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Efficient GTS Allocation Schemes for IEEE 802.15.4

Syed E. Haque
Georgia State University

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by

SYED HAQUE

Under the Direction of Anu Bourgeois

ABSTRACT

IEEE 802.15.4 is a standard defined for wireless sensor network applications with limited power and relaxed throughput needs. The devices transmit data during two periods: Contention Access Period (CAP) by accessing the channel using CSMA/CA and Contention Free Period (CFP), which consists of Guaranteed Time Slots (GTS) allocated to individual devices by the network coordinator. The GTS is used by devices for cyclic data transmission and the coordinator can allocate GTS to a maximum of only seven devices. In this work, we have proposed two algorithms for an efficient GTS allocation. The first algorithm is focused on improving the bandwidth utilization of devices, while the second algorithm uses traffic arrival information of devices to allow sharing of GTS slots between more than seven devices. The proposed schemes were tested through simulations and the results show that the new GTS allocation schemes perform better than the original IEEE 802.15.4 standard.

INDEX WORDS: IEEE 802.15.4, WPAN, GTS, MAC layer protocol, OMNET++, CSMA/CA, CFP, CAP

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SYED HAQUE

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SYED HAQUE

Committee Chair: Anu Bourgeois

Committee: Xiaojun Cao

Yingshu Li

Electronic Version Approved:

Office of Graduate Studies

College of Arts and Sciences

Georgia State University

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DEDICATION

This thesis is dedicated to my loving parents.

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LIST OF ABBREVIATIONS

BI	Beacon Interval
BO	Beacon Order
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
FFD	Full Function Devices
GTS	Guaranteed Time Slots
IFS	Interframe Space or Spacing
LR-WPAN	Low-Rate Wireless Personal Area Network
MAC	Medium Access Control
PAN	Personal Area Networks
PANC	PAN Coordinator
PHY	Physical Layer
POS	Personal Operating Space
RF	Radio Frequency
RFD	Reduced Function Devices
RX	Receiver
SD	Superframe Duration
SO	Superframe Order
TRX	Transceiver
TX	Transmitter
WSN	Wireless Sensor Network

1 INTRODUCTION

Recent developments in the wireless sensor technologies have brought the emergence of low-cost short transmission wireless devices and this has led to the expansion in Wireless Personal Area Networks (WPANs) [7]. Unlike Bluetooth (IEEE 802.15.1), which is designed for applications with high quality-of-service (QoS) requirements [3], WPANs are designed for applications with low data-rate and low-latency requirements. The network architecture of a WPAN is designed for a conceptually simple wireless network like home automation system with short range operation, low data-rate, low power consumption and low cost of deployment using inexpensive portable fixed or moving devices. IEEE 802.15.4 [2] defines the standard for low-rate Wireless Personal Area Networks (WPANs) with low power consumption and relaxed throughput requirements. ZigBee [1] is an open-specification of IEEE 802.15.4 built on LR-WPAN for a suite of high level communication protocols using small, low-power digital radios based on an IEEE 802 standard for personal area networks [6].

WPAN applications can be broadly classified into home automation and networking, commercial, industrial, Body Area Sensor networks [13] and Emergency Response applications [14]. Home Automation is one of the largest WPAN applications aimed at creating smarter homes with low-rate data communications and self-organizing capability [20]. In [20], the authors have proposed a standard for LR-WPAN for home networking. Body Area Sensor networks [13] and Emergency Response Applications [14] are commercial applications with stricter latency and reliability requirements than in the original standard. Some common applications of WPAN involve deploying the sensor nodes to monitor the heart rate of a person or to report to emergency services if a person is injured in a blast. So, in these applications a timely response is more critical than saving energy for the sensor nodes. Another important application of a WPAN involves remote sensing by deploying thousands of low-cost sensors in battlefields or dense forests in an ad-hoc fashion where the nodes sense and transmit the data to a central coordinator in the network, which in turn performs computation on the received data and transmits the result to a data center.

Sometimes, the devices are deployed in regions where battery replacement is not feasible, therefore low power consumption is very critical to increase the lifetime of the network in such applications. The IEEE 802.15.4 specifies beacon-enabled mode of operation for better energy-efficiency [5] .The works in [7,8] have tried to further address the energy consumption issue by proposing a modified energy-efficient Medium Access Control (MAC) protocol for the standard. Our work in this paper is focused on improving bandwidth utilization and fairness in GTS allocation.

The beacon-enabled mode in IEEE 802.15.4 [2] specifies a slotted superframe structure in which devices can transmit packets in two different regions within a superframe: Contention Access Period (CAP) using CSMA/CA and a Contention Free Period (CFP) using Guaranteed Time Slots (GTS) where GTS is a period of time that can be reserved by a device for its packet transmission. The GTS allocation mechanism is similar to Time Division Multiplexing (TDMA) in which individual devices are assigned dedicated bandwidth. The devices can use the assigned time-slots to transmit periodically generated data without having to compete for the channel. Since these GTS are exclusive allocation to the devices therefore inefficient allocation of the GTS can lead to significant loss of bandwidth and degradation of the overall system performance [7]. The work in [11] pointed out the slot-sized induced bandwidth waste problem inherent in IEEE 802.15.4 standard. In the first part of our work, we have tried to address the slot-sized induced bandwidth problem by reducing the size of the GTS allocated to devices in the Contention Free Period. The saved bandwidth in the CFP is assigned to the CAP period resulting in throughput improvement for the whole network.

The standard [2] allows allocation of GTS to a maximum of only seven devices in a First Come First Serve (FCFS) order. The devices hold the GTS until explicit or implicit deallocation. However, for smaller superframe interval values, the implict deallocation condition set by the standard can lead to Starvation problem [7] thus preventing other devices from having a guaranteed service in the Contention Free Period (CFP). In the second part of our work, we have proposed a revised GTS allocation scheme to improve the fairness in GTS allocation in the Contention Free Period. The proposed scheme collects traffic arrival information of the devices and allows sharing of GTS using packet average inter-arrival information.

The proposed schemes were tested in the OMNeT++ simulator with throughput, total bytes received, reliability and energy consumption as the evaluation metrics. The results of the simulations show that the newly proposed schemes improve the throughput of the network while also increasing the number of devices that can share the GTS from seven to thirteen. The proposed schemes are backward compatible with the original standard and require very small implementation changes.

The rest of the paper is organized as follows: Section 2 presents Related Work, Section 3 presents the first part of our work - GTS Slot Splitting Algorithm, Section 4 presents the second part of our work - GTS Sharing using Traffic Arrival Information, Section 5 presents the experimental set-up and configuration details followed by Results and Analysis in Section 6. Section 7 and Section 8 present performance comparison of our schemes with related works. Section 9 and Section 10 present the conclusions and future works respectively.

1.1 IEEE 802.15.4 SUMMARY

IEEE 802.15.4 [2] defines the physical layer (PHY) and MAC sublayer specifications for Low-Rate WPAN devices. The standard is defined for devices with short-range operation and low energy consumption. An LR-WPAN device architecture shown in Figure 1 below comprises a traffic generator at the top level responsible for generation of data packets, a PHY layer for managing the physical radio transceiver and other low-level control operation and a MAC sublayer which enables the transmission of MAC frames through the use of physical layer as shown. The devices are conceived to operate with each other over a conceptually simpler wireless network [2]. The standard defines two device types – FFD (Full-Function Device) and RFD (Reduced-Function Device). An FFD can function as a PAN coordinator (PANC), coordinator or a device. An RFD is a device with very limited computation capability and memory capacity and can only communicate with a FFD while an FFD can talk to both RFDs and FFDs.

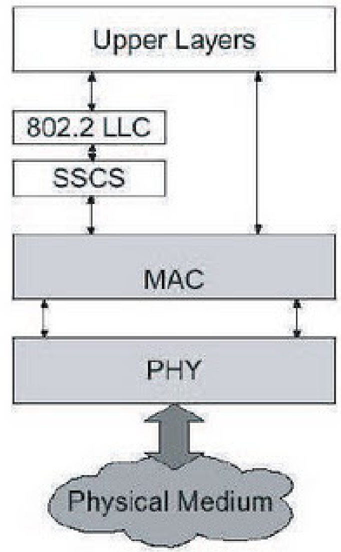


Figure 1. LR-WPAN Device Architecture

IEEE 802.15.4 supports three different network topologies shown below in Figure 2: star, peer-peer and cluster tree. Every network require atleast one FFD as a coordinator of the network which is often mains powered while all other devices in the network are most likely battery powered. In a peer-peer network, all devices in the range of one another can communicate with each other. The cluster tree network is a special-case of peer-peer network in which most devices are FFDs. The star network is structured on a star pattern with a PAN coordinator as a central network controller and communication takes place between the PAN coordinator and other devices in the network. All star networks operate independently from other star networks. An FFD initiates a star network by choosing a unique PAN identifier and broadcasting beacon packets as a PAN coordinator. The other devices can join the network after receiving the beacon packet from the PAN coordinator by sending an association request command to the PAN coordinator. In this paper, our work is focused on star networks.

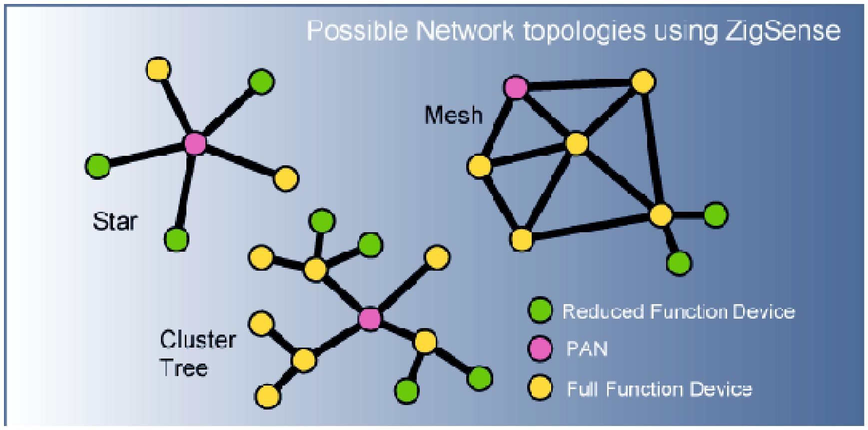


Figure 2. Network Topology

The IEEE 802.15.4 PHY layer [9] defines two functionalities: PHY data service for the transmission and reception of PHY layer packets and PHY management service that provides interface to the physical layer management entity (PLME). Apart from transmission and reception of packets, the PHY layer is also responsible for controlling the transceiver states, energy detection, link quality indication (LQI), channel selection and clear channel assessment (CCA). The devices can operate in one of the several available frequency channels depending on the channel data rate based on direct sequence spread spectrum (DSSS): 250kbps at 2.4GHz, 40kbps at 915MHz and 20kbps at 868MHz.

The IEEE 802.15.4 MAC sublayer supports two modes of operation: beacon-enabled and beaconless mode. In a beaconless mode, the PAN coordinator does not transmit any beacons and the devices communicate with the PAN coordinator using unslotted CSMA/CA. To achieve better energy efficiency, the standard provides for a beacon-enabled mode through the use of a superframe structure. In a beacon-enabled mode, the PAN coordinator transmits beacon packets at periodic Beacon Interval (BI) to allow devices to associate with it and synchronize to the superframe structure. The superframe structure shown in Figure 3 consists of a beacon, an active period and an inactive region. The active period further consists of a Contention Access Period (CAP) and a Contention Free Period (CFP) composed of Guaranteed Time Slots (GTS).

