of an a-quorum, energy efficiency is expected to be improved.	Does not guarantee intersection between cluster members.
EACDS & MACDS	Adaptive. Significantly reduce energy wasting in the listening mode. Active ratio close to the optimal.	Can be constructed when $k(k-1)+1=n$ and $k-1$ is a prime power. Unawareness of traffic conditions.
OFAA	Adaptive. Minimum duty cycle and maximum adaptation for IEEE 802.11-based multi-hop MANETs	All nodes maintain the same quorum with the same Repetition Pattern Interval. It is not very effective when the Repetition Pattern Interval of the nodes varies.
HQS	Adaptive. Allows more energy conservation specially for nodes with critical battery power or light traffic load provides controllable delay.	Cannot deal with asynchronous environments. The cycle length must be fixed. Assuming a symmetric or flat network structure.
AS-Grid	Adaptive. Easy to implement. More energy efficient when transmission cost is high. High neighbor sensibility. Nodes can change their quorum size based on their remaining energy.	High delay. All nodes in a same network should use the same t value (t is the number of rows in the array).

6. Conclusion

In this paper we have surveyed the main protocols to energy conservation in multi-hop networks. Special attention has been devoted to compare the protocols proposed in the survey and discussed their pros and cons. We did not limit our discussion to topics that have received wide interest in the past, but we have also stressed the importance of different protocols. It is worth noting that the considered approaches should not be considered as alternatives, they should rather be exploited together.

Another interesting point is that all protocols proposed in this survey are asynchronous protocols and time synchronization is no longer a consideration for these protocols. We think that the field of quorum-based power saving protocols has not been fully explored yet, so that there is room for developing convenient protocols to reduce the energy consumption and delay in data transfer and increase neighbor sensibility of the multi-hop networks. Specially, according to the new requirements in multi-hop networks and the emerging Internet of Things (IoT), research in this topic still will be hot and in the near future we will need protocols that must have the following features: 1) asynchronous; 2) low energy consumption; 3) high neighbor sensibility; 4) adaptive with network conditions and QoS support.

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lawsuit with damages awarded to him for a total of \$2.3 Million. Since this court case was one of the few cases of its kind in the United States, this ruling is considered to be important; Final Judgement for damages was issued in Leon County Courthouse of Tallahassee in Florida by Circuit Court Judge. Prof. Arabnia is Editor-in-Chief of The Journal of Supercomputing published by Springer. Dr. Arabnia is Fellow and Advisor of Center of Excellence in Terrorism, Resilience, Intelligence and Organized Crime Research (CENTRIC). He has published extensively in journals and refereed conference proceedings. He has about 200 peer-reviewed research publications as well as 250 edited research books in his areas of expertise. He has been a PI/Co-PI on about \$8 Million externally funded projects/initiatives and on about \$200,000 internally funded projects. He has also contributed projects for justification for equipment purchase (grant proposals worth over \$4 Million - awarded). During his tenure as Graduate Coordinator/Director of Computer Science (2002-2009), Dr. Arabnia secured the largest level of funding in the history of the department for supporting the research and education of graduate students (PhD, MS).



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