# 行政院國家科學委員會專題研究計畫 期中進度報告

## 數位家庭:網路、平台與應用--子計畫三：異質無線家庭網路之即時應用(2/3)

## 期中進度報告(完整版)

計畫類別：整合型
計畫編號：NSC 95-2219-E-002-016-
執行期間：95年08月01日至96年07月31日
執行單位：國立臺灣大學資訊網路與多媒體研究所

計畫主持人：逄愛君

報告附件：出席國際會議研究心得報告及發表論文

處理方式：期中報告不提供公開查詢

中華民國 96年05月29日

# 行政院國家科學委員會補助專題研究計畫

□成果報告
■期中進度報告

# 數位家庭：網路、平台與應用 －

# 子計畫三： 異質無線家庭網路之即時應用 (2/3)

計畫類別：□個別型計畫　　■整合型計畫
計畫編號：NSC 95-2219-E-002-016
執行期間：95 年 08 月 01 日至 96 年 07 月 31 日

計畫主持人：逄愛君教授
計畫參與人員： 楊鎮光、陳君豪、汪振宇、曾學文、江佳恩、
王信安、朱韋妮、賴啟屏

本成果報告包括以下應繳交之附件：

- □ 赴國外出差或研習心得報告一份
- □ 赴大陸地區出差或研習心得報告一份
- □ 出席國際學術會議心得報告及發表之論文各一份
- □ 國際合作研究計畫國外研究報告書一份

執行單位：國立台灣大學資訊網路與多媒體研究所

中華民國 96 年 5 月 30 日

# 行政院國家科學委員會補助專題研究計畫期中進度報告

計畫名稱：數位家庭：網路、平台與應用 – 子計畫三：
異質無線家庭網路之即時應用 (2/3)

計畫編號：NSC 95-2219-E-002-016
執行期限：計畫自民國 95 年 08 月 01 日起至民國 96 年 07 月 31 日止
主持人：逄愛君教授
計畫參與人員：楊鎮光、陳君豪、汪振宇、曾學文、江佳恩、
王信安、朱韋妮、賴啟屏

國立台灣大學資訊網路與多媒體研究所

## 1. 摘要

### 中文摘要：

IEEE 802.15.4 是一個針對低功率無線個人區域網路 (LR-WPAN)所設計的新的通訊協定。它針對低成本、低複雜度、低能量消耗的固定或可攜裝置提供了一個低速的無線連結。在此規格中的保證時槽 (GTS)功能中，提供了一個高優先權的傳輸方式。此為一個保證各裝置有一段獨占的時間傳輸資料的設計，可用來提供服務品質 (QoS)。一些應用例如醫療儀器或者安全系統，由於這些資料極為重要且不能被遺失或延遲，因此尤其需要這個服務的提供。我們提出了一個新的保證時槽方法，是根據過去的保證時槽回應來提供更好的服務品質，實驗結果證實我們的方法比規格上的不管在資料延遲時間上，或者各裝置之間的公平性，都具有更好的效能。

### *Abstract*：

IEEE 802.15.4 is a new standard uniquely designed for low-rate wireless personal area networks. It targets ultra-low complexity, cost, and power for low-rate wireless connectivity among inexpensive, portable, and moving devices. IEEE 802.15.4 provides a Guaranteed Time Slots (GTS) mechanism to allocate a specific duration within a superframe for time-critical transmissions. In this paper, we propose an adaptive GTS allocation (AGA) scheme for IEEE 802.15.4 with the considerations of low-latency and fairness. The scheme is designed based on the existing IEEE 802.15.4 medium access control protocol without any modification. A simulation model validated by the developed mathematical analysis is presented to investigate the performance of our AGA scheme. The capability of the proposed AGA scheme is evaluated by a series of experiments. It is shown that the proposed scheme significantly outperforms the existing IEEE 802.15.4 implementations.

**關鍵詞：**

ZigBee, IEEE 802.15.4, GTS, QoS, Fairness

## 2. Introduction

With the success of wireless local area networks (WLANs), the wireless networking community has been looking for new avenues to enable wireless connectivity to existing and new applications [6]. The emerging of short-transmission-range wireless devices with low transmission rates further boosts the development of wireless personal area networks (WPANs), where a WPAN is a wireless network centered around an individual person's workspace for device interconnection. Among the well-known WPAN specifications, ultra wideband (i.e., IEEE 802.15.3) is designed for high-rate WPANs [2]. Bluetooth (i.e., IEEE 802.15.1) supports various applications, such as wireless headsets of home appliances and computer peripherals, and provides quality of service (QoS) transmissions, especially for audio traffics [16]. As low cost and low-power consumption are considered, ZigBee (i.e., IEEE 802.15.4) emerges as a good alternative for WPANS [3].

IEEE 802.15.4 targets ultra-low complexity, cost and power for low-rate wireless connectivity among inexpensive, portable, and moving devices [4]. Such a WPAN might consist of multiple traffic types, including periodic data, intermittent data and repetitive low-latency data [1]. Some data transfers might be time-critical (such as medicare or security applications with repetitive low-latency data). Others might be sporadic (such as home-automation applications that issue data transfer requests when needed) or periodic (such as sensor/meter applications that issue requests at a constant interval). In order to support time-critical data transfers generated by repetitive low-latency applications, IEEE 802.15.4 provides a GTS (Guaranteed Time Slots) mechanism to allocate a specific duration within a superframe for frame transmissions. Although the dedicated bandwidth could guarantee the reliability and performance of data deliveries, the abusing of dedicated resources might also result in the exclusion of other transmissions. The data transmission problem is further complicated by the first-come-first-serve (FCFS) GTS allocation policy [3] because of the lack of scheduling flexibility to respond to the network workload and application needs in low-latency data delivery. Starvation is even possible for devices with low data-transmission frequencies due to a fixed timer maintained in IEEE 802.15.4 for GTS deallocation.

