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A Tier-Based Duty-Cycling Scheme for Forest Monitoring

Fuquan Zhang*, Deming Gao*, and In-Whee Joe**

Abstract

Wireless sensor networks for forest monitoring are typically deployed in fields in which manual intervention cannot be easily accessed. An interesting approach to extending the lifetime of sensor nodes is the use of energy harvested from the environment. Design constraints are application-dependent and based on the monitored environment in which the energy harvesting takes place. To reduce energy consumption, we designed a power management scheme that combines dynamic duty cycle scheduling at the network layer to plan node duty time. The dynamic duty cycle scheduling is realized based on a tier structure in which the network is concentrically organized around the sink node. In addition, the multi-paths preserved in the tier structure can be used to deliver residual packets when a path failure occurs. Experimental results show that the proposed method has a better performance.

Keywords

Link Redundancy, Rechargeable Dynamic Duty Cycle, Tier, Wireless Sensor Networks

1. Introduction

In recent years, wireless sensor networks (WSNs) have dramatically grown and enabled significant advancements in many applications. However, the limited power source of wireless sensor nodes has restricted the development and application of WSNs, which often require a very long lifespan for better performance [1]. To this end, a significant amount of work has been carried out across the protocol stack to prolong the lifetime of WSNs. Notable examples include energy-efficient medium access control (MAC) protocols [2-4], duty-cycling strategies [5], energy-efficient routing [6], topology-control mechanisms [7], and even operating systems [8].

An interesting approach for extending the lifetime of sensor nodes is the use of energy harvested from the environment. Energy harvesting is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy, salinity gradients, and kinetic energy) and captured and stored in a variety of ways, such as in sensor nodes [9]. Energy-rechargeable devices and energy storage devices used as the energy supplement components of energy harvesting systems replace the batteries of traditional WSNs (T-WSNs), marking the key difference between current WSNs and T-WSNs.

Design constraints are application-dependent and based on the monitored environment in energy

harvesting or rechargeable WSNs (R-WSNs). For example, a node that relies on the wind extracts no energy when the environment is windless. The available energy in nodes dramatically varies over time on account of the varying environmental conditions.

In order to enhance results that are related to energy conservation, sleep and wake-up mechanisms are employed in case of node failure due to a lack of energy [10]. To regulate energy consumption, nodes adapt their duty cycle according to the application, which plays a key role in determining the power schedule, network topology, and routing protocol design. Because applications have diverse requirements in terms of lifetime, throughput, and robustness, the duty cycling mechanism employed for one scenario may not efficiently work for another. Duty cycling is currently a major trend in the design of WSNs. Duty cycling schemes can be classified into synchronous and asynchronous schemes in relation to the mechanism used to coordinate the schedules [5].

In synchronous duty cycling, nodes are expected to maintain common time references. To achieve and maintain the necessary degree of synchronization throughout the network, the nodes [11,12] require an exchange of synchronization information. The use of synchronization protocols, and occasionally extra hardware, is a prerequisite for many proposals. However, a global synchronous network is difficult to achieve because pairwise synchronization errors tend to accumulate in a multi-hop network. More recently, the synchronization requirement has been less strict than that of global proposals; nevertheless, these schemes [13,14] are topology-dependent and result in further topology discovery and maintenance.

In asynchronous duty cycling, each node asynchronously goes to sleep and periodically wakes to check for channel activity. An asynchronous random duty cycling [15] results in extremely high latencies. Schedule-based asynchronous duty cycling [16,17] requires two nodes to have overlapping active time. Another asynchronous method is detecting the preamble transmission [18-20] or wake-up signal [21,22]. The burden of extra energy expenditure lies on the transmitter, which must remain active until it receives the beacon from the intended receiver.

The above proposals mainly work in the MAC layer. They could reduce energy consumption to some extent. The implementation and execution of dynamic power management policies are possible at the operating system/software level. Thus, the energy efficiency of a sensor node can increase without requiring any specific power management hardware [23].