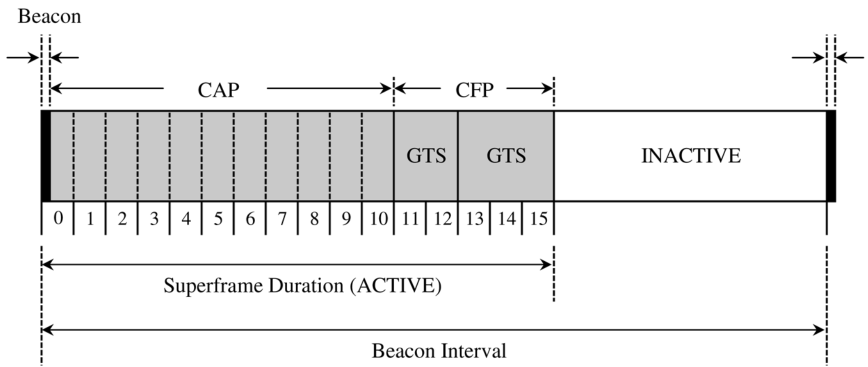


Figure 3. Superframe Structure

The active duration, also called the Superframe Duration (SD), is divided into 16 equal sized time slots used for data transmission while all the devices go into sleep mode during the inactive period to save power. The superframe structrure is defined by two parameters: Superframe Order (SO) and Beacon Order (BO). The BO and SO values satisfy the relation

$$0 \leq SO \leq BO \leq 14 \tag{1}$$

The superframe duration and the beacon interval are calculated using the following equation:

$$SD = aBaseSuperframeDuration * 2^{SO} \tag{2}$$

$$BI = aBaseSuperframeDuration * 2^{BO} \tag{3}$$

The superframe length is a constant value equal to aBaseSuperframeDuration when BO = SO = 0. The PAN coordinator transmits the beacon frame at the start of slot 0 of every superframe period. The beacon is followed by the Contention Access Period (CAP) during which the devices use slotted CSMA-CA to access the channel and transmit packets. In slotted CSMA-CA channel access mechanism, the backoff period boundaries of every device in the PAN are aligned with the superframe slot boundaries of the PAN coordinator [2]. The Contention Free Period (CFP) follows the CAP period and consists of Guaranteed Time Slots (GTS). The GTS slots are allocated by PAN coordinator to devices upon request and gives devices dedicated bandwidth to transmit the packets without having to compete for the channel. The standard limits the total number of devices that can be allocated GTS to seven [2] and the allocation of GTS should not reduce the length of CAP to less than a constant value of aMinCAPLength. Therefore, all devices with periodic data to transmit request PAN coordinator for GTS slots through a GTS request command. The PAN coordinator upon receiving a GTS request checks if the total number of GTS allocation is less than seven and the allocation of a new GTS does not reduce the length of CAP period to less than aMinCAPLength. All devices go into sleep mode during the inactive period and wake up at the start of next superframe to track the incoming beacon from the coordinator.

1.2 OMNeT++

OMNeT++ is a component-based, modular and open-architecture discrete event network simulation framework [4]. The most common use of OMNeT++ is as a structure for simulation of computer networks, but it is also used for queuing network simulations and other areas as well. OMNeT stands for "OMni-Network". OMNeT++ is popular in academia for its extensibility and plentiful online documentation. The software is licensed under its own Academic Public License, which allows GNU Public License-like freedom but only in noncommercial settings. OMNeT++ represents a simulation-framework. Instead of containing explicit and hardwired support for computer networks or other areas, it provides the infrastructure for writing such simulations. Specific application areas are catered by various simulation models and frameworks, most of them open source. These models are developed completely independently of OMNeT++, and follow their own release cycles. TKenv is the graphical interface in OMNeT++ that supports interactive execution of simulation, tracing and debugging [4]. An example internals of an IEEE 802.15.4 device under TKenv is shown in Figure 4 below.

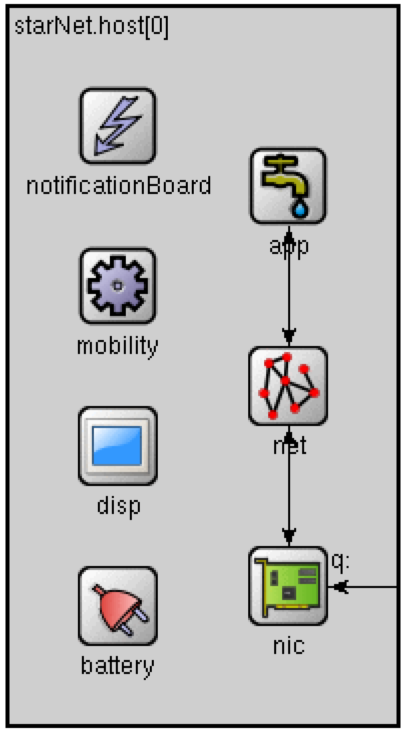


Figure 4. Node Internals in TKenv

1.3 NED LANGUAGE

OMNeT++ uses the NED language for network description. NED supports modular description of a network using simple, complex and system modules [4]. The NED file with network description has a .ned extension. The NED file is composed of import statements, simple and complex modules that represent individual components, system module that describes the network and channel definition to allow communication between modules. Each module has an input and output gate that form the connection points of the modules. The NED file is compiled into a C++ code which is then translated into an executable using the C++ compiler. NED also supports parallel execution so different parts of the model are executed on different hosts or processors. The GNED editor draws compound modules graphically by translating the NED file into an internal data structure.

2 RELATED WORK

Although with intense research and standardization in recent years for IEEE 802.15.4, a lot of issues still need to be addressed before WPAN can be efficiently deployed for large scale applications. The limitations of the standard can be categorized as: inefficiency in energy consumption, bandwidth under-utilization, high-latency, high packet loss rate, unfairness in allocation of GTS slots in the Contention Free Period. Various works have previously been done towards an efficient IEEE 802.15.4, but most of the works are focused on the Contention Access Period (CAP) of the superframe. Recent works in the area have tried to address the energy, bandwidth and latency issues in the standard. In [7], an adaptive GTS allocation scheme is proposed with consideration to low latency and fairness of data transmission to address the Starvation problem [7] in GTS allocation. The proposed algorithm has two phases: classification phase in which the PAN coordinator assigns priorities to the devices in the network using the frequency of arrival of packets and the scheduling phase in which GTS is allocated in non-decreasing order of priorities. The proposed scheme ensures fairness by providing a starvation avoidance mechanism where devices with high priority are dropped to low priority category if it does not transmit a packet for a given number of superframes and similarly the priority of a low priority device are exponentially increased if it starts to transmit packets. In [24], the authors have proposed an efficient scheme in which a central network controller collects the available energy and transmission rate of sensor devices to adjust standard parameters for an 802.11 network. The controller selects the transmission rate for each node with the goal of increasing the lifetime of the network through higher energy savings and higher packet delivery ratio.

In [23], the authors used network monitoring to dynamically adjust the duty cycle in a superframe to reduce energy consumption of devices. The PAN coordinator observes the behavior of surrounding devices for packet arrival frequency and uses it to adjust the beacon interval accordingly. The drawback of this work is that adjusting the beacon interval to save energy can considerably affect the message delay so this work is not effective for time-sensitive applications and the effect on throughput is not addressed in the paper. Another drawback is that the proposed algorithm is only applicable to Contention Access Period, as devices using GTS require dedicated bandwidth services and thus the beacon order of the superframe cannot be adjusted by the coordinator. Another work using the idea of network monitoring has been done in [22] similar to the work in [7] towards an efficient GTS allocation scheme using traffic arrival information at the PAN coordinator. The idea in the paper is to allocate GTS to devices with high packet arrival rate as these devices can impact the collision and delay bound of the network. In the proposed algorithm, PAN coordinator collects CAP and GTS traffic arrival information from devices in each superframe and uses the average arrival information to reallocate GTS to devices with higher packet arrival rate. Our GTS SHARING scheme is different from their work, as we monitor the GTS traffic information and use the traffic average arrival information to allow sharing of GTS among devices.

Performance evaluation and analysis of IEEE 802.15.4 have been done in [10,12,16,18]. The work in [10] have proposed a simulation model for IEEE 802.15.4 under OPNET Modeler to study the throughput in beacon enabled networks for different superframe order (SO) values, packet arrival rate and buffer capacities. The results of the paper have shown that for low arrival rates and low buffer capacities, efficient use of GTS in terms of data throughput is achieved for low SO values. SO values of seven and above resulted in high bandwidth wastage while maximum throughput is seen for lower SO values of two, three and four. In [16], the authors have done a complete analysis of GTS by studying the impact of standard parameters on the throughput and delay bound of GTS. In addition, the authors presented an analysis of the impact of duty cycle on the delay bound using network calculus.

Low-latency is another key requirement in many WPAN applications so many recent works have been focused on improving the latency. In [19], an optimal GTS scheduling algorithm is presented for applications with strict delay requirements. The authors proposed a GTS Scheduling Algorithm (GSA) that reduces average service start times of transactions while also allowing concurrent GTS services to more transactions to meet the delay constraints of time-sensitive applications. The devices instead of sending length of GTS requested transmit the flow specifications (delay, packet payload) to the coordinator in the GTS request command which in turn decides length of GTS to be allocated to device that satisfy the delay requirements of the device and to also spread payload across multiple superframes for maximal utilization of the Contention Free Period. Although the proposed algorithm improves the latency but it requires the additional overhead for each device to identify its flow specification and transmit it to the coordinator. The work in [8] has tried to present an efficient transmission scheduling scheme by the PAN coordinator. In this scheme, GTS slots are allocated according to the data generation period of each node using a data transmission scheduling scheme. PAN coordinator defines the transmission period for each device such that transmission occurs within the maximum delay constraint and GTS is allocated to devices only when needed. The work in [21] have also tried to address the delay constraints by requiring the PAN coordinator to decide the number of GTS slots to be allocated to the device using the network traffic information like total cluster load, remaining CAP size and information received from device (delay and data specifications). The authors have also addressed bandwidth underutilization and fairness by allowing more than seven devices to share the GTS. In [14], an algorithm for emergency response applications is proposed with emphasis on low latency and high reliability of packet transmissions. In the proposed algorithm, the PAN coordinator allocates a new Extended CFP (E-CFP) period to devices upon request by using a portion of inactive region of the beacon interval. The devices with failed transmissions in GTS can request for E-CFP slots from the coordinator to retransmit packets and thus the probability of packet drop and latency can be reduced. Although failed transmissions in GTS are considerably low but this work is focused on emergency response applications which have a very strict latency and reliability requirements.

The work on improving the throughput has been presented in [11], where the authors propose a novel multi-beacon superframe structure with greedy GTS allocation. The authors pointed out the slot-sized induced bandwidth problem inherent in the standard IEEE 802.15.4 and suggested that using lower superframe interval values can lead to channel under-utilization. The proposed algorithm uses multiple sub-beacon intervals in a superframe with different slot sizes to address the problem and improve bandwidth utilization. The network devices need to determine the most appropriate sub-beacon interval to transmit the frame according to their traffic characteristics. The work in [15] presents an Implicit GTS

Allocation Mechanism (i-GAME) to address the bandwidth underutilization problem for partially used GTS. The proposed algorithm allows devices to share the GTS in a round-robin fashion using a scheduling scheme at the PAN coordinator. The devices transmit their traffic characteristics and delay specifications to the PAN coordinator which runs an admission control algorithm to decide if the device is accepted to share the GTS with other devices in the network. i-GAME algorithm significantly improves the throughput however it involves an additional overhead of having each device to identify and transmit its flow specifications to the coordinator. The work in [17] have proposed a scheme to split the Contention Free Period into 16 equally sized slots to allocate smaller slots in GTS, but this algorithm does not specify a pre-determined Contention Free Period (CFP) which makes the implementation complicated. Our GTS SLOT SPLITTING scheme expands on the work in [17] and we propose a different and more simplified modification to the original protocol by reducing the GTS size to half resulting in significant bandwidth savings. Our scheme is also backward compatible with the original standard.

3 GTS SLOT SPLITTING WITH BACKWARD COMPATIBILITY

In this section, we present the first part of our work - **GTS SLOT SPLITTING WITH BACKWARD COMPATIBILITY** in which we have tried to address the bandwidth underutilization problem inherent in the GTS allocation scheme of the original standard. The proposed work is applicable to wide variety of WPAN applications such as home automation, remote sensing where the devices in the network have a low average packet arrival rate, small payload and requires minimal dedicated bandwidth for contention free transmissions. Applications with mostly contention-access traffic and with high reliability (high packet delivery ratio) and throughput requirements can significantly benefit from our proposed scheme. So, in this work we have tried to address the slot-sized induced bandwidth problem in the GTS allocation scheme as pointed out in [11] through a different perspective. Our work expands on the idea in [17] with a more efficient implementation resulting in significant bandwidth savings and our work is also backward compatible with the original standard.

IEEE 802.15.4 standard allows for the allocation of dedicated bandwidth to devices through GTS allocation. The Contention Free Period (CFP) of the superframe consists of GTS slots which the devices can use for contention free data transmission. The devices request for GTS allocation through the GTS request command by specifying the number of slots needed and direction of GTS transmission (from or to the coordinator). The GTS slots are allocated in every superframe so they consume a significant bandwidth of the superframe duration. Therefore, inefficient allocation of GTS can lead to significant loss of bandwidth and degradation of the overall system performance [7]. According to the IEEE 802.15.4 standard, the size of a GTS slot is the same as a CAP slot i.e 1 GTS slot = 1 CAP slot = Superframe Duration (SD) / 16. The maximum bandwidth available by GTS should also be higher than the packet arrival rate of a device for data transmission to be complete [15]. However, the packet transmission duration during GTS is much lower than the available bandwidth and thus a significant amount of bandwidth is wasted for every slot allocated in every superframe.

