Adaptive GTS Allocation in IEEE 802.15.4 for Real-Time Wireless Sensor Networks

Feng Xia, Ruonan Hao, Jie Li, Naixue Xiong, Laurence T. Yang, and Yan Zhang

Abstract—**The IEEE 802.15.4 standard is able to achieve low-power transmissions in low-rate and short-distance Wireless Personal Area Networks (WPANs). It supports a Guaranteed Time Slots (GTSs) allocation mechanism for time-critical and delay-sensitive data transmissions. However, the inflexible First-Come-First-Served (FCFS) GTS allocation policy and passive deallocation mechanism significantly impair network efficiency. This paper proposes an Adaptive and Real-Time GTS Allocation Scheme (ART-GAS) to provide differentiated services for devices with different priorities, which guarantees data transmissions for time-sensitive and high-traffic devices. The bandwidth utilization in IEEE 802.15.4-based PAN is thus improved. The proposed scheme is developed based on the IEEE 802.15.4 Medium Access Control (MAC) protocol and is fully compatible with the implementation of IEEE 802.15.4 devices. It is applicable to various real-time systems built upon wireless sensor networks. Simulation results demonstrate that our ART-GAS algorithm significantly outperforms the existing GTS mechanism specified in IEEE 802.15.4 in terms of success probability, average delay, average waiting time, and CFP bandwidth utilization.**

Index Terms—**IEEE 802.15.4, Wireless Sensor Networks, Real Time Systems, Medium Access Control, Guaranteed Time Slot.**

I. INTRODUCTION

WITH rapid improvements of wireless technologies, Wireless Sensor Networks (WSNs) are attracting growing attention from both academia and industry. The interest is mainly driven by the large amount of WSN applications, including environmental monitoring [1], industrial sensing and diagnostics [2], health care and data collection for battlefield awareness [3, 4], and most of them are developed by using low-rate, short-distance and low-cost wireless technologies. Among the well-known specifications, IEEE 802.15.4 [5], which was originally designed for Low-Rate Wireless Personal Area Networks (LR-WPANs), has become one of the most promising candidates for the next-generation wireless network technology [6].

The IEEE 802.15.4 standard provides specifications for the Physical Layer (PHY) and the Medium Access Control (MAC) sublayer [5]. Specifically, it supports two types of channel access mechanisms: beacon enabled mode and non-beacon enabled mode. The non-beacon enabled mode aims at providing fair access to all wireless nodes and does not support real-time applications. While in beacon enabled mode, the PAN coordinator generates periodic beacon frames with a provision of a superframe structure, which provides applications with a time frame property. Further, The beacon enabled mode also makes it possible to obtain 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 data transmissions. Admittedly, the GTS mechanism is able to support time-critical data transfers generated by repetitive low-latency applications and guarantee the reliability and performance of data deliveries, and from this perspective, the design of beacon enabled mode seems perfect in these situations. Nevertheless, it still has many weak points [7-10]. First, the fixed FCFS GTS scheduling mechanism may not satisfy the time constraints of real-time and high-traffic applications, which are commonly seen in medical or manufacturing sensor networks that monitor and signal emergencies. Second, the abuse of dedicated resources might result in the exclusion of other transmissions due to the scheduling inflexibility in low-latency data delivery, corresponding to network workload and application needs. Third, starvation might be caused for devices with low data transmission frequencies since a fixed timer is maintained in IEEE 802.15.4 for GTS deallocation. Hence, to resolve the above issues, it is critical to design a new GTS allocation scheme that can adaptively schedule GTSs to needy devices in an efficient and timely manner.

This paper mainly focuses on the GTS allocation mechanism in IEEE 802.15.4 and proposes an Adaptive and Real-Time GTS allocation Scheme (called ART-GAS) to support time-critical and delay-sensitive wireless applications. The proposed scheme is developed based on the standard of the IEEE 802.15.4 MAC protocol and completely follows the specifications defined in [5] without introducing any extra protocol overhead. A preliminary version of our ART-GTS was presented in [8]. This paper extends our previous work with substantially new contents including (1) applying the mechanism in a real scenario of health care application, (2) detailed description of (improved) mechanisms and algorithms. Besides, extensive numerical results and analysis are also presented here under the situations of diverse number of nodes. Major research contributions of this paper are as follows. (1) It provides differentiated services for devices in different priority levels, where both data-based priority and rate-based priority are considered in GTS allocation. Thus, data transmissions of time-critical and high-traffic devices are better guaranteed. (2) An adaptive GTS scheduling mechanism is further proposed by utilizing a dynamic threshold priority. This is based on both network load and application needs (that is, priorities),

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which provides a significant improvement in terms of average delay and fairness performance. Bandwidth utilization is thus improved. (3) We also presents a careful evaluation of ART-GAS performance in this paper and further analysis is given by comparing it with the existing IEEE 802.15.4 MAC through simulations. These evaluations examine the protocols from an implementation perspective and take into account environmental details like number of sensor nodes and traffic load.

The remainder of this paper is organized as follows. Section II presents the related work, which is followed by a brief overview of the IEEE 802.15.4 MAC protocol in Section III. In Section IV, we present basic principles and mechanisms of the ART-GAS algorithm, including service differentiation and GTS allocation. The design and implementation issues are described in Section V. The performance evaluation, including experimental results, is given in Section VI. Finally, Section VII concludes the paper.

II. Related Work

The performance of the IEEE 802.15.4 protocol has been subject of many research studies recently. These studies include the performance analysis of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [9-11] in Contention Access Period (CAP), as well as the GTS mechanism [12-14] operating in the Contention Free Period (CFP). Specifically, some interesting algorithms have been proposed to improve the performance of IEEE 802.15.4 MAC [15-18]. For example, energy is a valuable resource in sensor networks, and thus, tremendous research work is concerning MAC protocol optimization to conserve energy, throughput, and other similar performance metrics in the process [19]. In [15], Valero *et al.* propose an incrementally deployable energy efficient MAC protocol based on IEEE 802.15.4 to minimize energy consumption. Li *et al.* [16] present a brand new approach by utilizing a Synchronous Low Power Listening technique to achieve lower power consumption for low data rate applications. In [17], a channel feedback-based enhancement to the IEEE 802.15.4 MAC is proposed that is significantly more scalable, showing a relatively flat, slow-changing total system throughput and energy consumption. Kojima and Harada [18] adopt a low-power multi-hop data-frame transmission scheme to reduce power wastage due to periodic transmission and a dynamic re-association procedure for optimizing the allocated active period is used for low power consumption over the entire system. These protocols are able to render significant improvements in terms of energy efficiency compared with the standard IEEE 802.15.4 MAC. However, they are typically not suitable when applications demand better performance at the expense of some additional energy, especially in life-critical or safety-critical areas. In these cases, the issue of Quality of Service (QoS) provisioning should be given more attention.

Nowadays, with the ever-increasing usage of IEEE 802.15.4 networks in health care systems, community medical services, alarm systems, etc., where QoS is to be emphasized for emergency messages with energy consumption only a secondary issue, some researchers begin to seek solutions to meet requirements of these applications. For instance, Kobayashi and Sugiura [20] propose a Timing Group Division method to achieve faster communications by optimizing the traditional CSMA/CA mechanism. Khan [21] adopts an Improved Binary Exponential Backoff algorithm to avoid collision and decrease latency, which exhibits great QoS improvement in IEEE 802.15.4. In [22], a backoff control mechanism is given to improve the delay performance as well as keep throughput enhancement in cluster-based WSNs. However, these solutions only take into account the contention access period, while ignoring the GTS scheduling in contention free period, which may have much more significant impact on QoS. In [23], Yoo *et al.* presents a real-time message scheduling mechanism to schedule a large number of real-time messages to meet their timing constraints. Chen *et al.* [24] propose an Explicit Guaranteed time slot Sharing and Allocation scheme (EGSA) for beacon-enabled IEEE 802.15.4 networks, which is capable of providing tighter delay bounds for real-time communications. Additionally, the authors of [25], [26], and [27] also provide effective approaches for meeting delay constraints of time-sensitive applications. While these GTS scheduling solutions are able to guarantee real-time data transmissions in IEEE 802.15.4 networks, they have not devoted enough attention to the issue of bandwidth utilization, thus leading to unnecessary wastage of GTS resources.

