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An optimal GTS scheduling algorithm for time-sensitive transactions in IEEE 802.15.4 networks ☆

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ABSTRACT

IEEE 802.15.4 is a new enabling standard for low-rate wireless personal area networks and has been widely accepted as a *de facto* standard for wireless sensor networking. While primary motivations behind 802.15.4 are low power and low cost wireless communications, the standard also supports time and rate sensitive applications because of its ability to operate in TDMA access modes. The TDMA mode of operation is supported via the Guaranteed Time Slot (GTS) feature of the standard. In a beacon-enabled network topology, the Personal Area Network (PAN) coordinator reserves and assigns the GTS to applications on a *first-come-first-served* (FCFS) basis in response to requests from wireless sensor nodes. This fixed FCFS scheduling service offered by the standard may not satisfy the time constraints of time-sensitive transactions with delay deadlines. Such operating scenarios often arise in wireless video surveillance and target detection applications running on sensor networks. In this paper, we design an optimal work-conserving scheduling algorithm for meeting the delay constraints of time-sensitive transactions and show that the proposed algorithm outperforms the existing scheduling model specified in IEEE 802.15.4.
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1. Introduction

Recently there has been a growing interest in the use of low rate wireless personal area networks (LR-WPAN) [3] driven by the large number of emerging applications such as home automation, health-care monitoring, environmental surveillance, and so forth. To fulfill the needs of these emerging applications, IEEE has created a new standard called IEEE 802.15.4 for LR-WPAN. This standard has been widely accepted as the *de facto* standard for wireless sensor networks. Different from IEEE 802.11 [1], which is designed for wireless local area networks (WLAN), IEEE 802.15.4 focuses on short range wireless communications.

The goal of IEEE 802.15.4 is to support low data rate connectivity among wireless sensor nodes with low complexity, cost and power consumption [5]. It specifies two types of channel access mechanisms. One is beacon mode and the other is non-beacon mode. The non-beacon mode aims at providing fair access to all wireless nodes and does not support time-sensitive applications. The beacon mode provides real-time guaranteed service by allocating the guaranteed time slot (GTS) on a first-come-first-served (FCFS) basis, where a GTS is a period of time that can be reserved by a sensor node for its packet transmission. While the beacon mode is preferred by time-sensitive wireless applications, the fixed FCFS-based scheduling offered by the standard may not satisfy the time constraints of time-sensitive transactions with delay deadlines. Such transactions are commonly seen in medical or manufacturing sensor networks that monitor and signal emergencies. Hence, to support transactions with time constraints, it is critical to design a new scheduling algorithm that dynamically allocates GTSs to meet the delay requirements of these transactions.

In this paper, we present a new GTS scheduling algorithm, named **G**TS **S**cheduling **A**lgoirthm (GSA), for beacon

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mode to meet the delay constraints of time-sensitive transactions in star topology. GSA is proved to be optimal and work-conserving. Different from the Earliest Deadline First (EDF) scheduling [4], which results in bursty transmissions of payloads for transactions with delay constraints, GSA smooths out the traffic of a transaction by distributing the GTSs of a transaction over as many beacon intervals as possible while satisfying the time constraint of the transaction. By doing so, GSA reduces the average service starting time of transactions and enables concurrent services to more transactions. This can significantly benefit many time-sensitive applications, where the starting time of the first message and the stability of traffic have great impact on the performance of these applications. Simulation results also demonstrate that GSA significantly outperforms IEEE 802.15.4's scheduling algorithm. Our performance evaluation indicates that the *time constraint meet ratio* (TMR) of our algorithm is up to 100% higher than the FCFS-based scheduling algorithm. Our algorithm differs from the existing ones in that it is an on-line scheduling algorithm and allows transmissions of bursty and periodic messages with time constraints even when the network is overloaded.

