Heterogenous Quorum-based Wakeup Scheduling in Wireless Sensor Networks

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Abstract

We present *heterogenous* quorum-based asynchronous wakeup scheduling schemes for wireless sensor networks. The schemes can ensure that two nodes that adopt *different* quorum systems as their wakeup schedules can hear each other at least once in bounded time intervals. We propose two such schemes: *cyclic quorum system pair* (*cqs-pair*) and *grid quorum system pair* (*gqs-pair*). The cqs-pair which contains two cyclic quorum systems provides an optimal solution in terms of energy saving ratio for asynchronous wakeup scheduling. To quickly assemble a cqs-pair, we present a fast construction scheme which is based on the *multiplier theorem* and the (N, k, M, l)-difference pair defined by us. Regarding the gqs-pair, we prove that any two grid quorum systems will automatically form a gqs-pair. We further analyze the performance of both designs, in terms of average discovery delay, quorum ratio, and energy saving ratio. We show that our designs achieve better trade-off between the average discovery delay and quorum ratio (and thus energy consumption) for different cycle lengthes. We implemented the proposed designs in a wireless sensor network platform of Telosb motes. Our implementation-based measurements further validate the analytically-established performance trade-off of our designs.

Index Terms

wakeup scheduling, asynchronous wakeup, quorum, wireless sensor networks, difference set, multiplier theorem

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1 INTRODUCTION

Wireless sensor networks (WSNs) have recently received increased attention for a broad array of applications such as surveillance, environment monitoring, medical diagnostics, and industrial control. As wireless sensor nodes usually rely on portable power sources such as batteries to provide the necessary power, their power management has become a crucial issue. It has been observed that idle energy plays an important role for saving energy in wireless sensor networks [1]. Most existing radios (i.e., CC2420 [2]) used in wireless sensor networks support different modes, like transmit/receive mode, idle mode, and sleep mode. In idle mode, the radio is not communicating but the radio circuitry is still turned on, resulting in energy consumption which is only slightly less than that in the transmitting or receiving states. Thus, a better way is to shut down the radio as much as possible in idle mode [1].

In order to save more idle energy, it is necessary to introduce a wakeup mechanism [3] for sensor nodes in the presence of pending transmissions. The major objective of a wakeup mechanism is to maintain network connectivity while reducing the idle state energy consumption. Existing wakeup mechanisms fall into three categories: on-demand wakeup [4], [5], scheduled rendezvous [6], [7], and asynchronous wakeup [8], [9], as pointed out by the previous work [9].

In on-demand wakeup mechanisms [4], [5], [10], out-of-band signaling is used to wake up sleeping nodes in an on-demand manner. For example, with the help of a paging signal, a node listening on a page channel can be woken up. As page radios can operate at lower power consumption, this strategy is very energy efficient. However, it suffers from increased implementation complexity.

In scheduled rendezvous wakeup mechanisms, low-power sleeping nodes wake up at the same time periodically to communicate with one another. Examples include the S-MAC protocol [6], [7] and the multi-parent schemes protocol [3].

The third category, asynchronous wakeup [9], [11], is also well studied. Compared to the scheduled rendezvous wakeup mechanism, asynchronous wakeup does not require clock synchronization. In this approach, each node follows its own wakeup schedule in idle state, as long as the wakeup intervals among neighbors overlap. To meet this requirement, nodes usually have to wakeup more frequently than in the scheduled rendezvous mechanism. However, there are many advantages of asynchronous wakeup, such as easiness in implementation and low message overhead for communication. Furthermore, it can ensure network connectivity even in highly dynamic networks.

The quorum-based wakeup scheduling paradigm, also called quorum-based power saving (QPS) protocol [8], [12], has recently been proposed as a solution for asynchronous wakeup scheduling. In a QPS protocol, the time axis on each node is evenly divided into beacon intervals. Given an integer n, a quorum system defines a cycle pattern, which specifies the awake/sleep scheduling pattern during n continuous beacon intervals for each node. We call n the *cycle length*, since the pattern repeats every n beacon intervals. A node may stay awake or sleep during each beacon interval. QPS protocols can guarantee that at least one awake interval overlaps between two adjacent nodes, with each node being awake for only $O(\sqrt{n})$ beacon intervals.

Most previous works only consider *homogenous* quorum systems for asynchronous wakeup scheduling [8], [12], which means that quorum systems for all nodes have the same *cycle length* and same pattern. However, many WSNs are increasingly heterogenous in nature—i.e., the network nodes are grouped into clusters, with each cluster having a high-power cluster head node and low-power cluster member nodes [13]. Thus, it is desirable that heterogenous sensor nodes (i.e., clusterheads and cluster members) have *heterogenous* quorum-based wakeup schedules (or different *cycle lengthes*).

We denote two quorums from different quorum systems as *heterogenous quorums* in this paper. If two adjacent nodes adopt heterogenous quorums as their wakeup schedules, they have different cycle lengthes and different wakeup patterns. The heterogeneous quorum-based power saving problem (or *h-QPS*; defined formally in Section 2.4) is therefore how to guarantee that two nodes with heterogenous quorums as their wakeup schedules can discover each other within bounded delay in the presence of clock drift.

In this paper, we present the *heterogenous quorum system pair* which can be applied as a solution for the problem of heterogeneous quorum-based power saving (h-QPS, defined in Section 2.4) in wireless sensor networks, and propose two designs: *cyclic quorum system pair* (*cqs-pair*) and *grid quorum system pair* (*gqs-pair*). For cqs-pair, a fast constructing scheme is proposed via the *multiplier theorem* and (N, k, M, l)-difference pair defined by us. The cqs-pair is an optimal design in terms of energy saving ratios given a pair of cycle lengths (n and m, $n \leq m$). The fast constructing scheme can greatly improve the speed of finding an optimal quorum comparing with previous exhaustive methods [14]. We also analyze the performance of cqs-pair in aspects of expected delay ($\frac{n-1}{2} < E(delay) < \frac{m-1}{2}$), quorum ratio, energy saving ratio, and practical issues on how to support multicast/broadcast. Regarding gqs-pair, the prove that any two grid quorum systems can form a gqs-pair [14].

Comparing with the work in [9], our contributions are in three aspects: (1) we explicitly propose a formal algorithm based on Multiplier Theorem [15] for quick quorum scheduling assembling (i.e. $O(n^2)$), especially for the case of $n = q^2 + q + 1$. This is the first formal algorithm for cyclic quorum construction; and (2) we propose a solution to the heterogeneous cyclic quorum design which is referred as asymmetric design and is claimed to be NP-complete in [9]. Although our work cannot address the general case of asymmetric design, it provide a solution to a simple and practical scenario: there are only two different schedules for the entire network; and (3) we explicitly analyze the performance of cqs-pair and gqs-pair and highlight the trade-off between average neighbor discovery and energy consumption ratio, which was not done in previous work [9]. Comparing with our preliminary results in [16], we propose an additional heterogenous quorum system pair, qps-pair and analyze its performance in terms of average discovery delay and energy saving ratio. We also present more implementation details over a wireless sensor network platform of Telosb motes, and present extensive experimental evaluations to validate the analytically-established performance trade-off of our designs.

With the help of the *heterogenous quorum system pair*, sensor nodes can achieve better trade-off between energy consumption and average discovery delay. For example, in a tiered topology [17], the cluster-heads or gateway nodes can select a quorum from the system with smaller cycle length as their wake up schedules, to obtain smaller discovery delay. In addition, all members in a cluster can choose a quorum from the system with longer cycle length as their wakeup schedules, in order to save more idle energy.

The rest of the paper is organized as follows: In Section 2, we outline basic preliminaries of quorum-based power-saving protocols. The detailed design of heterogenous quorum systems pair is discussed in Section 3. We present our cqs-pair construction scheme in Section 4, and analyze the performance of cqs-pair and gqs-pair in Section 5. We describe our implementation in Section 6, and report our experimental measurements in Section 7. Finally, we overview past and related works in Section 8 and conclude in Section 9.

2 Preliminaries

2.1 Network Model and Assumptions

We represent a multi-hop wireless sensor network by a directed graph $G(V, E)$, where V is the set of network nodes ($|V| = N$), and E is the set of edges. If node v_j is within the transmission range of node v_i, then an edge (v_i, v_j) is in E. We assume bidirectional links. The major objective of quorum-based wakeup scheduling is to maintain network connectivity regardless of clock drift. Here, we use the term "connectivity" loosely, in the sense that a topologically connected network in our context may not be connected at any time; instead, all the nodes are reachable from a node within a finite amount of time.

We also make the following assumptions: (1) All time intervals/slots have equal lengthes (this is for convenient presentation); (2) At the beginning of a beacon interval, beacon messages will be sent out so that nodes can hear each other; and (3) The overhead of turning on and shutting down radio is negligibly small.

As for the first assumption, the length of one time interval depends on application-specific requirements. For example, for a radio compliant with IEEE 802.15.4, the bandwidth is approximately 128kb/s and a typical packet size is less than 512KB. Given this, the slot length (i.e., the beacon interval) can be approximately $50ms$.

Regarding the second assumption, the beacon message is adopted by a node to inform its neighbors that it is awake.

The third assumption, also adopted by previous works [8], [9], is for convenience in theoretical analysis.

2.2 Quorum-based Power-Saving Protocols (QPS)

We use the following definitions for quorum system. Given a cycle length n, let $U = \{0, \cdots, n-1\}$ be an universal set. We will also use definitions from [15] to denote $\mathbb{Z}_n$ as an finite field of order n and $(\mathbb{Z}_n, +)$ as an Abelian Group.

Definition 1: A quorum system $\mathcal{Q}$ under U is a superset of non-empty subsets of U, each called a quorum, which satisfies the intersection property: $\forall G, H \in \mathcal{Q} : G \cap H \neq \emptyset$.

Definition 2: Given an integer $i \geq 0$ and quorum G in a quorum system $\mathcal{Q}$ under U, we define the rotation of G by i by $G + i = \{(x+i) \ mod \ n : x \in G\}$.

