A Fair Distributed Resource Allocation Method in UWB Wireless PANs with WiMedia MAC

Seokhwan Kim, Kyeong Hur, Jongsun Park, Doo-Seop Eom, and Kwang-Il Hwang

Abstract: **The WiMedia alliance has specified a distributed medium access control (WiMedia MAC) protocol based on ultra wideband (UWB) for high data rate WPANs (HR-WPANs). The merits of WiMedia MAC such as distributed nature and high data rate make it a favorite candidate in HR-WPAN. Although QoS parameters such as the range of service rates are provided to a traffic stream, the WiMedia MAC is not able to use the QoS parameters and to determine or adjust a service rate using the QoS parameters for the traffic stream. In this paper, we propose a fair and adaptive resource allocation method that allocates time slots to isochronous streams according to QoS parameters and the current traffic load condition in a fully distributed manner. Although the traffic load condition changes, each device independently recognizes the changes and calculates fair and maximum allowable service rates for traffic streams. From the numerical and simulation results, it is proved that the proposed method achieves high capacity of traffic streams and fair QoS provisioning under various traffic load condition.**

Index Terms: **Fairness, high rate WPAN, resource allocation, ultra wideband, WiMedia MAC.**

I. INTRODUCTION

Ultra wide-band (UWB) technologies are being feverishly developed in the technical community and will enable extremely high rate, short-range wireless networks. UWB devices are expected to operate at rates of up to 0.5 Gbps and communicate with other devices at a range of up to 10 m, thus enabling high-speed wireless personal area networks (WPANs). The salient features of UWB networks — high-rate communications, low interference with other radio systems, and low power consumption bring many benefits to users, thus enabling several new applications such as real time video streaming between portable devices and wireless universal serial bus (WUSB) for connecting personal computers (PCs) to their peripherals and the consumer-electronics (CE) in people's living rooms [1]. Such applications as real time video streaming require guaranteed QoS provisioning, and without the MAC layer's support QoS provisioning solely in higher layers is not possible.

The MAC for high rate WPANs can be designed in the centralized approach or the distributed approach. One example of the centralized MAC approach is IEEE 802.15.3 protocol [2]. In IEEE 802.15.3 MAC, devices form a piconet in which a device, referred to as a piconet coordinator (PNC), controls and manages the networking of all devices. This centralized architecture reveals several problems in QoS provisioning. The disappearance of PNCs results in PNC re-election procedure during which the quality of service (QoS) of all traffic streams in the piconet cannot be guaranteed. When devices in a piconet come into the radio range of other piconets, devices in overlapping area interfere with each other, which affect transmission quality of all the involved piconets. This problem at simultaneously operating piconets is fatal to home networking applications where mobility support and QoS provisioning are core requirements [3]. On the other hand, the WiMedia Alliance has specified a distributed medium access control (WiMedia MAC) protocol based on UWB for WPANs [4]. WiMedia MAC is a distributed TDMA-based MAC protocols, and it fundamentally removes the problems of the centralized MAC approach revealed at IEEE 802.15.3 MAC by adopting the distributed architecture. All devices carry out the same functions such as access to the medium, data transmission, quality of service and synchronization in a distributed manner. This distributed nature of WiMedia MAC provides full mobility support and achieves scalable and fault tolerant medium access method [5].

WiMedia MAC provides asynchronous and isochronous data communication services. The asynchronous service is provided by a prioritized carrier sense multiple access with collision avoidance (CSMA/CA) protocol called prioritized channel access (PCA). The isochronous service is supported by the distributed reservation protocol (DRP) which allows bandwidth reservation to be handled in a fully distributed manner [1]. On WiMedia MAC, a WiMedia logical link control protocol (WLP) [6] is specified by the WiMedia Alliance to support transfer of network layer IP packets over the WiMedia radio platform. In WLP, traffic characteristics and service quality of an application are encoded in the form of a traffic specification (TSPEC) [7]–[9]. In other words, a token bucket TSPEC provides a standard set of parameters to characterize the behavior of an isochronous stream with time requirement, based on which a range of service rates can be derived for guaranteed QoS provisioning. Accordingly, WiMedia MAC is required to transmit the stream at a service rate within the range.