Le *et al.* [28] propose an unbalanced GTS allocation scheme (UGAS), which divides the CFP into different duration time slots for different bandwidth requirements to minimize the under-utilization. In [29], a new GTS scheme is designed to allow more devices to share bandwidth within the same period. These two methods can improve the bandwidth resource efficiency but real-time performance is not ensured in the meanwhile. Shrestha *et al.* [30] present an optimization-based GTS allocation scheme that can improve reliability and bandwidth utilization, as well as support time-critical or delay-sensitive data transmissions. However, it cannot adapt to different traffic conditions in network, thus lacking flexibility in GTS allocation. A delay-sensitive GTS allocation scheme is presented in [31] based on GTS usage feedback to satisfy the delay constraints of devices in different traffic conditions. Nevertheless, priorities of devices are specified as fixed values in this approach so that it may not give satisfactory performance in a dynamic environment.

In contrast to previous solutions [32], the proposed ART-GAS algorithm in this paper is based on a two stage approach. Services are differentiated in the first stage through a dynamic priority assignment policy. GTSs are scheduled in the following stage to needy devices in an efficient manner. The important features of ART-GAS are as follows: (1) Both data-based priority and rate-based priority are considered in service differentiation, thus real-time and high-traffic data transmissions are guaranteed; (2) GTS allocation is highly adaptive to network load and application needs and can be easily applied to a dynamic environment; and meanwhile, (3) GTS resources are more efficiently utilized. The detailed description of ART-GAS will be presented in Section IV.

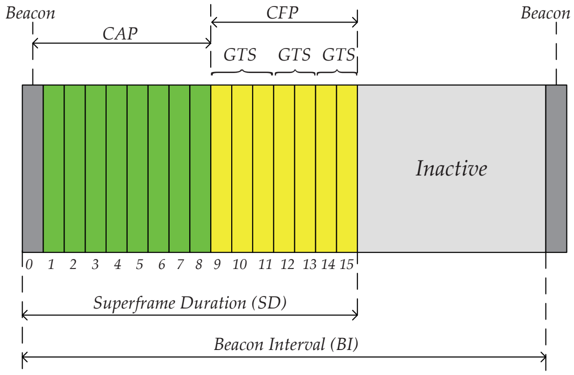

Fig. 1. IEEE 802.15.4 superframe structure

III. Overview of IEEE 802.15.4 MAC Protocol

IEEE 802.15.4 is a standard for low-rate, low-power and low-cost Personal Area Networks (PANs) [5]. It defines two different channel access methods: beacon enabled mode and non-beacon enabled mode. The non-beacon enabled mode is entirely contention based. It uses unslotted CSMA/CA to manage access to the channel. There is no provision for service requirement guarantees in this mode of operation. Whereas, the beacon enabled mode provides a contention-free GTS mechanism to support time-sensitive data transmissions. Hence, we only focus on the more commonly used beacon enabled mode in this paper.

In beacon enabled mode, beacon frames are periodically sent by the PAN coordinator to identify its PAN and synchronize nodes that are associated with it. The PAN coordinator defines a superframe structure characterized by a $Beacon\ Interval\ (BI)$ and a $Superframe\ Duration\ (SD)$. $Beacon\ Interval$ specifies the time between two consecutive beacons, and includes an active period and, optionally an inactive period. The active period, also called superframe, is corresponding to $Superframe\ Duration$ and can be divided into 16 equally-sized time slots, during which frame transmissions are allowed. During the inactive period (if it exists), all nodes may enter into a low-power state to save energy. The superframe structure of beacon enabled mode is depicted in Fig. 1.

BI and SD are determined by two parameters, the $Beacon\ Order\ (BO)$ and the $Superframe\ Order\ (SO)$ respectively, which are broadcasted by the coordinator via a beacon to all nodes.

BI and SD are defined as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO}, \quad for\ 0 \leq BO \leq 14 \tag{1}$$

$$SD = aBaseSuperframeDuration \times 2^{SO}, \quad for\ 0 \leq SO \leq BO \leq 14 \tag{2}$$

In Eqs. (1) and (2), $aBaseSuperframeDuration$ denotes the minimum duration of the superframe, corresponding to $SO = 0$. This value also corresponds to 15.36 ms, assuming 250 kbps in the 2.4 GHz frequency band, which will be considered throughout the rest of this paper.

The $Superframe\ Duration$ can be further divided into CAP and CFP. The beacon is transmitted by the coordinator at the start of slot 0, and the CAP follows immediately after the beacon. During the CAP, a slotted CSMA/CA algorithm is used for channel access. A node computes its backoff delay based on a random number of backoff periods, and performs two CCAs (Clear Channel Assessments) before accessing the medium. In addition to non time-critical data frames, MAC commands such as association requests and GTS requests are transmitted in the CAP.

In the CFP, which is for the use of devices requiring dedicated bandwidth, the communication occurs in a TDMA (Time Division Multiple Access) style by using a number of GTSs, pre-assigned to the individual sensor nodes. Whenever a device requires a certain guaranteed bandwidth for transmission, the device sends GTS request command using CSMA/CA during CAP. Upon receiving the request, the coordinator first checks the availability of GTS slots in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS. The superframe shall have available capacity if the maximum number of GTSs has not been reached and allocating a GTS of the desired length would not reduce the length of the CAP to less than $aMinCAPLength$. Provided there is sufficient capacity in the current superframe, the coordinator determines, based on a FCFS fashion, a device list for GTS allocation in the next superframe, and informs the devices about the allocation of slots in the GTS descriptor in the following beacon frame.

GTS deallocation can be performed by the coordinator or by the device itself. For device initialized deallocation, it sends GTS request with characteristic type subfield set to zero using CSMA/CA during CAP. From this point onward, the GTS to be deallocated shall not be used by the device, and its stored characteristics shall be reset. In this way, devices can return the GTS resources by explicitly requesting that the PAN coordinator provide deallocation. However, in most cases, the PAN coordinator has to detect the activities of the devices occupying GTSs and determine when the devices stop using their GTSs. If the coordinator does not receive data from the device in the GTS for at least $2 \times n$ super frames, the coordinator will deallocate the GTS with starting slot subfield set to zero in the GTS descriptor field of the beacon frame for that device, where $n = 2^{8-BO}\ for\ 0 \leq BO \leq 8$, and $n = 1\ for\ 9 \leq BO \leq 14$.

IV. ART-GAS: Adaptive GTS Allocation

The objective of this section is to describe the basic ideas and mechanisms of our ART-GAS scheme for the IEEE 802.15.4 standard using a star topology. As an example, consider an application of health care with wireless body sensor networks (see Fig. 2). The PAN coordinator collects data from different sensors deployed in the body of the people. These sensor devices can be electrocardiogram (ECG), blood pressure, temperature, and accelerometer. Data from these sensors are collected periodically. However, emergency data may be generated randomly and need to be transmitted immediately. Furthermore, the GTS resources should be carefully

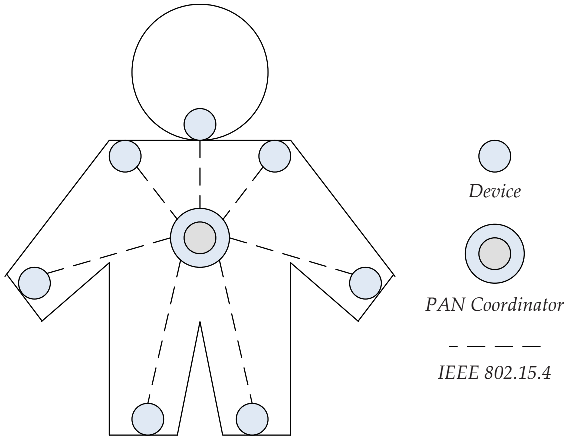

Fig. 2. Star topology of a PAN

allocated to needy devices with higher frequencies of sending data and the previously allocated but unused GTSs should be reclaimed in time to improve network efficiency.