In this thesis, we propose a new scheme to allocate smaller sized GTS slots to the devices. As mentioned before, the PAN coordinator allocates the GTS slots according to the standard slot duration in the superframe. However, only a small fraction of the allocated slot is used for data transmission as shown by the shaded region in Figure 5 below. The remaining bandwidth is wasted in every GTS slot in every superframe for applications with low average packet arrival rate and low data payload. Thus, the allocation of GTS slots according to the standard CAP slot size is inefficient for these applications. We proposed a new scheme in which the GTS slots are still allocated as a standard value, but half of the standard slot duration, i.e 1 GTS = SD / 32. Each device before requesting a GTS calculates its transmission duration and then requests the slots based on the new slot size. The coordinator allocates smaller slots for GTS transmission to devices and the resulting savings in bandwidth in the Contention Free Period is allocated to the Contention Access Period which increases the overall throughput of the network. The new scheme requires minimal modifications to the original protocol and the implementation is backward compatible with devices using the old IEEE 802.15.4. In the next section, we present the throughput analysis of our new scheme.

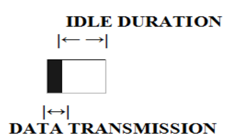


Figure 5. Duration of data transmission - GTS

3.1 THROUGHPUT ANALYSIS OF THE GTS SLOT SPLITTING SCHEME

A mathematical model of the throughput analysis of the GTS allocation has been presented in [10]. The authors have tried to study the impact of buffer capacity and data frame transmission rate on the throughput. In this section, we present the bandwidth savings of our new scheme compared to the original standard. We assume low packet arrival rate and low data payload during GTS transmission,

T_{data} = Duration of data transmission in GTS (including the Ack time and IFS time)

T_{idle} = Idle time in GTS

SD = Superframe Duration

BI = Beacon Interval

C = PHY data rate = 250 kbps

GTS Slot Duration in original IEEE 802.15.4 is

$$T_s = SD/16 = (aBaseSuperframeDuration * 2^{SO}) / 16 \quad (4)$$

GTS Slot Duration in our proposed scheme is

$$T_{s'} = (1 \text{ GTS Slot Duration in original IEEE 802.15.4}) / 2 = (aBaseSuperframeDuration * 2^{SO}) / 32 \quad (5)$$

Max. Throughput for GTS Allocation (Max. Bandwidth used for data transmission/Max. Time used for data transmission) is

$$(T_{data} * C) / BI \quad (6)$$

Under the original IEEE 802.15.4 scheme,

$$T_{data} = T_s - T_{idle} \quad (7)$$

Under our proposed scheme,

$$T_{data} = T_{s'} - T_{idle'} \quad (8)$$

Therefore, bandwidth saved in each allocated GTS using our scheme is

$$C * (T_s - T_{s'}) / BI \quad (9)$$

For 'n' allocated slots in a superframe total bandwidth saved is

$$n * C * (T_s - T_{s'}) / BI \quad (10)$$

The saved bandwidth shown in Equation 10 is allocated to the CAP period in each superframe and thereby increasing the duration for the contention access period. The work on throughput analysis of IEEE 802.15.4 in [10] have shown that for a given frame arrival rate and buffer size the higher the SO values the higher is the bandwidth wastage since increasing the SO value also increases the slot size. So, our proposed scheme provides higher bandwidth savings as the SO values are increased. In the next section, we present the implementation details of our work.

3.2 IMPLEMENTATION OF GTS SLOT SPLITTING SCHEME

The proposed scheme is implemented using three simple algorithms: **GTS REQUEST BY DEVICES**, **GTS ALLOCATION AT COORDINATOR** and **GTS ALLOCATION RECEIVED AT DEVICE**. The new scheme is backward compatible with the original IEEE 802.15.4 standard. The steps of allocation are shown in Figure 6 below where the PAN coordinator receives request for GTS allocation from two new devices (using the new GTS Slot Splitting Scheme) followed by a request from an old device (using the old IEEE 802.15.4). A similar GTS allocation request in the original standard is depicted in Figure 7. Thus, the resulting allocation using the new proposed scheme saves one full GTS slot in the above case while also being backward compatible. The total bandwidth saved increases as more GTS slots are allocated by the coordinator. In our experiments, seven devices using the new protocol request for one GTS slot each and thus our scheme saved three full GTS slots compared to the original standard. In addition, our scheme increases the length of the CAP period by allocating the saved bandwidth in the CFP to the CAP period. So, the increased CAP length represents the throughput improvement by our scheme.

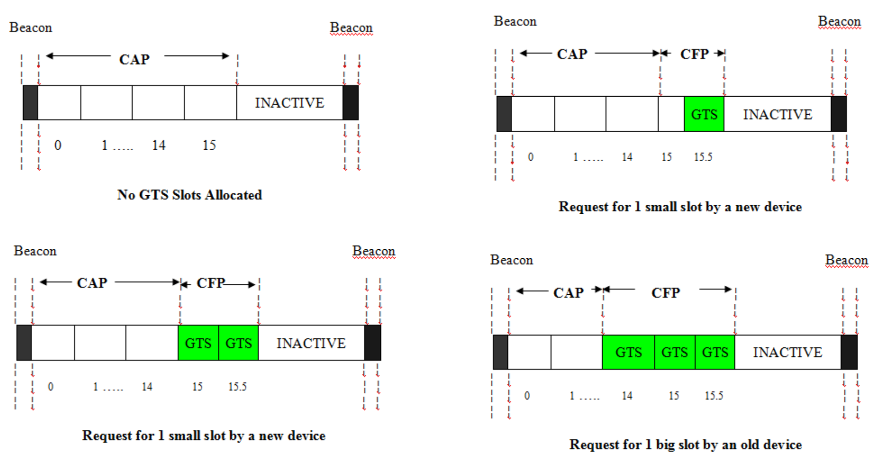


Figure 6. GTS Allocation using GTS SLOT SPLITTING SCHEME

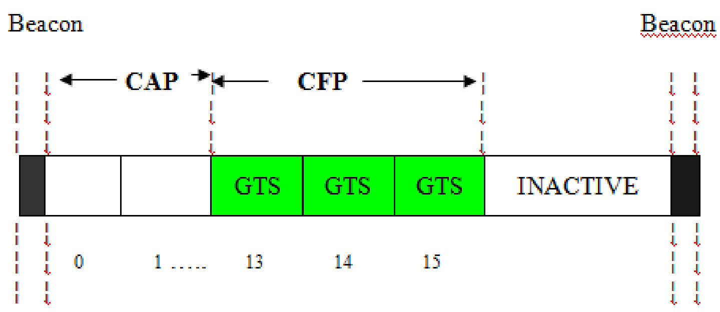


Figure 7. GTS Allocation using standard IEEE 802.15.4

3.2.1 GTS Request by Devices

The first algorithm shown below is initiated at the devices requesting for GTS slots. All devices using the new scheme calculate the GTS transmission duration and request GTS_LENGTH slots using the reduced GTS slot size. The algorithm uses the Reserved bits in the GTS Field Characteristics of the GTS Request Command (Figure 8) to make the scheme backward compatible with the original standard.

Bits: 0-3	4	5	6-7
GTS Length	GTS Direction	Characteristics Type	Reserved

Figure 8. GTS Field Characteristics – GTS Request Command

The devices specify their type (using the old or new protocol) through the Reserved 2 bits in the GTS Request Command as: -

00/Not Used - Old IEEE 802.15.4 device

01 - new IEEE 802.15.4 device requesting with new GTS slot size and number of smaller slots requested <= 15

02 - new IEEE 802.15.4 device requesting with new GTS slot size and number of smaller slots requested => 15

GTS SLOT SPLITTING ALGORITHM - GTS REQUEST BY DEVICES

```
if the device using old IEEE 802.15.4 then
    GTS slot size = Superframe Duration /16
else
    GTS slot size = Superframe Duration /32
end if
Calculate data transmission duration in GTS
if device using new IEEE 802.15.4 then
    if number_of_GTS_slots needed < 16 then
        reserved = 01
        request GTS according to new GTS slot size
    else
        reserved = 02
        request GTS according to standard GTS slot size
    end if
else
    request GTS according to standard GTS slot size
end if
```

Figure 9. ALGORITHM - GTS REQUEST BY DEVICES

3.2.2 GTS Allocation at Coordinator

The second algorithm is run at the PAN coordinator for accepting the GTS request and allocating the GTS according to availability. The coordinator first checks the RESERVED bits in the GTS request command for the protocol running on the device. If the device type is not set in the RESERVED bits then the requesting device is using the old IEEE 802.15.4 protocol, so all the allocation is done using the standard GTS slot size. If the device type is set to 1, then the coordinator allocates GTS slots with reduced GTS slot size. The slot allocation may set the GTS_START_SLOT to a fraction for the requested GTS (Under the new scheme 7 small slots requested means 3.5 original slots). The coordinator updates the FINAL_CAP value after allocation and returns the GTS_START_SLOT and GTS_LENGTH_ALLOCATED to the device. The GTS_START_SLOT and FINAL_CAP value are always an integer for backward compatibility as other devices in the network using the old IEEE 802.15.4 may not understand fractional GTS_START_SLOT and FINAL_CAP value. The coordinator indicates the new devices requesting for GTS of a fractional GTS_START_SLOT value by returning GTS_LENGTH_ALLOCATED as GTS_LENGTH + 1 to those devices. So, in our scheme only the new devices can understand non-integer GTS_START_SLOT value by comparing GTS_LENGTH_ALLOCATED and GTS_LENGTH values. The coordinator can also adjust the GTS_START_SLOT of all devices if the allocation leads to creation of holes in the Contention Free Period.

GTS SLOT SPLITTING ALGORITHM - GTS ALLOCATION AT COORDINATOR

```
if reserved = 00 || reserved = 02 then
    allocate slots according to standard GTS slot size
    GTS_start_slot = current_GTS_ start_slot – GTS_slots_requested
else
    allocate slots according to new GTS slot size
    GTS_start_slot = current_GTS_ start_slot – GTS_slots_requested
end if
if GTS_start_slot is fractional then
    if reserved = 01 // reserved = 02 then
        GTS_start_slot = integer_part_of GTS_start_slot
        final_CAP = GTS_start_slot – 1    // final_CAP is always an integer for backward compatibility
        GTS_slot_allocated = GTS_length_requested + 1
    else
        GTS_start_slot = integer_part_of GTS_start_slot
        GTS_slot_allocated = GTS_length_requested
        final_CAP = GTS_start_slot - 1
    end if
else
    GTS_slot_allocated = GTS_length_requested
    final_CAP = GTS_start_slot – 1
end if
adjust GTS_start_slot of devices if there are holes in CFP //optional
add GTS_start_slot and GTS_slot_allocated to beacon descriptor
```

Figure 10. ALGORITHM - GTS ALLOCATION AT COORDINATOR

3.2.3 GTS Allocation Received at Device

The third algorithm shown below is run by the device to process the GTS allocation. The old device first checks the GTS_LENGTH_ALLOCATED field and if it is zero then no GTS slot is allocated to the device by the PAN coordinator. If the GTS_LENGTH_ALLOCATED is not zero then the old device sets its timer to GTS_START_SLOT and waits for the timer to expire. The new device also compares the GTS_LENGTH_REQUESTED and GTS_LENGTH_ALLOCATED values to see if the GTS_START_SLOT is a fraction or not. If the two are unequal, then it knows its allocated

GTS_START_SLOT is a fractional value and so the device sets its GTS timer to GTS_START_SLOT + 0.5 otherwise it sets the timer to GTS_START_SLOT. The device starts the timer and waits for the timer to expire.

GTS SLOT SPLITTING ALGORITHM - GTS ALLOCATION RECEIVED AT DEVICE

```
if the device using old IEEE 802.15.4 || reserved = 02 then
    GTS slot size = Superframe Duration /16
else
    GTS slot size = Superframe Duration /32
end if
if (reserved = 01 || reserved = 02) && GTS_length_allocated = GTS_length_requested + 1 then
    GTS_start_slot = GTS_start_slot + 0.5
    GTS_length = GTS_length_requested
end if
start_GTS_timer
```

Figure 11. ALGORITHM - GTS ALLOCATION RECEIVED AT DEVICE

The new scheme was tested under the OMNeT++ simulator for a range of SO/BO values and the results show that our modified protocol significantly improves the reliability and bandwidth compared to the original standard. The experimental setup, results and analysis are presented in Section 5 and Section 6 respectively. In the next section, we present the second part of our thesis work – **GTS SHARING USING TRAFFIC ARRIVAL INFORMATION**.