Although QoS parameters such as the range of service rates are provided to a traffic stream, the current WiMedia MAC is still not well-defined to support QoS of the traffic stream. It is

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because the WiMedia MAC is not able to use the QoS parameters and to determine or adjust a service rate using the QoS parameters for the traffic stream. [4] and [6] present just some examples for Service interval-based MAS allocation (SIMA), which show MAS allocation pattern according to Service Interval (SI) to provide a traffic stream with a required service rate. However, prior to MAS allocation, WiMedia MAC should determine a proper service rate for a traffic stream, by considering its QoS parameters and QoS of other traffic streams. Since an allocated service rate determines the QoS of a traffic stream, the service rate should be carefully selected according to its QoS parameters. If possible, WiMedia MAC should fairly guarantees QoS of all traffic streams which interfere with each other. To the best of our knowledge, there has been no detailed study about fair and distributed resource allocation method on WiMedia MAC, particularly with regard to QoS provisioning of traffic streams with a token bucket TSPEC. Zhai [10] proposed MAS reservation algorithm which supports QoS requirement of bandwidth and delay, but it just insures that the scheduled transmissions do not interfere with each other or with existing transmissions. Kuo [11] proposed a traffic predictor and resource allocation algorithm for MPEG VBR video, but it just concentrated on the selection of allocation interval per superframe to decrease the delay. Xu [12] proposed an improved service interval-based medium access slot allocation algorithm (ISIMA) which improves bandwidth utilization efficiency compared with existing SIMA. Although [10]–[12] proposed resource allocation methods, they consider only one traffic stream but not other traffic streams. Thus, in the previous researches [10]–[12], there is no consideration for both fairness with traffic streams and distributed QoS provisioning at each device.

In this paper, we propose a novel distributed resource allocation method to provide fair QoS for isochronous streams with requested QoS parameters on WiMedia MAC. The proposed method provides all traffic streams with service rates as high as possible and fair QoS in a beacon group which consists of a device and its neighbors that can directly exchange beacons with the device. Even if the number of traffic streams varies in a beacon group, our method adaptively adjusts all service rates to maximize and to equalize QoS for all the traffic streams. Also, our method makes all operation perform in a completely distributed manner. To do this, we define a fair satisfaction ratio of QoS (SoQ_F) which determines the fair service rates of all traffic streams in a beacon group. Whenever devices detect changes of traffic load condition in a beacon group, each device independently calculates SoQ_F for the beacon group. Our method makes all devices calculate the same value of SoQ_F in a beacon group. Accordingly, all traffic streams in a beacon group can be provided with fair QoS.

The rest of this paper is organized as follows. In Section II, we describe the current method for time slot allocation in WiMedia MAC and explain problems in QoS provisioning. In Section III, the proposed fair distributed resource allocation method in WiMedia MAC is explained. And in Section IV, we present numerical and simulation results to analyze performances of the proposed method. Finally, conclusions are presented in Section V.

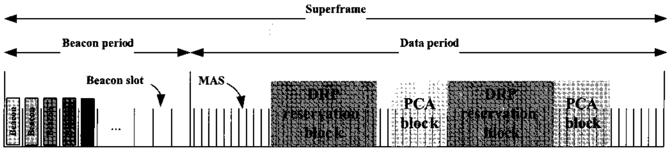


Fig. 1. Superframe structure in WiMedia MAC.

II. WIMEDIA MAC PROTOCOL

A. DRP (Distributed Reservation Protocol)

WiMedia MAC operates per a time unit of a superframe. The superframe has a fixed length of time, and it is divided into multiple time slots. The time slot is also referred to as a medium access slot (MAS). The superframe comprises 256 MASs. In Fig. 1, each superframe starts with a beacon period (BP) which may extend over one or more contiguous MASs. Each device transmits its own beacon in a non-overlapping beacon slot with others. Thus, devices need to search free beacon slots unused in the beacon period so as to send their beacons without interference. As devices exchange beacons with each other, they use several information elements (IEs) in received beacons for synchronization, MAS reservation, mobility supports and so on [4]. The remainder of MASs in the superframe are used to transmit data, and it is referred to as a data period. A data period is divided into two types of MAS blocks. PCA works during the one MAS block, and DRP works during another MAS block. PCA is similar to IEEE 802.11e for multiple prioritized access classes. DRP enables a device to reserve one or more MASs for communication with one or more neighbors. A device which wants to use DRP for data transmission or reception should negotiate with neighbors to reserve a set of MASs by including DRP IE in its beacon. DRP IE is used to negotiate a reservation and to announce the reservation. DRP reservation negotiation is always initiated by a device that will begin frame transactions in the reserved MAS block, referred to as a reservation owner. A device that receives the information for reservation negotiation is referred to as a reservation target. In a reserved MAS block, DRP provides the reservation owner and target devices with exclusive access to the medium. The DRP has the important role to guarantee QoS of isochronous traffic. In TDMA based systems such as DRP, a service rate allocated to a traffic stream is proportional to MASs allocated to the traffic stream. Therefore, the terms ‘time slots,’ ‘MASs,’ and ‘data rate’ are used interchangeably in this paper. WiMedia MAC also allows a device to request that its neighbor release MASs from the neighbor's reservation block by including relinquish request IE in its beacons [4].