To solve these problems, our ART-GAS adopts a priority-based GTS scheduling approach, which is based on both the service differentiation mechanism and the GTS allocation mechanism. In the service differentiation mechanism, devices are assigned two different kinds of priorities in a dynamic fashion: data-based priority and rate-based priority. Devices sending data of greater importance or with real-time requirements are given higher data-based priorities, while devices with higher frequencies of sending data are given higher rate-based priorities. In other words, data-based priorities are assigned according to "data", and rate-based priorities are assigned according to "rate". In the GTS allocation mechanism, a comprehensive policy of utilizing the two priorities is proposed. GTSs are given to devices in a decreasing order of their priorities. Further, various scenarios of different data-based priorities and rate-based priorities are discussed, CAP and CFP traffic loads have also been taken into consideration. Additionally, a starvation avoidance mechanism is presented to regain service attention for lower priority devices. Finally, we provide a GTS allocation scheme which can satisfy the needs of both time-critical and high-frequency devices. Details of the service differentiation mechanism and the GTS allocation mechanism are presented in the following sections.

A. Service Differentiation

In the service differentiation mechanism, each device is adaptively assigned a data-based priority and a rate-based priority by the PAN coordinator, according to the importance of data and past transmission feedback respectively. Assume that there are N devices in an IEEE 802.15.4-based PAN, and that there are $N_d(0, 1, ..., N_{d-1})$ data-based priority numbers and $N_r(0, 1, ..., N_{r-1})$ rate-based priority numbers dynamically assigned to the N devices. The data-based priority number assigned to the device n is defined as P_{d_n}, and the rate-based priority number assigned to the device n is defined as P_{r_n}, then we have $0 \leq P_{d_n} \leq N_{d-1}$ and $0 \leq P_{r_n} \leq N_{r-1}$. In our ART-GAS, a larger priority number represents a higher

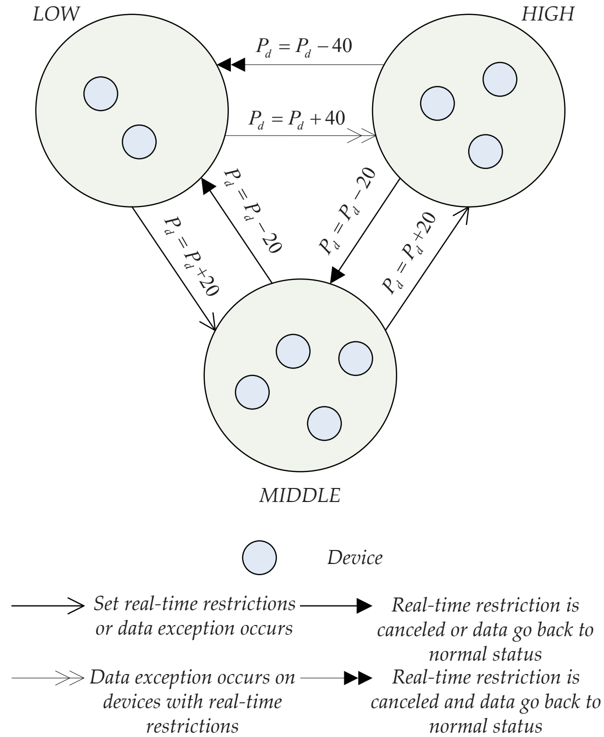

Fig. 3. State transition diagram

priority for GTS allocation. Devices with higher data-based priorities are assumed to send time-critical data, such as alarms and emergency messages, and devices with higher rate-based priorities are considered to have more recent traffic and thus having higher probabilities to transmit their data in the following superframe. The priority numbers of a device are internally maintained by the PAN coordinator.

1) Data-based Priority: In the MAC modifications, we set the total number of data-based priorities, N_d to 60 and classify all devices into three data-based priority levels according to whether there are exceptions or real-time requirements related to the data. The process is depicted by the state transition diagram in Fig. 3.

Each device has three states: LOW, MIDDLE, and HIGH, corresponding to its three levels respectively, and LOW has the data-based priority numbers from 0 to 19, MIDDLE has the numbers from 20 to 39, and HIGH has the numbers from 40 to 59. States LOW, MIDDLE, and HIGH are defined as follows:

- *LOW:* All devices are placed in the LOW state initially. There are neither transmission time restrictions nor exceptions in any of these data in this state. Their different data-based priority numbers are only determined only by their degree of importance without any other considerations. For example, data of heart rate will have a higher data-based priority than data of temperature in terms of importance.
- *MIDDLE:* Devices in the MIDDLE state are sending data that have real-time requirements or indicate that certain exceptional phenomenon related to the data value occurs during the current superframe. For example, if the data

STEP-1
All devices are initialized to the LOW state, which indicates there is no exceptions or real-time restrictions.

STEP-2
When a device detects that an exception occurs or real-time restriction is set, it will switch the current state to MIDDLE and increase its data-based priority by 20.

STEP-3
For devices in the LOW state, whenever an exception occurs, and meanwhile, the real-time restriction is set, the MIDDLE state is skipped and the HIGH state is set. Correspondingly, P_d will be increased by 40 instead of 20. For devices in the MIDDLE state, whenever an exception occurs upon data with real-time restrictions, the HIGH state is set with P_d increased by 20.

STEP-4
For devices in the MIDDLE state and the HIGH state, whenever requirements of the particular state cannot be satisfied, the device will be set to the matching state and its data-based priority will be decreased by 20 or 40.

Fig. 4. Basic steps of the state transition scheme

value of temperature (we assume there is no real-time restrictions in this case) exceeds the normal upper bound value $37°C$, then we consider that an exception occurs, and the corresponding data-based priority of temperature will be increased and the MIDDLE state is set. Whenever the real-time restrictions are canceled or the data value goes back within the normal interval, the device will leave the MIDDLE state for its original LOW state.

- *HIGH:* The state HIGH means that there are certain exceptions in data with real-time restrictions. This represents the highest level of data-based priority, which always indicates an emergency message or an alarm. In this case, we will set HIGH state to the device and increase its data-based priority in order to privilege the time-critical data over the less critical data, and meanwhile, related adaptive performance can be supported.

Fig. 4 shows the basic steps of the state transition scheme. The three states are switched dynamically as shown in Fig. 4.

2) Rate-based Priority: In addition to the data-based priorities, rate-based priorities are also dynamically assigned to each device by the PAN coordinator according to its recent transmission feedback. This method provides a good estimate of the future GTS usage behaviors of devices. Hence, GTS resources can be allocated to the needy devices with high frequencies of sending data, according to their different rate-based priorities. A waste of GTS resources is avoided in this way. Before presenting details of the rate-based priority assignment policy, we define CSMA/CA hit and CSMA/CA miss, GTS hit and GTS miss as follows:

- *CSMA/CA hit and CSMA/CA miss:* If one device has attempted to access the channel in the CAP of the current superframe, the device is defined to have a CSMA/CA hit, no matter whether the attempt was successful or not. Otherwise, the device is considered to have a CSMA/CA miss.
- *GTS hit and GTS miss:* If one device has issued a successful GTS request in the CAP or transmitted data within its allocated GTS to the PAN coordinator during the period of the current superframe, the device is defined to have a GTS hit. Otherwise, the device is considered to have a GTS miss [33].

It is obvious that a CSMA/CA hit or GTS hit indicates more recent traffic for a certain device, whereas a CSMA/CA miss or GTS miss represents a comparatively light traffic. Consequently, we can know about the recent data transmission behaviors of devices through the occurrence of CSMA/CA hit/miss and GTS hit/miss. Then the rate-based priorities can be set dynamically according to the transmission feedback.