How to adequately and efficiently provide an GTS allocation scheme with low-latency and fairness is a very challenging problem. Among the work related to this problem, Zheng et al [18] did a feasibility study for IEEE 802.15.4 standard over ubiquitous networks. Lu et al [12] worked on the energy-cost analysis of IEEE 802.15.4 beacon-enabled and nonbeacon-enabled transmission modes. A performance analysis of IEEE 802.15.4-based body area networks (BANs) for medical sensors was presented by Timmons et al [17], and the system throughput and the probability distribution of access delay are derived for a beacon-enabled WPAN [13]. An adaptive algorithm [14] for beacon-interval adjustment in IEEE 802.15.4 star-topology networks was proposed. Kim et al [9] developed an o®-line real-time message scheduling algorithm based on the GTS parameters, such as the length of a beacon interval. Although the performance analysis for IEEE 802.15.4 was investigated extensively, little work has been done on the problems of IEEE 802.15.4 GTS allocation. We must point out that many existing polling algorithms, e.g., those for IEEE 802.11 contention free period (CFP) [5, 10, 8], can not be applied to IEEE 802.15.4 GTS allocation, due to the extremely low power-consumption of IEEE 802.15.4-based wireless devices and the scarce bandwidth of IEEE 802.15.4 networks (compared to that of IEEE 802.11).

In this paper, we propose an adaptive GTS allocation (AGA) scheme for IEEE 802.15.4 with the considerations of low-latency and fairness. There are two phases for the proposed scheme: In the classification phase, devices are assigned priorities in a dynamic fashion based on recent GTS usage feedbacks. Devices that need more attention from the coordinator are given higher priorities. In the GTS scheduling phase, GTSs are given to devices in a non-decreasing order of their priorities. A starvation-avoidance mechanism is presented to regain service attention for lower-priority devices that need more GTSs for data transmissions. The scheme is designed based on the existing IEEE 802.15.4 medium access control (MAC) protocol without any modification. A simulation model validated by the developed mathematical analysis is presented to investigate average packet waiting times and fairness for our adaptive scheme. The capability of the proposed scheme is evaluated by a series of experiments. It is shown that the proposed scheme significantly outperforms the existing implementations with FCFS.

The rest of this paper is organized as follows: Section 2 describes the MAC protocol for IEEE 802.15.4. Section 3 defines the problem under investigation and proposes an adaptive GTS allocation (AGA) algorithm to provide low-latency and fair transmissions for IEEE 802.15.4. Section 4 presents the developed simulation model and summarizes our experimental results to demonstrate the capability of the proposed scheme. Section 5 is the conclusion.

## 3. IEEE 802.15.4 MAC

The IEEE standard, 802.15.4, defines the physical layer and medium access control (MAC) sublayer specifications for low-rate wireless personal area networks (LR-WPANs) [3]. It supports wireless communications between devices with minimal power consumption and typically operates in a personal operating space of 10 meter or less. The IEEE 802.15.4 defines two medium-access modes: beacon-enabled mode and nonbeacon-enabled mode. In the nonbeacon-enabled mode, arbitration of medium accesses is purely distributed among wireless devices based on CSMA(Carrier Sense Multiple Access)/CA(Collision Avoidance). In addition to CSMA/CA-based transmissions, the beacon-enabled mode provides a contention-free GTS (Guaranteed Time Slots) mechanism to support time-critical data deliveries. In this paper, we focus on the IEEE 802.15.4 beacon-enabled mode, and the details for the nonbeacon-enabled mode can be found in [3]. Figure 1 shows a superframe structure adopted by the IEEE 802.15.4 beacon-enabled mode. A superframe begins with a beacon issued by a PAN coordinator, and consists of an active portion and an inactive portion. The duration (also called beacon interval) of a superframe ranges from 15ms to 245s. The coordinator and devices can communicate with each other during the active period and enter the low-power mode during the inactive period. The parameter macBeaconOrder(BO) determines the length of beacon interval (BI) (i.e., BI = 2BO * aBaseSuperFrameDuration), and the parameter macSuperFrameOrder(SO) decides the length of active period (SD = 2SO * aBaseSuperFrameDuration) in a superframe. The active portion with 16 time slots is composed of three parts: a beacon, a contention access period (CAP), and a contention free period (CFP). The beacon is transmitted by the coordinator at the start of slot 0, and the CAP follows immediately after the beacon. In the CAP, a slotted CSMA-CA mechanism is used for devices to access the channel. In addition to non-time-critical data frames, MAC commands such as association requests and GTS requests shall be transmitted in the CAP.

The IEEE 802.15.4 standard defines the use of CFP for devices requiring dedicated bandwidth. The PAN coordinator is responsible for the GTS allocation, and determines the length of the CFP in a superframe. Basically, the CFP length depends on the GTS requests and the current available capacity in the superframe. Provided that there is sufficient capacity in a superframe, the maximum number of GTSs that the PAN coordinator can allocate in the superframe is seven. The GTS direction relative to the data flow from the device that owns the GTS is specified as either transmit or receive. The transmit GTSs are used for transmitting data from devices to the PAN coordinator, and the downlink frames from the PAN coordinator to devices are delivered over the receive GTSs.