B. Token Bucket TSPEC

A token bucket TSPEC is an aggregate TSPEC [7]–[9] that provides a standard set of parameters to characterize a traffic source, based on which networking resources can be reserved for parameterized QoS provisioning. The behavior of a traffic stream with a token bucket TSPEC is confined by the theoretical model of a fluid twin token bucket. The fluid twin token bucket model provides standard terminology to describe the behavior of a network traffic source [6]. This model characterizes a traffic stream by three parameters, mean rate r, peak rate p,

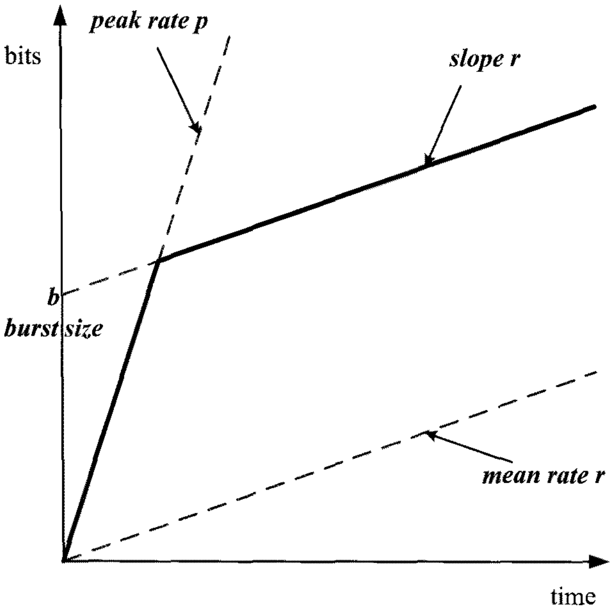


Fig. 2. Arrival curve of a token bucket model [6].

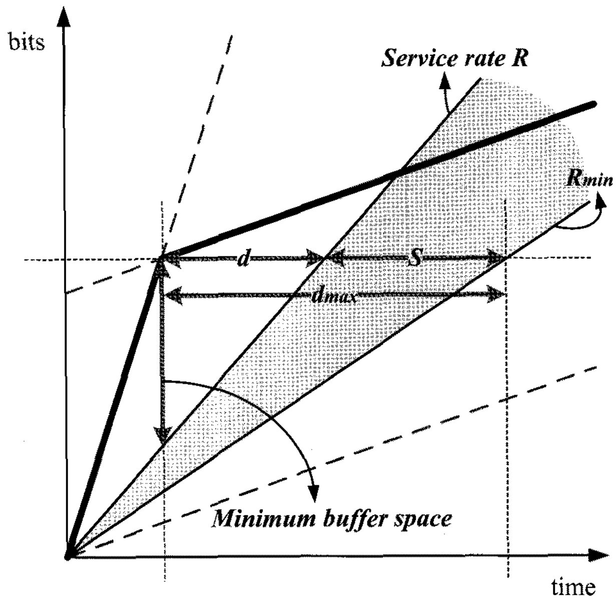


Fig. 3. Introduction of Service TSPEC {R,S}.

and maximum burst size b. In Fig. 2, the solid line represents the arrival curve of a token bucket model. The arrival curve represents the cumulative maximum number of bits that the traffic source may possibly inject during any time interval t.

Fig. 3 depicts the general relationship between service rate and token bucket TSPEC. The bold line represents the arrival curve of a traffic stream with traffic characteristics of $\{r, b, p\}$. The slope of the service rate line is the real effective rate at which the traffic stream is serviced. The vertical line represents minimum buffer space necessary to avoid overflow for the traffic stream with the service rate R. d is the delay experienced by the traffic stream with a service rate R, which is shown with a horizontal line that is also the maximum horizontal distance between the arrival curve and the service rate line.