Definition 3: A quorum system $\mathcal{Q}$ under U is said to have the *rotation closure property* if $\forall G, H \in \mathcal{Q}$, $i \in \{0, 1, ...n-1\}$: $G \cap (H + i) \neq \emptyset$.

The formal definition of a quorum system satisfying rotation closure property is given in Definition 4.

Definition 4: Let A be a set in $(\mathbb{Z}_n, +)$. For $\forall g \in \mathbb{Z}_n$, if $A \cap (A + g) \neq \emptyset$, then $\{A, A+1, \cdots, A+n-1\}$ is a quorum system which satisfying the rotation closure property, and is defined as $C(A, \mathbb{Z}_n)$.

There are two widely used quorum systems, *grid quorum system* and *cyclic quorum system*, that satisfy the *rotation closure property*.

Grid quorum system [14]. In a grid quorum system, shown in Figure 1, elements are arranged as a $\sqrt{n} \times \sqrt{n}$ array (square). A quorum can be any set containing a column and a row of elements in the array. The quorum size in a square grid quorum system is $2\sqrt{n} - 1$. An alternative is a "triangle" grid-based quorum in which all elements are organized in a triangle fashion. The quorum size in "triangle" quorum system is approximately $\sqrt{2}\sqrt{n}$.

Cyclic quorum system [14]. A cyclic quorum system is based on the ideas of cyclic block design and cyclic difference sets in combinatorial theory [15]. The solution set can be strictly symmetric for arbitrary n. For example, the set $\{1, 2, 4\}$ is a quorum from a cyclic quorum system with cycle length $= 7$. Figure 1 illustrates three quorums

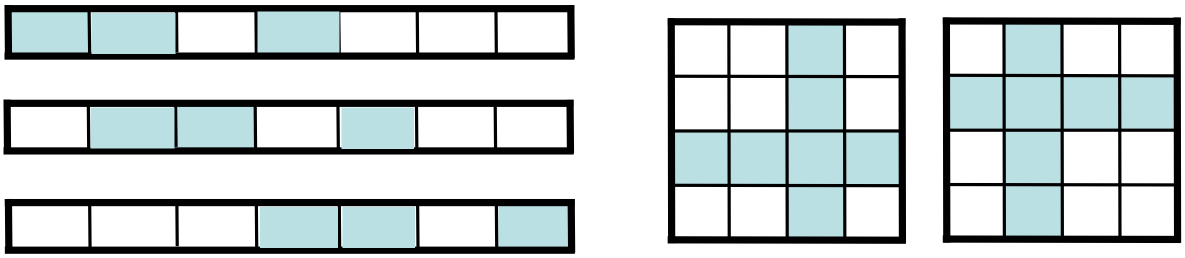


Fig. 1. Cyclic Quorum System (left) and Grid Quorum System (right): Each arrangement is a schedule. The slots with dark color correspond to wakeup slots and slots marked by white color are sleeping slots. The overlap means two schedules have wakeup slots in same position.

from a cyclic quorum system with cycle length 7. Based on Definition 4, the cyclic quorum system containing the quorum $\{1,2,4\}$ can be denoted as $C(\{1,2,4\},\mathbb{Z}_7) = \{\{1,2,4\},\{2,3,5\}\cdots,\{7,1,3\}\}$.

Previous work [8] has defined the **QPS** (quorum-based power-saving) problem as follows: Given an universal set $U = \{0,1,...n-1\}$ ($n > 2$) and a quorum system $\mathcal{Q}$ over U, two nodes that select any quorum from $\mathcal{Q}$ as their wakeup schedules must have at least one overlap in every n consecutive time slots.

Theorem 1: $\mathcal{Q}$ is a solution to the QPS problem if $\mathcal{Q}$ is a quorum system satisfying the *rotation closure property*.

Theorem 2: Both grid quorum systems and cyclic quorum systems satisfy the rotation closure property and can be applied as a solution for the QPS problem in wireless sensor networks.

Proofs of Theorems 1 and 2 can be found in [8].

2.3 Neighbor Discovery under Partial Overlap

Since sensor nodes are subject to clock drift, the time slots are not exactly aligned to their boundaries in practical deployments. In most cases, two nodes only have *partial overlap* during a certain time interval. It has been shown that two nodes that adopt quorum-based wakeup schedules can discover each other even under *partial overlap*.

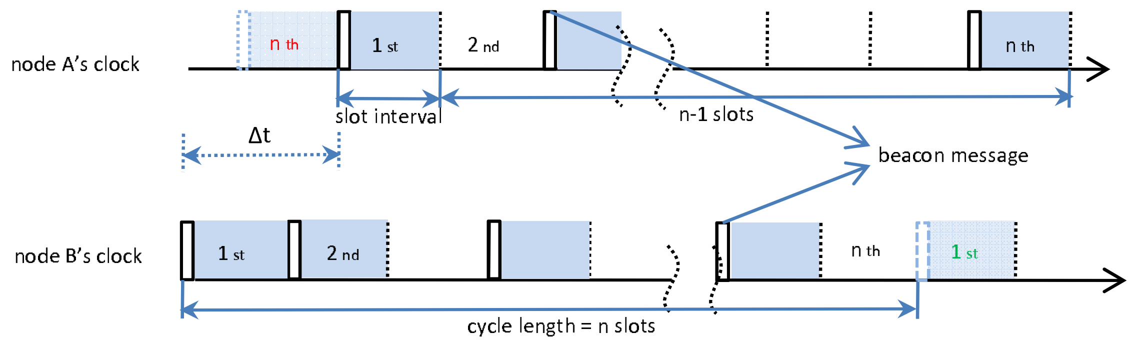


Fig. 2. Neighbor discovery under partial overlap

Theorem 3: [9] If two quorums ensure a minimum of one overlapping slot, then with the help of a beacon message at the beginning of each slot, two neighboring nodes can hear each others' beacons at least once.

Theorem 3's proof is presented in [9]. An illustration is given in Figure 2. Suppose that node A's quorum and node B's quorum intersect with each other in the first element and that the clock drift between the two nodes is Δt ($1\ slot < \Delta t < 2\ slots$). We can see that node A's 1^{st} beacon message in the current cycle (beacon messages are marked with solid lines) will be heard by node B during node B's 2^{nd} time slot interval in its current cycle. Meanwhile, node B's 2^{nd} beacon message in the current cycle will be heard by node A during its n^{th} time slot interval in the previous cycle (beacon messages are marked with dash lines).

This theorem ensures that two neighboring nodes can always discover each other within bounded time if all beacon messages are transmitted successfully. This property also holds true even in the case when two originally disconnected subsets of nodes join together as long as they use the same quorum system.

2.4 Heterogeneous Quorum-Based Power Saving (h-QPS)

We introduce the h-QPS (heterogeneous quorum-based power saving) problem in this section. In WSNs, it is often desirable that different nodes wakeup according to heterogeneous quorum-based schedules. There are several reasons for this. First, many WSNs have heterogeneous nodes such as cluster-heads, gateways, and relay nodes [18]. They often have different requirements regarding average neighbor discovery delay and energy saving ratio. For cyclic quorum systems, generally, cluster-heads should wakeup based on a quorum system with small cycle length, and member nodes should wakeup based on a longer cycle length. Second, WSNs that are used in applications such as environment monitoring typically have seasonally-varying power saving requirements. For example, a sensor network for wild fire monitoring may require a larger energy saving ratio during winter seasons. Thus, they often desire variable cycle-length wakeups during different seasons.

However, in the transition from a lower duty cycle to a larger duty cycle due to seasonal change, some early updated nodes may have larger cycle (i.e., n=13), whereas its neighbor may be still operating with original low cycle (i.e., n=7). In this scenario, two neighbor nodes have heterogeneous wakeup scheduling, we should address the non-empty intersection problem to secure neighbor discovery in such scenario.

We define the **h-QPS** problem as follows. Given two heterogeneous quorum systems $\mathcal{X}$ over $\{0, 1, \cdots, n-1\}$ and $\mathcal{Y}$ over $\{0, 1, \cdots, m-1\}$ ($n \leq m$), design a pair ($\mathcal{X}, \mathcal{Y}$) in order to guarantee that:

1) two nodes that select two quorums $G \in \mathcal{X}$ and $H \in \mathcal{Y}$ as their wakeup schedules, respectively, can hear each other at least once within every m consecutive slots; and
2) $\mathcal{X}$ and $\mathcal{Y}$ are solutions to QPS, individually.

The problem is non-trivial since the super problem of asymmetric design [9] is NP-complete. Our approach is not to address the whole problem of asymmetric design where there are non-empty intersection among multiple quorum systems (i.e. ≥ 3), but to consider a simple scenario where there are only two different systems.

A solution to the h-QPS problem is important toward ensuring connectivity when we want to dynamically change the quorum systems between all nodes. For example, suppose that all nodes in a WSN initially wakeup via a larger cycle length. When there is a need to reduce the cycle length (e.g., to meet a delay requirement or due to changing seasons), the sink node can send a request to the whole network gradually through some relay nodes. If a source node changes its wakeup scheduling first but the relay nodes keep unchanged, the two nodes may have heterogeneous wakeup scheduling. The connectivity between them will be lost when the two heterogeneous wakeup schedules do not have non-empty intersection property.

Although cqs and qps can be applied as a solution for the QPS problem, that does not necessarily mean that any pair of such systems can be a solution to the h-QPS problem. We will show this in Section 3.2.

3 HETEROGENOUS QUORUM SYSTEM PAIR

3.1 Heterogeneous Rotation Closure Property

First, we define a few concepts to facilitate our presentation.

Definition 5: (*p*-extension). Given two positive integers n and p, for a set $A = \{a_i | 1 \leq i \leq k, a_i \in \mathbb{Z}_n\}$, the *p-extension* of A is defined as $A^p = \{a_i + j * n | 1 \leq i \leq k, 0 \leq j \leq p-1, a_i \in \mathbb{Z}_n\}$. For a quorum system $\mathcal{Q} = \{A_1, \cdots, A_m\}$, the *p-extension* of $\mathcal{Q}$ is defined as $\mathcal{Q}^p = \{A_1^p, \cdots, A_m^p\}$.