Recently, duty cycle schemes have been designed based on topology control. Adaptive duty cycling (ADC) is a notable example, which groups nodes by using topology control, and then applies adaptive duty-cycle depending on group size to balance energy consumption [24].

Firstly, ADC estimates the maximum group size based on distributed information. The size of the group is broadcast within a two-hop distance by the group head node. After receiving the group size information from other groups, each head node estimates the average group size in the network.

Secondly, it is assumed that the largest group operates with a full duty-cycle. Each group calculates its own duty-cycle by comparing its group size with the maximum group size. This ensures that all the nodes in the network have a similar lifetime. For example, if the maximum group size is 10, then the group formed by 10 nodes always operates any one node in an active mode during 10 unit times. Conversely, the group with two nodes operates any one node in the active mode for only 2 out of 10 unit times. This represents a 20% duty cycle; all nodes in the group remain in sleep mode for the remaining eight unit times.

ADC solves unbalanced energy consumption generated from conventional topology control schemes by applying a different duty cycle to each group based on group size. However, the ADC scheme does not consider the various network environments (e.g., traffic amount) in which the nodes are deployed.

In this paper, we design dynamic duty cycle scheduling at the network layer for forest monitoring. In a forest environment, harvested solar energy is used as the energy source. Such R-WSNs show some distinct characteristics [25].

First, the dynamic duty cycle of a node is the most intuitive characteristic of R-WSNs. Energy harvesting sensor networks are an environment-dependent network. When a sensor node lies in direct sunlight at 12 pm, for example, the power density can reach 3,700 $\mu W/cm^2$, the energy harvesting rate is 320 mW, and the duty cycle achievable by the Crossbow MICAz can reach approximately 45%. Even though various nodes exist in the same environmental conditions, each node may harvest different amounts of energy on account of unpredictable factors, such as differing solar panel angles.

Second, the harvested energy is still significantly less than the power consumption for sensor nodes. Thus, a node must operate in a very low duty cycle, which means that a node must be shortly activated and remain in the sleep state most of the time to recharge.

Third, it is unrealistic for a sensor node set at a constant duty cycle to meet special requirements. Actually, the duty cycle of a node is passively adjusted according to the energy harvesting rate. This significantly differs from that in T-WSNs, in which a sensor node can freely change its duty cycle only if it must.

These characteristics have not been considered in T-WSNs, which pose significant challenges for duty cycle scheme design in R-WSNs. Considering the dynamic energy supply, low duty cycle, and different energy harvesting rates, routing is difficult to predict and more critical than that of traditional WSNs.

The intuition is that the characteristic of the duty cycle in R-WSNs should be considered in the routing design. Thus, the problem of how to utilize redundancy paths to maintain the routing function, while working with dynamic low duty cycles, is the primary motivation behind our scheme. In this paper, unlike earlier works, which focus either on static battery-powered networks or the MAC layer, we designed a power management scheme that combines dynamic duty cycle scheduling at the network layer to plan the node duty time. The dynamic duty cycle scheduling is realized based on a tier structure in which the network is concentrically organized around the sink node.

The remainder of this paper is organized as follows. Section 2 presents the network model of the proposed scheme. We present the dynamic duty cycle control scheme in Section 3. Simulation results are discussed in Section 4. Conclusions are in Section 5.

