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# Towards energy-fairness for broadcast scheduling with minimum delay in low-duty-cycle sensor networks

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ABSTRACT

Broadcast scheduling for low-duty-cycle wireless sensor networks (WSNs) has been extensively studied recently. However, existing solutions mainly focused on optimizing delay and (or) total energy consumption without considering load distribution among nodes. Due to limited energy supply for sensor nodes, heavily loaded sensors often run out of energy quickly, reducing the lifetime of the whole network. In this paper, we target at minimizing the maximum transmission load of a broadcast schedule for low-duty-cycle WSNs, subject to the constraint that each node should have the minimum end-to-end delay under the broadcast schedule. We prove that it is NP-hard to find the optimal schedule. Then, we devise a *Load-Balanced Parents Assignment Algorithm* (LBPA-A) that achieves λ-approximation ratio, where λ denotes the maximum number of neighbors that are scheduled to wake up at the same time and is typically a small number in low-duty-cycle WSNs. Further, we introduce how to solve this problem in a distributed manner. Our simulation results reveal that compared with the traditional solutions, our proposed LBPA-A and distributed solution both exhibit much better average performance in terms of energy-fairness, total energy consumption and delivery ratio.



## 1. Introduction

As an important fundamental function, multi-hop broadcasting in wireless sensor networks (WSNs) has been extensively studied in the past few years. Many applications in WSNs, e.g., environmental monitoring, medical care system and scientific exploration, require that the sink node should disseminate the system configurations to all sensor nodes in a timely and energy-efficient manner. In practice, it has been verified [1] that idle listening is the major source of energy waste in WSNs. As shown in [2], the commonly adopted ChipCon CC2420 radio draws 18.8 mA at receiving mode or idle listening mode, and draws 17.4 mA at sending mode, which implies that idle listening actually consumes approximately the same amount of power as in receiving and sending mode. In order to significantly reduce the energy waste caused by idle listening, sensor nodes are often put in a low-duty-cycle mode where every sensor node has its own working schedule to alternate periods of work with sleep.

How to optimize the energy efficiency of broadcasting in low-duty-cycle WSNs has been well-investigated by many existing works, in which the proposed solutions can achieve high energy efficiency in terms of total energy consumption. However, it may not be appropriate to take total energy consumption as the main metric to characterize energy efficiency in sensor networks. As we know, it is typically hard to replace or recharge batteries for sensor nodes as many WSNs are deployed in a tough environment that human beings are not easy to access to. This fact implies it is more important for sensor networks to take energy-fairness as the first concern, since unbalanced load could make nodes with heavy workload deplete their energy much faster so that the network is disabled earlier, e.g., the monitoring field cannot be fully covered, or the network becomes disconnected. Currently, most of the existing works mainly pay attention to load-balanced *data collection* in low-duty-cycle WSNs. However, very few of them consider load balancing of *data dissemination*, which is an important function in sensor networks. In low-duty-cycle WSNs, one-hop broadcasting is usually implemented by multiple unicasts. Once the broadcasting schedule is established, it is normally performed for a rather long duration and is unlikely

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to be updated frequently due to high update overhead. Therefore, a broadcasting schedule without careful design may lead to highly unbalanced broadcasting load among sensor nodes. As the number of broadcasting increases, this unbalancing will be further intensified. For low-duty-cycle WSNs where load-balanced data collection are adopted, designing a broadcasting schedule to guarantee energy fairness among sensor nodes is an important issue.

Compared with always-awake networks, low-duty-cycle sensor networks usually yield a notable increase on communication delay due to the periodic sleeping, and thus delay is always taken as the first consideration in such networks. In many broadcasting applications without cooperation requirement such as *configuration dissemination*, each node is expected to receive the broadcasting message as soon as possible to update the configuration so that the new system requirement can be satisfied in a short period of time. In other words, the end-to-end (E2E) delay from the sink node to each sensing node is desired to be minimized for broadcasting in such applications. For example, GreenOrbs is a consistently operating sensor network system deployed on Tianmu mountain of China for the aim of forest monitoring. It periodically collects various sensory data including temperature, humidity, illumination, and carbon dioxide titer. The collected information is utilized to support various significant applications, such as forest surveillance, forestry observation and research, fire risk evaluation, and succor in the wild. Occasionally, we need to change the sampling period or other parameters of each node. In this case, the sink node needs to broadcast the updated configuration in the network as soon as possible so that the new system requirement can be satisfied as soon as possible. As for another example, alarm detection system is also a type of widely used applications for WSNs. Upon detecting that a parameter (e.g., temperature, and humidity) is above or below some threshold, the sensor node will report it to the sink quickly so that a prompt action can be taken. For this kind of applications, we sometimes need to change the system requirement (e.g., to change the alarm threshold), and the sink needs to broadcast the message attached with the updated alarm threshold in the network as soon as possible so that the chance of false positive or false negative can be reduced as much as possible. To this end, we identify the minimum E2E delay as a firm requirement, and thus our optimization goal becomes balancing the energy consumption among nodes while guaranteeing the minimum E2E delay.