Since time axes is infinite, the physical meaning of *p*-extension of a schedule is same as the original schedule. Thus, *p*-extension is just a different logical presentation for a specified schedule of a quorum system. Example: Let $A = \{1, 2, 4\}$ in $(\mathbb{Z}_7, +)$. Now, $A^3 = \{1, 2, 4, 8, 9, 11, 15, 16, 18\}$ in $(\mathbb{Z}_{21}, +)$. If a quorum system $\mathcal{Q} = \{\{1, 2, 4\}, \{2, 3, 5\}, \cdots, \{7, 1, 3\}\}$, then we have $\mathcal{Q}^2 = \{\{1, 2, 4, 8, 9, 11\}, \{2, 3, 5, 9, 10, 12\}, \{3, 4, 6, 10, 11, 13\}, \cdots, \{7, 1, 3, 14, 8, 10\}\}$.

Definition 6: (Heterogeneous rotation closure property). Given two positive integers N and M where $N \leq M$ and $p = \lceil \frac{M}{N} \rceil$, consider two quorum systems $\mathcal{X}$ over the universal set $\{0, \cdots N-1\}$ and $\mathcal{Y}$ over the universal set $\{0, \cdots M-1\}$. The pair ($\mathcal{X}$,$\mathcal{Y}$) is said to satisfy the *heterogeneous rotation closure property* if :

1) $\forall G \in \mathcal{X}^p, H \in \mathcal{Y}$, $i \in N+$: $G \cap (H + i) \neq \emptyset$, and
2) $\mathcal{X}$ and $\mathcal{Y}$ satisfy the *rotation closure property* (Definition 1), respectively.

Example: Let $A = \{1, 2, 4\}$ in $(\mathbb{Z}_7, +)$ and $B = \{1, 2, 4, 10\}$ in $(\mathbb{Z}_{13}, +)$. Consider two cyclic quorum systems $\mathcal{Q}_{\mathcal{A}} = C(A, \mathbb{Z}_7)$ and $\mathcal{Q}_{\mathcal{B}} = C(B, \mathbb{Z}_{13})$. Now, ${\mathcal{Q}_{\mathcal{A}}}^2 = C(\{1, 2, 4, 8, 9, 11\}, \mathbb{Z}_{14})$. We can verify that any two quorums from ${\mathcal{Q}_{\mathcal{A}}}^2$ and $\mathcal{Q}_{\mathcal{B}}$

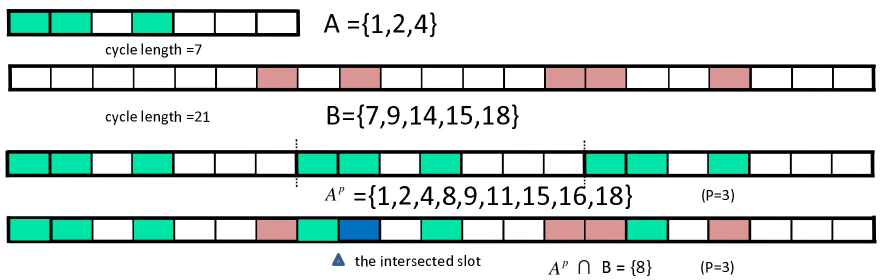


Fig. 3. Heterogenous rotation closure property between two cyclic quorum systems: A with cycle length of 7 and B with cycle length of 21. A quorum from A's p-extension A^p will overlap with a quorum from B.

must have non-empty intersection. Thus, the pair ($\mathcal{Q}_{\mathcal{A}}$,$\mathcal{Q}_{\mathcal{B}}$) satisfies the *heterogeneous rotation closure property*.

Lemma 1: If two quorum systems $\mathcal{X}$ and $\mathcal{Y}$ satisfy the heterogeneous rotation closure property, then the pair $(\mathcal{X}, \mathcal{Y})$ is a solution to the h-QPS problem.

Proof: According to Definition 6, if two quorum systems $\mathcal{X}$ and $\mathcal{Y}$ satisfy the heterogeneous rotation closure property, a quorum G from $\mathcal{X}$ and a quorum H from $\mathcal{Y}$ must overlap at least once within the larger cycle length of $\mathcal{X}$ and $\mathcal{Y}$. Thus, two nodes can hear each other if they select G and H as their wakeup schedules, respectively, based on Theorem 3. This implies that $(\mathcal{X}, \mathcal{Y})$ is a solution to the h-QPS problem. □

Example: In Figure 3, there are two cyclic quorum systems $C(A, \mathbb{Z}_7)$ and $C(B, \mathbb{Z}_{21})$. Since they have different cycle lengthes, we extend A's cycle by 3 ($3 = \lceil \frac{21}{7} \rceil$) times and denote its extension as A^p. Now, A^p will have an intersection with B within 21 time slot intervals. We can further verify that B and its rotations will overlap with A^p. Thus, $(C(A, \mathbb{Z}_7), C(B, \mathbb{Z}_{21}))$ has the *heterogeneous rotation closure property* and it can be a solution to the h-QPS problem.

Negative example: In Figure 4, $A = \{3, 5, 6\}$ and $B = \{7, 9, 14, 15, 18\}$ are from two cyclic quorum systems $C(A, \mathbb{Z}_7)$ and $C(B, \mathbb{Z}_{21})$. We extend A's cycle by 3 ($3 = \lceil \frac{21}{7} \rceil$) times and denote its extension as $A^p = \{3, 5, 6, 10, 12, 13, 17, 19, 20\}$. Now, $A^p \cap B = \emptyset$, which means that $(C(A, \mathbb{Z}_7), C(B, \mathbb{Z}_{21}))$ does not stratify the *heterogeneous rotation closure property* and it can NOT be a solution to the h-QPS problem.

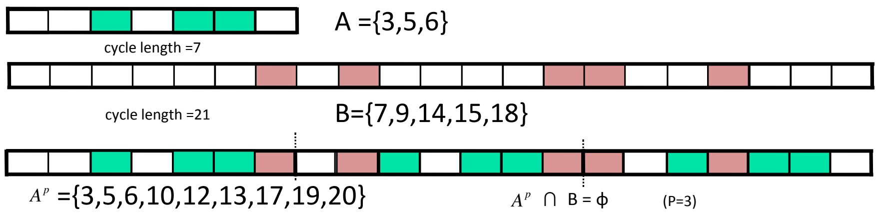


Fig. 4. Two quorums do not satisfy heterogenous rotation closure property although they are from cyclic quorum systems respectively.

3.2 Cyclic Quorum System Pair (CQS-Pair)

In this section, we present one design of heterogenous quorum systems: *cqs-pair* which is based on the cyclic block design concept and cyclic difference sets in combinatorial theory [15]. We first review two definitions which were originally introduced in [14].

Definition 7: (N, k, λ)**- difference set**. A set D : $\{a_1, ..., a_k\}(\mod N)$, $a_i \in [0, N-1]$, is called a (N, k, λ)-difference set if for every $d \neq 0$, there are *exactly* λ ordered pairs (a_i, a_j), $a_i, a_j \in D$ such that $a_i - a_j \equiv d\ (modN)$.

We now introduce a new definition which is extended from (N, k, λ)- difference set.

Definition 8: (N, k, M, l)**-difference pair.** Suppose $N \leq M$ and $p = \lceil \frac{M}{N} \rceil$. Suppose there are sets $A : \{a_1, \cdots a_k\}$ in $(\mathbb{Z}_N, +)$ and $B : \{b_1, \cdots b_l\}$ in $(\mathbb{Z}_M, +)$. The pair (A, B) is defined as a (N, k, M, l)-difference pair if $\forall d \in \{0, \cdots, M-1\}$, there exists at least one ordered pair $b_i \in B$ and $a_j^p \in A^p$ such that $b_i - a_j^p \equiv\ d\ (mod\ M)$.

Consider an example where $A = \{1, 2, 4\}$ and $B = \{1, 3, 6, 7\}$ be two subsets in $(\mathbb{Z}_7, +)$ and $(\mathbb{Z}_{13}, +)$, respectively. Then (A, B) is a $(7, 3, 13, 4)$-difference pair, since for A^2 $(\{1, 2, 4, 8, 9, 11\})$ and B, there exists at least one ordered pair $b_i \in B$ and $a_j^p \in A^p$ such that $b_i - a_j^p \equiv\ d\ (mod\ M)$ for $\forall d \in \{0, \cdots, M-1\}$.

$$\begin{array}{lllll} 1 \equiv 3-2 & 2 \equiv 6-4 & 3 \equiv 1-11 & 4 \equiv 6-2 & 5 \equiv 6-1 \\ 6 \equiv 7-1 & 7 \equiv 3-9 & 8 \equiv 6-11 & 9 \equiv 7-11 & 10 \equiv 1-4 \\ 11 \equiv 6-8 & 12 \equiv 1-2 & 13 \equiv 1-1 & & \end{array} (mod\ 13)$$

Definition 9: **cyclic quorum system pair (cqs-pair).** Given two cyclic quorum $\mathcal{X} =$

$C(A, \mathbb{Z}_N)$ and $\mathcal{Y} = C(B, \mathbb{Z}_M)$, suppose $N \leq M$. We call $(\mathcal{X}, \mathcal{Y})$ a *cqs-pair* if: $\forall (A+i)^p \subseteq \mathcal{X}^p$ and $(B+j) \subseteq \mathcal{Y}$, $(A+i)^p \cap (B+j) \neq \emptyset$.

Theorem 4: Given two cyclic quorum $\mathcal{X} = C(A, \mathbb{Z}_N)$ and $\mathcal{Y} = C(B, \mathbb{Z}_M)$ $(N \leq M)$, the pair $(\mathcal{X}, \mathcal{Y})$ is a *cqs-pair* if and only if: (A, B) is a (N, k, M, l)-difference pair.