The device that requests new GTS allocation sends a GTS request command to the PAN coordinator during the CAP. Upon receipt of the GTS request command, the PAN coordinator first checks if there is available capacity in the current superframe. Provided that there is sufficient bandwidth in the current superframe, the coordinator determines a device list for GTS allocation in the next superframe based on a FCFS fashion. Then the PAN coordinator includes the GTS descriptor (i.e., the device list that obtains GTSs) in the following beacon to announce the allocation information. For GTS deallocation, devices can return the GTS resources by explicitly sending a GTS deallocation request command to the PAN coordinator. 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. In IEEE 802.15.4, a fixed expiration timer is used to manage the GTS usage. Once the allocated GTSs would not be utilized for 2n superframes, the PAN coordinator shall reclaim the previously allocated GTS bandwidth for those devices, where n is defined as follows.

$$\begin{cases} n = 2^{8-BO}, & 0 \leq BO \leq 8 \\ n = 1, & 9 \leq BO \leq 14 \end{cases}$$

## 4. An Adaptive GTS Allocation (AGA) Scheme

The objective of this section is to propose an adaptive GTS allocation (AGA) scheme for IEEE 802.15.4-based WPANs with the considerations of low-latency and fairness. In IEEE 802.15.4, GTS is provided by the coordinator in a star network topology (see Figure 2). The communication is established between a PAN coordinator and up to 255 devices. By periodically broadcasting a beacon frame, a PAN coordinator updates its GTS descriptor to surrounding devices.

An ideal GTS allocation scheme should have a good guess for the future GTS transmitting behaviors of devices. By using the prediction, the PAN coordinator allocates GTS resources to devices in need, and reclaims the previously allocated GTSs that will not be used. Our adaptive GTS allocation (AGA) scheme is a two-phase approach. In the classification phase, devices are assigned priorities in a dynamic fashion based on recent GTS usage feedbacks. Devices that need more attention from the coordinator are given higher priorities. In the GTS scheduling phase, GTSs are given to devices in a non-decreasing order of their priorities. A starvation-avoidance mechanism is presented to regain service attention for lower-priority devices. Before presenting the details for the device classification and GTS scheduling phases, we define two terms, GTS hit and GTS miss, as follows.

- **Definition 1:**

*If one device has issued a 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.

### 4.1. Device Classification Phase

In this phase, each device is adaptively classified into one state maintained by the coordinator, and dynamically assigned a priority number by the coordinator based on past GTS usage feedbacks. Assume that there are N devices in an IEEE 802.15.4-based WPAN, and there are M+1 (0, 1, ⋯, M) priority numbers dynamically assigned to the N devices. A large priority number represents a low priority for GTS allocation. The priority number assigned to the device n is defined as $\mathrm{Pri}_n$, and then we have $0 \cdot \mathrm{Pri}_n \cdot M$. In our AGA scheme, the devices with higher priorities are expected to have more recent traffic, and thus have higher probabilities to transmit their data in the coming superframe. The state and priority number of a device are internally maintained by the PAN coordinator. The maintenance of the state and priority number of each device is based on the concept for Dynamic Branch Prediction for computer architecture design [15] and the Additive Increase/Multiplicative Decrease (AIMD) algorithm for network congestion control [11] with some improvement, and will be described as follows.

#### 4.1.1. State Transition

All devices in our AGA scheme are classified into four traffic-levels according to the state diagram shown in Figure 3. In this figure, the four traffic-levels of devices are accordingly mapped to the four states, i.e., HH (High Heavy), LH (Low Heavy), HL (High Light) and LL (Low Light). The order of traffic levels for these states are HH > LH > HL > LL.

Initially, all devices are placed in the LL state. At the end of each superframe, the PAN coordinator examines the GTS usage of all devices, and then decides next states the devices transit to. The transition follows the solid and dashed lines in Figure 3. The solid and dashed lines respectively represent the occurrence of a GTS hit and a GTS miss. With the state diagram, the devices with more frequently GTS usage will have larger probabilities to stay in heavy-traffic states (e.g., HH and LH). Also, temporarily unstable transmission behaviors of devices could be more tolerated so that the devices residing in the heaviest-traffic state (i.e., HH) with an occasional transmission interruption have second-chance before being degraded to the light-traffic states. On the other hand, the devices in the LL state can be promoted to heavy-traffic states by having consecutive GTS hits.

In original IEEE 802.15.4 specification [3], the devices intending to utilize GTSs for data transmission may wait for the expiration of GTSs (i.e., the allocated GTSs that have not been used for a specific period) of high-priority transmissions. This passively deallocation scheme for GTS resources would result in starvation of light-traffic devices. Conversely, by using our AGA scheme, starvation of light-traffic devices can be avoided since these devices can be gradually promoted to the heavy-traffic state with the existing GTS-request facility to notify the PAN coordinator for traffic-level promotion.

### 4.1.2. Priority Assignment

By using the above state diagram, the PAN coordinator can monitor the recent transmission behaviors of devices, and classify the devices into proper traffic types. However, with scarce GTS resources (i.e., 7 time-slots) of IEEE 802.15.4-based networks, the four-state classification for devices is somewhat rough and can not be sufficient for precisely classifying transmission behaviors of devices. Thus the state diagram in Figure 3 is further revised so that each device is dynamically assigned a priority number for GTS allocation. Upon the occurrence of GTS hit of a device, the priority number of the device is decreased by the PAN coordinator, and the priority of GTS allocation for the device upgrades. On the other hand, when GTS miss occurs to a device, the PAN coordinator increases the priority number of the device, and hence the opportunity for obtaining a GTS for the device reduces. Maintenance of priority numbers of devices depends on the transmission feedback as well as the traffic-level states of devices, and the details for maintaining priority numbers of devices are presented below.

