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Fast convergecast for low-duty-cycled multi-channel wireless sensor networks

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ABSTRACT

Convergecast is a fundamental operation in many wireless sensor network (WSN) applications. To conserve energy, many previous WSN protocols discuss to periodically schedule active timings (or say *slots*) of transmission links in the network. When collecting data, the slots should be carefully assigned to conserve latency. Recently, the multichannel concept is utilized to facilitate slot assignment. When the network has multiple channels, the convergecast latency can be further reduced since the interferences between transmission links can be eliminated. In this work, we model the above scenario as a *minimal delay scheduling* (*MDS*) problem, and prove it as an NP-complete problem. We propose a heuristic algorithm, which contains three phases. In our design, the first phase connects nodes by a shortest path tree with constrained degrees. Then, the second phase assigns slots to links to achieve optimal report latency (regardless of interferences). Finally, the third phase assigns frequency channels to nodes to eliminate interferences between links, and carefully adjust some slots if necessary. Simulation and implementation results indicate that the proposed scheme can effectively reduce the convergecast latency in WSNs with multiple channels.

1. Introduction

Convergecast is a fundamental operation in many *wireless sensor network* (*WSN*) applications including monitoring [9,16], health care [11,17], smart environment [26], and so on. It involves a set of nodes in a network to periodically report their sensory data via a *data reporting tree* to the sink node. In this scenario, there are two main technical issues: (i) how to conserve energy consumption, and (ii) how to reduce convergecast latency. To conserve energy, many previous works propose to allow nodes to switch between active and sleep mode. More specifically, each parent and child pair is demanded to periodically wake up in the assigned *time slots* to communicate with each other. In the scenario, a parent node may need to wake up at multiple time slots to collect data from all of its child nodes. After receiving reports from child nodes, the parent node can relay the collected reports to its parent in the corresponding slots. We can see that the slots of parent and child pairs should be carefully designed to conserve report latency.

Assume that a network has n slots, labeled as $0 \ldots (n-1)$, which will be periodically repeated by the sequence from slot numbered 0 to $(n-1)$. Fig. 1(a) shows an example of slot assignment, where a digit nearby a tree link is the assigned slot for the link. To reduce report latency, a link should be assigned to a slot with a larger slot number than its descendant links. However, when deciding slots, some adjacent links cannot use the same slot to avoid interferences. For example, in Fig. 1(a), when the links (u, v) and (z, y) use the same slot, the receiver of y will be interfered by u. The links $(v, sink)$ and (x, y) cannot use the

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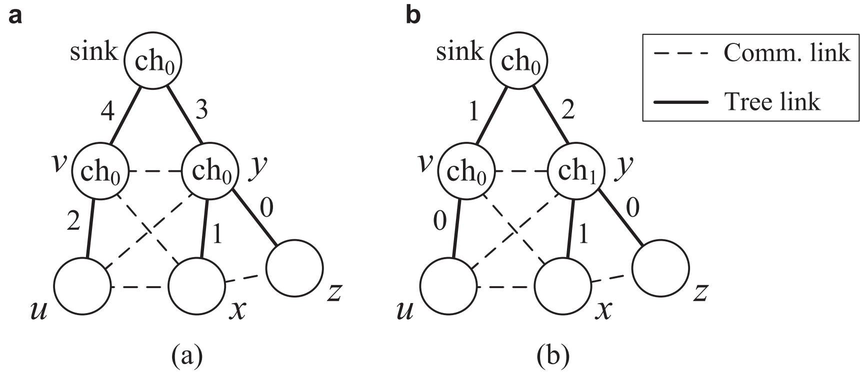

Fig. 1. The network scenario.

same slot because that the transmissions of v will interfere with the receptions of y. Moreover, in this example, the reports from node z will have the longest report latency, i.e., z's reports need three slots to arrive the sink.

Recently, some works (e.g., [6,7]) utilize the multichannel concept to facilitate slot assignment. When the network has multiple channels, each in-tree node can be assigned to a frequency channel. In the scenario, an in-tree node, say v, may need to switch between two channels. More specifically, v stays in its channel to collect reports from its child nodes (at the slots that assigned to the tree links between v and v's child nodes). Then, node v switches to its parent's channel to report data to its parent (at the slot that assigned to the tree link between v and v's parent). For a leaf node, it only needs to stay in its parent's channel. With multiple channels, some interferences between links can be eliminated, and the report latency can be reduced. For example, in Fig. 1(b), we assign channel 1 to node y, and then the link (u, v) can be assigned to slot 0. The links $(v, sink)$ and (x, y) can also be assigned to the same slot since these two links operate on different channels. Compare to the assignment in Fig. 1(a), the longest report latency, i.e., the report latency of z, will be reduced from three slots to two slots. In Fig. 1(b), the report latency of u is also reduced. Moreover, according to the above example, it is not hard to see that an improper assignment will increase the report latency. So, a good slot and channel assignment scheme is important in this network scenario.

In this work, we consider the scenario that (i) network nodes are connected by a tree topology, (ii) each tree link is assigned to one of n available slots, and (iii) each in-tree node is assigned to one of k available frequency channels. We aim to find a slot and channel assignment that can minimize the report latency of the network. We model the above scenario as a *minimal delay scheduling* (*MDS*) problem, and prove it as an NP-complete problem. In this paper, we propose a heuristic scheme, which contains three phases: *tree formation phase*, *slot assignment phase*, and *channel assignment phase*. First, we observe that a good tree topology (that has less degree and depth) can help to reduce latency. So, the tree formation phase connects nodes using a shortest path tree with constrained degrees. Then, the slot assignment phase assigns slots to links regardless of interferences between links. This phase first assigns slots to tree links in a bottom-up manner, and then reassigns slots in a top-down manner to compact the slot assignment. We prove that given a tree structure, the slot assignment phase can achieve optimized convergecast latency. Finally, the channel assignment phase eliminates interferences among links. However, it is possible that k channels are not sufficient to eliminate all interferences. So, this phase may modify some links' slots to facilitate channel assignment. We prove that compare to the optimized solution (derived in the second phase), the increased latency after adjusting slots can be bounded. Moreover, in this work, we verify the proposed scheme by both simulation programs and implementation on wireless platforms. Both simulation and experiment results indicate that the proposed scheme can effectively reduce convergecast latency in WSNs with multiple channels. In addition, since the proposed algorithm is a centralized one, we further discuss how to establish and maintain a network in a distributed manner. Our contributions and findings are summarized as below:

- Given a network with fixed numbers of slots and frequency channels, we discuss how to connect nodes and how to assign slots and channels. We formally model an MDS problem, which goal is to minimize network report latency in this network scenario. In this work, we further prove that the MDS problem is an NP-complete problem. To the best of our knowledge, this is the first work that formally models the problem and shows the difficulty of the problem under such network scenario.
- Most previous works propose to assign channels before assign slots. However, we observe that network report latency is mainly induced by the arrangement of slots. So, in this work, we first find slots for links such that the network report latency can be minimized. Then, we further assign frequency channels to nodes to eliminate interferences between links. Compare to previous works, our scheme can reduce at least 25% of network report latency.
- Given a tree topology, the proposed slot assignment phase can minimize network report latency (under the condition that the links that having common end points