In [6], the theoretical service rate R is derived from the fluid twin token bucket model to guarantee delay bound d for a traffic stream with characteristics of $\{r, b, p\}$. It is given by [4] and [6]:

$$R = \frac{p}{1 + d \cdot \frac{p-r}{b}}. \tag{1}$$

From using (1), we can also calculate the delay d which a traffic stream experiences at service rate R. Slack term S means the difference between maximum allowed delay d_{max} and the delay d resulting from the service rate R. Hence, the requirement of a maximum allowed delay can be expressed in terms of service TSPEC$\{R, S\}$ as below [4], [6]:

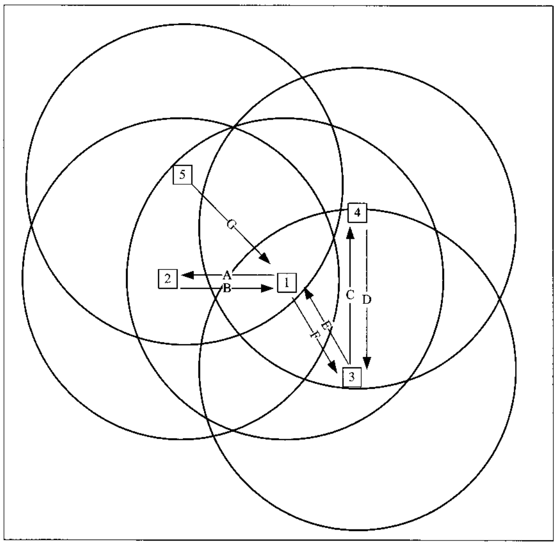
$$d_{max} = \frac{p-R}{p-r} \cdot \frac{b}{R} + S. \tag{2}$$

Consequently, when a traffic stream (TS) with traffic characteristics of $\{r, b, p\}$ has the requirement of a maximum allowed delay, the upper and lower bounds of a service rate R can be calculated at p with 0 delay and R_{min} with d_{max} delay from (1), respectively. And slack term S can take a value within the range of $(0, d_{max})$ according to the service rate R.

C. Problems in QoS provisioning of WiMedia MAC

A QoS system has several components such as QoS mapping, admission control and resource allocation. In the current WiMedia MAC, QoS provisioning mechanisms for the above three components are still not defined completely; the WiMedia MAC is not able to use TSPEC parameters of traffic streams (TSs); it cannot calculate and allocate the fair service rates to all TSs considering each TS's QoS and the current traffic load adaptively, as the number of TSs or current available MASs (CAMs) varies due to mobility or changes in radio circumstance.

For example, whereas the WiMedia MAC provides prior TSs with enough service rates such as peak rates, it may not assure requested QoS of TSs arriving later at MAC entity due to lack of CAMs. This situation is unfair and makes some TSs experience unpredictable delay. In Fig. 4, there are five devices (DEV1–5) in the beacon group of DEV1. Each arrow corresponds to a TS, and a circle around a device presents the communication range of the device. Minimum service rate (MR) and peak service rate (PR), respectively, indicate lower and upper bounds of service rates required to guarantee maximum delay, d_{max}, of a TS, calculated from (1). The seven TSs (A–G) are sequentially created and request guaranteed QoS to the MAC entity. Initially, since CAMs are sufficient, devices assign peak service rates to all TSs (A–F) by using DRP IEs [4]. Then, a new TS G is created and requests guaranteed QoS. Although the existing TSs reserve surplus MASs which can be relinquished to the TS G, because the WiMedia MAC does not support fair resource allocation in which each device can adjust service rates of the existing TSs to accommodate the new TS G, the TS G cannot reserved any MAS. Accordingly, the service of TS G is blocked until other TSs release their surplus MASs, and the TS capacity of WiMedia MAC cannot increase.