Proof: We first prove the following claim (sufficient condition): if (A, B) is a (N, k, M, l)-difference pair, we have $\forall (A+i)^p \subseteq \mathcal{X}^p$ and $(B+j) \subseteq \mathcal{Y}$, $(A+i)^p \cap (B+j) \neq \emptyset$. Without loss of generality, we assume that $j > i$ regarding two sets B_i and A_j^p, where $p = \lceil \frac{M}{N} \rceil$. Consider the r^{th} element of B_i and s^{th} element of A_j^p, denoted by $b_{i,r}$ and $a_{j,s}^p$, respectively. We will now show that $b_{i,r} = a_{j,s}^p$.

Let the r^{th} element of B be b_r and the s^{th} element of A^p be a_s^p. Then $b_{i,r} - a_{j,s}^p = (b_r - a_s^p + i - j)\ mod\ M$. According to the definition of (N, k, M, l)-difference pair, there must be some r and s such that $b_r - a_s^p \equiv j - i\ (mod\ M)$. Therefore, we can always choose a pair of r and s such that $b_{i,r} - a_{j,s}^p \equiv 0\ (mod\ M)$. This implies that $B_j \cap A_i^P \neq \emptyset$.

Now we prove the another claim (necessary condition): if $\forall (A+i)^p \subseteq \mathcal{X}^p$ and $(B+j) \subseteq \mathcal{Y}$, $(A+i)^p \cap (B+j) \neq \emptyset$, we have that$(A, B)$ is a (N, k, M, l)-difference pair. We prove the necessity by contradiction. Assume that $B_j \cap A_i^P \neq \emptyset$, but (A, B) is not a (N, k, M, l)-difference pair. Then, there exists a number $\in \{0, \cdots, M-1\}$, say t, for which $b_i - a_j^p \neq t\ (mod\ M)$, $\forall i, j$.

Consider the r^{th} element of B_t and the s^{th} element of A^p. We have $b_{t,r} - a_s^p \equiv b_r - a_s^p + t\ (mod\ M)$. Since $B_t \cap A_i^P \neq \emptyset$, $b_{t,r} - a_s^p = 0$ for some r and s. This implies that $b_r - a_s^p \equiv t\ (mod\ M)$ for some r and s, which contradicts the derivation of $b_i - a_j^p \neq t\ (mod\ M)\ \forall i, j$ from the assumption. Therefore, the theorem holds. □

Corollary 1: Given a cyclic quorum system $\mathcal{X}$, $(\mathcal{X}, \mathcal{X})$ is a cqs-pair.

Theorem 5: The cyclic quorum system pair (*cqs-pair*) is a solution to the h-QPS problem.

Proof: According to the definition of cqs-pair, a cqs-pair satisfies the heterogeneous rotation closure property. Thus, the cqs-pair can be a solution to the h-QPS problem according to Lemma 1. □

Example 1: Let $A = \{1, 2, 4\}$ and $\mathcal{X} = C(A, \mathbb{Z}_7)$; $B = \{7, 9, 14, 15, 18\}$ and $\mathcal{Y} = C(B, \mathbb{Z}_{21})$. The pair $(\mathcal{X}, \mathcal{Y})$ is a cqs-pair, as illustrated in Figure 3. Also, both $(\mathcal{X}, \mathcal{X})$

and $(\mathcal{Y}, \mathcal{Y})$ are cqs-pairs.

Example 2: Let $A = \{3, 5, 6\}$ and $B = \{7, 9, 14, 15, 18\}$. The pair $(\mathcal{X}, \mathcal{Y})$ is *not* a cqs-pair, although $\mathcal{X}$ and $\mathcal{Y}$ are cqs, respectively, as illustrated in Figure 4.

3.3 Grid Quorum System Pair

Now, we introduce another design, *grid quorum system pair* (gqs-pair) of heterogenous quorum systems.

Definition 10: **Grid quorum system pair (gqs-pair).** If a quorum in a grid quorum system contains one row and one column of elements, the *gqs-pair* is a pair consisting of any two qps.

Lemma 2: The *gqs-pair* satisfies the heterogeneous rotation closure property and can be a solution to the h-QPS problem.

Proof: It has been proven in [8] that the grid quorum system satisfies the rotation closure property. Thus, we only need to prove that for two grid quorum systems $\mathcal{X}$ over $\{0, \cdots, n-1\}$ and $\mathcal{Y}$ over $\{0, \cdots, m-1\}$ ($n \le m$, $p = \lceil \frac{m}{n} \rceil$), $\forall G^p \in \mathcal{X}^p, H \in \mathcal{Y}$, $i \in \{0, \cdots M-1\}$, there is $G^p \cap (H+i) \neq \emptyset$ or $(G+i)^p \cap H \neq \emptyset$.

Consider a quorum G from $\mathcal{X}$ which contains all elements in the column c, namely c,$c+\sqrt{n}$,$\cdots$,$c+\sqrt{n}(\sqrt{n}-1)$, where $0 \le c < \sqrt{n}$. Then, a quorum $(G+i)^p$ from the $p-extension$ of $\mathcal{X}$ contains elements, which has the largest distance of $\sqrt{n}$ between any two consecutive elements. $(G+i)^p$ must have an intersection with H since H contains a full row which has $\sqrt{m}$ ($\ge \sqrt{n}$) consecutive integers. Thus, the *grid quorum system pair* satisfies the heterogeneous rotation closure property and can be a solution to the h-QPS problem. □

An illustration on the heterogeneous rotation closure property of the gqs-pair is given in Figure 5. There are two grid quorum systems in Figure 5, A with the size of 4×4 and B with the size of 6×6. Without considering clock drift, we can see that A's quorums will intersect with B's quorums in the 10^{th}, 3^{rd}, 7^{th}, and the 12^{th} slot.

4 Construction Scheme for CQS-Pair

It is straightforward to construct a *gqs-pair* since it contains two arbitrary grid quorum systems. Therefore, we only discuss the construction of *cqs-pair*, which is non-trivial.

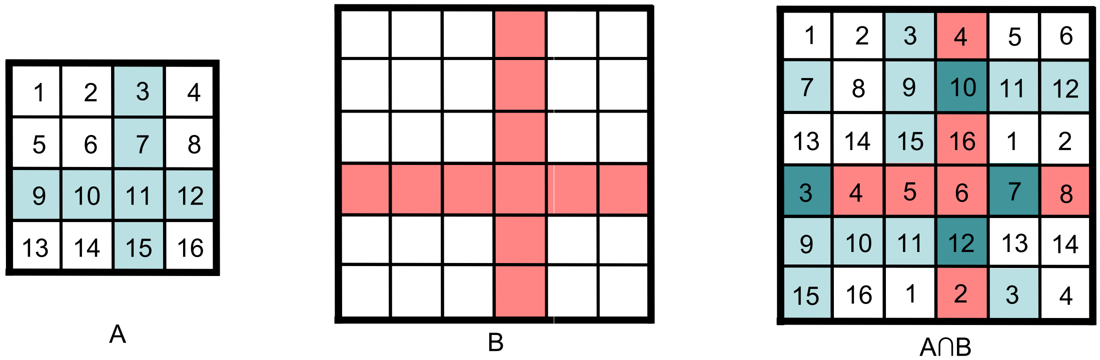


Fig. 5. An example grid quorum system pair and its rotation closure property: grid quorum system A has a grid 4×4 and B has a grid 6×6. A quorum from A and a quorum from B overlap at 3 slots with B's cycle length.

In previous works, exhaustive search has been used to find an optimal solution for the cyclic quorum design [14]. This is not practical when cycle length (n) is large. In this section, we first present a fast construction scheme for cyclic quorum systems and then apply it to the design of a cqs-pair.

4.1 Multiplier Theorem

We introduce a few concepts to facilitate our presentation.

Definition 11: Let D be a (v, k, λ)-difference set in an Abelian group $(G, +)$ of order v. For an integer m, we define

$$mD = \{mx : x \in D\}$$

Then, m is called a multiplier of D if $mD = D + g$ for some $g \in G$. Also, we say that D is fixed by the multiplier m if $mD = D$.

Example: The set $D = \{0, 1, 5, 11\}$ is a $(13, 4, 1)$-difference set in $(\mathbb{Z}_{13}, +)$. Then, $3D = \{0, 2, 3, 7\} = D + 2$, and hence 3 is a multiplier of D.

Definition 12: **Automorphism.** Suppose $(X, \mathcal{A})$ is a design. A transform function α is an automorphism of $(X, \mathcal{A})$ if

$$[\{\alpha(x) : x \in A\} : A \in \mathcal{A}] = \mathcal{A}$$

.

Definition 13: **Disjoint cycle representation:** The disjoint cycle representation of a set X is a group of disjoint cycles in which each cycle has the form $(x\ \alpha(x)\ \alpha(\alpha(x)) \cdots)$ for some $x \in X$.

Suppose the automorphism is $x \mapsto 2x\ mod\ 7$. The disjoint cycle representation of $\mathbb{Z}_7$ is as follows: (0) (1 2 4) (3 6 5).

Theorem 6: **(Multiplier Theorem).** Suppose there exists a (v, k, λ)-difference set D. Suppose also that the following four conditions are satisfied:

1) p is *prime*;
2) $gcd(p, v) = 1$;
3) $k - \lambda \equiv 0\ (mod\ p)$; and
4) $p > \lambda$.

Then p is a multiplier of D.

Theorem 7: Suppose that m is a multiplier of a (v, k, λ)-difference set D in an Abelian group $(G, +)$ of order v. Then there exists a translate of D that is fixed by the multiplier m.

The proofs of Theorem 6 and Theorem 7 are given in [15]. According to the Theorem of Singer Difference Set, there must exist a $(q^2 + q + 1, q + 1, 1)$-difference set when q is a prime power. Thus, we only consider the $(q^2 + q + 1, q + 1, 1)$-design, where q is a prime power, in our construction scheme.

In the following, we first give an example to illustrate the application of the Multiplier Theorem for the construction of difference sets.

