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Time slot assignment for convergecast in wireless sensor networks

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HIGHLIGHTS

- Convergecast with minimum delay and minimum energy consumption is addressed.
- A theoretical lower bound on the number of TDMA time slots required is presented.
- Proposed time slot assignment algorithm performs close to the theoretical bound.

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ABSTRACT

Convergecast, which is essentially the inverse of broadcast, can be used for data collection in a wireless sensor network. This paper addresses the problem of convergecast in a wireless sensor network that uses time division multiplexing in order to schedule its node-to-node communication in a time-bounded manner. A realistic system model and problem for convergecast with minimum delay and minimum energy consumption is formulated for wireless sensor networks. Then, based on a detailed analysis of this problem, a heuristic solution based on time slot assignments is proposed. Simulation results are used to show that the proposed algorithm performs significantly better than alternative methods for this problem. The simulation results also show that the data delivery time of the proposed algorithm is close to the theoretical bound. Furthermore, total energy consumption is significantly reduced, when compared to the alternatives, due to the time slot assignment method used in the proposed algorithm.

1. Introduction

A wireless sensor network (WSN) consists of autonomous devices, called sensor nodes, that are capable of wireless communication and use sensors to monitor various types of physical phenomena. Sensor nodes usually operate with batteries and are exposed to various threats such as rain or sabotage in the sensing field. It is hard to recharge the batteries of sensor nodes or to replace damaged sensor nodes. For this reason, sensor nodes are designed for low power consumption with low performance processors and low power radio modules. In general, sensor nodes are deployed to monitor physical conditions such as temperature, sound or images. Sensor nodes send monitored data to compute nodes with high performance, and these compute nodes analyze the collected data in order to make informed decisions.

Convergecast is a communication pattern used for collection of sensor data in a WSN [8]. In convergecast, sensor nodes in the network send data to a sink node using wireless communication links, possibly over multiple hops. Two types of data collection exist: (1) aggregated convergecast, in which, at each intermediate node on a multihop path, the data in individual packets are processed, typically to reduce the amount of information that has to be sent, before being packetized for the next hop, and (2) raw data convergecast, in which intermediate nodes relay data packets towards the sink node without modification [11]. Although aggregated convergecast can significantly shorten the data packets that have to be transmitted, raw data convergecast must be used with some WSN applications because intermediate nodes use low performance and low power processors that are not suitable for the required processing of data packets.

There are various WSN applications, such as video surveillance [3] and sniper localization [20], that require a guarantee on the data delivery time rather than simple throughput guarantees. A guarantee on the data delivery time is mandatory for hard

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real-time applications and highly desirable for soft real-time applications.

Contention-based medium access control, such as Carrier Sense Multiple Access (CSMA), is inadequate for guaranteeing data delivery time because of the possible loss of packets due to collisions and nondeterministic packets delays under high data rate conditions. On the other hand, in contention-free medium access control, such as Time Division Multiple Access (TDMA), time is divided into time slots and each sensor node transmits data only in its assigned time slots to avoid collisions. Under this scheme, a frame is defined as a period of time with a sequence of time slots that repeat in a periodic manner. The use of TDMA results in a deterministic packet delay and a guarantee on the data delivery time. Furthermore, in a wireless network, the use of fixed packet scheduling in TDMA eliminates the need for idle-time listening. This capability can be used to significantly reduce energy usage since the wireless radio modules of sensor nodes can be turned off during the time slots when no communication is assigned.

This paper focuses on raw data convergecast in a WSN. It is assumed that wireless communication in the WSN is tightly controlled. TDMA is used as the medium access protocol, and each node is only permitted to send or receive data during its allotted time slots. Data generated by a sensor node is sent to the sink node over a multi-hop network formed by wireless links. The links used during this process form a tree topology, which is referred to as a data gathering tree. This paper addresses the problem of selecting the time slots to use over each link of a data gathering tree such as to minimize the data delivery time and energy usage. This problem is formalized and analyzed, and a heuristic solution is then proposed based on the analysis. While variants of this problem have been addressed by previous researchers, the novel aspect of the proposed approach is that time synchronization and wake-up delays are added to time slots. Not only does this make the model much more practical, it also results in interesting performance and energy savings differences based on the order in which nodes go to sleep and wake up. To summarize, the main contributions of this paper are as follows.