Compared to the priority assignment by purely using AIMD [5], our scheme provides a multi-level AIMD algorithm for the updating of priority numbers. In our multi-level priority updating, the decrease/increase of a priority number of a device depends on the traffic-level state the device resides. The high-priority devices with temporary interruption of GTS usage will be slightly demoted to lower priorities. On the other hand, if a low-priority device starts to request the GTS service to transmit data, its priority will be greatly promoted to have GTS service as soon as possible, and starvation of such a low-priority device can be avoided. What our priority assignment focuses on is whether devices have continuous data to be transmitted over the GTSs. The devices with consecutive transmissions are favored by our scheme. However, a device that has idled for a period of time would be considered not to need the GTS service, and it is reasonable to greatly degrade the device's priority.

From Figure 3, we can see that if the device n in state HH uses the GTS service all the time and occasionally has a GTS miss, its priority $Pri_n$ will be increased by 1. Once device n resumes to request for the GTS service in the following superframe and then has continuous data to be transmitted, the increased priority number for device n will be exponentially halved so that the priority of device n can be \recovered" rapidly. For device k in LL state, a similar and even more greatly priority promotion occurs if the device k has consecutive GTS hits. On the other hand, if the device k in state LL just has one GTS hit and ceases transmitting data, the degradation of the priority for device k would be more serious than that for the high-traffic-level device n. Our design for device classification can prevent low-priority devices from starvation, and simultaneously maintain the GTS service for heavy-traffic devices with occasionally transmission interruption.

## 4.2. GTS Scheduling Phase

With the device classification phase, priorities for GTS allocation for all devices under the supervision of the PAN coordinator are determined. Next, in the GTS scheduling phase, the GTS resources are adequately scheduled and allocated to the devices. The scheduling criteria are based on the priority numbers, the superframe length depending on the BO value, and the GTS capacity in the superframe. The GTS scheduling algorithm is shown in Procedure 1. Assume that there are N devices in the WPAN, and P is a set including the priority numbers for the N devices. In Procedure 1, the PAN coordinator first checks if the GTS capacity is overloaded. In the IEEE 802.15.4 specification[3], the GTS capacity in a superframe shall meet the following two requirements.

- The maximum number of GTS slots to be allocated to devices is seven.
- The minimum length of a CAP shall be aMinCAPLength. The increase of the total GTS period shall not result in the reduction of the CAP length to be less than aMinCAPLength.

If the requirements are met, the GTS capacity is considered not to be overloaded. Provided that there is sufficient GTS resources to accommodate more devices, lines 5-11 of the WHILE loop are executed. At each iteration of the WHILE loop, a minimum $Pri_k$ is selected among P, and its value is compared with a threshold value $T_h$. $T_h$ is defined as

$$T_h = MR^{BO}.$$

where R is a constant, and $0 < R < 1$.

The threshold $T_h$ is presented here due to the consideration of the GTS traffic load. When the traffic load is light (i.e., most of the devices have high priority numbers), there is no need to allocate too many GTS resources for the devices. Too much dedicated bandwidth for GTS usage in this case leads to the resource wastage and even the degradation of overall system performance. Instead, the GTS bandwidth shall be transferred for contention-based accesses in CAP. To achieve such a goal, the PAN coordinator has to detect the workload for GTS traffic and filter unnecessary GTS allocation by using the threshold Th. From (1), the value of $T_h$ is dynamically adjusted and depends on the maximum priority number M, a constant R and the beacon interval determined from BO. As the beacon interval increases, there is higher probability that many devices have requested the GTS service in the superframe. Based on our priority assignment, the devices having requested GTS are assigned small priority numbers even though they only have one request in the whole superframe. To prevent the scarce GTS resources from distributing to those devices with extremely low-frequency GTS requests in such a long superframe, a stricter threshold is needed.

In this case, the $T_h$ value is set to be much smaller than M. On the other hand, in a short beacon interval, the value of $T_h$ can be increased, and the limitation for the device selection can be more relaxed.

Based on the above discussions, the priority number of the selected device k is compared with the dynamic threshold $T_h$. If $Pri_k \cdot T_h$ (line 6), then the device k is scheduled in the GTS of the current superframe.

## 5. Performance Evaluation

This section develops an simulation model to investigate the performance of our adaptive GTS allocation (AGA) scheme. Our developed simulation follows the specification of IEEE 802.15.4 MAC protocol, and is validated by our mathematical analysis. Without loss of generality, several assumptions are made to reduce the complexity of the simulation model and described as follows.

- Only the GTS traffic is considered.
- All GTS transmissions are successful. That is, we do not consider GTS retransmissions.
- Only the transmit GTSs for the uplink traffic are adopted.

In the simulation model, a star topology with one PAN coordinator and N devices (N=5 and 10) is adopted. Each simulation run lasts 100,000 beacon intervals (i.e., 49; 152 seconds). The packet arrivals for each device form a Poisson stream with the inter-arrival rate ¸. Two traffic types generated by devices are considered, heavy traffic and light traffic. ¸h and ¸l represent respectively the inter-arrival rates for the heavy-traffic and light-traffic devices. In the simulations, we have $\lambda_h$ = 0.3/s and $\lambda_l$ = 0.1/s. Such the rate setting is reasonable in IEEE 802.15.4-based WPAN since IEEE 802.15.4 targets low-rate wireless communications. Also, the ratio of the number of heavy-traffic devices to that of all devices is defined as v. Table 1 lists the input parameters for our simulation model.

