Nature Inspired Energy Efficient Wireless Sensor Networks: Using Duty-Cycled Wake-up Scheduling Swarm Intelligence

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ABSTRACT : **The most Wireless sensors are battery powered, limited energy capacity computing devices, so it is necessary for them to use their battery resources efficiently. Existing power-saving protocols achieve power saving by putting sensor nodes to sleep periodically. The mechanism of Regular sleep/awake fails to adjust a sensor node's sleep duration based on its traffic load, thus causing either lower power efficiency or higher latency. The model proposed is based on the nature inspired energy efficient technique of the Polar Bears which survive for more than 6 months without food in winter. In order to save energy consumption in idle states, low duty-cycled operation is used in Wireless Sensor Networks (WSNs), where each node periodically switches between sleeping mode and awake mode.**

***Keywords* - Duty cycle, Energy consumption, Sleep/ Wake, Wireless Sensor Networks WSN**

1. INTRODUCTION

The Napping helps Polar bears conserve energy. Bears nap just about anywhere and anytime, and especially after feeding on a seal. Existence of a polar bear is centric on hunting and conserving energy. Duty-cycling causes many challenges, such as difficulty in neighbor discovery due to asynchronous wake-up/sleep scheduling, time-varying transmission latencies due to varying neighbor discovery latencies, and difficulty on multihop broadcasting due to non-simultaneous wake-up in neighborhood. This paper focuses on this problem space. We focus specifically, on problems in duty-cycled WSNs wake-up scheduling.

An asynchronous quorum-based wake-up scheduling scheme proposed by us, which optimizes heterogeneous energy saving ratio and achieves bounded neighbor discovery latency, without requiring time synchronization. Our solution is based on quorum system design. Two designs by us were a periodic quorum system pair (pqs-pair) and another, grid quorum system pair (gqs-pair). We show our analytical and experimental results on pqs-pair and gqs-pair to achieve better trade-off between the average discovery delay and energy consumption ratio. Further to improve energy efficiency. We also study asymmetric quorum-based wake-up scheduling for two-tiered network topologies.

2. Duty-cycled Wireless Sensor Networks

To save energy in WSNs [1]. It has been observed that idle energy plays an important role.

Table 2.1: Energy consumption of different components in Telosb

Module	Power	Remark
Processor/memory mode	1.8 mA	Active
Processor/memory mode	5.1 µA	Sleep
Radio RX mode	18.8 mA	receiving
Radio TX mode	17.4 mA	transmission
Radio Idle mode	21 µA	
Radio Sleep mode	1 µA	

Existing radios (i.e., CC2420 [2]) used in WSNs support different modes, such as transmit/receive mode, idle mode, and sleep mode. In the 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 the idle mode [1]. The typical energy consumption parameters for a Telosb [3] are shown in Table 2.1.

If the time is arranged into consecutive and equal time slots. Now, two modes for low duty cycle operation can be identified: slotted listening mode [4, 5] and low power listening mode [6]. In the slotted listening mode, as shown in Fig 2.1(a), a node is wholly awake in select slots and asleep in the remaining slots when there is no data transmission or reception. In the low power listening (LPL) mode, as shown in Fig 2.1(b), a node will be fractionally awake in every slot.

Here we define duty cycle as the percentage of time a node is active in the whole operational time. In most of the cases the duty cycle in the LPL mode is lower than that in the slotted listening mode.

In the recent works on energy-harvesting [7,8], technologies an adaptive duty-cycling has been proposed, such as solar power [9], to replenish battery supply in WSNs. Due to high costs and the unavailability of a continuous power supply, it is not feasible to have instantly sufficient energy output. Hence, saving idle energy consumption is still necessary. Thus the adaptive duty cycling [9,10] is proposed to save energy consumption and to prolong the sustainable workable time per node. The duty cycle setting can be based on the residual energy [12], node location, or the rechargeable energy [11] on each node, independently

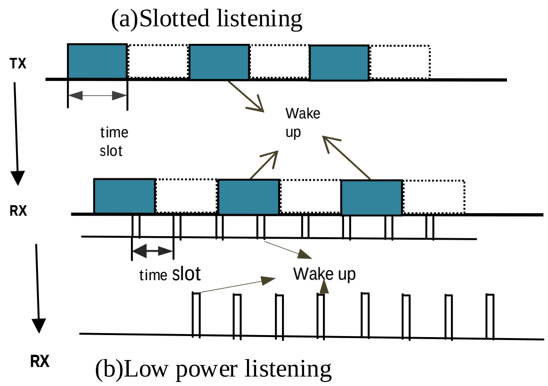

Fig 2.1: Duty-cycled operation in WSNs

Any low and adaptively duty-cycled operations can yield greater energy efficiency for WSNs, neighbor discovery becomes more complex than that in conventional works for always-on mechanisms (e.g., CSMA), there is no guarantee that two nodes are awake simultaneously.