- A new WSN data gathering tree model that takes into account time synchronization and wake-up delays.
- A theoretical lower bound on the total number of time slots required per frame.
- Analysis of energy savings based on the order in which time slots are used.
- Problem formulation for minimum data delivery time with energy conservation.
- A new heuristic algorithm for time slot assignment specifically designed to address the proposed problem.

2. Related work

In TDMA scheduling, time slots are assigned to avoid wireless interference. Time slot assignment algorithms assign time slots either to the nodes [19,14] or to the wireless links [23,7]. These algorithms are typically targeted towards minimizing the number of time slots required by each node in order to be able to communicate with all of its neighbors. In a tree topology, such as that used for raw data convergecast, sensor nodes closer to the sink node require more data transfers for forwarding. General-purpose time slot assignment algorithms such as [19,14,23,7] do not take such traits into account, and are thus inadequate for convergecast.

While static sinks are normally used to collect sensor data, it is also possible to use a mobile sink for data collection. The mobile sink is assumed to traverse the sensor field in order to collect its data [18,17]. Pazzi et al. presented E-TRAIL, a trail-based mechanism with clustering and sleep–wake cycles, in order to improve network lifetime [18]. The algorithm enables sensor nodes in the cluster to find paths to the mobile sink, with only a small overhead for routing maintenance. Park et al. presented a stop-and-move algorithm for mobile sinks [17]. The mobile sink traverses a fixed path to collect data from sensor nodes, and the algorithm finds the set of stop points that result in minimal energy consumption.

Given static sink nodes, the problem of assigning time slots in order to minimize TDMA data collection time using data aggregation has been studied in [2,16]. With data aggregation, the information collected by sensor nodes is processed and summarized in intermediate nodes before being relayed to the sink node with a fixed number of time slots. There have also been more recent works that have addressed this problem. For event detection, Gherairi et al. presented an adaptive TDMA-based clustering method [9]. To reduce data delivery time and energy consumption, time slots are only assigned to sensor nodes in the event detection area and only for wireless links on paths to the sink node rather than to the entire network. Vasavada et al. presented TDMA scheduling of a group aware tree for heterogeneous sensor nodes [24]. The tree is formed using group formations based on the types and applications of sensor nodes, and time slots are assigned to sensor nodes based on the number of their children, types of the children and their data generation rates. The data generated by sensor nodes in the same group are aggregated and does not require an additional time slot. Villas et al. presented a spatial correlation-aware algorithm to reduce redundant data for energy conservation [25]. Data aggregation of similar data generated by a region's sensor nodes are maximized by the algorithm. Dynamic aggregation-aware routes are used for load balancing according to the residual energy of each sensor node.

Static sink raw data convergecast has been studied in [22,21,8,6,1,11]. Song et al. presented time-optimal and energy-efficient packet scheduling algorithms, and used analysis to show that $\max(2N(v_1) - 1, N - 1)$ is the number of time slots required for a time-optimum algorithm, where $N(v_1)$ is the number of sensor nodes in the subtree with the largest number of sensor nodes [22]. They considered the half-duplex nature of sensor nodes only rather than wireless interference based on communication ranges. Their other work, TreeMAC, adopts a 2-dimensional frame–slot assignment where a TDMA cycle consists of multiple frames with time slots related to the depth and amount of data to be sent [21]. The assignment considers 2-hop interference and attempts to achieve high throughput and low congestion during data collection.

Gandham et al. presented distributed scheduling to minimize the total time required to complete the convergecast [8]. The upper bound on the maximum number of time slots for the algorithm is shown as $\max(3n_k - 1, N)$, where n_k is the number of nodes in the largest subtree rooted at a child of the sink node and N is the total number of nodes. Ergen et al. proposed a level-based scheduling algorithm, where a *level* is the distance from the sink node [6]. The algorithm is based on the distributed coloring of nodes, and an upper bound for the number of time slots required is presented as $\alpha(|V| - 1)$, where α is the number of colors used in a network of nodes laid out along a single line, referred to as a linear network $G = (V, E)$. Amdouni et al. presented a traffic-aware time slot assignment method for minimizing the schedule length [1]. The minimum number of time slots in linear and multi-linear topologies were analyzed. In [11], Incel et al. evaluated the impacts of transmission power control, multichannel scheduling, and the routing tree structure used in order to minimize the number of time slots required for both aggregated and raw data convergecast.

The problem of minimizing the schedule length for raw data convergecast on a single channel in general graphs is shown to be NP-hard by Choi et al. [4]. Nevertheless, Jung et al. presented an algorithm for finding the minimum scheduling time for convergecast in general networks [13].