As to the output measures, average packet waiting time is an important metric for our proposed AGA scheme. Furthermore, a fairness index F for packet waiting times is utilized to measure the fairness among different traffic-type devices for our scheme. From [7], F is defined as

$$F = \frac{(\sum_{i=1}^{N} W_i)^2}{N \sum_{i=1}^{N} W_i^2}$$

where N is the total number of devices in the network, and $W_i$ is the average waiting time of packets generated by the device i. In equation (2), it is clear that $0 \leqq F \leqq 1$. When the average waiting times for all devices are close, the F value approaches to 1. On the other hand, if the variation of the $W_i$ values becomes large, F approaches to 0. Therefore, a large F implies that each device obtains the GTS bandwidth more fairly, and much probably, starvation will not occur.

Figures 4 and 5 show the effect of v (the percentage of heavy-traffic devices) on the average packet waiting time and the fairness index F for our AGA scheme and the original scheme proposed by IEEE 802.15.4 standard. When N = 5, Figure 4 (a) indicates that as v increases (i.e., the number of heavy-traffic devices increases), both the curves for average packet waiting times of our AGA and the original schemes decrease. The reason is that for a small v, the dedicated GTS bandwidth is almost occupied by the light-traffic devices. The resources allocated to the light-traffic devices would be released soon due to the low-frequency packet arrivals. In this case, any packet arrival at the light-traffic devices can not have the immediate GTS usage, which incurs the longer average waiting time. Conversely, when the number of heavy-traffic devices is large, most packet arrivals are placed in some GTSs pre-allocated for the heavy-traffic devices. Specifically, with more GTS usage, a more precise prediction for our AGA scheme leads to a smaller average packet waiting time. From Figure 4 (a), for all v under investigation, our proposed AGA scheme achieves a smaller average waiting time that the original scheme specified in IEEE 802.15.4 standard.

Based on the index F, Figure 4 (b) shows the comparison of fairness provided by our AGA scheme and the IEEE 802.15.4 original one. In Figure 4 (b), we observe that F decreases and then increases as v increases, which implies that the un-fairness problem comes from heterogeneity of devices. Also, the decreasing/increasing rate of F for AGA is smaller than that for the original scheme. In other words, our proposed scheme is equipped with the capability to provide more fair transmissions among different kinds of devices than the original IEEE 802.15.4 scheme. However, we can observe that both the scheme will not have serious unfairness when the network is sparse (i.e., when N is small).

A similar phenomenon for the average waiting time of our AGA scheme is observed in Figure 5 (a) compared with that in Figure 4 (a). However, from 5 (a), we find out that for the original scheme, the average waiting time significantly increases and then slightly decreases when v increases. This is because the original scheme can not resist the rapid workload increase with its un-flexible GTS allocation presented by IEEE 802.15.4 specification. The raising of average waiting time in the original scheme results from the long-term GTS occupancy of heavy-traffic devices. On the other hand, for a dense network, our adaptive scheme provides much lower waiting times than that for a sparse network shown in Figure 4 (a). The curves for the fairness index in Figure 5 (b) can further explain why the rapid increase of the average waiting time occurs at the original scheme. Figure 5 (b) indicates that when 80% · v · 90%, a serious unfair situation is observed in the original IEEE 802.15.4 scheme, which implies that most GTS resources are distributed to the heavy-traffic devices and starvation of the light-traffic devices may occur. However, our proposed approach can retain a small waiting time, and provide more fair GTS transmissions for all devices.

## 6. Conclusion

To improve the performance of the GTS mechanism for IEEE 802.15.4 WPANs in the beacon-enabled mode, this paper presented a new GTS scheme with dynamic resource allocation with the considerations of low-latency and fairness. Our proposed scheme consists of two phases: device-classification phase and GTS-scheduling phase. In the device-classification phase, the priority for each device intending to transmit data is determined, and the GTS slots are adequately scheduled and allocated according to the priorities in the GTS-scheduling phase. Performance evaluation for our AGA scheme was conducted, and the capability of the proposed AGA scheme was evaluated by a series of experiments. Numerical results indicated that in terms of average packet waiting time and fairness, our proposed scheme greatly outperforms the existing IEEE 802.15.4 implementations. This work has been accepted in IEEE International Conference on Communications (ICC’06), and is under revision in IEEE Transaction on Parallel and Distributed Systems.

## 7. Reference

[1] Zigbee Alliance. http://www.zigbee.org..

[2] 802.15.3-2003 IEEE Standard for Information Technology-Part 15.3: wireless medium access control (MAC) and physical layer (PHY) specifications for wireless personal area networks (WPANs). 2003.

[3] 802.15.4-2003 IEEE Standard for Information Technology-Part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs). 2003.

[4] E. Callaway, P. Gorday, and L. Hester. Home Networking with IEEE 802.15.4: A Developing Standard for Low-Rate Wireless Personal Area Networks. In IEEE Communications Magazine, August 2002.

[5] X. Dong, P. Varaiya, and A. Puri. Adaptive polling algorithm for PCF mode of IEEE 802.11 wireless LANs. In Electronics Letters, April 2004.