4 GTS SHARING USING TRAFFIC ARRIVAL INFORMATION

In this chapter, we present the second part of our work – **GTS SHARING USING TRAFFIC ARRIVAL INFORMATION** in which we have tried to address the unfairness in GTS allocation in the original standard. The proposed work is most suitable to remote sensing applications where the devices constantly sense for events and transmit the data to the network coordinator at periodic intervals. The average interval between the occurrences of events for these applications is constant and high so the devices only have to transmit infrequently. So, in this work we propose a new scheme to allow more devices to share the GTS in the Contention Free Period by collecting the traffic arrival information at the PAN coordinator. The work is implemented by running the new algorithm at the coordinator and our work is backward compatible with the original IEEE 802.15.4 standard.

The IEEE 802.15.4 GTS allocation by the PAN coordinator uses First Come First Serve (FCFS) algorithm to allocate the GTS. Therefore, once the network starts all the GTS slots get quickly consumed by a few numbers of devices in the network. According to the standard, the PAN coordinator can allocate GTS slots to a maximum of only seven devices and the devices hold the GTS slots until explicit or implicit deallocation. However, most devices do not have data to transmit in each superframe, especially for remote sensing applications where sometimes the occurrence of events is very infrequent. Thus, if the expiration time for implicit deallocation is set very high then, other devices in the network that may have data to transmit are prevented from having a guaranteed service due to unavailability of GTS slots. This leads to unfairness in the GTS allocation mechanism in the original scheme. In this work, we propose a new algorithm in which the PAN coordinator collects traffic arrival information from devices to allow sharing of GTS among devices. i-Game [15] uses an implicit GTS allocation mechanism to share the GTS among a number of devices in a round-robin fashion. However, the i-Game implementation has an additional overhead as each device need to identify and transmit its flow specification (packet arrival rate, delay, burst size) to the coordinator, which may not be suited to remote sensing applications. Our scheme involves minimal overhead as the PAN coordinator only need to collect and store packet average arrival information for the devices.

The work on throughput analysis of IEEE 802.15.4 in [10,12] have shown that high SO/BO values contribute to high bandwidth wastage. According to the work in [10], for a given frame rate and buffer size, maximum throughput is achieved for lower SO values (1,2,3,4,5) while high SO values (6, 7) result in the least throughput. Thus, high SO values are not suitable to ensure efficient usage of GTS and optimal network performance so SO/BO should be set to smaller values. IEEE 802.15.4 specifies the Contention Free Period for allowing devices with contention-free data transmission. GTS is allocated in every superframe and the devices hold the GTS until explicit or implicit deallocation. GTS can be deallocated in two ways: 1) The device sends a request to the PAN coordinator for explicit deallocation 2) Implicit deallocation is handled by the PAN coordinator and is based upon timer expiration. IEEE 802.15.4 specifies the condition for implicit deallocation – The PAN coordinator can assume the device is no longer using the GTS if a packet/acknowledgement is not received in a transmit/receive GTS for 2*n superframes [2] where, n is an integer and

$$n = 2^{(8 - BO)},\ 0 <= BO <= 8 \tag{11}$$

$$= 1, \qquad 9 <= BO <= 14 \tag{12}$$

So, for BO = 0,1,2,3.....8, if the PAN coordinator does not receive any packet/acknowledgement from the device in 512, 256, 128, 64,......., 2 superframes respectively, then the GTS slot is implicitly deallocated by the coordinator. Most common remote sensing applications have low average event occurences so the devices do not have data to transmit in every superframe. Smaller SO/BO values are suited for high throughput and higher network performance, however, lower SO/BO values means larger timer interval for implicit deallocation, eg. 256 supeframes for BO = 1. Packets received at coordinator during the GTS can be categorized as: -

Case 0: - Packet received in every superframe by the coordinator from the device

Case 1: - Packet received in non-consecutive superframe by the coordinator but do not satisfy implicit deallocation (Low SO/BO values)

Case 2: - Packet received in non-consecutive superframe by the coordinator which satisfy implicit deallocation of GTS under the standard IEEE 802.15.4(High SO/BO values)

The current work is focused on Case 1 with smaller SO/BO values. So, in this paper we have proposed an algorithm to allow sharing of GTS among devices which can increase the number of devices using the GTS from seven to thirteen.

4.1 IMPLEMENTATION OF GTS SLOT SHARING USING TRAFFIC ARRIVAL INFORMATION

We assume our work is directed to applications with low SO/BO values and devices with low average packet arrival rate in the CFP, but the arrival rates do not satisfy implicit deallocation, i.e once the devices are allocated a GTS slot, it holds it forever or until they request for explicit deallocation. The algorithm is implemented at the MAC layer at PAN coordinator and the implementation requires additional computation and memory resources. The PAN coordinator is a Full Function Device (FFD), so it can perform the above computations. The memory requirement for our algorithm is considerably low, so memory constraint is also not an issue. The PAN coordinator only needs to store the device_short_address and average_arrival values for a maximum of thirteen devices in our current scheme.

The PAN coordinator allocates the GTS slots at the start of network to the first seven devices in a First Come First Serve order as shown in Figure 12. Under the original IEEE 802.15.4, these seven devices hold the GTS until implict or explicit deallocation. Our goal is to increase fairness in GTS allocation by allowing more than seven devices to use the contention free service. Applications with low average packet arrival rate do not have packets to transmit in each superframe although GTS is allocated to the device in every superframe. In our work, we use the unused GTS slots in the subsequent superframes to reallocate the GTS to another device which has packet to transmit. Thus, we reallocate the GTS slots (allocated to the first seven devices) in unused superframes to another device using the average traffic arrival information of that device stored at the PAN coordinator. The next section presents the details of the algorithm implementation.

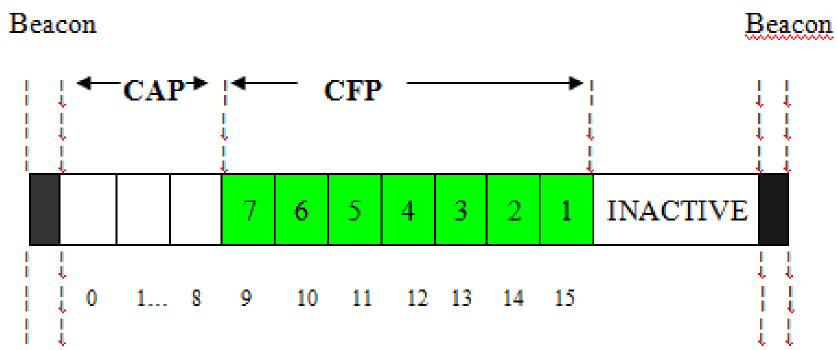


Figure 12. Initial GTS Allocation to first seven devices

The PAN coordinator initiates the WPAN by selecting a unique PAN ID and starts broadcasting beacons with the PAN identifier. The devices after being associated with the PAN coordinator request for GTS slots through GTS request command. The PAN coordinator receives the incoming GTS request and allocates GTS slots to the first seven devices in a First Come First Serve order in the next superframe. The coordinator starts collecting the traffic (packet) arrival information during GTS in each superframe for the next 'n' superframes (in our implementation was 'n' was set to 20). The value of 'n' should be set to a large value according to the beacon interval since higher values allow to more precisely record the average arrival information. Thus, every time a packet is received by the PAN coordinator in the contention free period it collects the following information in memory for that device as shown in Figure 13 below.

CA = Current Arrival Time of the GTS packet at the coordinator

PA = Past Arrival Time of the GTS packet at the coordinator

IA = Interarrival Time = CA – PA

AA = Average Arrival Time = (AA + IA) / 2

Figure 13. Traffic Parameters

The idea in our work is to accommodate the device with the 7th GTS allocation to share the GTS with one of the first six devices. In the (n+1)th superframe we run the GTS reallocation test shown below in Figure 14 to check if the device can be accommodated or not.

```
GTS_LENGTH_MAX - maximum GTS slot length by any of the first six GTS devices
GTS_LENGTH - length of GTS needed by 7th GTS device
GTS_DIRECTION (DIRECTION OF GTS TRANSMISSION) – TRANSMIT/RECEIVE
If GTS_LENGTH <= GTS_LENGTH_MAX && GTS_DIRECTION = TRANSMIT
RETURN TRUE
ELSE
RETURN FALSE
```

Figure 14. GTS Reallocation Test

If the device 7 returns true to the above test, then it will be sharing the GTS with any one of the six devices. For example, if device 1 is selected to share GTS with device 7, then at every Average Arrival Time of device 7, GTS of device 1 is reallocated to device 7. After the reallocation test, the PAN coordinator deallocates the GTS slot of the 7th device (since the 7th device is now sharing the GTS slot with device 1) and allocates it to another device in the network requesting it (device 8) as shown below in Figure 15. Thus, device 1 and device 7 start sharing the same GTS slot to transmit the packet in Contention Free Period i.e if the current timer equals the Average Arrival Time of device 7 then the allocation is as shown in Figure 16 otherwise device 1 holds the GTS as shown in Figure 17. The PAN coordinator repeats the process for the new device (device 8) and collects the traffic information for this device for the next 'n' supeframes and again this device will share the GTS with one of the first six devices if it satisfies the reallocation test. The whole process is repeated until the total number of devices sharing the GTS is thirteen.

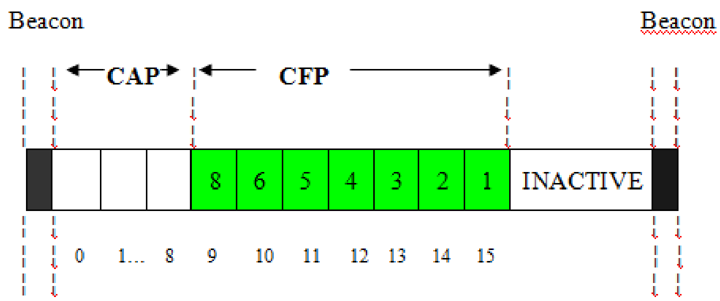


Figure 15. Deallocation of 7th GTS to device 8

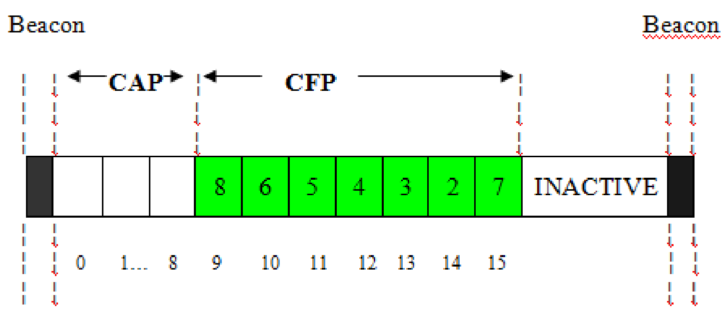


Figure 16. Reallocation of GTS of device 1 to device 7

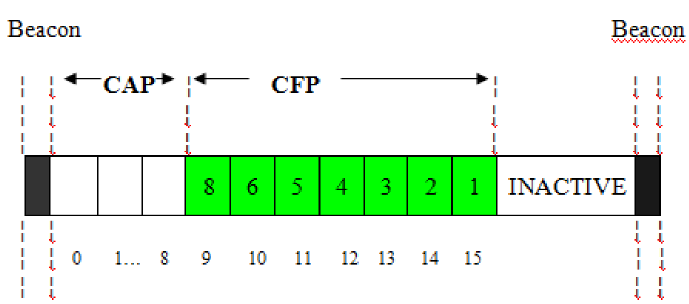


Figure 17. Device 1 holding the GTS

The steps of the algorithm are listed below:

GTS SHARING ALGORITHM USING TRAFFIC ARRIVAL INFORMATION

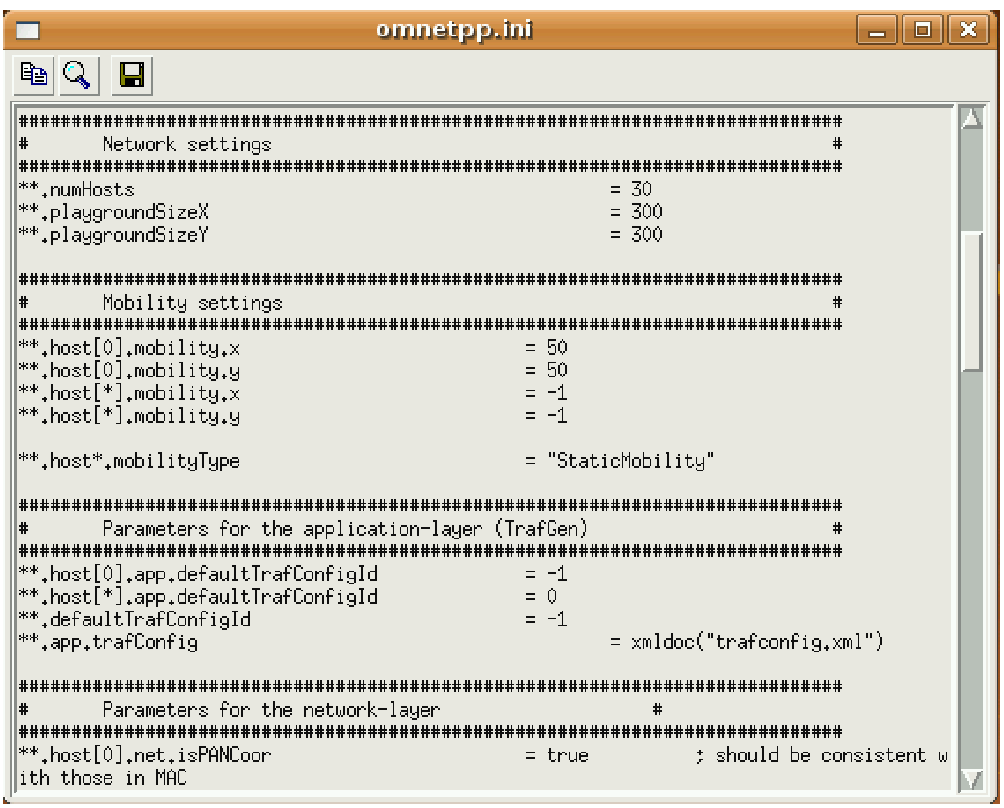
1: All devices request for GTS allocation at the start.
2: The PAN allocates all the 7 GTS to the devices on a first come first serve basis.
3: Start collecting traffic arrival information parameters for the next 'n' superframes for all the 7 GTS.
4: At each superframe:
5: Store and update the values for PA, IA and AA
6: At $(n+1)^{th}$ superframe apply the GTS reallocation algorithm. The device with the 7^{th} GTS allocated will be accommodated in any one of the first 6 GTS based on its Average Arrival values or else not granted any GTS sharing. Deallocate the 7^{th} GTS and assign it to a new device and start tracking its arrival information.
7: Repeat step 3, 4, 5, 6 for the 7^{th} GTS and again it will be either accomodated in the first 6 GTS using average arrival values or not granted any GTS sharing.
8: The whole process is repeated until total number of devices sharing the GTS is 13

Figure 18. GTS SHARING ALGORITHM USING TRAFFIC ARRIVAL INFORMATION

Our current work allows a total of thirteen devices to share the GTS. However, the PAN coordinator can use the average arrival information for all devices to generate a predictive model for GTS allocation exclusively based on average arrival information. This approach expands on the current work to allow more than thirteen devices to share the GTS and will be the basis of our future work. The above algorithm is implemented in a simulation model under OMNeT++ to study the performance of the new scheme in comparison to the original IEEE 802.15.4. The metrics used in the study are total bytes received at PAN coordinator in CFP, packets dropped during the contention free period and total devices using the GTS service. The next section presents the details of the experiment setup and configuration settings and in the following section a detailed analysis of the results are discussed.

5 EXPERIMENT

We used OMNeT++ simulator to compare the performance of our proposed schemes with the standard IEEE 802.15.4. OMNeT++ is public-source and very suitable for simulating wireless networks [4] owing to its modular structure and using NED language for ease of simulation configuration. The IEEE 802.15.4 model in [5] is built conforming to the latest IEEE Std. 802.15.4-2006 and implements the GTS transfer as well as energy model. The model consists of the following modules: application layer implementing the traffic generator, Battery module, Network module and Physical layer module. The model has two data transmission modes: Direct Transmissions and GTS Transmissions. The environment parameter settings are done by adjusting the variables in the omnetpp.ini configuration file of the model. A sample omnetpp.ini file is shown below in Figure 19.



```
omnetpp.ini
###############################################################################
#       Network settings                                                      #
###############################################################################
**.numHosts                                          = 30
**.playgroundSizeX                                   = 300
**.playgroundSizeY                                   = 300

###############################################################################
#       Mobility settings                                                     #
###############################################################################
**.host[0].mobility.x                        = 50
**.host[0].mobility.y                        = 50
**.host[*].mobility.x                        = -1
**.host[*].mobility.y                        = -1

**.host*.mobilityType                        = "StaticMobility"

###############################################################################
#       Parameters for the application-layer (TrafGen)                        #
###############################################################################
**.host[0].app.defaultTrafConfigId           = -1
**.host[*].app.defaultTrafConfigId           = 0
**.defaultTrafConfigId                       = -1
**.app.trafConfig                                    = xmldoc("trafconfig.xml")

###############################################################################
#       Parameters for the network-layer                        #
###############################################################################
**.host[0].net.isPANCoor                     = true          ; should be consistent w
ith those in MAC
```

Figure 19. omnetpp.ini file

5.1 EXPERIMENT OVERVIEW

We ran two different series of experiments to test each of our new proposed schemes. The first set of experiments is a comparison of our GTS Slot Splitting Scheme and the standard IEEE 802.15.4. The parameters in the study include average energy consumption, total data packets transmitted, average packet delivered/packet drop ratio. Our proposed work results in improved bandwidth by allocating the saved bandwidth in the Contention Free Period to the CAP period so we have used total data packets transmitted, average packet delivered/packet drop ratio for CAP traffic in the comparison to study the improvement in bandwidth utilization by the GTS Slot Splitting Scheme. The second set of experiments is a comparison of GTS Sharing Scheme using Traffic Arrival Information with the original IEEE 802.15.4 standard. The metrics used for evaluation are average energy consumption, total GTS packets transmitted, total GTS packets dropped by devices holding the GTS, number of devices using the GTS. We are only focusing on GTS traffic here, as the objective of the proposed scheme is to increase the fairness in allocation of GTS slots in the Contention Free Period.

5.2 EXPERIMENT CONFIGURATION DETAILS

We used Exponential and On-OFF traffic generators for packet generation at the application module. The energy model in [5] defines four states for the radio: Transmitting, Receiving, Idle and Sleep. The energy consumption is calculated by calculating the time spent by radio in each state multiplied by the energy consumption in that state. The CPU consumption is very low compared to energy consumption by the radio so it is not considered in the model in [5].

The radio calibration used in experiments for GTS Slot Splitting Scheme is according to CC2420 radio. The radio energy consumption for different states is listed below:

Initial Battery Capacity = 25 mAh

Battery Usage in Idle State = 0.37 mA

Battery Usage in Receiving State = 19.47 mA

Battery Usage in Transmit State = 16.24 mA

Battery Usage in Sleep State = 0.02 mA

The radio calibration used in experiments for GTS Traffic Sharing scheme is according to CC1000 radio. The radio energy consumption for different states is listed below:

Initial Battery Capacity = 25 mAh

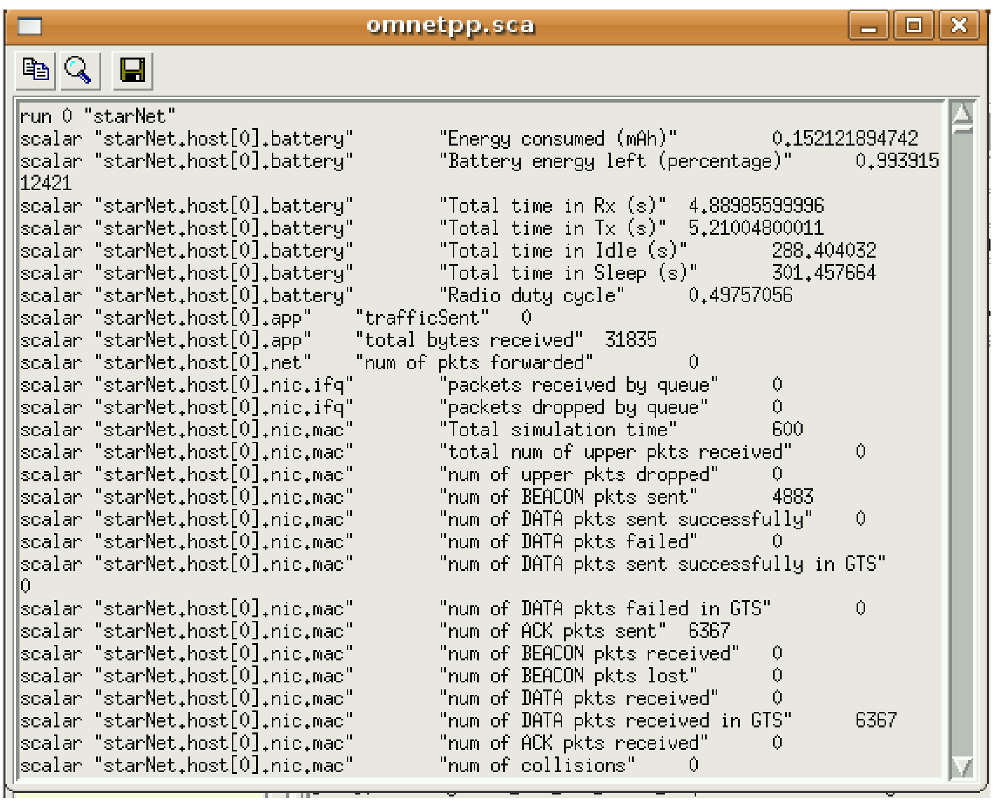
Battery Usage in Idle State = 1.38 mA

Battery Usage in Receiving State = 9.6 mA

Battery Usage in Receiving State = 17.00 mA

Battery Usage in Sleep State = 0.02 mA

The PHY layer parameters are set to the standard values defined in the IEEE 802.15.4-2006. The metric values are recorded as scalar values using the 'record scalar' function available in NED language. A sample scalar output file in OMNeT++ after the simulation run is shown below in Figure 20.


omnetpp.sca

```
run 0 "starNet"
scalar "starNet.host[0].battery"        "Energy consumed (mAh)"         0.152121894742
scalar "starNet.host[0].battery"        "Battery energy left (percentage)"      0.993915
12421
scalar "starNet.host[0].battery"        "Total time in Rx (s)"  4.88985599996
scalar "starNet.host[0].battery"        "Total time in Tx (s)"  5.21004800011
scalar "starNet.host[0].battery"        "Total time in Idle (s)"        288.404032
scalar "starNet.host[0].battery"        "Total time in Sleep (s)"       301.457664
scalar "starNet.host[0].battery"        "Radio duty cycle"      0.49757056
scalar "starNet.host[0].app"    "trafficSent"   0
scalar "starNet.host[0].app"    "total bytes received"  31835
scalar "starNet.host[0].net"    "num of pkts forwarded"         0
scalar "starNet.host[0].nic.ifq"        "packets received by queue"     0
scalar "starNet.host[0].nic.ifq"        "packets dropped by queue"      0
scalar "starNet.host[0].nic.mac"        "Total simulation time"         600
scalar "starNet.host[0].nic.mac"        "total num of upper pkts received"      0
scalar "starNet.host[0].nic.mac"        "num of upper pkts dropped"     0
scalar "starNet.host[0].nic.mac"        "num of BEACON pkts sent"       4883
scalar "starNet.host[0].nic.mac"        "num of DATA pkts sent successfully"    0
scalar "starNet.host[0].nic.mac"        "num of DATA pkts failed"       0
scalar "starNet.host[0].nic.mac"        "num of DATA pkts sent successfully in GTS"
0
scalar "starNet.host[0].nic.mac"        "num of DATA pkts failed in GTS"        0
scalar "starNet.host[0].nic.mac"        "num of ACK pkts sent"  6367
scalar "starNet.host[0].nic.mac"        "num of BEACON pkts received"   0
scalar "starNet.host[0].nic.mac"        "num of BEACON pkts lost"       0
scalar "starNet.host[0].nic.mac"        "num of DATA pkts received"     0
scalar "starNet.host[0].nic.mac"        "num of DATA pkts received in GTS"      6367
scalar "starNet.host[0].nic.mac"        "num of ACK pkts received"      0
scalar "starNet.host[0].nic.mac"        "num of collisions"     0
```

Figure 20. Scalar Output File in OMNeT++

6 RESULTS

In this chapter, we present the experimental results comparing the performance of our proposed schemes with the original IEEE 802.15.4 standard. All the experiments are carried out using the IEEE 802.15.4 model [5] implemented in the OMNeT++ simulator [4]. The network topology used in the experiments is a star network with a central PAN coordinator and 30 Reduced Function Devices (RFD) devices. All devices communicate with the PAN coordinator according to a superframe structure specified in the beacon frame. The physical and MAC layer standard parameters are set according to the values defined in the original standard [2].