2. Network Model

In a connected sensor topology where the sensors having two or more neighbors between them are connected, if a failure occurs in any of the paths, the other paths should provide redundancy to the network. In the proposed scheme, a tier-based architecture is utilized to preserve the local paths of neighbor nodes. Moreover, a dynamic duty cycle scheduling scheme is used to resolve sleeping node selection for power saving based on the tier structure, as shown in Fig. 1. The tiers are numbered 1, 2, 3… starting from the innermost tier (sink node) in such a way that a node in the n-th tier can relay a message to the sink node in n hops, as shown in Fig. 1. With this approach, routing can be performed at the level of a tier.
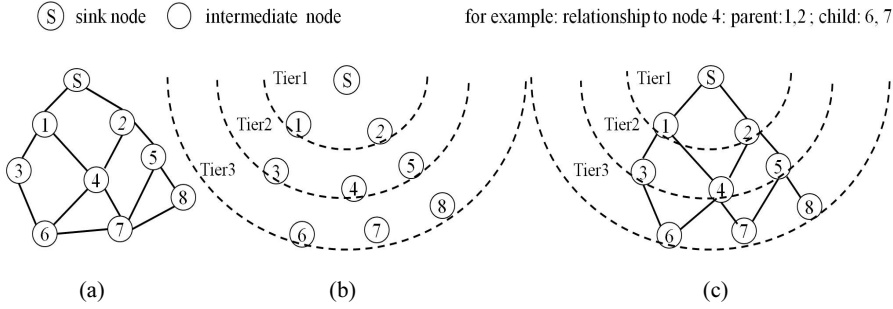
Fig. 1. Parts of local redundancy links are preserved in the tier structure. (a) Initial topology, (b) tier construction, and (c) resulting topology.

Sensor nodes rotate through active/sleep based on a cyclic schedule, wherein each cycle contains m equal-length time slots of length τ. Each node maintains a local power schedule of the operations it performs over the course of a cycle.

For a node, when it is in an active state within a cycle c, its working schedules can be represented by a set of time instances including one or multiple time slots with length τ. For example, we have $m_i = \{m_1, m_4, m_7, m_8,\}$ for node i when it is in an active state for a working schedule, as shown in Fig. 2.
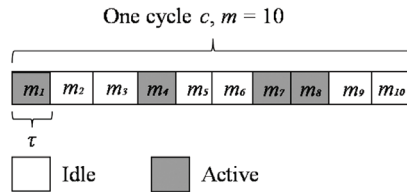

Fig. 2. An illustrative example of the duty cycle.

3. Duty Cycle Control Scheme

This paper proposes a power management scheme that combines dynamic duty cycle scheduling at the network layer to plan node duty time by organizing the network into concentric tiers around the sink node.

3.1 Definition

During each slot of the cycle, the node can be in one of four states:

(1) Reservation (R): A receive/transmit pair between a parent node and child node, remains in schedule until topology or requirement changes (Active state).

(2) Advertisement (A): An advertisement is broadcasted from a parent node for an available reservation slot for each child node. This remains at most for one cycle. Advertisement messages carry the node ID, tier-rank, the current slot number, listen slot number, and reservation slot number for children (Active state).

(3) Listen (L): The node listens for a reservation request from a child node (Active state).

(4) Idle (I): After all current demands at this node have been met, the node can power down during idle slots (Idle state).

3.2 Initialization

After tier construction, the sink node initializes by randomly assigning a reservation slot during the following cycle. Nodes are fully powered on in the initialization phase until they acquire an advertised slot, as shown in Fig. 3.

Because local redundancy links preserved in the tier structure may form multipaths, a child node may obtain multiple reservation slots from its different parent nodes. In the example in Fig. 3, node 4 may obtain reservation slots from node 1 and node 2, respectively. In this case, node 4 will mark all advertised reservation slots and use the first one for transmission. Moreover, if a failure occurs in any of the paths, the other path can provide redundancy to the network. Once a node has acquired sufficient reservation slots to meet its initial demand, it begins to advertise itself and sleep during idle slots.

In R-WSNs, a node must operate in a very low duty cycle, which means that a node must be shortly activated and remain in the sleep state most of the time to recharge. It is unrealistic for a sensor node set at a constant duty cycle to meet special requirements. In the proposed scheme, a node sets its duty cycle and synchronizes with its parent independently. When a child node selects a parent it synchronizes its current time slot and slot number to that of the parent. Thereafter, the child node periodically resynchronizes with its parent.
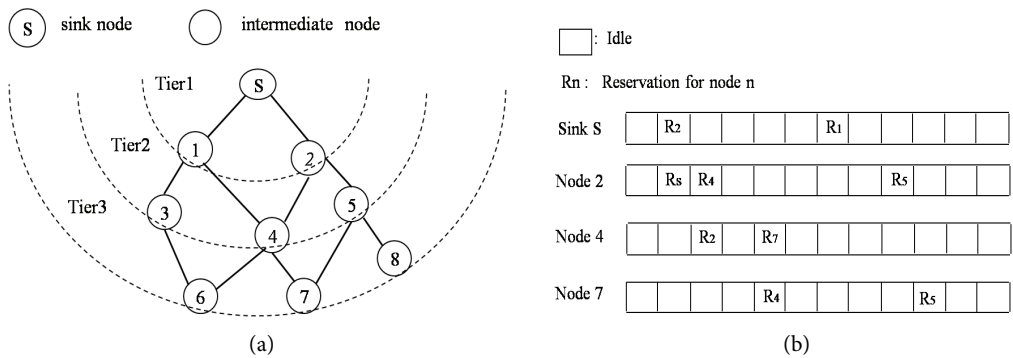