Example. We use the Multiplier Theorem to find a $(21, 5, 1)$-difference set. Observe that $p = 2$ satisfies the conditions of Theorem 6. Hence 2 is a multiplier of any such difference set. By Theorem 7, we can assume that there exists a $(21, 5, 1)$-difference set in $(\mathbb{Z}_{21}, +)$ that is fixed by the multiplier 2. Therefore, the *automorphism* is $\alpha(x) \mapsto 2x\ mod\ 21$. Thus, we obtain the disjoint cycle representation of the permutation defined by $\alpha(x)$ of $\mathbb{Z}_{21}$ as follows:

$$(0)\quad (1\ 2\ 4\ 8\ 16\ 11)\quad (3\ 6\ 12)\quad (5\ 10\ 20\ 19\ 17\ 13)\quad (7\ 14)\quad (9\ 18\ 15)$$

The difference set we are looking for must consist of a union of cycles in the list above. Since the difference set has a size five, it must be the union of one cycle of length two and one cycle of length three. There are two possible ways to do this, both of which happen to produce the difference set:

$$(3\ 6\ 7\ 12\ 14)\ and\ \ (7\ 9\ 14\ 15\ 18)$$

With the Multiplier Theorem, we can quickly construct $(q^2+q+1, q+1, 1)$-difference sets, where q is a prime power. This mechanism significantly improves the speed of finding the optimal solution relative to the exhaustive method in [14].

After obtaining the difference sets, we use Theorem 4 to build a *cqs-pair*.

4.2 Verification Matrix

Armed with Theorem 4, we adopt a verification matrix to check the non-empty intersection property of two heterogeneous difference sets.

Suppose that $A = \{a_1, a_2, \cdots, a_k\}$ in $(\mathbb{Z}_N, +)$ and $B = \{b_1, b_2, \cdots, b_l\}$ in $(\mathbb{Z}_M, +)$ where $N \leq M$ and $p = \lceil \frac{M}{N} \rceil$. The verification matrix is defined as a $pk \times l$ matrix $\mathcal{M}_{l\times pk}$ whose element $m_{i,j}$ is equal to $(b_i - a_j^p)$ mod M, where $a_j^p \in A^p$, as shown below:

$$\mathcal{M}_{l\times pk} = \begin{bmatrix} b_1 - a_1^p & \cdots & b_1 - a_{pk}^p \\ \vdots & b_i - a_j^p & \cdots \\ b_l - a_1^p & \cdots & b_l - a_{pk}^p \end{bmatrix}$$

We can check whether (A, B) is a *heterogeneous cyclic coterie pair* by checking whether $\mathcal{M}_{l\times pk}$ contains all elements from 0 to $M-1$ or not. If the checking result is true, it means that:

$$\forall d \in \{0, \cdots, M-1\},\ \exists b_i \in B\ and\ a_j^p \in A^p,\ b_i - a_j^p \equiv\ d\ (mod\ M).$$

This indicates that (A, B) is a *heterogeneous cyclic coterie* based on Theorem 4. Otherwise, (A, B) is *not* a *heterogeneous cyclic coterie*. (An example of the verification matrix will be shown in Section 4.4.)

If two quorum systems $C(A_N, \mathbb{Z}_N))$ and $C(B_M, \mathbb{Z}_M))$ are cyclic quorum systems, respectively, we can verify whether the pair $[C(A_N, \mathbb{Z}_N)), C(B_M, \mathbb{Z}_M)]$ is a cqs-pair by checking whether or not the *verification matrix* constructed from A and B contains all elements from 0 to $M-1$.

4.3 Construction Algorithm

In our proposed algorithm for constructing a cqs-pair, we only consider cyclic quorum systems with a cycle length of $(q^2+q+1, q+1, 1)$, where q is a prime power. This is because, we can prove that when q is a prime power, there must exist a $(q^2+q+1, q+1, 1)$-difference set in $(\mathbb{Z}_{q^2+q+1,q+1,1}, +)$ [15].

We describe our algorithm for constructing a cqs-pair at a high-level of abstraction in Algorithm 1. The input of the algorithm is two numbers n and m, which satisfy $n = q^2+q+1$ and $m = r^2+r+1$ and where q and r are prime powers.

By employing our construction algorithm, for two different integers n and m that satisfy $n = q^2+q+1$ and $m = r^2+r+1$ (q and r being two prime powers, $n \leq m$), it will take $O(n^2)$ and $O(m^2)$ time to build the *disjoint cycle representations*, respectively. After that, the algorithm will check $u \times v \times l \times pk \approx uvm^{3/2}n^{-1/2}$ elements, since $l \approx \sqrt{m}$ and $k \approx \sqrt{n}$, where u and v are numbers of $(n, k, 1)$-difference sets and $(m, l, 1)$-difference sets, respectively. Thus, the total time complexity is $O(uvm^{3/2}n^{-1/2} + m^2)$ for constructing a cqs-pair with input parameters n and m ($n \leq m$).

4.4 A Complete Application Example

As an example, consider $n = 7$ and $m = 21$. By the Multiplier Theorem, we can easily obtain two $(7, 3, 1)$-difference sets $\{1, 2, 4\}$ and $\{3, 6, 5\}$ in $(\mathbb{Z}_7, +)$. Similarly, there are two $(21, 5, 1)$-difference sets, $\{3, 6, 7, 12, 14\}$ and $\{7, 9, 14, 15, 18\}$ in $(\mathbb{Z}_{21}, +)$. Let $A_7 = \{1, 2, 4\}$, $B_7 = \{3, 6, 5\}$, $A_{21} = \{3, 6, 7, 12, 14\}$, and $B_{21} = \{7, 9, 14, 15, 18\}$.

Totally, there are four pairs of $(7, 3, 1)$-difference sets and $(21, 5, 1)$-difference sets. First, we check the pair $(C(A_7, \mathbb{Z}_7), C(A_{21}, \mathbb{Z}_{21}))$. The constructed verification matrix is as follows:

$$\begin{bmatrix} 2 & 1 & 20 & 16 & 15 & 13 & 9 & 8 & 6 \\ 5 & 4 & 2 & 19 & 18 & 16 & 12 & 11 & 9 \\ 6 & 5 & 3 & 20 & 19 & 17 & 13 & 12 & 10 \\ 11 & 10 & 8 & 4 & 3 & 1 & 18 & 17 & 15 \\ 13 & 12 & 10 & 6 & 5 & 3 & 20 & 19 & 17 \end{bmatrix}$$

We find that 7 and 14 are not in the matrix. Thus, the pair $(C(A_7, \mathbb{Z}_7), C(A_{21}, \mathbb{Z}_{21}))$ is *not* a cqs-pair. Similarly, we can check that $(C(B_7, \mathbb{Z}_7), C(B_{21}, \mathbb{Z}_{21}))$ is *not* a cqs-pair.

Algorithm 1 Constructing cqs-pair

Require: $n = q^2 + q + 1$ and $m = r^2 + r + 1$, q, r are prime powers

$n \leftarrow q^2 + q + 1$

$m \leftarrow r^2 + r + 1$

$p_a \leftarrow$ Multiplier of $(n, k, 1)$-difference set

$p_b \leftarrow$ Multiplier of $(m, l, 1)$-difference set

$\alpha_n(x) \leftarrow p_a \cdot x \ (mod\ n)$

$\alpha_m(x) \leftarrow p_b \cdot x \ (mod\ m)$

Construct the disjoint cycle representation for $\mathbb{Z}_n$ with $\alpha_n(x)$

Construct the disjoint cycle representation for $\mathbb{Z}_m$ with $\alpha_m(x)$

$u \leftarrow$#Num of unions of disjoint cycle being $(n, k, 1)$-difference set

$\{A_1, \cdots, A_u\} \leftarrow$ the set of unions of disjoint cycles being $(n, k, 1)$-difference set

$v \leftarrow$#Num of unions of disjoint cycle being $(m, l, 1)$-difference set

$\{B_1, \cdots, B_v\} \leftarrow$ the set of unions of disjoint cycles being $(m, l, 1)$-difference set

for i = 1 to u **do**

  for j = 1 to v **do**

    $M_{i,j} \leftarrow$ verification matrix (A_i, B_j)

    $\mathcal{X}_i \leftarrow C(A_i, \mathbb{Z}_n)$

    $\mathcal{Y}_j \leftarrow C(B_j, \mathbb{Z}_m)$

    if $M_{i,j}$ contains all elements from 0 to $m - 1$ **then**

      $(\mathcal{X}_i, \mathcal{Y}_j)$ is a cqs-pair

    else

      $(\mathcal{X}_i, \mathcal{Y}_j)$ is not a cqs-pair

    end if

  end for

end for

But $(C(A_7, \mathbb{Z}_7), C(B_{21}, \mathbb{Z}_{21}))$ and $(C(B_7, \mathbb{Z}_7), C(A_{21}, \mathbb{Z}_{21}))$ are cqs-pairs, respectively.

The cqs-pair can be applied to WSNs for dynamically changing the quorum system (i.e., the cycle length) at each node, in order to meet end-to-end delay constraints and without loosing network connectivity. Table 1 shows the available pairs for cycle lengthes ≤ 21.

TABLE 1

cqs-pair (for $n, m \leq 21$)

cycle length	7 $A_7 = \{1, 2, 4\}$ $B_7 = \{3, 5, 6\}$	13 $A_{13} = \{0, 1, 3, 9\}$ $B_{13} = \{0, 2, 6, 5\}$ $C_{13} = \{0, 4, 12, 10\}$ $D_{13} = \{0, 7, 8, 11\}$	21 $A_{21} = \{3, 6, 7, 12, 14\}$ $B_{21} = \{7, 9, 14, 15, 18\}$
7	$(C(A_7, \mathbb{Z}_7), C(A_7, \mathbb{Z}_7))$ $(C(B_7, \mathbb{Z}_7), C(B_7, \mathbb{Z}_7))$	$(C(A_7, \mathbb{Z}_7), C(A_{13}, \mathbb{Z}_{13}))$ $(C(A_7, \mathbb{Z}_7), C(B_{13}, \mathbb{Z}_{13}))$ $(C(B_7, \mathbb{Z}_7), C(C_{13}, \mathbb{Z}_{13}))$ $(C(B_7, \mathbb{Z}_7), C(D_{13}, \mathbb{Z}_{13}))$	$(C(A_7, \mathbb{Z}_7), C(B_{21}, \mathbb{Z}_{21}))$ $(C(B_7, \mathbb{Z}_7), C(A_{21}, \mathbb{Z}_{21}))$
13		$(C(A_{13}, \mathbb{Z}_{13}), C(A_{13}, \mathbb{Z}_{13}))$ $(C(B_{13}, \mathbb{Z}_{13}), C(B_{13}, \mathbb{Z}_{13}))$ $(C(C_{13}, \mathbb{Z}_{13}), C(C_{13}, \mathbb{Z}_{13}))$ $(C(D_{13}, \mathbb{Z}_{13}), C(D_{13}, \mathbb{Z}_{13}))$	$(C(B_{13}, \mathbb{Z}_{13}), C(A_{21}, \mathbb{Z}_{21}))$

5 PERFORMANCE ANALYSIS

5.1 Average Discovery Delay

We denote the *average discovery delay* as the time between data arrival and discovery of the adjacent receiver (i.e., the simultaneous wake-up of two nodes). Note that this metric does not include the time for delivering a message.