Specifically, whenever a CSMA/CA hit or GTS hit occurs on a device, the rate-based priority number will be increased by the PAN coordinator, and the priority of GTS allocation for the device upgrades. On the other hand, upon occurrence of a CSMA/CA miss or a GTS miss, the PAN coordinator decreases the rate-based priority number of the device to reduce its opportunity for obtaining the GTS resources. In this way, devices with more frequent data transmissions will have larger probabilities to obtain GTS allocation in the subsequent superframe, while devices with a light recent traffic will have smaller probabilities of gaining GTS resources.

Furthermore, when a CSMA/CA hit/miss or a GTS hit/miss occurs, devices should not be treated equally if they have different rate-based priority numbers. For example, devices with high rate-based priorities, which stay in a high traffic level, can tolerate more easily temporarily-unstable transmission behaviors. Such devices are slightly demoted to lower rate-based priorities upon occurrence of a CSMA/CA miss or a GTS miss. Whereas, devices with comparatively low rate-based priorities are demoted more greatly for the same CSMA/CA miss or GTS miss. Additionally, when there is a CSMA/CA hit or a GTS hit, devices with lower rate-based priorities will be more greatly promoted to higher priorities to receive GTS service as soon as possible. As a result, starvation of such a low-priority device can be avoided.

This rate-based priority assignment policy focuses on whether devices have continuous data to be transmitted over the GTSs. The devices with consecutive transmissions are favored by our scheme, and for a device that is idle for a period of time, its rate-based priority will be greatly degraded by the PAN coordinator and the unused GTSs will be reclaimed immediately for high traffic devices. In this way, GTS resources are more efficiently used by devices.

Let us assume that device i maintains the following parameters at the beginning of the t^{th} superframe. $P_{r_i}^{t-1}$ and $P_{r_i}^{t}$ are the rate-based priorities in the previous superframe and the current superframe respectively. $N_{CSMA/CA,hit_i}^{t-1}$ and N_{GTS,hit_i}^{t-1} are the numbers of CSMA/CA hit and GTS hit that occur on device i in the previous superframe, respectively. Assume that each device receives the beacon at the beginning of the current superframe, then the rate-based priority of device i, i.e. $P_{r_i}^{t}$, will be updated as follows:

$$\begin{aligned} P_{r_i}^{t} = P_{r_i}^{t-1} - M_{CSMA/CA}(P_{r_i}^{t-1}) - M_{GTS}(P_{r_i}^{t-1}) \\ +H_{CSMA/CA}(P_{r_i}^{t-1}) + H_{GTS}(P_{r_i}^{t-1}) \end{aligned} \tag{3}$$

$M_{CSMA/CA}(P_{r_i}^{t-1}), M_{GTS}(P_{r_i}^{t-1}), H_{CSMA/CA}(P_{r_i}^{t-1})$, and $H_{GTS}(P_{r_i}^{t-1})$ can be determined by:

$$M_{CSMA/CA}(P_{r_i}^{t-1}) = \frac{\lambda_{CSMA/CA,miss}}{P_{r_i}^{t-1}} \tag{4}$$

$$M_{GTS}(P_{r_i}^{t-1}) = \frac{\lambda_{GTS,miss}}{P_{r_i}^{t-1}} \tag{5}$$

$$H_{CSMA/CA}(P_{r_i}^{t-1}) = \frac{\lambda_{CSMA/CA,hit}}{P_{r_i}^{t-1}} \times 2^{N_{CSMA/CA,hit_i}^{t-1}} \tag{6}$$

$$H_{GTS}(P_{r_i}^{t-1}) = \frac{\lambda_{GTS,hit}}{P_{r_i}^{t-1}} \times 2^{N_{GTS,hit_i}^{t-1}} \tag{7}$$

where $\lambda_{CSMA/CA,miss}$, $\lambda_{GTS,miss}$, $\lambda_{CSMA/CA,hit}$, and $\lambda_{GTS,hit}$ are all constants, and $\lambda_{CSMA/CA,miss}$, $\lambda_{GTS,miss}$, $\lambda_{GTS,hit}$, and $\lambda_{CSMA/CA,hit}$ are greater than zero.

As an example, consider $P_{r_1}^{t-1} = 5$ for device 1, and $P_{r_2}^{t-1} = 10$ for device 2. Suppose there is a GTS miss for both devices during the $(t-1)^{th}$ superframe (CSMA/CA hit and CSMA/CA miss are not considered), then at the beginning of the t^{th} superframe, their rate-based priorities can be obtained from:

$$\begin{aligned} P_{r_1}^{t} &= P_{r_1}^{t-1} - M_{GTS}(P_{r_1}^{t-1}) \\ &= P_{r_1}^{t-1} - \tfrac{\lambda_{GTS,miss}}{P_{r_1}^{t-1}} = 5 - \lambda_{GTS,miss}/5 \end{aligned}$$

$$\begin{aligned} P_{r_2}^{t} &= P_{r_2}^{t-1} - M_{GTS}(P_{r_2}^{t-1}) \\ &= P_{r_2}^{t-1} - \tfrac{\lambda_{GTS,miss}}{P_{r_2}^{t-1}} = 10 - \lambda_{GTS,miss}/10 \end{aligned}$$

In the above case, device 2 has a higher previous rate-based priority than device 1. When there is a GTS miss in the current superframe, the two devices' priorities are both decreased. However, they are decreased by different values, $\lambda_{GTS,miss}/5$ for device 1 and $\lambda_{GTS,miss}/10$ for device 2. This is because devices with higher rate-based priorities, which indicate consecutive transmissions, can tolerate temporarily unstable transmission behaviors in a relatively easy way. Such devices will be slightly demoted to lower priorities on the occurrence of a GTS miss, compared with the low priority devices.

Fig. 5. presents the flowchart of the rate-based priority assignment process in a superframe.

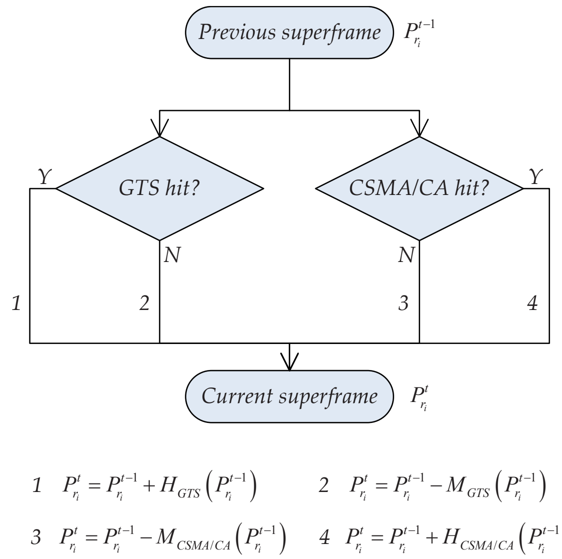

Fig. 5. Rate-based priority assignment process

B. Guaranteed Time Slots Allocation

According to the IEEE 802.15.4 Specification [1], on receipt of a GTS request, the PAN coordinator shall first check if there is available capacity in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS. GTSs shall be allocated if the maximum number of GTSs (seven) has not been reached and allocating a GTS of the desired length would not reduce the length of the CAP to less than $aMinCAPLength$.

Here we describe the GTS allocation mechanism for our ART-GAS algorithm. The proposed mechanism will modify the FCFS GTS allocation policy in IEEE 802.15.4 standard, and optimize the traditional GTS deallocation scheme which may lead to starvation of light-traffic devices.

In our GTS allocation mechanism, the GTS scheduling criteria are based on the priority numbers (data-based priorities and rate-based priorities), the superframe length (depending on the BO value), and the GTS capacity of the superframe, compared with the original GTS mechanism. In this method, time-critical devices with higher frequencies of sending data are privileged over non time-critical and light-traffic devices. Details of the algorithm are presented as follows:

At first, we classify all devices into three states, LOW, MIDDLE, and HIGH, according to their data-based priority levels described in Section III(A). For each state, we define a GTS scheduling criterion, which determines whether the GTS resources will be allocated to certain device. Criteria for different states are different, hence service for devices with LOW, MIDDLE and HIGH data-based priority levels will be differentiated.