Fig. 3. An illustrative example of the proposed scheduling scheme. (a) Resulting topology and (b) proposed scheduling scheme of a duty cycle for nodes S, 2, 4 and 7.

3.3 Active Phase

If the demand is unmet, the children can get one more unit of a reservation (R slot) by listening to the parent's A slot in each cycle after the initialization phase. The reservation process requires three cycles. The first is the advertisement from the parent, the second is marking the corresponding reservation in the child, and the third is the first actual transmission of data during the R slot. The parent will randomly assign one more R slot for the child if transmissions occur in all the reserved R slots.

The R slot remains in effect until the parent node times out the reservation and cancels the reservation if no transmissions occur after a specific number of cycles. With dynamic slot control, a

parent node can recycle the unused slots of child nodes. The parent stops assigning more R slots for the child if a reservation is cancelled.

Algorithm 1. Active procedure

for each cycle c,
    randomly pick an advertisement slot A from idle slots
    if (demand is met)
        sleep during idle slots
        schedule an advertisement during an A slot
    else
        radio on and listen for advertisements
        mark the reservation slot (in advertisements from the parent) in its own schedule
    end if
    for each slot s,
        check the power schedule
        case (A): broadcast an advertisement
        case (R): receive/transmit data
        case (L): listen for a reservation request
        case (I): power down the radio
    end for
    if (no transmissions occur after a specific number of cycles)
        recycle unused slots
    end if
end for

The parent resumes assignment of the reservation for the child until it receives a reservation request in the L slot from the child. Once all node demands have been met, it can power down its radio during idle slots to conserve energy; otherwise, it listens for advertisements. Each node runs the above active procedures after initialization. A list of these processes is summarized in Algorithm 1.

Compared to the overhead caused by routing request and routing maintenance, dynamic overhead caused by duty cycling tends to be small. Nevertheless, the existence of the dynamic overhead and the lack of data routing are reasons for including duty cycling in the routing design. The main goal is to eliminate the execution overhead of duty cycling associated with routing. Our scheme combines dynamic duty cycle scheduling at the network layer by organizing the network into concentric tiers around the sink node. Moreover, the multiple local paths between tiers are preserved for route maintenance. This preservation also eliminates the execution overhead of duty cycling to some extent.

Even though we present duty-cycling in a specific tier-architecture, the scope in which the approach can be applied is much broader. The principal requirement is tier construction. The requirement is satisfied even in a very simple static wireless sensor network environment. Therefore, the presented scheme is easily applied.

3.4 Factors Affecting Path Reliability

The nodes may harvest different amounts of energy in unpredictable environmental factors, however

the harvested energy is still significantly less than the power consumption for sensor nodes in R-WSNs. Our proposal utilizes the potential links that are preserved in the concentric tiers to provide redundancy to the path. By organizing the network into concentric tiers, the proposed dynamic duty cycle control (DDCC) utilizes the potential links to provide redundancy to the network. This can improve path stability to some extent in theory.

We first define the stability of the path as follows.

The probability, $S(t)$, that an SD pair provides a stable communication link for a given length of time t is called the stability of the path.

