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Distributed adaptive node-specific signal estimation in heterogeneous and mixed-topology wireless sensor networks ☆

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ABSTRACT

A wireless sensor network (WSN) is considered where each node estimates a number of node-specific desired signals by means of the distributed adaptive node-specific signal estimation (DANSE) algorithm. It is assumed that the topology of the WSN is constructed based on one of the two approaches, either a top-down approach where the WSN is composed of heterogeneous nodes, or a bottom-up approach where the nodes are not necessarily heterogeneous. In the top-down approach, nodes with the largest energy budgets are designated as cluster heads and the remaining nodes form clusters around these nodes. In the bottom–up approach, an ad hoc WSN is partitioned into a set of smaller substructures consisting of non-overlapping cliques that are arranged in a tree topology. These two approaches are shown to be conceptually equivalent, in that the same building blocks constitute both envisaged topologies, and the functionality of the DANSE algorithm is extended to such topologies. In using the DANSE algorithm in such topologies, the WSN converges to the same solution as if all nodes had access to all of the sensor signal observations, and provides faster convergence when compared to DANSE in a single tree topology with only a slight increase in per-node energy usage.

1. Introduction

A wireless sensor network (WSN) is deployed in a sensing environment in order to monitor or estimate a set of desired signals or set of environmental parameters. The sensing devices, or *nodes*, that form the WSN are typically able to accomplish this estimation by means of cooperative communication, by combining the sensor data

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collected by the different nodes. Instead of each node relaying this information to a fusion center, the nodes themselves can perform a local estimation which incorporates information from neighboring nodes, thereby distributing the estimation of the desired signals or parameters throughout the WSN.

In this paper, we consider WSNs where each node is tasked with estimating a number of node-specific desired signals based on sensor signal observations of the entire WSN. The nodes can accomplish this estimation by means of the distributed adaptive node-specific signal estimation (DANSE) algorithm. In the DANSE algorithm each node transmits only a fused version of the sensor signal observations to other nodes in the WSN, and yet the algorithm converges to the same solution as if each node receives all of the sensor signal observations from every node in the WSN. The DANSE algorithm has been introduced in fully connected WSNs [1,2] and in tree topologies [3] (T-DANSE) and it has been applied for, e.g., speech enhancement in wireless acoustic sensor networks [4,5] and artifact removal in electroencephalography (EEG) networks [6].

However, in these existing versions of the DANSE algorithm, the adherence to a single topological structure can have a negative impact on the resources and performance of the algorithm. In the fully connected case, each node must communicate with every other node in the WSN, which over large distances can quickly deplete the energy resources of the nodes. Conversely, while a tree topology can rely on a nearest neighbor communication strategy to reduce energy consumption, the branching of the tree will lead to an increased number of hops in between nodes which affects the input–output delay as well as the convergence speed of the DANSE algorithm. We therefore look to implement the DANSE algorithm in WSNs with more than a single topological structure, which will allow for a trade-off in performance which lies in between that of a single fully connected network and a single tree topology. The topology of these WSNs will be constructed based on one of the two approaches, namely either a top-down approach where the WSN is composed of heterogeneous nodes, or a bottom-up approach where the nodes are not necessarily heterogeneous.

With the multitude of different devices that can form a WSN, it is natural to assume that some of these devices come equipped with larger energy budgets and processing capabilities. In the *top-down* approach the nodes with the largest energy budgets are designated as cluster heads and the remaining nodes of the WSN form clusters around these nodes. Such heterogeneous WSNs offer many benefits compared to homogeneous WSNs and have been explored in order to extend the lifetime of WSNs [7,8]. They have been used for such applications as wireless body area networks [9,10] and their benefits have been outlined for use in wireless multimedia sensor networks in [11]. The heterogeneous nodes can be thought of as a partitioning of the WSN into two layers, where the top layer consists of the cluster heads, and the bottom layer consists of the member nodes of the clusters. This type of partitioning can then easily be abstracted to a WSN that is primarily hierarchical in nature.

WSNs with a hierarchical structure for distributed *parameter* estimation have been studied where the actual estimation is performed at a fusion center [12] whereas in this paper we look to distribute the estimation throughout the network. These methods have also been extended to distributed hierarchical WSNs, as the one envisaged in this paper, where the *parameter* estimation takes place using diffusion or consensus based algorithms [13–16]. In [17,18] the WSN is tasked with estimating a desired *signal* where each of the received signals at the individual clusters are correlated with one another. However, all of the information is again transmitted to a fusion center which is the only location in the WSN that performs an estimation of the desired signals.

Contrary to the top-down approach, in the *bottom-up* approach, the nodes are no longer necessarily heterogeneous in nature and the WSN is first formed in an ad hoc topology. An attractive attribute of an ad hoc WSN is a lack of fixed infrastructure which allows for greater flexibility in node deployment. This ad hoc WSN can initially be formed with a variety of constraints in mind such as: energy conservation [19,20]; communication bandwidth [21,22]; and security [23]. However, due to the lack of fixed infrastructure, it has been shown that ad hoc WSNs can suffer from scalability issues[2] due to the fact that nodes must monitor and retain network wide routing tables which can require a significant portion of the available network resources [24,25]. This problem becomes even more prevalent if the nodes are mobile requiring constant reconfiguration of these routing tables to pass information throughout the network [26].

Fortunately many of the routing and scalability challenges associated with ad hoc WSNs can be mitigated by partitioning the ad hoc configuration into a set of smaller, simpler topologies or substructures [27–29]. These substructures also lessen the impact of mobile nodes as only a relatively small number of these substructures is affected at any one time [30]. In order to determine these substructures the WSN can rely on a so-called *topology control*, which looks to extract these substructures from the original ad hoc configuration [28,31–34]. In the bottom-up approach the WSN is partitioned into a set of smaller substructures, namely non-overlapping cliques, which are connected with each other in a tree topology.

The proposed top-down and bottom-up approaches will be shown to be conceptually equivalent, in that the same building blocks constitute both the envisaged heterogeneous and mixed-topology WSNs. By way of predefined fusion rules, the functionality of the DANSE algorithm is then extended to such mixed-topology WSNs. The DANSE algorithm in a mixed-topology will be shown to converge to the same solution as if the nodes had access to all of the sensor signal observations in the WSN. Simulations will show that the mixed-topology WSN consumes a significantly lower amount of energy on a per-node basis

[2] Since the DANSE algorithm relies on in-network signal fusion, the nodes do not perform explicit routing tasks through the network, and hence these scalability issues do not really apply here. Nevertheless, we will show that pruning of an ad hoc network into a set of smaller substructures is still advantageous within the context of DANSE.