6.1 GTS SLOT SPLITTING SCHEME - SIMULATION RESULTS

We ran a series of experiments to study the bandwidth utilization of the GTS Slot Splitting scheme. Our scheme allocates smaller GTS slots for contention free transmissions and the saved bandwidth duration in the Contention Free Period is allocated to Contention Access Period. In our experiment, we have only considered the direct transmission CAP traffic to compare the bandwidth improvement between our scheme and the original standard. The performance improvement by our scheme is demonstrated by higher average packets delivered and higher reliability. The next section presents the details of the experimental configurations.

6.1.1 Experiment Parameters

The analysis on the performance of IEEE 802.15.4 for various standard parameter values have been done in [10, 12] and the results have shown that the standard parameters have significant impact on the performance. The lower superframe interval values result in better overall network performance compared to higher values. To test the performance of our new scheme we ran experiments for different SO/BO values to thoroughly study the performance impact. Table 1 below lists the SO/BO pair values used in the experiment. We did not consider extremely low/extremely high superframe intervals as these values are not suitable for most WPAN applications. We also see from the Table 1 below that the Beacon

Interval and superframe duration are directly impacted by the SO/BO values. The data payload was chosen as a constant value and all devices transmit the packet in the GTS in fixed time duration. We also varied the simulation time and the total number of devices in the network was set to 30. The data transmission duration in GTS is a constant so higher SO/BO value means larger slot sizes and thus higher bandwidth savings in our proposed scheme. The details of the experiment parameters are listed below in Table 1.

Table 1. Experiment Parameters – GTS SLOT SPLITTING SCHEME

SO	BO	TOTAL SIMULATION TIME (s)	SUPERFRAME DURATION (s)	BEACON INTERVAL (s)	DATA TRANSMISSION PERIOD DURING GTS (s)	TOTAL BEACON PACKETS TRANSMITTED
2	**4**	**200**	**0.06144**	**0.24576**	**0.001824**	**811**
3	**5**	**355**	**0.12288**	**0.49152**	**0.001824**	**724**
6	**8**	**1010**	**0.98304**	**3.93216**	**0.001824**	**258**
8	**10**	**1008**	**3.93216**	**15.7286**	**0.001824**	**65**

6.1.2 Results Summary

The experiments were run to compare the performance of our proposed scheme with the original IEEE 802.15.4. The metrics used in the results analysis are: total bytes received by PAN coordinator, reliability (average packet delivered/packet drop ratio), average energy consumption of devices.

i) Total Bytes Received by PANC:– WPAN applications deployed for remote sensing large amounts of surrounding data can significantly benefit from higher packets received by PAN coordinator. The larger the data set the better the analysis that can be done on the object under study. The graph in Figure 21 shows the performance of our scheme compared to the original standard. Our proposed scheme resulted in significant higher average packets received by the PAN coordinator. For smaller SO (=2) value, our scheme increases the total bytes received by the PAN coordinator by 54 percent. For higher SO (=6) value our proposed scheme resulted in 21 percent increase in total bytes received. Since our proposed scheme allocates the saved bandwidth in the CFP to the CAP period thus the increase in the CAP period duration resulted in higher average packet received values.

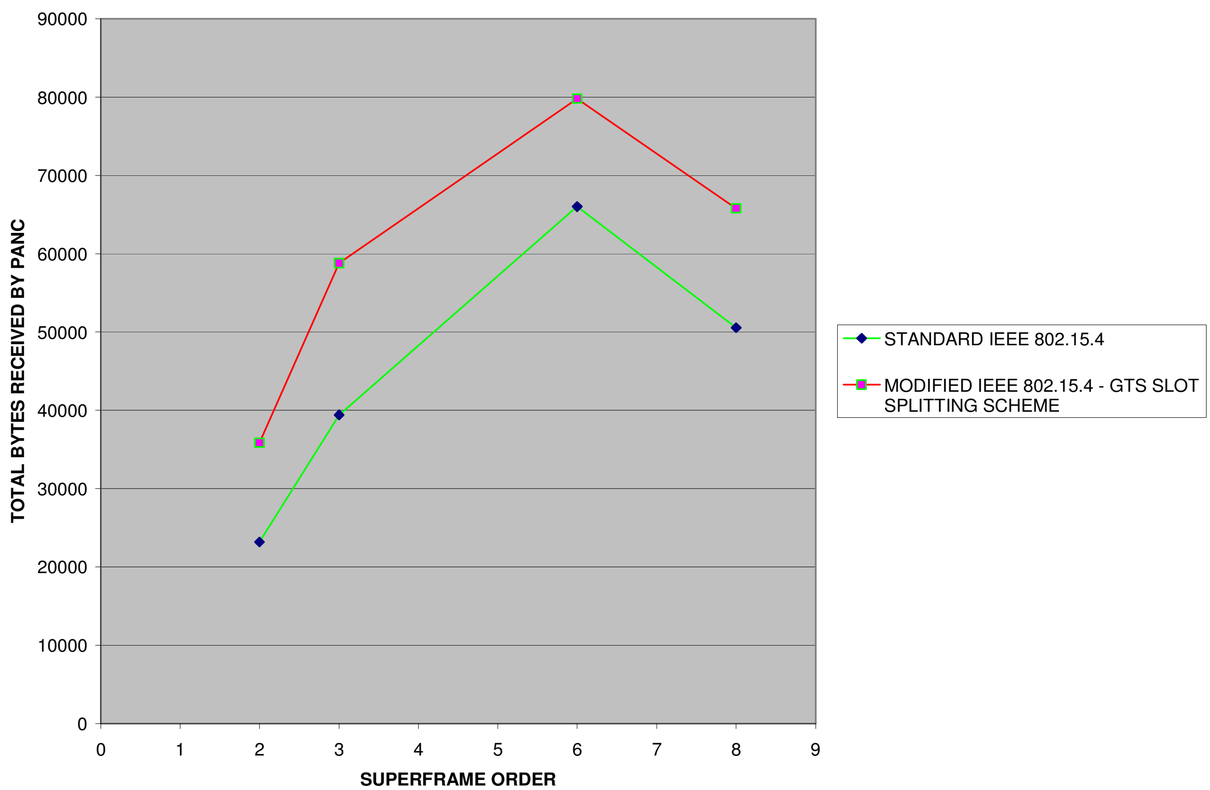


Figure 21. Total Bytes Received by PANC

ii) RELIABILITY (AVERAGE PACKET DELIVERED/PACKET DROPPED RATIO):– As mentioned earlier, some specific WPAN applications have higher emphasis on reliability of packet delivery than any other requirement. Reliability is highest priority for applications deployed for emergency situations such as medical sensor devices. The graph in Figure 22 shows the performance of our scheme compared to the original standard in terms of reliability. Our proposed scheme performs better than the original standard for all SO/BO pair values. For, SO = 2 our scheme resulted in 64 percent higher average packet delivered/packet drop ratio while for SO = 8 the performance improvement by our scheme was 29 percent.

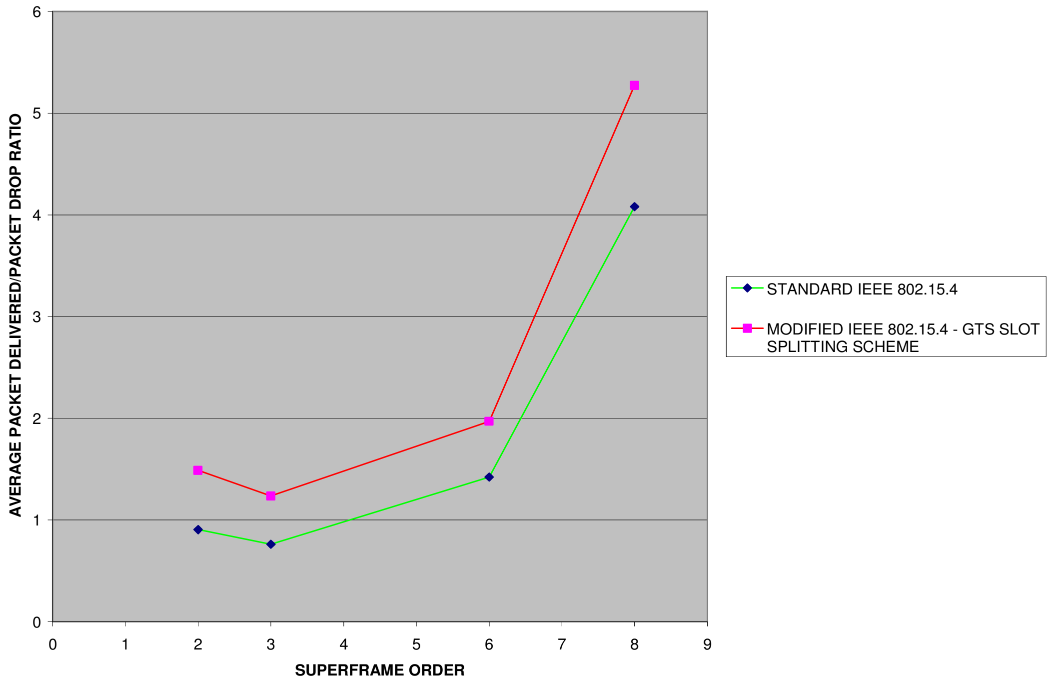


Figure 22. Reliability Results

iii) AVERAGE ENERGY CONSUMPTION: - The average energy consumption of our proposed scheme was found to be slightly higher than the original standard as shown in Figure 23 below. Reducing the slot size as proposed in our scheme did not produce any extra energy savings as the devices go to sleep mode after transmitting the packets in GTS so the additional unused duration in a GTS slot in the standard scheme is only bandwidth wastage. Energy Consumption in a sensor device for different operation states are described in the Experimental Overview section. Packet transmissions and acknowledgement reception contribute most to the energy consumption and idle transceiver state contributes to maximum energy wastage. Our proposed scheme is focused on remote sensing WPAN applications with reliability of packet delivery and higher packet received count as highest priority while having minimum idle energy wastage. Our proposed scheme performs well for low SO value (=2) by increasing the total bytes received by 54 percent and average packet delivery/packet drop ratio by 64 percent but the average energy consumption increase is only 20 percent. Thus, our scheme increases the total bytes transmitted by 64 percent (which contributes most to the energy consumption), but the overall increase in energy consumption is only 20 percent. For high SO values (=6) the increase in bytes transmission was 21 percent and overall average energy consumption increased by 9.5 percent. Higher packet transmitted means higher time spent by devices in data transmission and acknowledgement receipt, but our scheme reduces the idle and sleep duration and thus the overall energy consumption increase in not linearly proportional to the increase in packet transmission.

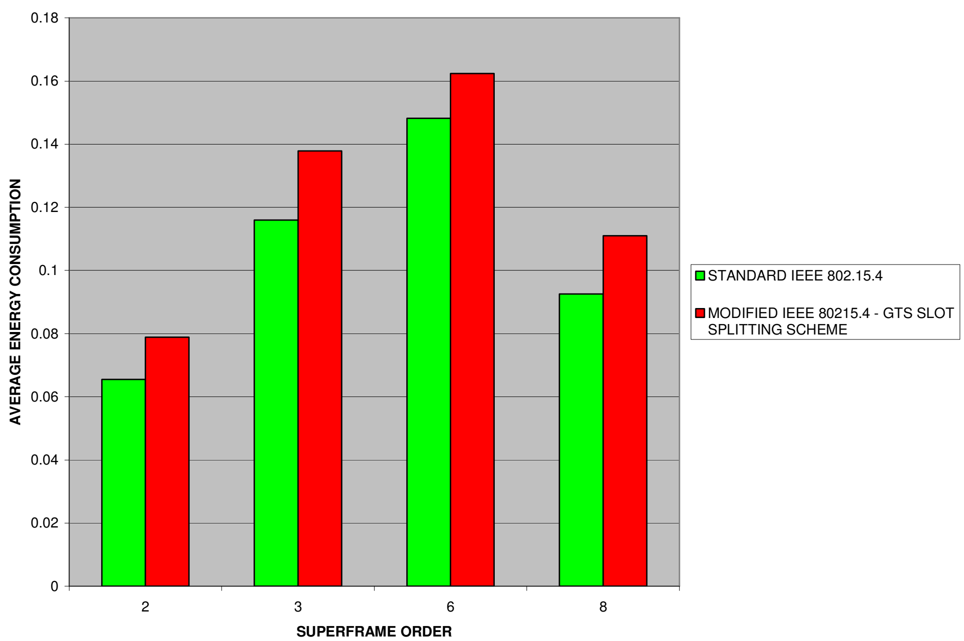


Figure 23. Average Energy Consumption Results

The detailed result summary is shown below in Table 2.