Traffic stream index	Minimum service rate	Peak service rate	service rate	CAMs (Current available MASs)
A(DEV1 DEV2)	30 Mbps	50 Mbps	50 Mbps	310 Mbps (After TS A is joined)
B(DEV2 DEV1)	50 Mbps	70 Mbps	70 Mbps	240 Mbps (After TS B is joined)
C(DEV3 DEV4)	60 Mbps	70 Mbps	70 Mbps	170 Mbps (After TS C is joined)
D(DEV4 DEV3)	20 Mbps	50 Mbps	50 Mbps	120 Mbps (After TS D is joined)
E(DEV3 DEV1)	35 Mbps	60 Mbps	60 Mbps	60 Mbps (After TS E is joined)
F(DEV1 DEV3)	50 Mbps	60 Mbps	60 Mbps	0 Mbps (After TS F is joined)
G(DEV5 DEV1)	30 Mbps	50 Mbps	Blocked	

Fig. 4. Blocked service request of a new TS G (Total BW=360 Mbps for all 210 MASs).

Table 1. Traffic streams that each DEV detects.

Device	Detected traffic stream
DEV1	A,B,C,D,E,F,G
DEV2	A,B,E,F,G
DEV3	A,B,C,D,E,F
DEV4	A,B,C,D,E,F
DEV5	A,B,E,F,G

Fig. 5. QoS IE format.

III. PROPOSED FAIR DISTRIBUTED RESOURCE ALLOCATION METHOD

We first introduce some definitions for the proposed method. Let K denote the total number of TSs that request for guaranteed QoS in the beacon group of a DEV, MR_j and PR_j denote respectively the lower and upper bounds of a service rate to guarantee QoS of TS_j, $SR_{j,n}$ denote a service rate allocated to TS_j at the nth superframe, RR_j denote the number of MASs that TS_j relinquishes to accommodate more TSs in a beacon group, and BW denote the total number of MASs forming the data period in a superframe.

We define a Satisfaction ratio of QoS (SoQ_j) for a TS_j at the nth superframe, which can be expressed as,

$$SoQ_{j,n} = \frac{SR_{j,n} - MR_j}{PR_j - MR_j}. \qquad (3)$$

Our goal is to make each TS have the same $SoQ_{j,n}$ equal to $SoQ_{F,n}$ in a beacon group although K varies. Hence, for all j, $SoQ_{j,n}$ is equal to $SoQ_{F,n}$, and $SoQ_{j,n+1}$ is equal to $SoQ_{F,n+1}$. According to $SoQ_{F,n}$, the service rate of each TS at the nth superframe can be expressed as,

$$SR_{j,n} = SoQ_{F,n}(PR_j - MR_j) + MR_j. \qquad (4)$$

Then, $SoQ_{F,n}$ is derived from (5) to make $SoQ_{j,n}$ of all K TSs in a beacon group the same for fair QoS provisioning, as in (6)

$$\begin{aligned}\sum_{i=1}^{K}(SoQ_{j,n}(PR_j - MR_j) + MR_j) &= \sum_{i=1}^{K} SR_{j,n} \\ &= BW \qquad (5)\end{aligned}$$

$$SoQ_{F,n} = min\left\{\frac{BW - \sum_{i=1}^{K} MR_j}{\sum_{i=1}^{K}(PR_j - MR_j)}, 1\right\}. \qquad (6)$$

$SoQ_{F,n}$ takes a value between 0 and 1 according to K, MR_j and PR_j. If $SoQ_{F,n}$ is computed as 1, each TS_j in a beacon group is provided with PR_j. In contrary, if $SoQ_{F,n}$ is computed as 0, each TS_j in the beacon group is serviced at MR_j. To calculate $SoQ_{F,n}$ independently, each DEV needs to know MR and PR of other TSs in the beacon group, which can be achieved by beaconing. Hence, we define a new IE, QoS IE, for exchange of TSs' QoS parameters. As illustrated in Fig. 5, QoS IE conveys QoS parameters of a TS. TS index field consists of source DEV address, destination DEV address and TS ID. Accordingly, both the source and destination DEVs involved in transmitting a TS with QoS parameters should include the corresponding QoS IE in their beacons at every superframe.