Let P_i denote the priority of device i to obtain GTS allocation, and GTSs shall be given to devices in a decreasing order of their priorities. P_L, P_M, and P_H denote the minimum priority of a device to be allocated the GTS resources in state LOW, MIDDLE and HIGH respectively. In other words, GTSs can be allocated to device i only when one of the following requirements is met:

- For device i in LOW state: $P_i \geq P_L$;
- For device i in MIDDLE state: $P_i \geq P_M$;
- For device i in HIGH state: $P_i \geq P_H$.

For devices in the HIGH state, which means the highest level of data-based priorities, the real-time guarantee for emergency messages is the primary concern, whereas the frequencies of data transmission are considered to be less important. In this scenario, we define P_i as $P_i = P_{d_i}$ and P_H as $P_H = Min(P_i) = 40$. Hence there will be no extra limitations for devices in the HIGH state whenever they have data to transmit, provided that there is available capacity in the current superfame.

For devices in the MIDDLE state, both the data-based priority and rate-based priority are considered to determine a GTS allocation. The priority P_i is defined as $P_i = \sqrt{P_{d_i} \times P_{r_i}}$, which is based on the device's data-based priority P_d and rate-based priority P_r. Furthermore, we define the threshold priority P_M as follows:

$$P_M = \frac{\mu_M \phi_M(\sum_{i=1}^{N} \sqrt{P_i^2})}{N\Delta^{BO}} \tag{8}$$

where μ_M and Δ are both constants, and $\mu_M > 0,\ 0 < \Delta \leq 1$. N is the number of devices in the current IEEE 802.15.4-based PAN.

P_M is used here to filter unnecessary GTS allocations. It is dynamically adjusted and mainly depends on $\frac{\phi(\sum_{i=1}^{N} \sqrt{P_i^2})}{N}$ and Δ^{BO}. BO is an indication of CAP and CFP traffic load. As BO increases, there is a higher probability that a great number of devices have requested the GTS service in a superframe. Based on our service differentiation mechanism, the devices requesting GTS allocation are assigned big priority numbers, even though they only have one request in the whole superframe. To prevent the scarce GTS resources from being distributed to those devices with extremely low frequency GTS requests in such a long superframe, a stricter threshold is needed. In this case, P_M will be set to a larger value to filter low priority devices. On the other hand, with a small BO, the value of P_M can be decreased and the limitation for the device selection can be relaxed. $\frac{\sum_{i=1}^{N} \sqrt{P_i^2}}{N}$ represents an average level of devices' priorities in a superframe. ϕ is a function of $\sum_{i=1}^{N} \sqrt{P_i^2}$. Its output is a particular percentage of the input value, which can be 80%, 90%, 100%, 110% or 120% of the given $\sum_{i=1}^{N} \sqrt{P_i^2}$. The value depends on the overall level of devices' priorities. When $\sum_{i=1}^{N} \sqrt{P_i^2}$ has a larger value, the corresponding percentage might be 80% or 90%. On the contrary, the percentage might be 110% or 120% when a relatively small $\sum_{i=1}^{N} \sqrt{P_i^2}$ is obtained. The ϕ function is designed to provide multi-level restrictions for devices in different traffic conditions. Specifically, when most of the devices have low priorities, the input value $\sum_{i=1}^{N} \sqrt{P_i^2}$ is smaller, and there is no need to allocate too many GTS resources for the devices. Too much dedicated bandwidth for GTS usage leads to resource wastage and to the degradation of the overall system performance. Instead, the GTS bandwidth should be transferred for contention-based accesses in CAP. In this case, a larger percentage is used to increment ϕ and the threshold value will also be increased, rendering a strict limitation for devices in the current superframe. Otherwise, a smaller output of function ϕ is obtained, which means a more relaxed restriction for devices in the high-priority environment.

For devices in the LOW state, rate-based priorities are considered to be more important since they all stay in low data-based priority levels. In this case, P_i is defined as $P_i = P_{r_i}$. As in the MIDDLE state, the threshold value P_L is defined as:

$$P_L = \frac{\mu_L \phi_L(\sum_{i=1}^{N} \sqrt{P_i{}^2})}{N\Delta^{BO}} \tag{9}$$

However, this is a more restricted limitation for GTS allocation compared with the MIDDLE state since we have different μ_M and μ_L values.

The P_i values and the threshold priorities of states HIGH, MIDDLE and LOW respectively are given below:

$$\begin{cases} HIGH: P_i = P_{d_i}, P_H = Min(P_i) \\ MIDDLE: P_i = \sqrt{P_{d_i} \times P_{r_i}}, P_M = \frac{\mu_M \phi_M(\sum_{i=1}^{N} \sqrt{P_i{}^2})}{N\Delta^{BO}} \\ LOW: P_i = P_{r_i}, P_L = \frac{\mu_L \phi_L(\sum_{i=1}^{N} \sqrt{P_i{}^2})}{N\Delta^{BO}} \end{cases}$$

V. Algorithm Design and Implementation

In this section, we describe the design and implementation of the algorithm of our ART-GAS scheme. From an application perspective, ART-GAS will be invoked before the PAN coordinator transmits the beacon frame to the devices within its transmission range.

A. Algorithm Description

Here we present a Status Management Algorithm and a Priority Filter Algorithm for the ART-GTS scheme proposed in the previous section.

Algorithm 1 Status Management Algorithm

Assume that there are N devices in the WPAN
type $Device = (id, S, RT, InRange)$
type $DeviceSetType = (D_i,$ Devices in the current WPAN)
$DeviceSetType\ DeviceSet$
$Device\ D$
for device $D_i \in DeviceSet$ **do**
    $RT_i \Leftarrow FALSE$
    $InRange_i \Leftarrow TRUE$
    $S_i \Leftarrow LOW$
end for
$i \Leftarrow 1$
while $i \leq N$ **do**
    if $RT_i = TRUE$ and $InRange_i = FALSE$ **then**
        $S_i \Leftarrow HIGH$
    else if $RT_i = TRUE$ or $InRange_i = FALSE$ **then**
        $S_i \Leftarrow MIDDLE$
    else
        $S_i \Leftarrow LOW$
    end if
    $i \Leftarrow i + 1$
end while

Algorithm 1 is the Status Management Function of devices in the IEEE 802.15.4-based PAN. It maintains a set of active devices, denoted as $DeviceSet$, and is invoked at the beginning of each $Beacon\ Interval$. Whenever a change occurs on certain device concerning real-time requirements and data exceptions, its status will be changed correspondingly. Parameter RT will be $TRUE$ if real-time restriction is set, otherwise RT will be $FALSE$. Similarly, parameter $InRange$ is set to $TRUE$ or $FALSE$ depending on whether the data value beyond the normal boundary. In this way, all the devices are switched flexibly to different states according to different conditions of data transmissions (i.e., different data-based priorities).

In the GTS Allocation Mechanism (described in Section III(B)), the Priority Filter function is called, taking the following parameters as inputs: the number of allocated time slots T, the number of devices in the current WPAN, the set of such devices ($DeviceSet$), and each device's state (S_i) and priority (P_i). If a device's priority is not lower than its threshold value, the PAN coordinator will allocate GTS resources to the certain device, provided that the GTS capacity is not overloaded (that is, the maximum length of seven time slots is not reached). Otherwise, any new GTS requests shall be rejected since no more GTS can be allocated.