Table 2. Results Summary

SO	BO	TOTAL BYTES RECEIVED BY PANC		AVERAGE PACKET DELIVERD/PACKET DROP RATIO		GTS SLOT DURATION		AVERAGE DEVICE ENERGY CONSUMPTION	
		STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SLOT SPLITTING SCHEME)	STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SLOT SPLITTING SCHEME)	STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SLOT SPLITTING SCHEME)	STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SLOT SPLITTING SCHEME)
2	4	23205	35860	0.9037	1.4885	0.00384	0.00192	0.06548	0.07885
3	5	39410	58780	0.7608	1.235	0.00768	0.00384	0.1160	0.1378
6	8	66000	79800	1.4227	1.9663	0.06144	0.3072	0.1482	0.1624
8	10	50565	65780	4.0811	5.2729	0.24576	0.12288	0.09254	0.1110

6.2 GTS SHARING USING TRAFFIC ARRIVAL INFORMATION – SIMULATION RESULTS

We ran a series of experiments to compare the performance of our new scheme with the original IEEE 802.15.4 standard. In this work, our goal is to improve fairness in GTS allocation, i.e to allow more than seven devices to use the contention free service in applications where high timer expiration time for implicit GTS deallocation prevents other devices in the network from being allocated GTS slots. The star network is chosen as network topology and total number of devices communicating with the PAN coordinator is 30. This work is focused on applications where most packet transmissions take place during CFP and CAP transmissions only involves non-critical data.

6.2.1 Experiment Parameters

The experiments were run for only small SO/BO values since higher values highly degrade the overall network performance. Another reason we chose low SO/BO values is because our work is focused on allowing more than seven devices to use GTS in applications, where lower SO/BO values prevents other devices in the network from being allocated GTS slots (low SO/BO means higher timer expiration time for implicit GTS deallocation). The packet arrival rates was chosen as a constant ON-OFF traffic for SO (=2) and Exponential traffic for SO (=3) and SO (=4). The packet arrival rate at devices was set to lower values and did not satisfy implicit deallocation. The data payload for CFP transmission was chosen as a constant and so data transmission period during GTS is a constant shown below in Table 3. The experiments were run for variable simulation times to study the impact of the new protocol for shorter and longer network duration. The details of the experiment parameters are listed below in Table 3.

Table 3. Experiment Parameters – GTS SHARING SCHEME

SO	BO	TOTAL SIMU-LATION TIME (s)	SUPERFRAME DURATION (s)	BEACON INTERVAL (s)	DATA TRANSMISSION PE-RIOD DURING GTS (s)	TOTAL BEACON PACKETS TRANSMITTED
2	**3**	**600**	**0.06144**	**0.12288**	**0.001824**	**4883**
3	**4**	**1515**	**0.12288**	**0.24576**	**0.001824**	**6166**
4	**5**	**2012**	**0.24576**	**0.49152**	**0.001824**	**4096**

6.2.2 Results Summary

The experiments were run to compare the performance of our proposed scheme with the original IEEE 802.15.4. The evaluation metrics used for the comparative study were: total bytes received by PANC during the CFP period, Reliability (Average packet dropped during the CFP), Total devices using GTS transmission. The next section presents the results analysis of our new scheme for different metrics.

i) Total Bytes Received by PANC in CFP: - Remote sensing applications can significantly benefit from more data packets received by PAN coordinator by providing the remote database with a larger dataset for analysis and also compensating for dropped packets. Our proposed scheme increases the total bytes received by PAN coordinator during CFP by 82 percent for SO (=2) and by 70 percent for SO (=4). The increase in bytes received is attributed to more number of devices using the GTS for contention free transmission. So, our scheme significantly improves upon total bytes received. The Figure 24 below shows the performance of our scheme compared to the original IEEE 802.15.4.

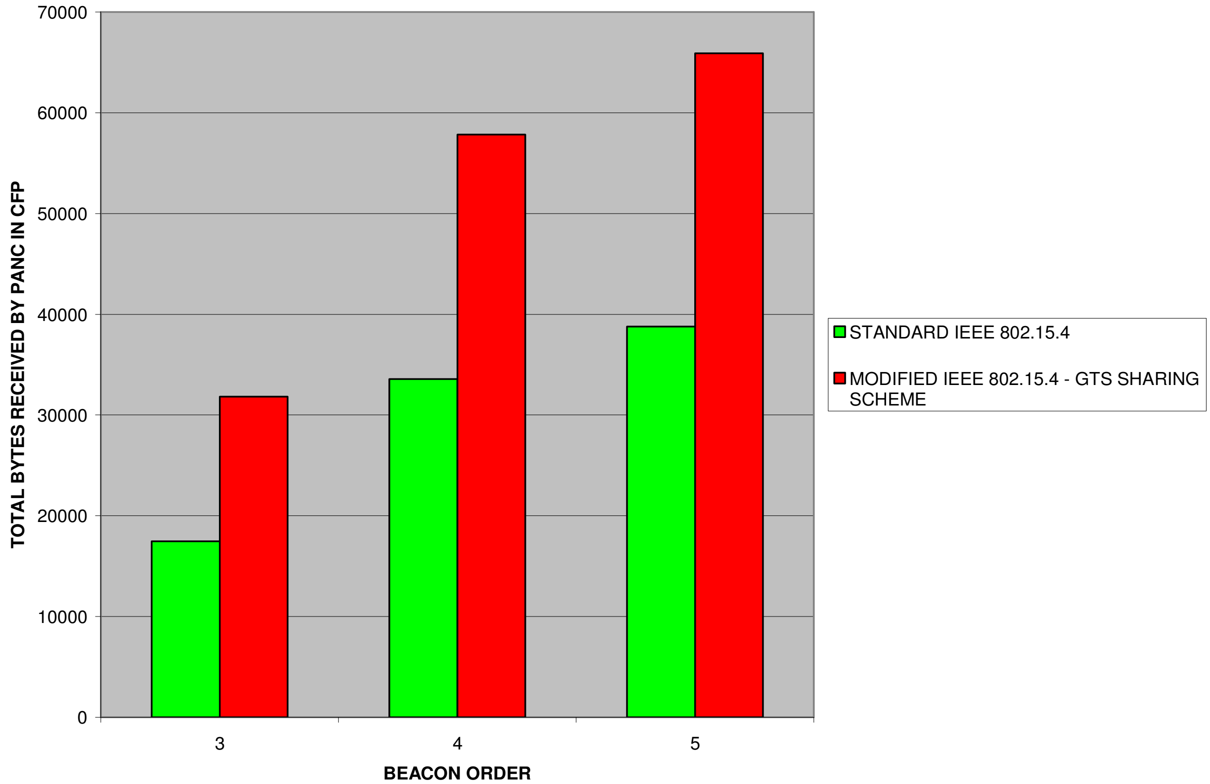


Figure 24. Total Bytes Received By PANC in CFP

ii) RELIABILITY (AVERAGE PACKET DROPPED DURING CFP): - Our work is focused on applications with low packet arrival rate i.e in a remote sensing scenario where the events occur infrequently. The average packet dropped during CFP was very low in our new scheme as shown in the Table 4 below. The reason for lower packet drop rate is low average packet arrival rate so that all devices are able to deliver the packets in their average arrival period without requiring buffering the packets. Higher average packet arrival rate would require larger buffer size for lower packet drop. In the current scheme, we used buffer size of one frame so our work requires minimal buffer size to ensure reliability.

iii) TOTAL DEVICES USING GTS: - The objective of our new scheme is to improve the fairness in GTS allocation by allowing more than seven devices to use the GTS slots. The results summary in Table 4 below shows our new scheme allows for thirteen devices to use the GTS slots for contention free transmission whereas the original standard allows for a maximum of seven devices. Our scheme has the potential to increase GTS sharing for more than thirteen devices which will be our future work.

The average energy consumption of devices in the new scheme is the same as that of original standard. The reason our scheme does not contribute any energy savings is that the unused GTS slots do not contribute much to energy wastage, i.e a device turns it transceiver to sleep mode if it does not have any packet to transmit in GTS. The future work on our scheme would include energy savings and allowing more than thirteen devices to share the GTS. The detailed results summary is shown below in Table 4.

Table 4. Results Summary

SO	BO	TOTAL BYTES RECEIVED BY PANC IN CFP		AVERAGE CFP PACKETS DROPPED		TOTAL DEVICES USING GTS	
		STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SHAR-ING SCHEME)	STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SHAR-ING SCHEME)	STANDARD IEEE 802.15.4	MODIFIED IEEE 802.15.4 (GTS SHAR-ING SCHEME)
2	3	17465	31835	1	4	7	13
3	4	33550	57830	1	7	7	13
4	5	38785	65895	1	11	7	13

7 GTS SLOT SPLITTING SCHEME VS i-GAME

In this section, we analyze the performance of our GTS SLOT SPLITTING scheme with i-GAME [15] in terms of bandwidth utilization. The IEEE 802.15.4 standard allocates GTS in an explicit manner i.e every time a request comes from a device for GTS allocation the coordinator checks the conditions and accordingly allocates a slot to the device or rejects the request. In the original standard, each device is strictly tied to its GTS slot and no other device can use that time slot. i-GAME [15] is an implicit GTS allocation algorithm in which the coordinator allocates slots in CFP by taking the device traffic specifications and delay requirements to allow sharing of slots among devices. The idea is to allow several devices with similar packet arrival characteristics to share a given number of GTS slots in a round-robin fashion. So, every time a device makes a request for a new GTS slot the coordinator runs an admission control algorithm to check if it can accept the device to share the GTS slots with other devices based on the device traffic specifications and delay requirements. However, i-GAME involves additional overhead of requiring every device to identify its traffic characteristics and delay requirements and pass that information to the PAN coordinator. In addition, the coordinator has to run the algorithm to determine the GTS allocation. In [15], the authors have presented a theoretical model of the bandwidth improvement using i-GAME algorithm. Figure 25 below shows the bandwidth utilization of i-GAME compared with the original standard for different delay bounds shown in Figure 26.

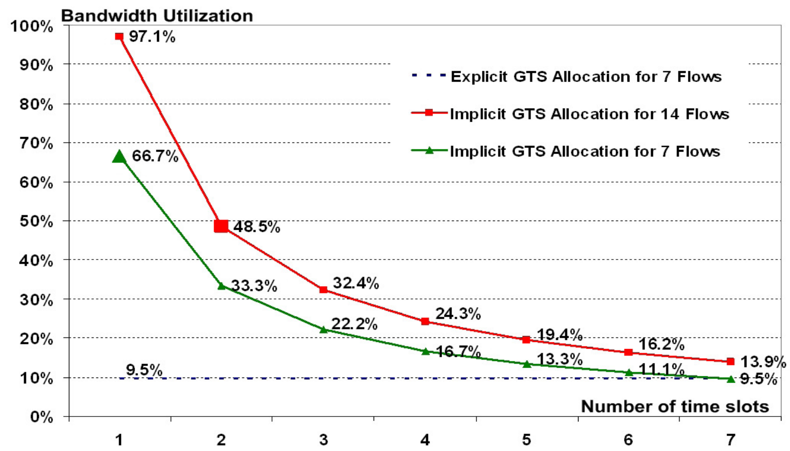


Figure 25. i-GAME Bandwidth Utilization Improvement

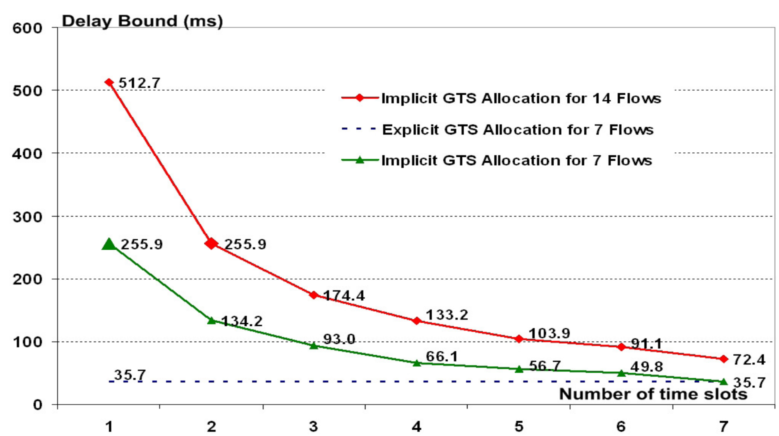


Figure 26. Delay Bounds Guaranteed by i-GAME

The next section presents the performance comparison of the two schemes categorized as Best Case, Worst Case and Average Case.

