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Level-based approach for minimum-transmission broadcast in duty-cycled wireless sensor networks[☆]

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HIGHLIGHTS

- The algorithm of finding covering nodes helps to reduce a number of transmissions.
- The concept of *duty-transmission* highlights the advantage of our scheme.
- Level-based traversal on covering nodes reduces a number of transmissions and the time complexity.
- Examining the impact of network density and duty cycle shows the advantage of our scheme.
- The trade-off between number of broadcast transmissions and broadcast delay is also disclosed.

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ABSTRACT

Broadcast is a fundamental activity in wireless sensor networks (WSNs) and many problems related to broadcast have been formulated and investigated in the literature. Among them, the minimum-transmission broadcast (MTB) problem, which aims to reduce broadcast redundancy, has been well studied in conventional wireless ad hoc networks, where network nodes are assumed to be active all the time. In this paper, we study the MTB problem in duty-cycled WSNs where sensor nodes operate under active/dormant cycle and propose a novel scheme to solve it efficiently. The proposed Level-Based Approximation Scheme first identifies the forwarding nodes and their corresponding receivers for all time slots; then constructs a broadcast backbone by connecting these forwarding nodes to the broadcast source. The backbone construction is accomplished by a two-stage traversal on all the forwarding nodes, which successfully exploits transmissions of each forwarding node to its receivers. We have also conducted extensive simulations to evaluate the performance of our proposed scheme. Simulation results indicate that our scheme significantly outperforms existing ones.

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1. Introduction

Broadcast is one of the most essential functions in wireless sensor networks (WSNs) [1]. On account of broadcasting, sensor nodes can disseminate messages across the whole network for many purposes such as networking configuration, routing discovery, or even coordinating operations of sensor nodes [2,3]. To evaluate the efficiency of a broadcast strategy, the number of transmissions is commonly used as a measurement metric. Thus, the Minimum-Transmission Broadcast (MTB) problem, which minimizes the total number of transmissions, has been formulated and investigated for a long time [4–7]. In this problem, network nodes are assumed to be active all the time for sending and receiving data. It means all nodes within the communication range of a transmitter can receive the broadcast message due to the essence of the wireless medium.

Many recent studies have identified that in WSNs, sensor nodes are mostly in the idle state during their lifetimes [8–10]. This leads to a significant amount of energy wasted. Accordingly, the duty-cycle mechanism, in which a node alternates between dormant and active states, is developed and applied to WSNs for energy conservation [10–13]. Diverse applications, such as wildlife surveillance, habitat monitoring, and object tracking, utilize this kind of duty-cycled WSN because of its energy efficiency [13–15]. In broadcast, due to this mechanism a node is required to transmit multiple times to broadcast the message to all its neighbor nodes at different moments. Evidently, solutions for broadcast in conventional wireless networks cannot be directly applied to duty-cycled environments because of the different operating mechanism. As a result, the MTB problem in duty-cycled networks (MTB-DC problem) needs to be investigated for solutions in which both the set of forwarding nodes and their broadcast schedules are identified.

Regarding the MTB-DC problem, a best known scheme, named the Set-Cover-based Approximation (SCA) scheme, has been designed in [16] to construct a broadcast backbone for disseminating the message over the network efficiently. The constructed backbone consists of a set of forwarding nodes responsible for transmitting the broadcast message. To minimize the total number of transmissions, the SCA scheme focuses on diminishing both the number of forwarding nodes in the backbone and the number of transmissions per node. This aim is achieved by two separate sub algorithms in a centralized SCA (CSCA) algorithm which is an implementation of the SCA scheme. The first one, derived from the solution for set-covering problem [17], finds a set of covering nodes (which are considered as forwarding nodes); and the second one is an approximation algorithm for constructing the broadcast backbone from these covering nodes. Besides the centralized approach, the authors also present a distributed approach to solve the problem in [16].

Since MTB-DC problem is proved to be NP-hard [16], it is still a challenge to design another algorithm which has better results. In this paper, we propose a novel scheme, named Level-Based Approximation Scheme (LBAS), to build a broadcast backbone in order to minimize the total number of transmissions more effectively than in earlier studies. Our scheme is still based on the solution for the set-covering problem to identify the set of covering nodes. However, we design an approximation algorithm for constructing the broadcast backbone for the network, which provides a near optimal solution for the MTB-DC problem. At first, each network node is assigned a level based on the distance from the node to the broadcast source. Then our scheme executes a two-stage algorithm for bidirectional traversing all predetermined forwarding nodes level by level to construct the backbone. In the first stage, a top-down traversal is performed to connect covering nodes based on the known relationship between each covering node and its covered nodes. Segments of the broadcast backbone are constructed through this stage. With a bottom-up traversal in the second stage, we finalize the backbone by linking these segments with connectors and additional transmissions for forwarding the broadcast message between segments.

Our contributions can be summarized as follows:

(1) We analyze factors which affect the total number of transmissions in a broadcast session, including the nature of the wireless communication and the essence of the direction of broadcast.
(2) Based on the analysis, we design a scheme, called LBAS, with the implemented algorithm having a low time complexity of $\mathcal{O}(n^2)$, compared with the $\mathcal{O}(n^3)$ complexity of the best known CSCA algorithm. Our algorithm provides the same approximation ratio of $3(\ln\Delta + 1)$ as the CSCA algorithm. Here n denotes the number of nodes in the network, and Δ denotes the maximum degree of the network.
(3) We conduct extensive simulations to examine the effectiveness of our proposed algorithm and other existing ones by comparing the simulation results. The simulation results show that our algorithm outperforms others, and the total number of transmissions obtained is close to the lower bound, especially when the network density is high.

The rest of the paper is organized as follows. Section 2 reviews studies related to the MTB problem, the duty-cycled wireless sensor network as well as wireless ad hoc networks (WANETs) in general; and then describes the network model, assumptions, and problem formulation. The proposed scheme and the algorithm design are presented in Section 3. We analyze the proposed scheme and then evaluate and compare the performance of our scheme with others in Section 4. Finally, we conclude the paper in Section 5.

2. Preliminaries

2.1. Related work

Due to the necessity of broadcast, diverse studies have been carried out on it in the literature. A basic problem of broadcast storm in mobile ad hoc networks was investigated in [2]. To alleviate the problem, redundant rebroadcasts, contention and collision were deeply analyzed. Then several schemes, which are based on probabilistic, counter-based, distance-based,