Whenever K varies in a beacon group, each DEV recognizes the changes from QoS IEs in received beacons at the nth superframe, and then it calculates a new $SoQ_{F,n+1}$ for QoS provisioning at the next $(n + 1)$th superframe. Based on the $SoQ_{F,n+1}$, DEVs decide to accommodate a new TS or not and how to allocate service rates to existing TSs and the new TS. When a new TS in a DEV requests guaranteed QoS, the DEV simply puts the QoS IE of the TS into its beacon. After exchanging beacons at the nth superframe, DEVs in the same beacon group recognize the request of the new TS, and they individually calculate $SoQ_{F,n+1}$ based on received QoS IEs to provide fair QoS at the $(n + 1)$th superframe. Then, each DEV puts its QoS IEs with $SoQ_{F,n+1}$ into its beacon at the $(n + 1)$th superframe. Although DEVs belong to a beacon group, they may compute different $SoQ_{F,n+1}$ since a DEV cannot receive QoS IEs of DEVs two hop away from the DEV due to the limit of communication range. In Fig. 4, DEV2 and DEV4 calculate different $SoQ_{F,n+1}$ since they detect different TSs as in Table 1.

To maintain the same $SoQ_{F,n+2}$ in a beacon group, each DEV sets $SoQ_{F,n+2}$ to the smallest $SoQ_{F,n+1}$ among its and others' $SoQ_{F,n+1}$ after exchanging QoS IEs at the $(n + 1)$th superframe. It is because at least one DEV (e.g., DEV1 in Fig. 4)

Table 3. SoQ_F and SR_j at each superframe in Fig. 4.

TS	MR_j	PR_j	$SoQ_{j,n}$	$SR_{j,n}$	$SoQ_{j,n+2}$	$SR_{j,n+2}$	RR_j
A	30 Mbps	50 Mbps	1	50 Mbps	0.629	42.59 Mbps	7.41 Mbps
B	50 Mbps	70 Mbps	1	70 Mbps	0.629	62.59 Mbps	3.70 Mbps
C	60 Mbps	70 Mbps	1	70 Mbps	0.629	66.29 Mbps	11.11 Mbps
D	20 Mbps	50 Mbps	1	50 Mbps	0.629	38.88 Mbps	9.26 Mbps
E	35 Mbps	60 Mbps	1	60 Mbps	0.629	50.74 Mbps	3.70 Mbps
F	50 Mbps	60 Mbps	1	60 Mbps	0.629	56.29 Mbps	42.59 Mbps
G	30 Mbps	50 Mbps		blocked	0.629	42.59 Mbps	

Table 2. SoQ_F computed by each device at each superframe in Fig. 4.

	$SoQ_{F,n}$	$SoQ_{F,n+1}$	$SoQ_{F,n+2}$
DEV1	1	0.629	0.629
DEV2	1	1	0.629
DEV3	1	1	0.629
DEV4	1	1	0.629
DEV5	1	1	0.629

Table 4. A single token bucket TSPEC of traffic streams.

Mean data rate (r)	4.13 Mbps
Peak data rate (p)	14.8 Mbps
Maximum burst size (b)	131359 Bytes
Maximum allowable delay ($d_{j,max}$)	64 ms
Minimum service rate (MR_j)	8.97 Mbps
Peak service rate (PR_j)	14.8 Mbps

can receive QoS IEs of all K TSs in a beacon group, and it computes the smallest $SoQ_{F,n+1}$ in the beacon group. However, during the (n + 1)th superframe, $SR_{j,n+1}$ of the existing TSs are set to the previous $SR_{j,n}$, and the service of the new TS is blocked since $SoQ_{F,n+1}$ values are different from each other in the beacon group. Thus, when a device detects a change in TSs at the nth superframe, actual service rates of TSs in a beacon group are adjusted at the (n + 2)th superframe. If the smallest $SoQ_{F,n+1}$ is a negative value, the request of the new TS is denied, and $SoQ_{F,n+2}$ is set to the previous $SoQ_{F,n}$ since a negative $SoQ_{F,n+1}$ means that the BW cannot accommodate the new TS anymore. On the contrary, if the smallest $SoQ_{F,n+1}$ is a positive value, $SoQ_{F,n+2}$ is set to the smallest $SoQ_{F,n+1}$, service rates of all K TSs are newly calculated according to the $SoQ_{F,n+2}$, and the existing TSs relinquish RR_j MASs through DRP IEs to admit the request of the new TS. Hence, the service rate of the new TS can be equal to the sum of RR_j, and all TSs are fairly provided with guaranteed QoS at the (n + 2)th superframe. RR_j can be expressed as below,

$$RR_j = SR_{j,n} - SR_{j,n+2}. \qquad (7)$$

In the case that the number of TSs, K, decreases in a beacon group at the nth superframe, $SoQ_{F,n+2}$ becomes greater than $SoQ_{F,n}$ from (6). It means that existing TSs shall be provided with higher QoS at the next ($n+2$)th superframe. Hence, DEVs compute a new service rate of each TS from $SoQ_{F,n+2}$, based on which the additional MASs as many as $(SR_{j,n+2} - SR_{j,n})$ is reserved for each TS at the (n + 2)th superframe.