Algorithm 2 Priority Filter Algorithm

1: Assume that there are N devices in the current WPAN
2: The number of allocated GTS T
3: $DeviceSet = \{D_1, D_2, \cdots, D_N\}$
4: $P = \{P_1, P_2, \cdots, P_N\}$
5: $P_H = Min(P_i)$
6: $P_M = \frac{\mu_M \phi_M (\sum_{i=1}^{N} \sqrt{P_i{}^2})}{N\Delta^{BO}}$
7: $P_L = \frac{\mu_L \phi_L (\sum_{i=1}^{N} \sqrt{P_i{}^2})}{N\Delta^{BO}}$
8: **while** $T < 7$ **do**
9: Find a device D_i whose P_i is the maximum number in P
10: **if** $S_i = HIGH$ and $P_i \geq P_H$ **then**
11: Allocate GTS to device D_i and $T \Leftarrow T + 1$ **return** $TRUE$
12: **else if** $S_i = MIDDLE$ and $P_i \geq P_M$ **then**
13: **goto** line 11
14: **else if** $S_i = LOW$ and $P_i \geq P_L$ **then**
15: **goto** line 11
16: **else**
17: Device D_i will not be scheduled in the current superframe **return** $FALSE$
18: **end if**
19: **end while**

Algorithm 2 presents the Priority Filter function. It returns a Boolean value stating whether or not to accept a device's GTS request according to its transmission states and priorities. The return value is set to $TRUE$ if requirements of the GTS allocation are satisfied, otherwise, it will be set to $FALSE$. As we have mentioned before, devices in states HIGH, MIDDLE and LOW have different threshold priority values. Only when the device's priority exceeds or equals to its corresponding threshold, will the device be scheduled in GTSs of the current superframe.

B. Implementation Issues

From a practical point of view, ART-GAS can be easily granted into the IEEE 802.15.4 protocol with a minor change. In this section, we discuss some implementation issues of our ART-GAS algorithm in comparison with the original IEEE 802.15.4 GTS allocation mechanism.

To implement the ART-GAS in the IEEE 802.15.4-based PAN for adaptive and timely GTS allocation, some extra records for devices are required, compared with the original IEEE 802.15.4 GTS mechanism. For example, the priority numbers including data-based priority, rate-based priority, and overall priority are needed for each device and they are maintained in the PAN coordinator. Also, states information is also recorded for making decisions on GTS allocation. One thing to mention is that once the N is incremented, the memory space required for recording additional information should also be increased.

However, all IEEE 802.15.4 devices can implement our ART-GAS algorithm without any modification. In other words, ART-GAS is fully compatible with IEEE 802.15.4 applications. Further, our proposed scheme is developed based on the standard of IEEE 802.15.4 MAC protocol, which totally follows both the message type and flow defined in IEEE 802.15.4 specifications. The users of our ART-GAS for IEEE 802.15.4-based devices would only need to change the legacy GTS allocation/deallocation of the PAN coordinator to ART-GAS.

Another advantage of our ART-GAS in implementation is the lower cost of GTS request loss. When traffic load in CAP is heavy and GTS resources are almost fully occupied, loss of GTS requests would lead to long waiting time for the lost requests to be granted to GTS. Such negative performance are mainly attributable to the FCFS GTS allocation and passive GTS deallocation mechanism in the original IEEE 802.15.4. Nevertheless, our ART-GAS significantly alleviates this impact. The P_r will be quickly increased as long as successful CSMA/CA hits or GTS hits are issued in following superframes. In this case, a single loss of GTS request is more tolerable. Moreover, as the CAP traffic load increases, collisions would frequently occur and GTS requests will be more rarely delivered to the PAN coordinator as a result. However, this concern can be slightly relaxed by ART-GAS, which comes from the dynamically adjusted threshold priorities. Increase of the threshold value will result in shorter CFP and longer CAP for devices' competition.

VI. Performance Evaluation

A. Simulation Setup

In this section, we present a simulation study based on an accurate model of IEEE 802.15.4 using OMNeT++ simulator, to assess the performance of the proposed ART-GAS algorithm. On the OMNeT++ platform, we can simulate nearly all the connections of the network object model and make the complex traffic network and topology highly practical to the situation in reality. The model library of OMNeT++ can also satisfy the large-scale sensor network simulations on demand,

TABLE I
SIMULATION PARAMETERS

Parameters	Value
Network topology	Star topology
Synchronization mode	Beacon enabled
Carrier frequency	2.4 GHz
Transmitter power	1 mW
Carrier sense sensitivity	-85 dBm
Transmission range	172 m
Number of devices	10 and 20
Frame size	127 Bytes (default)
Transmission rate	250 Kbps
$macMaxBE$	5 (default)
$macMinBE$	3 (default)
$MaxNB$	4 (default)
$MaxFrameRetries$	3 (default)
$Beacon\ Order$	6 (default)
$Superframe\ Order$	6 (default)
χ_i	0.15/s
χ_h	0.35/s

TABLE II
SIMULATION SCENARIOS

Scenario	Data-based priority	Rate-based priority
Scenario 1	5	10
Scenario 2	10	10
Scenario 3	25	15
Scenario 4	25	20
Scenario 5	50	10

which is an important reason for choosing OMNeT++ as our simulator.

In the simulation, a star topology with single PAN coordinator and N devices deployed in the area of $1000\ mm \times 1000\ mm$ is considered. N can be 10 or 20. Each device is allocated at most one GTS slot, and according to the IEEE 802.15.4 Specifications, the maximum GTS number in a superframe is seven. The packet arrivals for each device form a Poisson stream, and each new arriving packet shall trigger the issuance of a GTS request in the superframe. If there are no sufficient GTS resources for the request, the device will reissue the request for the packet in the subsequent superframe.

Additionally, two traffic types generated by devices are considered: heavy traffic and light traffic. χ_h and χ_i represent respectively the interarrival rates for the heavy-traffic and light-traffic devices. In the simulations, we have $\chi_h = 0.35/s$ and $\chi_i = 0.15/s$. Such rate settings are reasonable in IEEE 802.15.4-based WPANs, since IEEE 802.15.4 targets low-rate wireless communications. In addition, let N_h denote the number of heavy-traffic devices. Thus the GTS traffic load will be $\Gamma = N_h\chi_h + (N - N_h)\chi_l$. Table I lists the input parameters for our simulation model.

We develop a simulation model-Path Loss Model to investigate the performance of our ART-GAS algorithm. Based on [34], the path loss model is suitable for both narrow band (NB) and Ultra-wide Bandwidth band (UWB). We assume that the human body is 171cm high and his weight is 63kg on average. The path loss with 400MHz can be calculated as the following formula:

$$PL(d)\,[dB] = a \lg d + b + c + N \tag{10}$$

With the assumption $PL(d, f)$ [35] in dB for body surface to body surface propagation at distance d ($150\ mm < d < 1000\ mm$) and frequency f = 2.4GHz ($400\ MHz < f < 2500\ GHz$), the following formula can be obtained from Eq. (10):

$$PL(d, f)\,[dB] = -27.6 \lg d - 46.5 \lg f + 157 + Q \tag{11}$$

where Q is the shadowing component which follows log-normal distribution with standard deviation of 4.12 dB.

The performance metrics analyzed in this paper are the following.

- *Success Probability:* This metric is computed as traffic correctly received by the network analyzer divided by overall traffic. It reflects the degree of reliability achieved by the device for successful transmissions. We denote by $S(\Gamma)$ the success probability as a function of traffic load Γ.
- *Average Delay:* It is the average delay experienced by a data frame from the start of its generation by the application layer to the end to the end of its reception by the analyzer. We denote by $D(\Gamma)$ the average delay as a function of traffic load Γ.
- *Average Waiting Time:* A device average waiting time W can be defined as the length of time it has to wait before a GTS allocation. W is also a function of traffic load Γ, denoted by $W(\Gamma)$.
- *CFP Bandwidth Utilization:* It is the percentage of time period in the CFP that is used for data transmissions. Idle period might occur due to excessive GTS allocation, inflexible GTS deallocation, FCFS GTS scheduling policy, and the like. We denote by $B(\Gamma)$ the CFP bandwidth utilization of traffic load Γ.

B. Numerical Results and Analysis

In this section, we will present a careful evaluation and analysis of our ART-GAS algorithm. In comparison, similar assessments of the traditional IEEE 802.15.4 MAC protocol and ART-GAS with no threshold are also provided. We ran the simulation 10 times. Since the fluctuation of results is very weak, we prefer to provide the average values. Detailed performance assessments are given in four parts according to the previously mentioned metrics.