Suppose that the length of one time slot is 1.

Theorem 8: The average discovery delay between two nodes that wakeup based on quorums from the same *cyclic quorum system* adopting the $(n, k, 1)$-difference set is:

$$E(Delay) = \frac{n-1}{2}.$$

Proof: Let the k elements in $(n, k, 1)$-difference set be denoted as a_1, a_2, $\cdots$, a_k. If a node has a message that arrived during the i^{th} time slot, the expected delay (from data arrival to the simultaneous wake-up of two nodes) is $\frac{1}{k}(a_1 - i)\ mod\ n + \frac{1}{k}(a_2 - i)\ mod\ n + \cdots + \frac{1}{k}(a_k - i)\ mod\ n$. If a message has arrived, the probability of the message arriving during the i^{th} time slot is $\frac{1}{n}$. Thus, the expected delay (average delay) is:

$$\begin{aligned} E(Delay) = \frac{1}{n}[&\frac{1}{k}(a_1 - 1)\ mod\ n + \frac{1}{k}(a_2 - 1)\ mod\ n + \cdots + \frac{1}{k}(a_k - 1)\ mod\ n \\ &+ \frac{1}{k}(a_1 - 2)\ mod\ n + \frac{1}{k}(a_2 - 2)\ mod\ n + \cdots + \frac{1}{k}(a_k - 2)\ mod\ n \\ &+ \quad \cdots\cdots \\ &+ \frac{1}{k}(a_1 - n)\ mod\ n + \frac{1}{k}(a_2 - n)\ mod\ n + \cdots + \frac{1}{k}(a_k - n)\ mod\ n] \\ = \frac{1}{nk} \cdot (k \cdot 1 + k \cdot 2 + \cdots + k \cdot n - 1) = \frac{n-1}{2} \end{aligned}$$

□

Corollary 2: The average discovery delay between two nodes that wakeup based on a cqs-pair in which two *cyclic quorum systems* have cycle lengthes n and m ($n \leq m$), respectively, is:

$$\frac{n-1}{2} < E(Delay) < \frac{m-1}{2}.$$

Corollary 2 indicates that the average discovery delay between two nodes that adopt a cqs-pair is bounded. When the average one-hop delay constraint is D, we must meet$\frac{m-1}{2} \leq D$.

Theorem 9: The average discovery delay between two nodes that wakeup based on quorums from the same *grid quorum system* with a grid of $\sqrt{N} \times \sqrt{N}$ elements is:

$$E(Delay) = \frac{(N-1)(\sqrt{N}+1)}{3\sqrt{N}}.$$

The detail proof is presented in Appendix A.

Corollary 3: The average discovery delay between two nodes that wakeup based on a gqs-pair in which two grid quorum systems adopt a grid of $\sqrt{n} \times \sqrt{n}$ and a grid of $\sqrt{m} \times \sqrt{m}$, respectively, is:

$$\frac{(n-1)(\sqrt{n}+1)}{3\sqrt{n}} < E(Delay) < \frac{(m-1)(\sqrt{m}+1)}{3\sqrt{m}}$$

.

The proof for Corollary 3 is not difficult so that we omit it.

5.2 Optimal Quorum Ratio and Energy Conservation

We define **quorum ratio**, denoted ϕ, as the proportion of the beacon intervals that is required to be awake in each cycle. Correspondingly, the energy conservation ratio of a node is $1-\phi$.

As claimed in [14], Cqs is an optimal design where the optimality means given a schedule with cycle length n, cqs design has the minimum quorum size k to make sure there is always not-empty intersection between this schedule and any rotations of the schedule. This is not difficult to explain. As discussed in Section 4, a cqs design is based on $(q^2+q+1, q+1, 1)$-difference set which means given a qualified set $A = \{a_1, ..., a_k\} (\mod N)$, there is *exactly* one ordered pairs (a_i, a_j), $a_i, a_j \in A$ such that $a_i - a_j \equiv d \ (modN)$ for every $d \neq 0$. Any reduction of elements in A will lead that $a_i - a_j \equiv d \ (modN)$ for every $d \neq 0$ cannot be met. Thus, given a cycle length n where $n = q^2+q+1$ and q is a prime power, for a cqs schedule which is based on a $(n, k, 1)$-difference set, its quorum ratio is the minimum one among all possible designs.

We restrain to the case of $n = q^2+q+1$ is because the authors in [15] have proved that a $(q^2+q+1, q+1, 1)$-difference set exists and that the optimal quorum ratio is $\phi = \frac{q+1}{q^2+q+1}$ for such a cyclic quorum system.

For a cqs-pair, the *quorum ratios* for systems in the pair which are based on (N, k, M, l)-difference pair are:

$$\phi_1 = \frac{\sqrt{4N-3}+1}{2N} \ and \ \phi_2 = \frac{\sqrt{4M-3}+1}{2M}$$

respectively, where $n = q^2+q+1$ and q is a prime power. Since cqs has optimal quorums ratio, the two systems in the cqs-pair have optimal quorum ratio respectively.

For a grid quorum system with $\sqrt{n} \times \sqrt{n}$ grid, the *quorum ratio* is:

$$\phi = \frac{2\sqrt{n}-1}{n}$$

and the corresponding energy saving ratio is:

$$1 - \phi = 1 - \frac{2\sqrt{n} - 1}{n}.$$

Recalling the average discovery delay in Section 5.1, we can observe that there is a trade-off between the average delay and the quorum ratio. Larger the cycle length of a quorum system, larger is the discovery delay, but smaller is the quorum ratio.

6 IMPLEMENTATIONS OF CQS-PAIR AND QQS-PAIR

We implemented heterogenous quorum systems in a WSN platform comprised of Telosb motes [19]. There are three key issues in converting the Cqs-pair and Qqs-pair concepts into practical implementations. The first key issue is to ensure that two nodes can discover each other in the presence of clock drift. The second one is that a node should keep awake if there is pending data for receiving or for transmitting. The third issue is how to support multicast or broadcast.

6.1 Beacon Messages

Previous work on the implementation of QPS protocol over IEEE 802.11 adopts the concept of ATIM (Ad hoc Traffic Indication Map) windows [12], in which a node can optionally enter the sleep mode if it receives no ATIM frame in an ATIM window.

In our implementation, we do not use the notion of ATIM windows. We define the time interval that a node is scheduled to be awake as an *active slot*, and the time interval that the node is scheduled to sleep as a *silent slot*. In an *active slot*, a node has to transmit its own *beacon message* to inform its neighbors about its wakeup status, and listen to *beacons* from other nodes for which it may have buffered packets that are waiting for transmission.

In our scheme, to ensure the correctness of the protocol, a node remains awake throughout its entire active slot. It may be possible for nodes to be only partially awake during their active slots – such optimizations can be considered in future works. In a *silent slot*, a node will shut down its radio.

The beacon message contains three fields:{*indic, node_id, time_stamp*}. The *indic* field can have only two types of value: indic=0, which indicates that the message

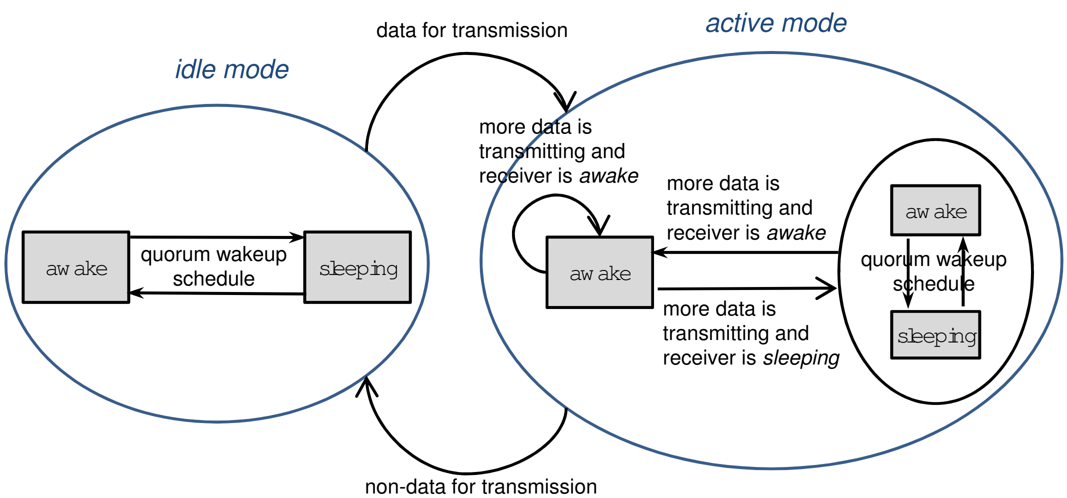


Fig. 6. Power Management at the Transmitter Side: Communication Schedule and Wakeup schedule

is a beacon message, and indic = 1, which indicates that the message is data. The *node_id* field is used to distinguish among different nodes. The *time_stamp* field is used to identify whether or not two beacon messages are identical.