3. Problem Spaces and Motivations

It is necessary to introduce a wake-up scheduling scheme in which a node sleeps in more slots in idle state, to support duty cycling, but maintains network connectivity. Towards energy saving goal, existing neighbor discovery mechanisms fall into three categories: on-demand wake-up, scheduled neighbor discovery, and asynchronous neighbor discovery.

In first category, On-demand wake-up mechanisms[13–16], uses out-of-band signaling or operational cycle 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 awakened. As page radios can operate at lower power consumption, this strategy is very energy efficient. But, it suffers from increased implementation complexity.

Secondly, scheduled wake-up mechanisms [17–19], low-power sleeping nodes wake up at the same time, periodically, to communicate with one another. Two examples are the S-MAC protocol [17] and the multi-parent schemes protocol [20]. In such schemes, all nodes maintain periodic sleep-listen schedules based on locally managed synchronization. Neighboring nodes form virtual clusters to set up a common sleep schedule.

And finally the third category, asynchronous wake-up mechanisms [6, 7, 21–23] is also well studied. Compared to the scheduled neighbor discovery wake-up mechanism, no clock synchronization requires for asynchronous wake-up. This approach follows its own wake-up schedule in the idle state for each node, as long as the wake-up intervals among neighbors overlap. To meet this requirement, nodes usually have to wake-up more frequently than in the scheduled neighbor discovery mechanism. But, there are many advantages of asynchronous wake-up, such as easiness in implementation and low message overhead for communication. Moreover, it can ensure network connectivity even in highly dynamic networks.

The quorum-based wake-up scheduling paradigm, sometimes called quorum-based power saving (QPS) protocol [5,24–26], is an asynchronous wake-up mechanism in slotted listening mode, and has been proposed as a powerful solution for asynchronous wake-up 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 period *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 earlier works consider only homogenous quorum systems for asynchronous wake-up scheduling [6], that means quorum systems for all nodes have the same cycle length and same pattern. But, many WSNs are increasingly heterogeneous 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 [27–32].

Thus, the first problem that we focus in this paper is heterogeneous quorum systems design, where heterogeneous sensor nodes like cluster heads and cluster members have different quorum-based wake-up schedules or different cycle lengths. Here in this paper we represent two quorums from different quorum systems as heterogeneous quorums. We observe different cycle lengths and different wake-up patterns, if two adjacent nodes adopt heterogeneous quorums as their wake-up schedules. Hence the problem continues for wake-up scheduling in WSNs with slotted listening mode, which asks the guarantee of intersection property for heterogeneous quorums and then how to apply for them.

Secondly, as we can see, the two desirable types of quorums: read and write, for an asymmetric design. The size of read quorum is always smaller write quorum size. If we can assure that a read quorum and a write quorum have the non-empty intersection property (i.e., write ∩ write ≠ ∅, read ∩ write ≠ ∅ but not necessarily read ∩ read ≠ ∅), then we can apply write quorum to cluster head and read quorum to cluster members, usually there is no communication between cluster members. We can achieve higher energy saving ratio comparing with that of write quorums, if the read quorums have smaller quorum size.

Thus an excellent idle energy savings, scalability, and easiness in implementation, is achieved by the quorum-based wake-up scheduling, but, as referred by Ye *et.al.* [33] time-varying neighbor discovery latencies are a major drawback.

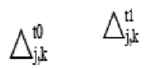

Fig 3.1: Varying neighbor discovery latency in heterogeneous LPL mode.

As shown in Figure 3.1, a difference is observed with the departure times, when the latency between two neighbors is varying, for neighbor discovery. Figure 3.1, depicts the adaptive duty cycle setting, the neighbor discovery latency is varies at different time moments, even with synchronized duty cycling, Here another fundamental problem arises: with the link costs time-variance and to discover optimal paths with least nodes-to-sink latency for all nodes at all discrete departure time moments.

The multihop broadcasting [34], which is an important network service in WSNs is our last problem that we consider for applications such as code update, remote network configuration, route discovery and so on. Although neighbor connectivity is not a problem in wireless ad hoc networks for broadcasting, which has been well studied in always-on net-works [35, 36], but broadcast is more difficult in duty-cycled WSNs where each node stays awake only for a fraction of the time slots and neighborhood nodes are not simultaneously awake for receiving data. Leads to a difficult in asynchronous [6] and heterogeneous duty-cycling [37] scenarios.

The paper focuses on the solution to the first two problems described above, by an efficient protocol design and algorithm which are efficient in terms of energy efficiency, latency bound, and run-time complexity.