[6] J. A. Gutierrez. On the use of IEEE 802.15.4 to enable wireless sensor networks in building automation. In Personal, Indoor and Mobile Radio Communications (PIMRC 2004),

September 2004.

[7] R. K. Jain, D. W. Chiu, and W. R. Hawe. A quantitative measure of fairness and discrimination for resource allocation in shared computer systems. In Technical Report TR-301, DEC, September 1984.

[8] B. Kim, S. W. Kim, Y. Fang, and T. F. Wong. Link-adaptable polling-based MAC protocol for wireless LANs. In Global Telecommunications Conference (GLOBECOM 2004), November 2004.

[9] D. Kim, M. Pham, Y. Doh, and E. Choi. Scheduling Support for Guaranteed Time Services in IEEE 802.15.4 Low Rate WPAN. In IEEE RTCSA 2005, August 2005.

[10] Y. Kim and Y. Sun. Adaptive polling MAC schemes for IEEE 802.11 wireless LANs. In Vehicular Technology Conference, 2003. The 57th IEEE Semiannual, April 2003.

[11] J. F. Kurose and K. W. Ross. Computer Networks. Addison Wesley, 2003.

[12] G. Lu, B. Krishnamachari, and C. S. Raghavendra. Performance evaluation of the IEEE 802.15.4 MAC for low-rate low-power wireless networks. In Proceedings of the 23rd IEEE International Performance, Computing and Communications COnference (IPCCC 2004), April 2004.

[13] J. Misic, S. Shaf, and V. B. Misic. Performance of a beacon enabled IEEE 802.15.4 cluster with downlink and uplink traffic. In IEEE Transactions on Parallel and Distributed Systems, Volume 17, Issue 4, Page(s):361 - 376, April 2006.

[14] M. Neugebauer, J. Plonnigs, and K. Kabitzsch. A New Beacon Order Adaptation Algorithm for IEEE 802.15.4 Networks. In Proceedings of the 2nd European Workshop on Wireless Sensor Networks (EWSN 2005), January 2005.

[15] David A. Patterson and John L. Hennessy. Computer Organization and Design. Morgan Kaufmann, 1997.

[16] Bluetooth SIG. Bluetooth Specification. 1999.

[17] N. F. Timmons and W. G. Scanlon. Analysis of the Performance of IEEE 802.15.4 for Medical Sensor Body Area Networking. In IEEE SECON 2004, October 2004.

[18] J. Zheng and M. J. Lee. Will IEEE 802.15.4 make ubiquitous networking a reality?: a discussion on a potential low power, low bit rate standard. In Communications Magazine, IEEE, June 2004.