Tables 2 and 3 show example results when the proposed method is applied to the network topology in Fig. 4. We assume that BW is 360 Mbps, 210 MASs. Initially, $SoQ_{F,n}$ is 1 and TSs(A–F) are serviced at PR_j. Then, DEV5 sends a beacon with the QoS IE of a new TS G to notify the new request at the nth superframe. After exchanging beacons, only three DEVs (DEV1, DEV2, and DEV5) receive the new QoS IE, and they independently calculate $SoQ_{F,n+1}$ as in Table 2. After exchanging beacons at the (n + 1)th superframe, each DEV in the beacon group synchronizes $SoQ_{F,n+2}$ to the smallest $SoQ_{F,n+1}$, 0.629, among its received $SoQ_{F,n+1}$. Consequently, DEVs adjust service rates of all K TSs to accommodate the TS G. As shown in Table 3, service rates allocated to existing TSs (A–F), $SR_{j,n+2}$, decrease while TS G is serviced at 42.59 Mbps which is equal to the sum of RR_j relinquished by the existing TSs (A–F) at the (n + 2)th superframe.

IV. PERFORMANCE EVALUATION

In this section, we analyze and evaluate the performance of the proposed resource allocation method. To evaluate the performance of the proposed method (denoted by Distributed SoQ (D_SoQ)), we compare it with Minimum QoS (Min_QoS) and Maximum QoS (Max_QoS). In Min_QoS, a TS_j is provided with minimum service rate, MR_j, as SR_j whereas a TS_j is provided with peak service rate, PR_j, as SR_j in Max_QoS. It is because the current WiMedia MAC includes no resource allocation method considering the QoS parameters of TSs and, as Max_QoS and Min_QoS allocate marginal service rates to TSs, they can give the references for evaluation of D_SoQ. Firstly, we propose two performance measures, from which numerical analysis is conducted. Then, simulation results using ns-2 [13] are compared with the numerical results. We evaluate three methods under two cases. In first case, we consider only the TSs with the same token bucket TSPEC characteristics to observe TS capacity and fairness. In the other case, TSs with different token bucket TSPEC characteristics are considered to demonstrate the effectiveness and validity of D_SoQ.

A. Case of a Single TSPEC Traffic Characteristics

We first introduce definitions to explain three performance measures. Let $d_{j,n}$ denote the delay experienced by a TS_j at the nth superfrmae, $d_{j,max}$ denote the maximum allowable delay to guarantee QoS of a TS_j, K_{total} denote the total number of TSs requesting QoS in a beacon group at a superframe and K_{cur} denote the number of TSs serviced at the superframe. Accordingly, $(K_{total} - K_{cur})$ indicates the number of blocked TSs due to the lack of MASs. We assume that the length of BW is

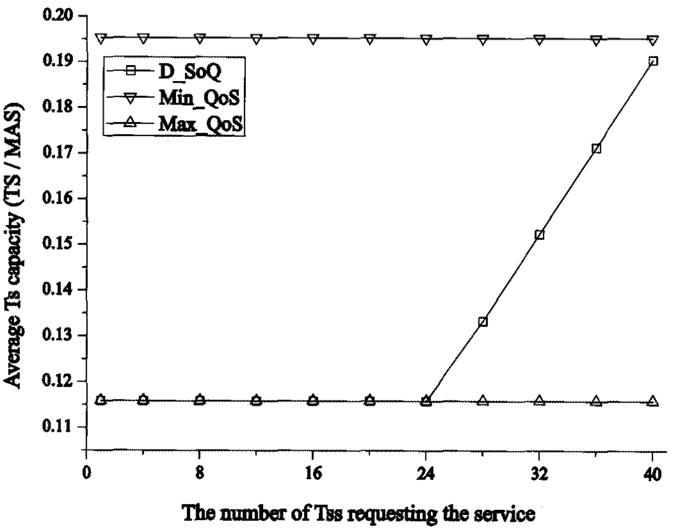


Fig. 6. Average TS capacity.