4. Research Contributions

Our contribution to address these two problems is the main goal in this paper which includes: Firstly Network connectivity maintenance in duty-cycled WSNs. The term "connectivity" loosely, here, we use in the sense that a topologically connected network in our context may not be connected at any given time; alternatively, within a finite amount of time all nodes are reachable from a node. Secondly to design of a fast distributed algorithm for the time-varying shortest path routing problem, which can efficiently establish all optimal paths with least end-to-sink latencies with infinite time intervals. Besides, an algorithm designed which maintains time-dependent least-latency paths and dynamically distributed in nature.

Our contributions as follows with the set of solutions developed toward these goals.

A the periodic quorum system pair (or pqs-pair)[1] developed, which guarantees the two adjacent nodes adopts heterogeneous cyclic quorums from such a pair as their wake-up schedules, can hear each other at least once within one super cycle length (i.e., the larger periodic length in the pqs-pair).

Another fast algorithm for constructing pqs-pairs is also developed, using the multiplier theorem[38] and the(N, k, M, l) difference pair defined by us. Given data, a pair of cycle lengths (n and m, $n \leq m$), an optimal pqs-pair design is shown, in terms of energy saving ratio. In contrast to previous exhaustive methods [39], our fast construction scheme significantly improves the speed of finding an optimal quorum, the performance of pqs-pair in terms of expected delay quorum ratio, and energy saving ratio is well analyzed,

Better trade-off between energy consumption and average delay in WSNs can achieved, with the help of the pqs-pair,. For example, all ((n-1)/2))<E(delay<)(m-1)/2 cluster-heads and gateway nodes can select a quo-rum from the quorum system with smaller cycle length as their wake up schedules, to obtain smaller discovery delay. Additionally, in accordance to save more idle energy, all cluster members can choose a quorum with longer cycle length as their wake-up schedules, from the quorum system. As for best of our knowledge, pqs-pair is the first solution which is applied to asynchronous WSNs for heterogeneous energy saving requirement and at the same time bounded neighbor discovery latency is guaranteed. Another design for heterogeneous quorum system pair is also developed by us, called the *grid quorum system pair* (or *gqs-pair*)[40], in which each quorum system of the pair is a grid quorum system [41].

We also prove that any two grid quorum systems can form a gqs-pair. As well we show that for a gqs-pair with $\sqrt{n} \times \sqrt{n}$ grid $\sqrt{m} \times \sqrt{m}$ grid, the average discovery delay is bounded within (((n-1) ($\sqrt{n}$+1))/ (3$\sqrt{n}$))<E (DELAY) < (((m-1) ($\sqrt{m}$+1)/ (3$\sqrt{n}$)) While the quorum ratios are (2$\sqrt{n}$-1)/n and (2$\sqrt{m}$-1)/m, respectively. As Compared with pqs-pair, gqs-pair this is easier to implement since any two gqs would form a gqs-pair, which can benefit practical deployment. However gqs-pair has better performance in terms of average neighbor discovery latency than pqs-pair.

A clustered WSNs uses asymmetric design to improve energy efficiency. It is observed that it is not necessary to always guarantee the intersection property for cluster members as there is usually no data transmission between the members and in the idle state they do not need to discover each other. If we consider the data transmission as a *write operation*, and the listening in the idle state as a *read operation*. Based on this, the concepts of read quorum and write quorum we try to propose, in order to save energy. As it is necessary to guarantee the intersection property between read and write quorums, i.e., *write* ∩ *write* = ∅ *read* ∩ *write* = ∅ and we see that there is no necessity of read quorums intersection with each other. Thus, in case of data transmission, if a node adopts a read quorum in the idle state, and switch to a write quorum, we can guarantee network connectivity, meanwhile providing higher energy efficiency.

An asymmetric quorum-based wake-up scheduling is based on such an observation. An example design is the grid quorum group, as a read quorum consists of a column of elements in a grid and a write quorum consists of a row of elements in the grid. A p-Grid protocol designed, based on quorum groups to achieve better energy saving ratio and latency discovery, which can be easily implemented.

The neighbor discovery protocols (conventional such as B-MAC [7]), is a more flexible p-Grid, to meet the demand of heterogeneous energy saving requirements and in unreliable environment it is more energy efficient by avoiding continuously sending out probing messages.

5. Conclusions

This paper is a motivation of the swarm intelligence of polar bears by saving idle energy consumption. The work is based on the observation that idle energy consumption cannot be neglected in sensor nodes for a large class of WSN applications (e.g., environment monitoring [42], target tracking [43]). Duty-cycling approach on sleep scheduling [44] is adopted in this paper, for saving idle energy. However, some of the challenges arises here, on neighbor discovery, data delivery with optimal latencies, and data broadcasting.

Our solutions are based on asynchronous wake-up scheduling which is inspired by the quorum-based power saving mechanism [5]. The two designs were proposed; pqs-pair and gqs-pair, which provide a general framework in that we can satisfy the heterogeneous energy saving requirement, by guaranteeing neighbor discovery latency. These generalization shown here by us is an extension from past works.

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