1) Success Probability (S): Performance of data transmissions with different data-based and rate-based priorities are given in this section, in terms of success probability. We consider five scenarios presented in Table II with 10 nodes and 20 nodes environment respectively. Five randomly selected nodes are adapted to the five scenarios and each scenario is simulated with the ART-GAS algorithm. The scenarios can be applied to applications with priorities like health care, alarm system. For example, scenario 5 is for heart rate. When someone's heart rate is abnormal, it is an emergency and it is assigned a higher data-based priority.

It is obvious in Fig. 6 that devices with different priorities are clearly differentiated in performance of data transmissions. This is because the devices with higher data-based priorities

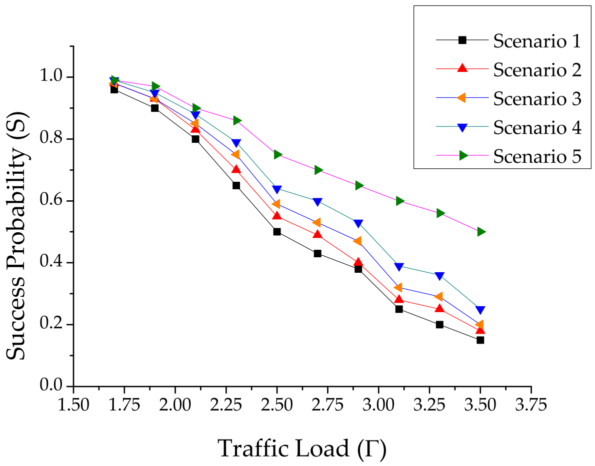

Fig. 6. Success probability of devices with different priorities (10 nodes)

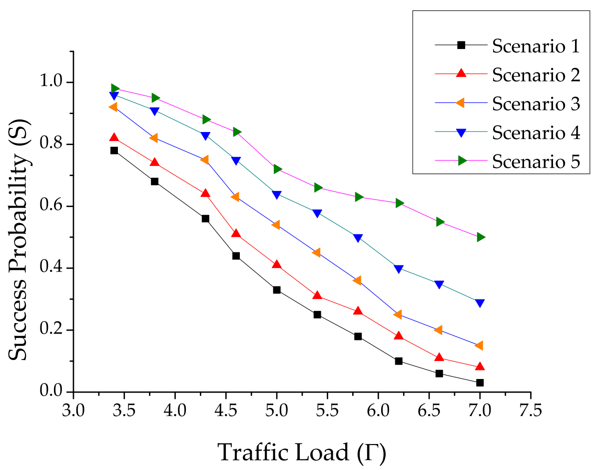

Fig. 7. Success probability of devices with different priorities (20 nodes)

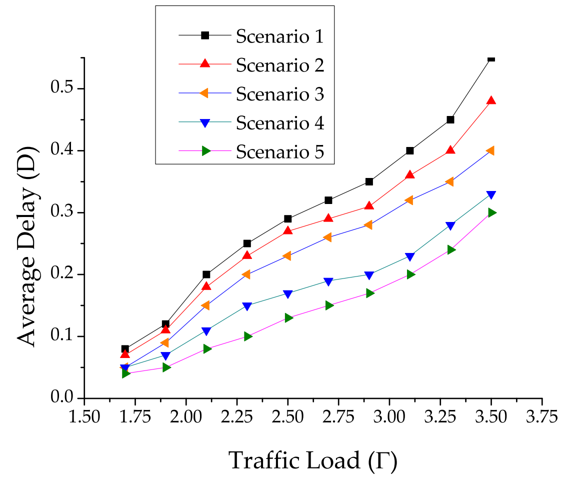

Fig. 8. Average delay of devices with different priorities (10 nodes)

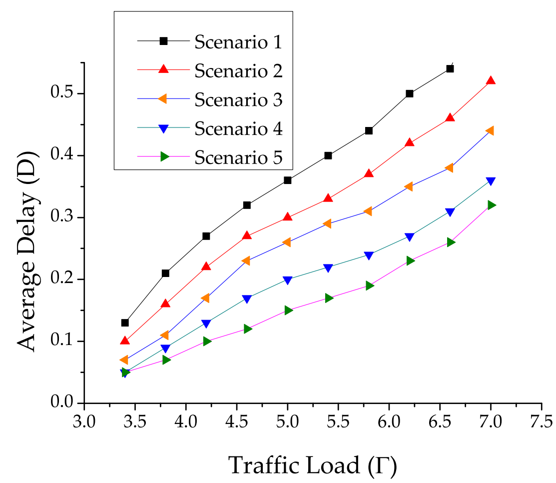

Fig. 9. Average delay of devices with different priorities (20 nodes)

or rate-based priorities are privileged to obtain sufficient GTS resources and their threshold priorities are also more relaxed than other devices. Therefore, time-sensitive and high-traffic data transmissions can be ensured with high reliability.

Furthermore, through comparison of Figs. 6 and 7, we can easily observe that when the traffic load Γ doubled with 10 more nodes added to the WPAN, success probability will decrease, since higher traffic load also means more severe competition, thus leading to more collisions. In this case, CAP tend to be more intensely occupied and it is more difficult for a device to obtain GTS resources in CFP. Hence, it becomes much easier for each node to have a transmission failure. However, high-priority devices experience a much smaller change than those low-priority ones. The reason is that a single GTS miss or CSMA/CA miss can be more tolerable for devices with higher priorities due to the adaptive design of priority assignment described in Section IV, hence their priorities are more slightly decreased when transmission failure occurs.

2) Average Delay (D): Similarly, devices with lower priorities have greater average delays (Figs. 8 and 9). This is because low priority devices have a smaller probability of obtaining GTS resources than high priority devices. Thus a longer time period will be needed for data transmissions.

Also, from Fig. 8 to Fig. 9, the average delay D increases as the traffic load Γ doubled since a higher traffic load leads to worse competition environment for data transmissions, which is for the same reason as the decreased success probability in change of traffic load.

Furthermore, high-priority devices tend to have a slighter increase in D, while low-priority devices will experience a much more significant change when traffic load doubled. This phenomenon is also attributable to the service differentiation mechanism and priority filter mechanism in ART-GAS, which enable high-priority devices have a better chance to obtain GTSs. This is also a clear indication that devices with higher priorities are better able to adapt themselves to an environmental change and hence, time-critical and high-traffic data transmissions are guaranteed from this perspective.

3) Average Waiting Time (W): Additionally, we compare the proposed ART-GAS with another two algorithms in terms of average waiting time W. The first algorithm is the GTS allocation mechanism specified in original IEEE 802.15.4 standard, which distributes GTS resources in a $Beacon\ Interval$

to all devices in a FCFS policy, regardless of their importance and transmission rates. The second algorithm, named non-threshold ART-GAS, is largely the same as the GTS allocation algorithm provided in ART-GAS, but with no threshold values. That is, GTSs are allocated to devices in a decreasing order of their priorities (P_i) as long as the GTS capacity is not overloaded.

Our evaluation considers two scenarios, 10 nodes environment in Fig. 10, and 20 nodes environment in Fig. 11. We can find in these two figures that ART-GAS has the best performance among the three algorithms. It obtains the lowest value of average waiting time at any given traffic load. This is due to the adaptive GTS scheduling mechanism described in Section IV, where the threshold value is able to be dynamically adjusted to network load and bandwidth resources are more efficiently utilized by needy devices with less wastage.

The non-threshold ART-GAS has an extremely similar performance with ART-GAS in Fig. 10. However, when the device number N is increased to 20, the increasing rate of W in ART-GAS is considerably smaller than that of non-threshold ART-GAS and IEEE 802.15.4. This indicates that our proposed ART-GAS provides more resistance to the increased traffic load as a result of its adaptive GTS scheduling. Adjustment of the threshold priority enables a better data-transmission environment, especially for high-priority devices. In this case, the non-threshold ART-GAS curve is no loner similar to that of ART-GAS, since it lacks the threshold restriction, which serves to alleviate CAP competition when traffic load is high.