Collision is inevitable in some case if all nodes send beacons simultaneously at the beginning of an interval. The collisions in the proposed protocol can be detected if a node does not hear any beacon messages in a cycle (i.e., 7 consecutive slots for (7,3,1)-design). To avoid collisions, each beacon can be led by a random backoff, i.e., k +1/2 slots where $0 < k < n$ (n is the cycle length).

6.2 Power Management

The goal of power management is to facilitate effective communication while saving as much energy as possible. In our power management scheme, a node determines its desirable *communication schedule*, i.e., when it should go to sleep or wake up. The relationship between the wakeup schedule and the communication schedule devised by a power management policy for a sender is illustrated in Figure 6.

At the MAC-layer, we propose a reservation mechanism for communication on top of the proposed quorum-based heterogenous wakeup scheduling scheme (cqs-pair or gqs-pair). Each node has two states, *idle mode* and *active mode*. In the *idle mode*, a node will follow its wakeup schedule to wake-up or to sleep. We also call this mode as power saving mode. Once there is data for receiving or for transmitting, the node will enter into the *active mode* as shown in Figure 6.

In the active mode, a sender maintains a table of timers for all its neighbors. The timers are triggered once the sender receives beacon messages from the neighbors. The initial value of each timer is one time slot. The sender will also record its own wakeup schedule via a timer. If both the sender and the receiver is in an *active slot*, then they can communicate. If the sender enters into a *silent slot* but there are more packets for transmission and the receiver is still in an *active slot*, then the sender will keep awake in its next slot. If there are more packets for transmission, but the receiver will enter a *silent slot*, then the sender will send a *keep-awake* message to the receiver at the end of the transmission of the current packet. The receiver that is being requested to stay awake will then send back an acknowledgment, indicating its willingness to remain awake in its next slot.

The power management scheme at the receiver side is simpler than that at the sender side. In active mode, if there is no *keep-awake* message, the receiver will continue communication until the end of its current slot interval; otherwise, it will keep awake in its next slot.

6.3 Multicast and Broadcast

Quorum-based asynchronous wakeup protocols cannot guarantee that more than one receiver is awake when a sender wishes to multicast or broadcast.

There are multiple ways to support multicast and broadcast. One method is to adopt relatively prime frequencies among all nodes for wakeup scheduling. This method does not need synchronization between the sender and all the receivers. The sender only needs to notify m receivers to wake-up via the pairwise relative primes p_1, p_2,..., p_m, respectively. Then each receiver generates its new wakeup frequency based on the received frequency. Through Chinese Remainder Theorem [20], [21], it can be proven that the m receivers must wakeup simultaneously at the I^{th} beacon interval ($0 \leq I \leq p_1 \times p_2 ... \times p_m$). The sender can then transmit a multicast/broadcast message at this interval.

Another way to multicast/broadcast is by using synchronization over quorum-based wakeup schedules. The sender can book-keep all neighbors' schedules, and synchronize their schedules so that neighboring nodes wake up in the same set of slots with the use of Lamport's clock synchronization algorithm [22]. When all nodes are awake simultaneously, the senders then send a message to multiple neighbors simultaneously.

The first mechanism has the advantage that no synchronization is needed between a sender and multiple receivers. But it cannot bound the average delay. The second approach can bound the average delay but it needs book-keeping and synchronization over asynchronous wakeup schedules.

For multicast/broadcast, we set a threshold L. If the number of multicast packets exceed the threshold L, the sender will send a Multicast-Notify to all neighbor receivers, requesting them to stay awake. Otherwise the sender will send the multicast data to each receiver one by one, by unicasting. The value of the threshold L depends on the configuration of time slot lengthes and packet lengthes.

To reduce the time of waiting before actual transmission, the Multicast-Notify message contains a field to notify all receivers on how long they should wait. The value of this field is the time between when the message is sent and when all receivers are awake.

7 Performance Evaluation

We evaluated the performance of our schemes through numerical studies and by real implementation over a WSN platform of Telosb motes [23]. In our experiments, a set of nodes was deployed. The radio range was configured to 10 meters for each node. There was one sink node which acted as the base station. The sink node communicated with a laptop computer (through a wireless USB serial port), which recorded performance measurements. The detailed radio parameters such as data rates default to the data sheet of TelosB [23].

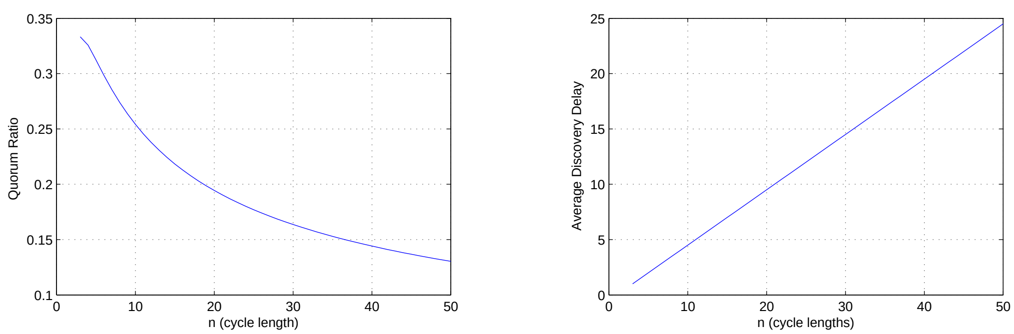
We built our wakeup scheduling schemes over the basic CSMA/CA protocol. We used MintRoute [24] as the routing protocol for end-to-end transmission. Traffic load was generated by a Poisson distribution [25] with rates in the range 10-100 packets/sec. Each packet only contains one Active Message whose size is defined in TinyOS 2.0 [19].

Two important performance metrics were measured in our experimental study: (1) quorum ratio and energy saving ratio; and (2) average neighbor discovery delay.

7.1 Performance Trade-off

We first evaluated the quorum ratio and average neighbor discovery delay by numerical analysis.

The performance of a *cyclic quorum system* is shown in Figure 7. There is a trade-off between quorum ratio and average discovery delay since they have reverse changing trends under increasing cycle lengthes.



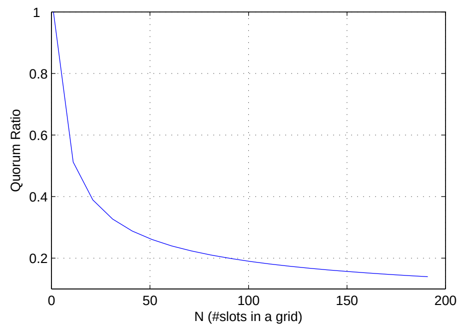
(a) Quorum Ratio (b) Average Discovery Delay

Fig. 7. Quorum Ratio and Average Discovery Delay for Cyclic Quorum Systems (Numerical Results)

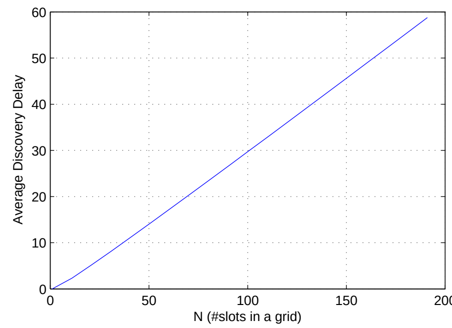
The performance of a *grid quorum system* is shown in Figure 8. The grid quorum system's quorum ratio is bigger than that of the cyclic quorum system with identical cycle length, but the average discovery delay is approximately $2/3$ of that of the corresponding cyclic quorum system.

7.2 Impact of Heterogeneity

For heterogenous quorum-based wakeup scheduling, like cqs-pair or gqs-pair, the cycle lengthes of two quorum systems are different. We evaluated the impact of



(a) Quorum Ratio



(b) Average Discovery Delay

Fig. 8. Quorum Ratio and Average Discovery Delay for Grid Quorum Systems (Numerical Results)

heterogeneity of two different cycle lengthes on the average discovery delay between two neighbor nodes.

For this set of experiment, we focused on the cqs-pair since it is an optimal design. We fixed the traffic load between two nodes at $10\ packets/sec$ in the experiment.

We varied the cycle lengthes of two neighbor nodes in two (different) quorum systems in a cqs-pair. The cycle length of one node was varied from 7 to 58. The neighbor node, which used a counterpart cyclic quorum system, had its cycle length varied from 7 to 21. We do not show the impact on the energy consumption ratio when the cycle lengthes of cqs-pair were varied, since the energy consumption ratio of a node is mainly dependent upon its own cycle length, which has already been evaluated in Section 7.1.

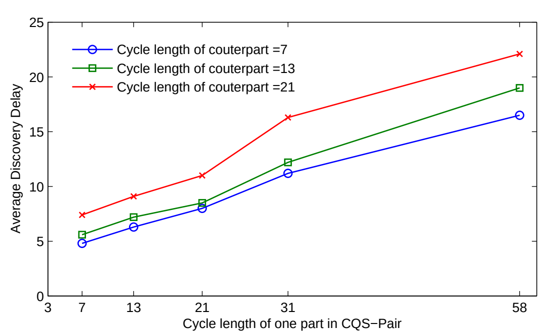


Fig. 9. Impact of Heterogeneity

Figure 9 shows how the average discovery delay changes with different cqs-pairs.

When one part in a pair keeps its cycle length constant and the counterpart increases its cycle length, the average discovery delay between them almost increases linearly.

7.3 Impact of traffic load

In this section, we report our experiments on measuring the impact of traffic load on the performance of cqs-pair and comparisons with the basic CSMA/CA MAC protocol. We varied the traffic load from 10 packets/sec to 100 packets/sec in the experiments. The cycle lengthes of cyclic quorum systems in the cqs-pair were chosen among 7, 13 and 21.

Figure 10 shows how the energy consumption ratios of nodes adopting different cyclic quorum systems increase under increasing traffic load between two neighboring nodes. The rationale is that higher traffic loads will cause a node to increase its wakeup time ratio in our implementation. When the traffic load is low, the impact is insignificant because a node will maintain its current wakeup schedule, without adding more wakeup slots into its communication schedule for transmitting or for receiving packets.