The remainder of this paper is organized as follows: Section 2 presents the related work, which is followed by a short description of the IEEE 802.15.4 standard in Section 3. In Section 4, we presents not only an optimal schedulability check for transactions, but also how to allocate the number of GTSs to the transactions as well as the mathematical model for analyzing the end-to-end delay in IEEE 802.15.4. The description of the proposed GSA is discussed in Section 5. The performance evaluation, including the experimental results, is given in Section 6. Finally, we present concluding remarks in Section 7.

2. Related work

Different from GSA, some researchers focus on scheduling issues to support other goals. In [17], the authors propose an *off-line* scheduling algorithm adjusting both superframe duration and beacon interval duration according to the periodic transmission of messages. The algorithm does not handle bursty arrivals of payloads from transactions and does not consider a per transaction time constraint that is smaller than the inter-packet arrival time. The authors in [14] present an approach to adapt the duration of the beacon interval based on the recorded communication frequency. In the approach, the duration of a beacon interval increases when the communication frequency is less than a lower bound b_l. On the other hand, the duration of beacon interval decreases when the communication frequency is greater than an upper bound b_u. The performance of the algorithm is highly sensitive to the settings of the lower bound b_l and upper bound b_u. In [8], the authors propose a prioritized services to urgent messages. It reduces the back-off duration of nodes with urgent messages to give it priority in the CAP, but it does not address how to assign GTSs to ensure time constraints of these messages. In the paper [7], the authors present a TDMA slot assignment protocol transmitted in a distributed manner. Its goal is to maximize slot utilization by changing the frame length. If there are no available time slots, it causes the sending nodes to change the frame length such that the length of time slots is reduced and thus the number of available time slots increases. Their approach does not consider the time constraint issue, while it needs exchanging additional control packets such as Request (REQ), Information (INF), Suggestion (SUG) and Reply (REP).

Some researchers focus on scheduling methods that avoid interference or collision between wireless network nodes. While the scheduling of GTS is not discussed in these works, these works can be combined with our algorithm to support larger networks where there are multiple PAN coordinators and interference is an issue among nodes that are not coordinated by the same PAN coordinator. The research work in [9] proposes a channel scheduling mechanism that allows for concurrent communication between Ultra Wideband (UWB) [2] transmitter–receiver pairs within a piconet. In [13], the authors present a time-based scheduling algorithm that assigns the time slots and variable-length guard times to the packets to avoid collision between network nodes. This approach is to maximize the network utilization by assigning a variable-length guard time between subsequent time slots. The research work in [16] proposes the maximal traffic (MT) scheduling algorithm that allocates the same time slot to the transmitter–receiver pairs that do not cause interference. To find these pairs, the authors utilize a graph coloring technique and location information provided by UWB MAC, thus guaranteeing the maximum traffic and minimum time slots. In [10], the researchers present an implicit GTS allocation mechanism, called i-GAME, in order to overcome the waste of time slots imposed by the explicit GTS allocation. Their goal is to improve the bandwidth utilization based on the delay and bandwidth requirements, by sharing the GTS among nodes. Since their approach starts the GTS allocation from the last time slot in a round-robin manner, it may fail to serve a flow with hard real-time deadline, which needs to be assigned the first GTS in the CFP. Furthermore, it requires an additional control packet for a flow specification in the higher layer. The authors in [6] propose a multi-cycle polling scheduling algorithm that yields a multi-cycle schedule for the periodic variables in the FieldBus networks. Their polling mechanism leads to an overhead for the context switching since a master device periodically polls each slave device. Furthermore, before starting polling, their algorithm requires preprocessing that determines the transmission sequence and the assignment of priorities for the variables. And, it underutilizes the time slots if there exist time spaces between the periods of the variables. This comes from the fact that their goal is only to meet the periods without consideration of the number of variables.

3. An overview of IEEE 802.15.4

Depending on the application requirements, IEEE 802.15.4 supports two topologies: the star topology and the peer-to-peer topology. In the star topology, communi-

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