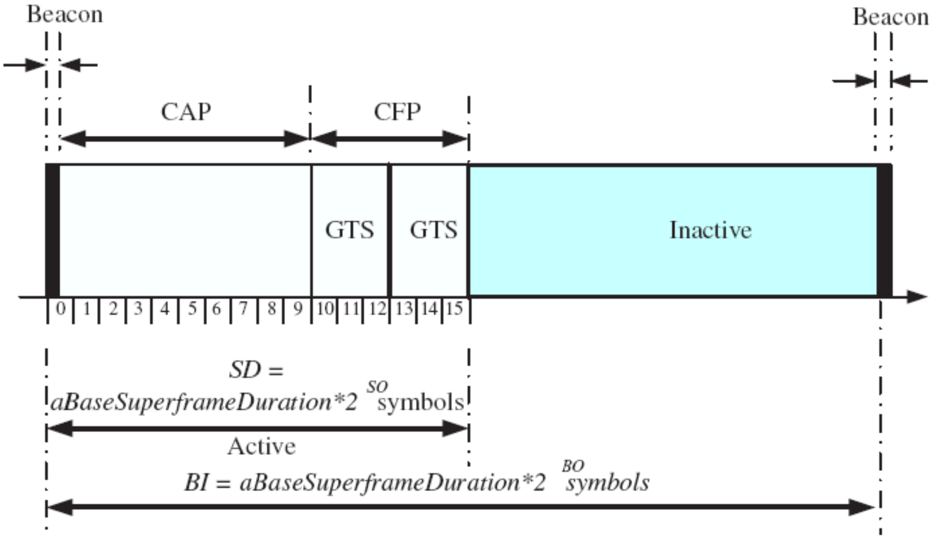


Figure 1: Superframe Structure in IEEE 802.15.4

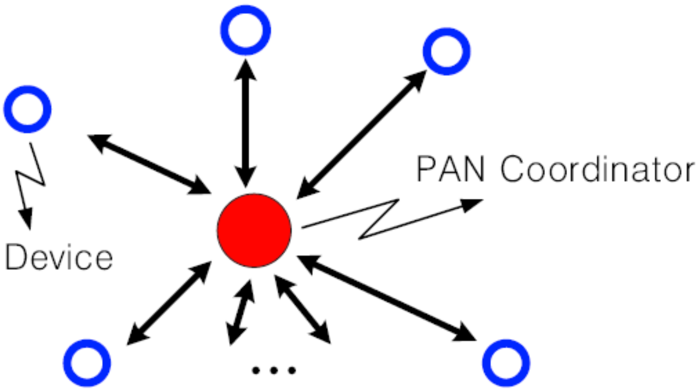


Figure 2: Star topology in WPAN

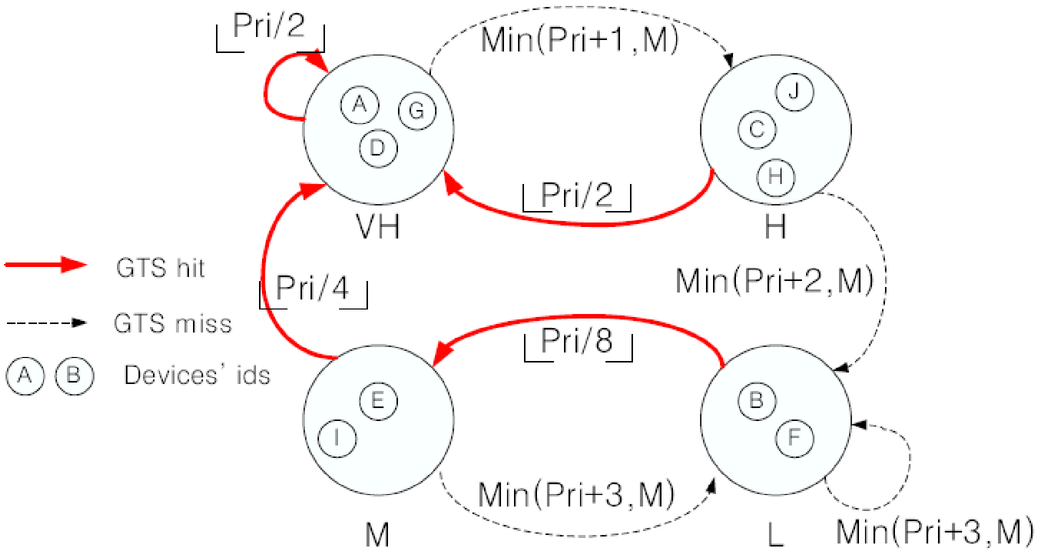


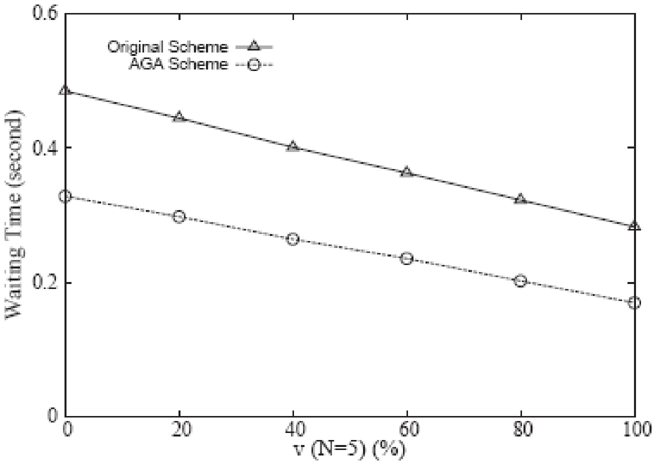
Figure 3: The State Diagram for Our Proposed AGA Scheme

**Procedure 1** DEVICE SCHEDULING()

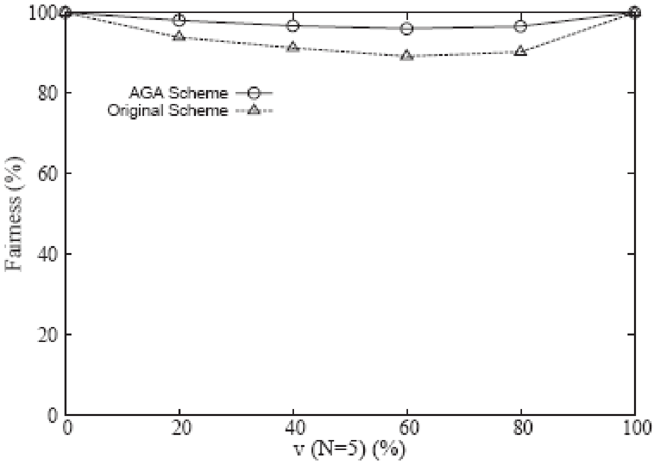
```
Assume that there are N devices in the WPAN
$P = \{Pri_1, Pri_2, \cdots, Pri_N\}$
$T_h = MR^{BO}$ where $K$ and $R$ are constants
while The GTS capacity is not overloaded do
    Find a device $k$ such that $Pri_k \in P$ is the minimum number of $P$
    if $Pri_k \leq T_h$ then
        The device $k$ will be scheduled in the GTS of the current superframe
        Remove $Pri_k$ from $P$
    else
        break;
    end if
end while
```

| Parameters | value |
|---|---|
| Frame Size | 128B |
| Transmission Rate | 250kbps |
| Network Topology | Star topology |
| Number of Devices | 5 and 10 |
| $BO$=$SO$ | 5 |
| Buffer Size of Each Device | 100 |
| $\lambda_h$ | $0.3/s$ |
| $\lambda_l$ | $0.1/s$ |

Table 1: System Parameters

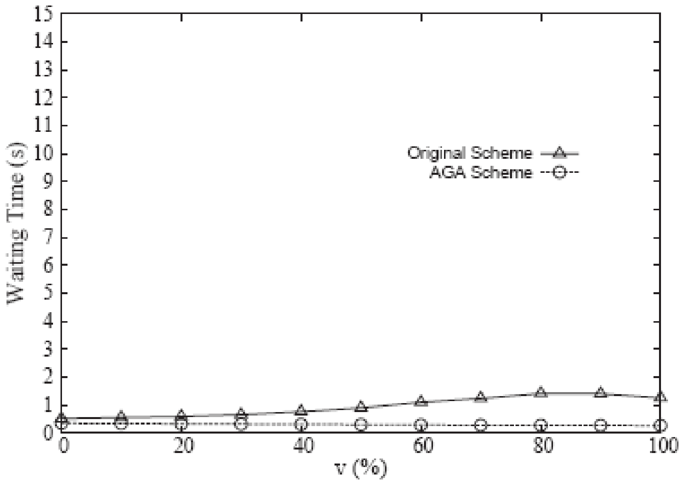


(a) Average waiting time (s)