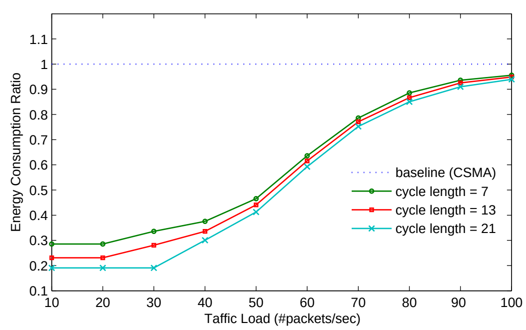


Fig. 10. Impact of Traffic Load: Energy Consumption Ratio

Figure 11 shows that the average discovery delay decreases with the increasing of traffic load. This is because, the communication schedule of a node will have more active slots, when compared with its quorum-based wakeup schedule during high traffic load. With more slots staying awake, the average discovery delay between two neighboring nodes will be significantly reduced.

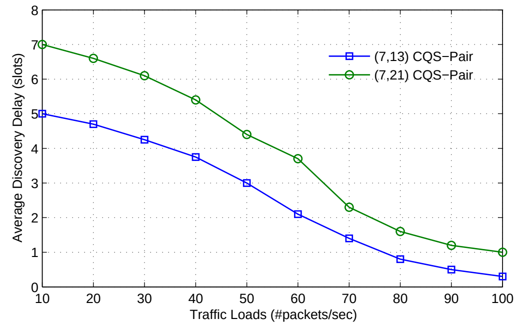


Fig. 11. Impact of Traffic Load: average discovery delay

8 Past and Related Works

Wakeup mechanisms for wireless sensor networks can be broadly classified into three categories. We summarize and overview them as follows.

On-Demand Wakeup [4], [26]. The implementation of on-demand wakeup schemes typically requires two different channels: a data channel and a wakeup channel for awaking nodes as and when needed. This allows for the immediate transmission of a signal on the wakeup channel if a packet transmission is in progress on the other channel, thus reducing the wakeup latency. The drawback is the additional cost for the second radio. The STEM (Sparse Topology and Energy Management) work [4] uses two different radios for wakeup signals and data packet transmissions, respectively. The key idea is that a node remains awake until it has not received any message destined for it for a certain period of time. STEM uses separate control and data channels, and hence the contention among control and data messages is alleviated. The energy efficiency of STEM is dependent on that of the control channel.

Scheduled Rendezvous Schemes [6], [27], [28]. These schemes require that all neighboring nodes wake up at the same time. Different scheduled rendezvous protocols differ in the way network nodes sleep and wakeup during their lifetimes. The simplest way is by using a Fully synchronized pattern, like that in the S-MAC protocol [6]. In this case, all nodes in the network wakeup at the same time according to a periodic pattern. A further improvement can be achieved by allowing nodes to switch off their radio when no activity is detected for at least a timeout value, like that in the T-MAC protocol [27]. The disadvantages include the complexity and the overhead for synchronization.

Asynchronous wakeup [9], [29]. This was first introduced in [12] in the context of IEEE 802.11 ad hoc networks. The authors proposed three different asynchronous sleep/wakeup schemes that require some modifications to the basic IEEE 802.11 Power Saving Mode (PSM). More recently, Zheng *et al.* [9] took a systematic approach toward designing asynchronous wakeup mechanisms for ad hoc networks (which is also applicable for WSNs). They formulate the problem of generating wakeup schedules as a block design problem and derive theoretical bounds under different communication models. The basic idea is that each node is associated with a Wakeup Schedule Function (WSF) that is used to generate a wakeup schedule. For two neighboring nodes to communicate, their wakeup schedules must overlap regardless of their clock difference.

For the quorum-based asynchronous wakeup design, Luk and Wong [14] designed a cyclic quorum system using difference sets. However, they perform an exhaustive search to obtain a solution for each cycle length N, which is impractical when N is large.

Asymmetric quorum design. In the clustered environment of sensor networks, it is not always necessary to guarantee all-pair neighbor discovery. The Asymmetric Cyclic Quorum (ACQ) system [30] was proposed to guarantee neighbor discovery between each member node and the clusterhead, and between clusterheads in a network. The authors also presented a construction scheme which assembles the ACQ system in $O(1)$ time to avoid exhaustive searching. ACQ is a generalization of the cyclic quorum system. The scheme is configurable for different networks to achieve different distribution of energy consumption between member nodes and the clusterhead.

However, it remains a challenging issue to efficiently design an asymmetric quorum system given an arbitrary value of n. One previous study [9] shows that the problem of finding an optimal asymmetric block design can be reduced to the minimum vertex cover problem, which is NP-complete. However, the ACQ [30] construction is not optimal in that the quorum ratio for symmetric-quorum is $\phi = \lceil \frac{n+1}{2} \rceil$ and the quorum ratio for asymmetric-quorum is $\phi' = \lceil \sqrt{\frac{n+1}{2}} \rceil$. Another drawback is that it cannot be a solution to the h-QPS problem since the two asymmetric-quorums cannot guarantee the intersection property.

Transport layer approach. Wang *et al.* [31] applied quorum-based wakeup scheduling at the transport layer which can cooperate with any MAC-layer protocol, allowing for the reuse of well-understood MAC protocols. The proposed technique saves idle energy by relaxing the requirement for end-to-end connectivity during data transmission and allowing the network to be disconnected intermittently via scheduled sleeping. The limitation of this work is that each node adopts the same grid quorum system as its wakeup schedule, and the quorum ratio is not optimal when compared with that of cyclic quorum systems.

9 Conclusions

In this paper, we presented a theoretical approach for heterogeneous asynchronous wakeup scheduling in wireless sensor networks. We first defined the h-QPS problem—i.e., given two cycle lengthes n and m ($n < m$), how to design a pair of heterogeneous quorum systems to guarantee that two adjacent nodes that select heterogenous quorums from the pair as their wakeup schedules can hear each other at least once in every m consecutive time slots. We proposed two designs for heterogeneous asynchronous wakeup scheduling: the cyclic quorum system pair (cqs-pair) and the grid quorum system pair (gqs-pair). We also presented a fast construction scheme to assemble a cqs-pair. In our construction scheme, we first quickly construct an $(n, k, 1)$-difference set and an $(m, l, 1)$-difference set. Based on two difference sets A in $(\mathbb{Z}_n, +)$ and B in $(\mathbb{Z}_m, +)$, we can construct a cqs-pair $(C(A, \mathbb{Z}_n), C(B, \mathbb{Z}_m))$ when A and B can form a (n, k, m, l)-difference pair.

The performance of a cqs-pair and a gqs-pair were analyzed in terms of average delay, quorum ratio, and energy saving ratio. We show that the average delay between two nodes that wakeup via heterogenous quorums from a cqs-pair is bounded between $\frac{n-1}{2}$ and $\frac{m-1}{2}$, and the quorum ratios of the two quorum systems in the pair are optimal, respectively, given their cycle lengthes n and m. For a gqs-pair with $\sqrt{n} \times \sqrt{n}$ grid and $\sqrt{m} \times \sqrt{m}$ grid, the average discovery delay is bounded within

$\frac{(n-1)(\sqrt{n}+1)}{3\sqrt{n}} < E(Delay) < \frac{(m-1)(\sqrt{m}+1)}{3\sqrt{m}}$, while the quorum ratios are $\frac{2\sqrt{n}-1}{n}$ and $\frac{2\sqrt{m}-1}{m}$, respectively.

There are several directions for future work. One direction is to further improve the energy saving ratios. Another direction is to extend the cqs-pair to cqs m-pair in which m cyclic quorum systems have the heterogenous rotation closure property with one another.

Appendix

Proof of Theorem 9

Proof: Let $L = \sqrt{N}$. Suppose there are two grid quorum systems $\mathcal{Q}_a$ and $\mathcal{Q}_b$ that adopt $\sqrt{N} \times \sqrt{N}$ grid.

Given a quorum from $\mathcal{Q}_a$ (i.e., i_a^{th} row plus j_a^{th} column), and a quorum from $\mathcal{Q}_b$ (i.e., i_b^{th} row plus j_b^{th} column), when $i_b < i_a$, the discovery delay is:

$$delay = \begin{cases} (i_b - 1)L + j_a - 1, & j_b \neq j_a \\ j_a - 1, & j_b = j_a \end{cases}$$

When $i_b \geq i_a$, the discovery delay is:

$$delay = \begin{cases} (i_a - 1)L + j - 1, & j_b \neq j_a \\ j_a - 1, & j_b = j_a \end{cases}$$

The probability of a quorum in $\mathcal{Q}_b$ to select the i_b^{th} row and j_b^{th} column is $1/L^2$. Thus, when the quorum from $\mathcal{Q}_a$ contains the i_a^{th} row plus j_a^{th} column, the average discovery delay between $\mathcal{Q}_a$ and $\mathcal{Q}_b$ is:

$$D = \frac{1}{L}[(L-1)\frac{(i-2)(i-1)}{2} + (j-1)(i-2) + (i - \frac{1}{2})(L - i + 1)(L-1)]$$

Therefore, the expected discovery delay (from data arrival to two nodes waking-up simultaneously) is:

$$
\begin{aligned}
E(Delay) &= \frac{1}{L^2}\sum_{i=1}^{L}\sum_{j=1}^{L} D && (1)\\
&= \frac{1}{L^3}\{\sum_{i=1}^{L}\frac{1}{L}[(L-1)\frac{(i-2)(i-1)}{2} + (j-1)(i-2) + (i-\frac{1}{2})(L-i+1)(L-1)]\} && (2)\\
&= \frac{L-1}{2L^2}\sum_{i=1}^{L}[(i-2)(i-1) + (i-2) + (2i-1)(L-i+1)] && (3)\\
&= \frac{L-1}{2L^2}\sum_{i=1}^{L}[(2L+1)i - i^2 - L - 1] && (4)\\
&= \frac{(L^2-1)(L+1)}{3L} && (5)\\
&= \frac{(N-1)(\sqrt{N}+1)}{3\sqrt{N}}. && (6)
\end{aligned}
$$

□

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