A single-path ha**s** a series of one-hop links between tiers that the failure of any one-hop link causes the entire path to fail. Thus, stability of a single path $S_s(t)$ is given by

$$S_s(t) = \prod_{i=1}^{N} S_i(t) \tag{1}$$

where $S_i(t)$ is the stability of one-hop link i, and N is the number of one-hop links. The life time of a radio link is most commonly modeled by an exponential distribution. We therefore assume that every one-hop link i has a failure rate λ_i. Eq. (1) can be expressed as

$$S_s(t) = e^{-\lambda_s t} = e^{-\Sigma \lambda_i t} \tag{2}$$

where, $\lambda_s = \Sigma \lambda_i$ is the failure rate of the whole path. Thus, the *Mean Time To Failure* of a single-path (*MTTFs*) is

$$MTTF_s = \int_0^{\infty} t \cdot \lambda_s e^{-\lambda_s t} dt = \frac{1}{\lambda_s} = \frac{1}{\Sigma \lambda_i} \tag{3}$$

A link-disjoint multipath that is reserved in the tiers has a set of parallel paths connected so that all the paths must fail before the source-destination communication fails. Thus, the stability of a multipath $S_m(t)$ is given by

$$S_m(t) = 1 - \prod_{j=1}^{N} [1 - S_{sj}(t)] \tag{4}$$

where $S_{sj}(t)$ is the stability of a single-path j, and N is the number of paths between the source and destination. Let λ_{sj} represents the failure rate of a single path j, Eq. (4) can be expressed as

$$S_m(t) = 1 - \prod_{j=1}^{N} [1 - e^{-\lambda_{sj} t}] \tag{5}$$

If we assume that life-time of all paths are independent and identically distributed with parameter λ_s (While this is not strictly the case, here we are seeking general trends, and therefore this approximation is appropriate), the *Mean Time To Failure* of a multi-path (*MTTF*m) can be expressed as:

$$MTTF_m = \frac{1}{\lambda_s} + \frac{1}{2\lambda_s} + ... + \frac{1}{N\lambda_s} = \sum_{j=1}^{N} \frac{1}{j\lambda_s} \tag{6}$$

Here, we can see that multipath can improve network robustness. DDCC utilizes the potential links to provide redundancy to the network. Thus, a redundancy path, between any two tiers, can improve the path stability to some extent.

4. Simulation and Analysis

In the simulation, the communication range is 50 m. All nodes have energy rechargeable devices: solar panel, eZ430-RF2500T target boards, and one rechargeable AAA battery pack. The target board comprises the MSP430 microcontroller, CC2500 radio transceiver, and an on-board antenna. The harvested energy is stored in a thin-film rechargeable energy storage device.
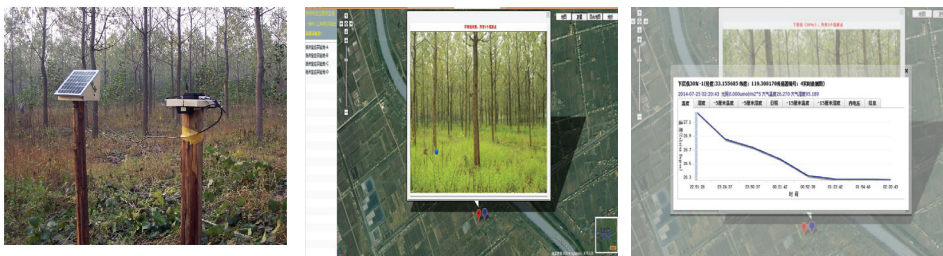

Fig. 4. Environment data-collecting system for forest research.

We have deployed the monitoring system with rechargeable sensors. The system is used to collect various sensory data from a forest (e.g., temperature, humidity, illumination), as shown in Fig. 4. This system was designed originally for the purpose of collecting accurate environmental data to support forest research and maintain the attainability of the network for as long as possible, the latter of which is also required for other sensor network applications.