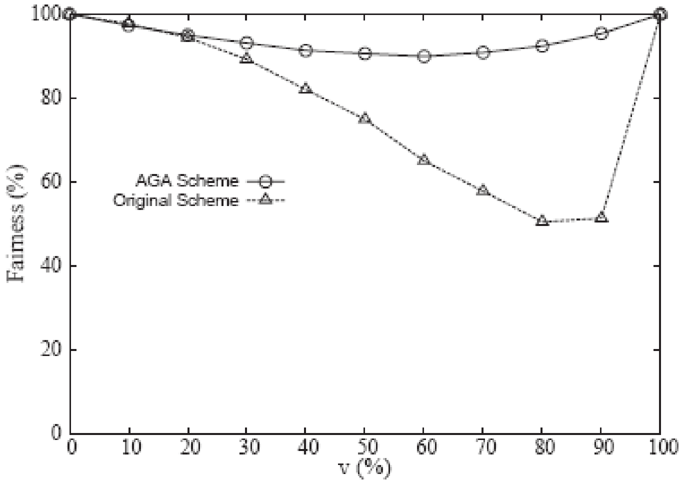


(b) Fairness (%)

Figure 4: Effect of $v$ on Average Packet Waiting Time and Fairness Index $F$ when $N = 5$



(a) Average waiting time (s)



(b) Fairness (%)

Figure 5: Effect of $v$ on Average Packet Waiting Time and Fairness Index $F$ when $N = 10$

# 出席國際學術會議報告

| | | | |
|---|---|---|---|
| 報告人<br>姓名 | 逄愛君 | 服務機構<br>及職稱 | 台灣大學<br>資訊網路與多媒體研究所<br>副教授 |
| 會議時間<br>地點 | 2007/03/11~2007/03/15<br>Hong Kong | | |
| 會議名稱 | IEEE Wireless Communications and Networking Conference (WCNC) 2007 | | |
| 發表論文題目 | QoS Routing and Scheduling in TDMA based Wireless Mesh Backhaul Networks | | |

一、參加會議經過

IEEE WCNC 2007 於 2007/03/11 ~ 2005/03/15 在香港舉行，由 IEEE Communications Society 主辦，香港科技大學協辦。本次參加 IEEE WCNC 2007 有兩項主要目的：其一是前往報告發表之論文(QoS Routing and Scheduling in TDMA based Wireless Mesh Backhaul Networks)，另外則是為觀摩國際間在無線網路通訊領域之趨勢、方法、以及發展現況。

IEEE WCNC 為數個 IEEE Communications Society 每年定期舉辦大型國際學術會議其中之一。本次會議所討論的議題主要分為三個 Tracks – PHY/MAC、Networks 和 Service。除了目前相當熱門的 Cognitive Radio 和 MIMO 相關研究外，亦包含了隨意及無線感測網路之網路協定設計與評估，及異質網路整合之服務與應用。此次會議的與會者，大部分為世界各個通訊產業頂尖國家（如：美國、歐洲各國以及日韓）之學術界與產業界相關技術研究與發展人員，除了理論技術相關研究，亦不乏產業界實作之發表。

此會議屬於 Communications Society 中數個頂尖國際會議之一，其與會者來自於世界各地專精於通訊領域的專家，包括了產業界、學術界以及政府相關之研究機構。在與會的過程中，本人除了聆聽 Plenary Keynote 的演說和各個 Technical Session 的論文發表外，也參與了一些 Panel Discussion 之議程，吸收與各個不同國家的專家們針對無線網路通訊產業與通訊市場的分析，並進行特定議題的面對面討論。在會議的各項活動中，本人對三月十三日所舉辦兩場 Keynote 印象最為深刻，收穫亦最多。這兩場 Keynote

分別為網路研究領域界的先驅 – Leonard Kleinrock 教授，和來自台灣暨南大學，目前為 IEEE Fellow 的張進福校長。尤其是張校長把目前台灣電信國家型計畫的推行成果，作一個概括性的說明，讓會議中向來自各個國家的專家學者，瞭解台灣網路通訊產業發展的概況，有極大的幫助。

本人參與今年度之 IEEE WCNC，於『Multimedia QoS and Traffic Mangement』Oral Session 中，發表“QoS Routing and Scheduling in TDMA based Wireless Mesh Backhaul Networks”一文。此篇論文之發表於會中受到廣泛的討論，本人並和與會的其他國家同領域之學者專家，如：目前任職加拿大 University of Victoria 的 Jianping Pan 教授，討論演說內容之相關議題。本人亦嘗試參與其他知名教授發表論文的 Session，不斷地就他們所發表的結果，提出自己的看法，並聆聽他們的意見，在此意見交換的過程中，對本人未來的研究有相當程度的影響。

三、攜回資料名稱之內容

2007 IEEE WCNC會議論文集光碟片一片。

四、結語

非常感謝國科會提供補助，使得我得以順利參加此次會議。也使得我們有機會與國外同領域的學者交換通訊網路系統發展及研究的心得。