Best Case: - The bandwidth utilization in Figure 25 above for i-GAME shows that for a delay bound of 512.7 ms or higher the coordinator needs to only allocate only one GTS and it can be shared by fourteen devices while for a delay bound of 255.9 ms or higher seven devices can share one GTS. Most WPAN applications have very strict latency requirements and the delay values are usually very low. IEEE

802.15.4 allocates GTS explicitly so every device is tied to one GTS and there is no sharing of the slots. Therefore, seven GTS slots can be allocated to a maximum of seven devices. In our scheme, we are allocated smaller sized GTS slots therefore seven GTS slots can result in a total savings of three and a half GTS slots. Although compared to i-GAME our scheme does not perform well for very high latency but it still produces significant savings compared to the original standard.

Worst Case: - In the Figure 25 above, for a low latency requirement of 35.7 ms i-GAME can allow sharing of seven GTS among only seven devices. So, for a low latency requirement i-GAME does not produce any savings from the original standard. In addition, i-GAME involves the additional overhead of the algorithm running at the coordinator and for every device to identify its traffic characteristics and passing that information to the coordinator. Our scheme is focused on applications with large CAP traffic so if network devices have high CFP traffic and if each device requires standard larger slots then no savings is generated by our scheme. However, our scheme requires minimum implementation overhead at the PAN coordinator. Thus, even if there is no saving the algorithm implementation does not introduce any additional overhead on either the device or the PAN coordinator. Our scheme is implemented with minor modifications to the original protocol.

Average Case: - The average savings provided by i-GAME is directly related to the delay requirements of every device. In addition, i-GAME requires the traffic arrival characteristics of all devices to be very similar. Figure 25 and Figure 26 above show the savings by i-GAME for different delay bounds. Our scheme produces bandwidth savings for every GTS slot allocated by allocating smaller sized slots to devices in applications where devices have high CAP traffic.

Our scheme and i-GAME both improve upon bandwidth utilization from the original standard. i-GAME performance is dependent on the delay bounds of devices and there is an implementation overhead. By implicitly allocating GTS, i-GAME can produce significant bandwidth savings for a wide variety of applications. Our scheme requires minimal implementation overhead and involves applications where most devices have high CAP traffic. We look to combine GTS Slot Splitting scheme with our work in GTS Sharing scheme to further improve upon bandwidth of the overall network.

8 GTS SHARING USING TRAFFIC ARRIVAL INFORMATION VS Efficient GTS Allocation Algorithm for IEEE 802.15.4

In this section, we used simulations to compare the performance of our scheme with the work in [22]. The work in [22] uses network monitoring to efficiently allocate GTS to the devices in the network. The idea is to allocate GTS to devices with high packet arrival rate as these devices can impact the collision and delay bound of the network. The coordinator runs a traffic collection algorithm which collects each end device's T_{CA} (Current Arrival Time), T_{PA} (Previous Arrival Time), T_{CI} (Current Interarrival Time), T_{AI} (Average Interarrival Time). So, every time the coordinator receives a packet in CAP/GTS it updates the device's packet arrival information. The coordinator collects this information for 'm' superframes and at every $(m+1)^{th}$ superframe it reallocates the GTS to devices with the highest average arrival rate using the values in T_{AI}. The value of 'm' was set to 20 in our experiment.

In the results in [22], the authors used three groups of devices: Group 1 (Devices 1 to 6), Group 2 (Devices 7 to 11) and Group 3 (Devices 12 to 16) with transmission rates of 1, 0.01 and 0.1 respectively. The authors compared the performance of their scheme with the standard IEEE 802.15.4 that only used CAP duration for transmission. The results of the simulation showed 18% average throughput improvement over the standard IEEE 802.15.4. The reason for higher performance is attributed to devices with higher packet arrival rate occupying the GTS.

In this section, we compare the performance of our scheme with the work in [22]. The work in [22] is focused on allocation of GTS to devices with higher packet arrival rate, while in our work, the goal is to improve fairness in GTS allocation by allowing more than seven devices to use the contention free service in applications where high expiration time for implicit GTS deallocation prevents other devices in the network from being allocated GTS slots. The scheme in [22] is focused on applications with large number of devices in the network with high packet arrival rate, whereas our scheme is focused on applications where most devices in the network have low packet arrival rate to allow sharing of GTS. The improved throughput in the scheme in [22] from standard IEEE 802.15.4 is due to devices with high packet arrival rate occupying the GTS, while our scheme improves throughput by allowing sharing of GTS between devices and thus increasing the number of devices using the GTS from seven to thirteen.

We ran a series of experiments to compare the performance of our scheme with the work in [22]. The network topology used in the experiments is a star network with a central PAN coordinator and 50 Reduced Function Devices (RFD) devices. The scheme in [22] is focused on improving throughput for applications in which network devices have different arrival rates and the algorithm tries to allocate GTS to devices with high packet arrival rate. Our scheme is focused on improving fairness in GTS allocation through GTS sharing in applications where network device have low packet arrival rate, but do not satisfy implicit deallocation at the coordinator. We categorized our comparison into three cases and in each case we have two different groups of devices Group 1 and Group 2 with different arrival rates. All devices generate GTS data traffic only and the GTS request commands are taken as the CAP traffic. Every device either has a GTS allocation or requesting the coordinator for allocation through the GTS request command in each superframe. The metrics used in the results analysis are: total bytes received by PAN coordinator and total devices using GTS to study the throughput improvement. The next section presents the detailed results for each case.

Case 1: - In this case, we used two groups of devices for the scheme in [22]: Group1 (Devices 1 to 25 with high packet arrival rate ~ 1kbps) and Group 2 (Devices 26 to 50 with low packet arrival rate ~ 0.2 kbps). This case is favorable to the scheme in [22] as the algorithm running at the coordinator tries to allocate GTS to device with high packet arrival rate. We only used Group 2 devices (packet arrival rate ~ 0.2 kbps) for our GTS Sharing scheme since our scheme is focused on applications with devices with low packet arrival rate and similar traffic arrival characteristics. Our goal is to improve fairness in GTS allocation for applications with low packet arrival rate through sharing of GTS slots and to allow more than seven devices to use GTS. The detailed results summary is shown below in Table 5.

Table 5. GTS SHARING SCHEME VS Efficient GTS Allocation Algorithm for IEEE 802.15.4 – Results Summary (Case 1)

SO	BO	Total Simulation Time	TOTAL BYTES RECEIVED BY PANC IN CFP (Group 2 Devices only)		TOTAL DEVICES USING GTS (Group 1 and Group 2 devices)	
			GTS TRAFFIC SHARING SCHEME	Efficient GTS Allocation Algorithm for IEEE 802.15.4	GTS TRAFFIC SHARING SCHEME	Efficient GTS Allocation Algorithm for IEEE 802.15.4
2	3	100	10305	28295	13	7
3	4	400	21325	57480	13	7
4	5	1000	26070	70760	13	7

The results summary in Table 5 shows higher total bytes received by the coordinator using the scheme in [22]. The higher bytes received by coordinator is attributed to GTS allocation to high packet arrival rate Group 1 devices for most of the network duration. Our scheme is using only Group 2 devices with low packet arrival rate and so the table shows lesser bytes received. However, our scheme still has more bytes transmitted than the original standard since we have thirteen devices transmitting data using GTS instead of seven. The total number of devices using the GTS in our scheme in thirteen while in [22] is same as the original standard i.e seven.

Case 2: - In the second case, we are considering applications in which most devices have low packet arrival rate e.g remote monitoring of a system where the frequency of occurrence of events is very less. We have taken two different groups of devices: Group 1 (Device 1 to 25 with low arrival rate ~ 0.2 kbps) and Group 2 (Device 26 to 50 with low arrival rate ~ 0.1 kbps). The detailed results summary is shown below in Table 6.

Table 6. GTS SHARING SCHEME VS Efficient GTS Allocation Algorithm for IEEE 802.15.4 – Results Summary (Case 2)

SO	BO	Total Simulation Time	TOTAL BYTES RECEIVED BY PANC IN CFP		TOTAL DEVICES USING GTS	
			GTS TRAFFIC SHARING SCHEME	Efficient GTS Allocation Algorithm for IEEE 802.15.4	GTS TRAFFIC SHARING SCHEME	Efficient GTS Allocation Algorithm for IEEE 802.15.4
2	3	100	6300	4615	13	7
3	4	400	13020	9155	13	7
4	5	1000	16130	11415	13	7

The results summary in Table 6 above shows higher bytes received by PAN coordinator in our scheme compared to the work in [22]. In addition, our scheme allows thirteen devices to share the GTS while in [22] only a maximum of seven devices can use the GTS. So, the work in [22] does not perform well for applications with devices with low packet arrival rate. The GTS slots are continuously being reallocated between Group 1 and Group 2 devices and vice versa by the coordinator in [22]. Since, devices in either group have low arrival rate so no device can hold on to the slot for entire network duration.

Case 3: - In this case, we tried to evaluate the performance of the work in [22] for applications where all devices in the network have similar packet arrival rate. The algorithm in [22] allocates GTS slots according to priority based on higher packet arrival rate at the coordinator which requires devices in network to have different arrival rates for the algorithm to generate best GTS allocations. So, in this case we have only one set of devices – Group 1 (Device 1 to 50 with similar packet arrival rate). In the first case, we set the packet arrival rate to high (~ 1 kbps) for all devices and the results showed similar performance as in Case 1 above. Similarly, in the second case we set the packet arrival rate to low for all devices (~ 0.1 - 0.2 kbps) and the simulation results showed same performance as Case 2. So, the performance of the work in [22] is strongly dependent on traffic arrival characteristics of devices in the network and if all devices have similar packet arrival rate then the algorithm does not produce any significant bandwidth improvement compared to the original standard.

Both our scheme and the work in [22] perform better than the original IEEE 802.15.4. Both the schemes improve upon the throughput through higher average total packets transmitted to the coordinator. Our scheme is focused on applications where the packet arrival rate at end devices is low and do not satisfy implicit deallocation so we improve throughput by allowing sharing of GTS among thirteen devices. The scheme in [22] is focused on applications where arrival rate of packet at end devices is high so they improve throughput by allocating GTS slots to devices with high arrival rate using traffic arrival information. In the future, we look to combine the two schemes to allow the coordinator to switch between the two algorithms dynamically according to the changing packet arrival information at the coordinator.

9 CONCLUSIONS

A lot of improvements still need to be made to the IEEE 802.15.4 standard before WPAN can be efficiently deployed for large scale applications. Recent works have been focused on improving latency, energy consumption, bandwidth utilization and reliability. In this thesis, we have presented improvements to the IEEE 802.15.4 protocol for LR-WPAN in terms of bandwidth utilization and fairness in GTS allocation. In the first part of our work, we tried to address the bandwidth underutilization problem in the original standard. Remote Sensing applications with high amount of CAP traffic and high reliability requirements can significantly benefit from our scheme. In the second part, our work is focused on improving the fairness in GTS allocation in applications where high expiration time for implicit GTS deallocation prevents other devices in the network from being allocated GTS slots. Remote sensing applications deployed for sensing critical data periodically with priority on goodput and reliability can benefit from our new scheme. We conducted a simulative performance study of LR-WPAN based on the simulation model [5] that has been implemented for OMNeT++ [4]. The work on analysis of beacon-enabled IEEE 802.15.4 in [10, 12, 27] have shown that SO/BO values directly impact the performance of the protocol so we tested our proposed schemes for a range of SO/BO values. The results were analyzed using the following metrics - average energy consumption, total data packets transmitted, average packet delivered/packet drop ratio, throughput. The results of the simulation show that our proposed work significantly improves bandwidth utilization, has higher packet reliability and improves fairness in the GTS allocation. The proposed works are backward compatible with the original IEEE 802.15.4 and can be implemented with simple modifications to the original protocol.

10 FUTURE WORKS

We have shown using simulation experiments that our proposed work performs better than the standard protocol in terms of throughput, fairness in GTS allocation and packet reliability. The future work involves testing our work under different simulation models using a wider range of protocol parameters and more complex network topologies. In our current work, we did not consider quality of service constraints in our study so we expect to study the performance of our work with consideration to delay constraints and variable buffer size. We also expect to investigate different applications where our proposed work can improve performance significantly as part of our future work. In the GTS Sharing algorithm, our current work allows a maximum of thirteen devices to share the GTS so in our future work we expect to expand on this work to allow more than thirteen devices to share the GTS. We also look to combine the two proposed schemes to improve overall performance for both CAP and CFP transmissions and also make it more energy efficient compared to the original standard. We also look to expand the work in [8] in which the network coordinator can generate an efficient transmission scheduling scheme for devices by making use of the traffic arrival characteristics. Another important area of future work involves testing our schemes by deploying it for real-time applications.

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