There is another interesting phenomenon in Fig. 11. As traffic load increases, the W of IEEE 802.15.4 slightly decrease after a significant increase. It is easy to understand that the increase in W is because of the inflexible FCFS GTS allocation and passive deallocation. In this case, most of the GTS resources are occupied by heavy-traffic devices for a long time, which probably leads to the starvation (or almost) of light traffic devices. As traffic load becomes close to the maximum value (all devices are in heavy traffic status), the number of starving devices with the light traffic load decreases, and thus the average waiting time will slightly decrease. However, for ART-GAS and non-threshold ART-GAS, starvation is hardly to occur due to the flexibility in GTS scheduling, hence no such phenomenon can be observed in these cases.

4) CFP Bandwidth Utilization (B): Our evaluation of CFP bandwidth utilization B also considers the three algorithms mentioned previously, ART-GAS, non-threshold ART-GAS, and IEEE 802.15.4. In Fig. 12, we can see that in low-traffic environment, as the traffic load Γ increases, bandwidth utilization of all the three algorithms will also increase. Because more unused GTSs are allocated to devices, which are requesting GTS resources, the CFP bandwidth utilization is increased. However, in this case, ART-GAS and non-threshold ART-GAS have much better performance than the traditional IEEE 802.15.4, since these two algorithms provide a service differentiation mechanism for heavy-traffic and light-traffic devices. The service differentiation mechanism allocates GTSs according to devices' states and priorities and GTSs are more fully used by needy devices with higher data transmission frequencies. While in standard IEEE 802.15.4 MAC, the inflexible FCFS-based GTS allocation treats all devices equally, leading to significant bandwidth wastage.

Furthermore, when the number of devices N is increased to 20 (Fig. 13), we can observe that both the IEEE 802.15.4

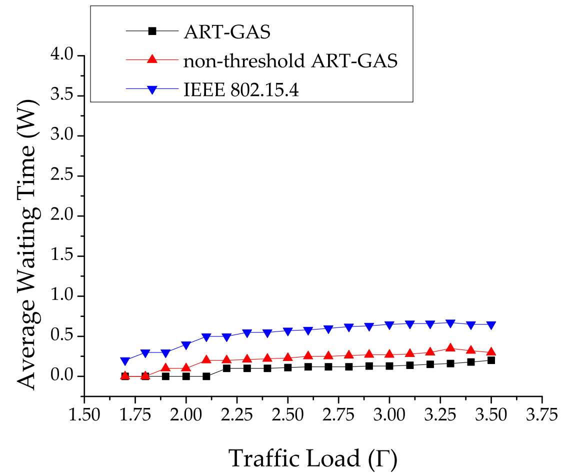

Fig. 10. Effect of traffic load on average waiting time (10 nodes)

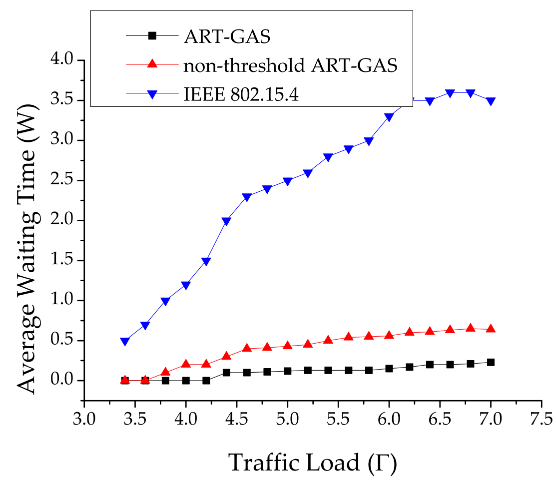

Fig. 11. Effect of traffic load on average waiting time (20 nodes)

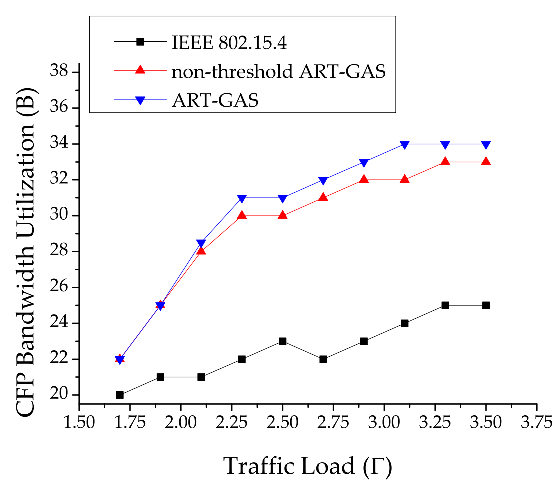

Fig. 12. Effect of traffic load on CFP bandwidth utilization (10 nodes)

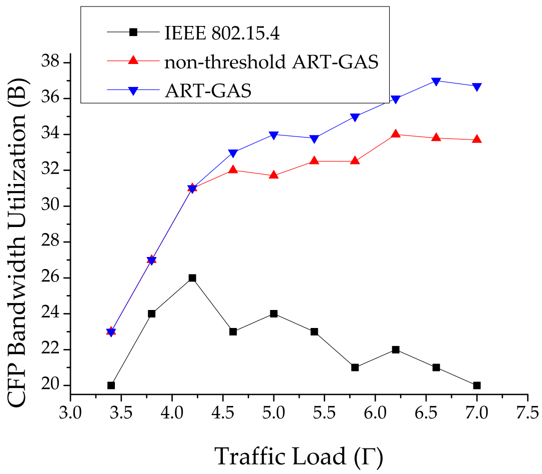

Fig. 13. Effect of traffic load on CFP bandwidth utilization (20 nodes)

and the non-threshold ART-GAS exhibit totally different performance compared with that in Fig. 12. The key point lies in the decrease of B when Γ is close to its maximum value. This phenomenon is named starvation. In the original IEEE 802.15.4, due to the FCFS GTS allocation mechanism, passive deallocation mechanism, and intense traffic load, many devices will hardly have access to GTS resources while most occupied GTSs are unused. This leads to a extremely low B. However, in ART-GAS, the problem of starvation can be solved by its adaptive priority assignment policy and flexible GTS scheduling. In this way, the allocated but unused GTSs can be reclaimed as soon as possible for new data transmissions, hence, no decrease of B can be observed in ART-GAS.

It is also worth mentioning that the non-threshold ART-GAS has a worse performance than that of ART-GAS in both of the two conditions. This comes from the function of threshold restrictions. In the ART-GAS algorithm, the threshold priority is dynamically adjusted to network load, which provides a better environment for data transmissions (e.g., a satisfactory CAP length contributes to successful deliveries of GTS requsts) and indirectly helps to achieve a higher bandwidth utilization.

VII. Conclusions

In this paper, we have proposed an adaptive and real-time GTS allocation mechanism (ART-GAS) based on a two stage approach. In the first stage of the proposed algorithm, we present a service differentiation mechanism that dynamically assigns data-based priorities and rate-based priorities to all devices. High priorities are distributed to time-critical and heavy-traffic devices, whereas non time-critical and light-traffic devices will have lower priorities. The second stage of the ART-GAS allocates GTS resources to devices according to their priorities assigned in the first stage, and a threshold priority is defined to filter unnecessary allocations, thus bandwidth wastage is avoided. Our proposed scheme can be implemented in the standard IEEE 802.15.4 MAC protocol without introducing any new message type. An analytic model was developed to evaluate the performance of ART-GAS in comparison with another two algorithms, which has been validated against simulation experiments. Simulation results demonstrate that the proposed scheme significantly improves the network performance in terms of success probability, average delay, average waiting time, and CFP bandwidth utilization.

Although we put the energy consumption a secondary issue, it is worth exploring how ART-GAS performs in real application/system scenario. We are planning applying the mechanism on a specific health care system and test the performance. Additionally, more quantitative comparisons with existing approaches are essential and we need put efforts on this area as well.

Acknowledgment

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