4.1 Varying Network Sizes

(a)   (b)
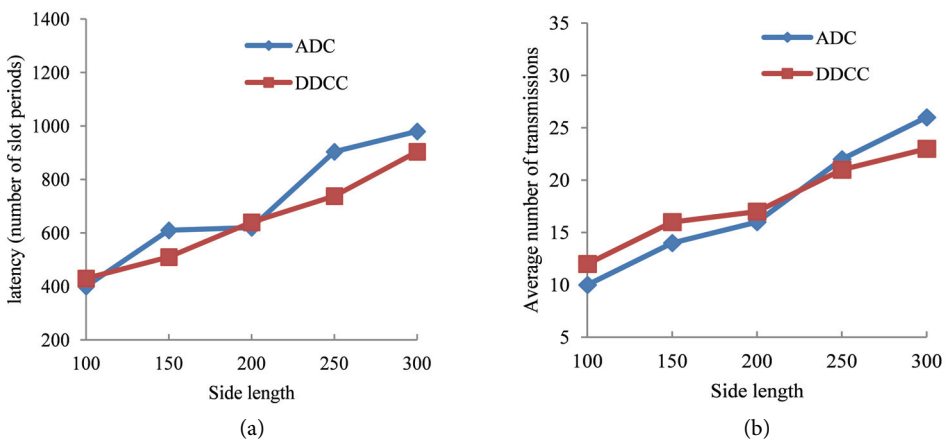
Fig. 5. Performance with varying side lengths. (a) Latency and (b) energy consumption.

We evaluate the performance of all algorithms in different network sizes. For a side length of 100 to 300, the number of nodes is set from 100 to 900 to maintain the same network density. Fig. 5(a) shows that the end-to-end delay increases as the size length of the network increases. DDCC has a shorter delivery delay compared with ADC. DDCC consumes slightly more energy compared to ADC with a small side length, as shown in Fig. 5(b).

4.2 Varying Network Densities

Experiments were executed in which the number of associated nodes in the network was increased from 100 to 500. In a dense network in which a node has a large number of neighbors (in which multiple paths are available for any pair of nodes), a high probability exists that slot assignment may lead to a short delay path. With an increase in nodes, the latency of all the algorithms decreases. By utilizing potentially available neighbors of tiers, DDCC shows a better ability to handle the stress of data delivery, as shown in Fig. 6(a). The impact on the energy cost of changing network densities is not very noticeable, as shown in Fig. 6(b).
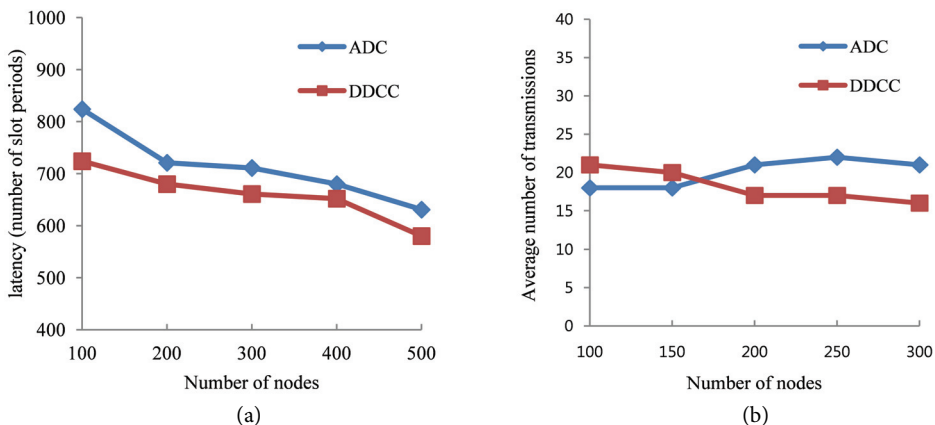

Fig. 6. Performance with varying number of nodes. (a) Latency and (b) energy consumption.

5. Conclusions

By organizing the network into concentric tiers, potential nodes can be utilized to provide network redundancy. In this paper, we presented a dynamic duty cycle control scheme based on tier construction of a network layer for forest monitoring in a rechargeable sensor network. The scheme considers both routing and duty cycling of sensor nodes. Simulations show that our algorithm achieves a better performance.

Acknowledgement

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