In this paper, we focus on the *Load-Balanced Minimum E2E-delay Broadcast Scheduling Problem* (LB-MEBS), namely how to minimize the maximum transmission load of a broadcasting schedule for low-duty-cycle WSNs, subject to the constraint that each node should have the minimum end-to-end delay under the broadcasting schedule.

The main contributions of this work are as follows:

- To the best of our knowledge, we are the first to investigate the load-balanced minimum delay broadcast scheduling problem for low-duty-cycle WSNs. We transform our problem into the equivalent *Load-Balanced Parents Assignment Problem* (LBPA), and prove its NP-hardness.
- We propose the *Load-Balanced Parents Assignment Algorithm* (LBPA-A) to tackle the LBPA problem, and show that LBPA-A can achieve $\lambda$-approximation, where $\lambda$ denotes the maximum number of neighbors that are scheduled to wake up at the same time and is typically a small number in low-duty-cycle WSNs.
- We also propose an efficient distributed solution, i.e., DLBPA-A, to solve our problem. The message complexity of this algorithm is $O(N^2 + N \cdot d_{max}^2)$ where $N$ and $d_{max}$ denote the number of nodes and the maximum node degree in the network, respectively.
- Our simulation results reveal that compared with the traditional solutions, LBPA-A and DLBPA-A both exhibit much better average performance in terms of energy-fairness, total energy consumption and delivery ratio.

The rest of the paper is organized as follows: Section 2 summarizes the related work. Section 3 illustrates the network model and formulates the problem. Section 4 analyzes the problem hardness. Detailed description and analysis of our proposed algorithm are presented in Section 5. Section 6 introduces an efficient distributed solution, followed by the discussion about practical issues and the simulation results in Section 7 and Section 8. Section 9 concludes our findings.

## 2. Related work

In recent years, a number of works that focus on energy-efficient broadcast scheduling problem in low-duty-cycle WSNs have been proposed [3–13]. Hong et al. [4] studied the Minimum-Transmission Broadcast problem in uncoordinated duty-cycled networks and proved its NP-hardness. They proposed a centralized approximation algorithm with a logarithmic approximation ratio and a distributed approximation algorithm with a constant approximation ratio for this problem. In [6], the authors considered link correlation and devised a novel flooding scheme to reduce energy consumption of broadcasting by letting nodes with high correlation be assigned to a common sender. Xu et al. [7] utilized the broadcasting spatiotemporal locality to address the latency-optimal minimum energy broadcast problem in low-duty-cycle WSNs. In [10], the authors studied the duty-cycle-aware Minimum-Energy Multicasting problem in WSNs both for one-to-many multicasting and for all-to-all multicasting. Han et al. [11] studied the problem of minimizing the expected total transmission power for reliable data dissemination in duty-cycled WSNs. Due to the NP-hardness of the problem, they designed efficient approximation algorithms with provable performance bounds for it. Cheng et al. [12] proposed a novel dynamic switching-based reliable flooding (DSRF) framework, which is designed as an enhancement layer to provide efficient and reliable delivery for a variety of existing flooding tree structures in low duty-cycle WSNs. In [13], the authors investigated the energy efficient broadcast problem with minimum latency constraint in low-duty-cycle WSNs with unreliable links, and proposed a distributed heuristic solution to tackle this problem. However, all of these works mainly focus on the minimization of total energy consumption rather than load balancing. Recently, Glossy broadcasting scheme [14] has gained much attraction amongst researchers, as it uses constructive interference for flooding and thus eliminates any need to establish a schedule for broadcasting. However, it mainly focuses on the latency and reliability of broadcasting but not the load balance problem.

Currently, load balancing for applications of data collection in sensor networks has also been extensively investigated by many works [15–22]. Wu et al. [15] proposed a novel nonuniform node distribution strategy to achieve nearly balanced energy depletion in the network. Jurdak et al. [16] proposed a cross-layer framework to balance the load in sensor networks via greedy local decisions. Xiong et al. [17] studied the multiple task scheduling problem for low-duty-cycle WSNs. They presented several efficient scheduling algorithms to achieve load balancing among sensor nodes in both spatial and temporal dimensions. In [18], the authors developed a delay-constrained data aggregation scheme for duty cycle sensor networks to balance the nodal lifetime of all nodes. Besides, some works such as [19] also consider employing a mobile sink or mobile relay to collect data so as to balance loads among sensor nodes. In [20], the authors investigated the problem of controlling node sleep intervals so as to achieve the min-max energy fairness in asynchronous duty-cycling sensor networks, the proposed algorithm is self-adjustable to the traffic load variance and is able to serve as a unified framework for a variety of asynchronous duty-cycling MAC protocols. However, to the best of our knowledge, none of the existing works consider load balancing of broadcasting applications for sensor networks under low-duty-cycle