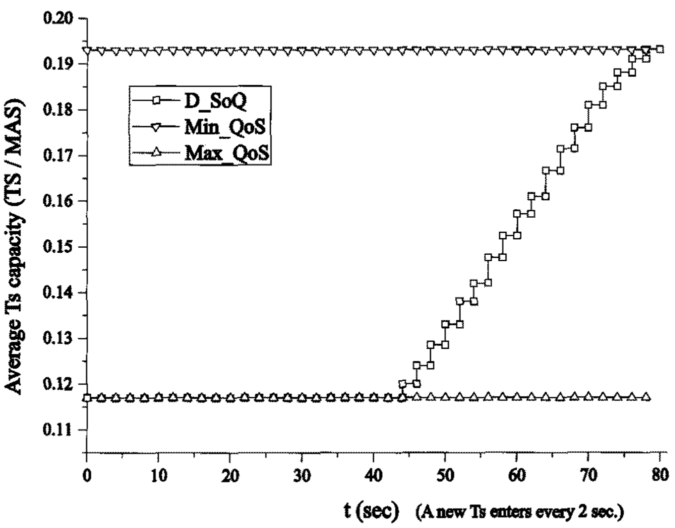


Fig. 7. Simulation result of average TS capacity.

equal to 210 MASs, 360 Mbps. A single token bucket TSPEC of considered TSs is shown as in Table 4.

A.1 TS Capacity, c_{TS}

We define c_{TS} to measure the TS capacity. c_{TS} presents the average number of TSs which a reserved MAS accommodates at a supeframe. It is given by:

$$c_{TS} = \frac{K_{cur}}{\sum_{j=1}^{K_{cur}} SR_{j,n}}(TS/MAS). \qquad (8)$$

The maximum K_{cur} which Max_QoS and Min_QoS can admit are obtained as 24 and 40, respectively, by dividing the BW, 360 Mbps, with the peak service rate of 14.8 Mbps and the minimum service rate of 8.97 Mbps. Whereas Max_QoS cannot guarantee QoS of additional TSs after the K_{total} exceeds the limit of 24, the Min_QoS continuously admits all TSs until the K_{cur} reaches 40. As shown in Fig. 6, both Min_QoS and Max_QoS have fixed TS capacity, and the TS capacity of Min_QoS is higher than that of Max_QoS because of its smaller fixed service rates for TSs. On the other hand, since D_SoQ dynamically provides TSs with a fair and maximum allowable QoS according the current traffic load, the TS capacity of D_SoQ adaptively varies from that of Max_QoS to that of Min_QoS as K_{total} increases. Until K_{total} reaches 24, the TS capacity of D_SoQ is similar to that of Max_QoS since D_SoQ provides peak service rates to TSs at light traffic load. However, as K_{total} increases larger than 24, D_SoQ decreases service rates of existing TSs to accommodate more TSs. Hence, as K_{total} reaches 40, the TS capacity of D_SoQ becomes the same as that of Min_QoS. In Fig. 7, it can be shown that the similar observation is obtained from the simulation experiment. In simulation results, a new TS requests the same TSPEC service of Table 4 at a randomly chosen device in the network topology of Fig. 4 every two seconds.

A.2 An Average Delay at the nth Superframe, $E(d_n)$

$E(d_n)$ indicates an average delay of K_{total} TSs at the nth superframe. $d_{j,n}$ of a TS$_j$ at the nth superframe is determined by an allocated $SR_{j,n}$, by setting S to 0 and R to $SR_{j,n}$ in (2). Accordingly, at nth superframe, K_{cur} TSs experience $d_{j,n}$ calculated from (2) whereas $(K_{total} - K_{cur})$ TSs experience delay of $T_{superframe}$ since the services of $(K_{total} - K_{cur})$ TSs are blocked during the nth superframe. Delay is an important factor to evaluate QoS since the guaranteed QoS provisioning is achieved by maintaining $d_{j,n}$ within the $d_{j,max}$. $d_{j,n}$ and $E(d_n)$ in the nth superframe can be expressed as below

$$\begin{aligned} d_{j,n} &= \begin{cases} \frac{p-SR_{j,n}}{p-r} \cdot \frac{b}{SR_{j,n}} & \text{if } SR_{j,n} > 0 \\ T_{superframe} & \text{if } SR_{j,n} = 0 \end{cases} \\ E(d_n) &= \sum_{j=1}^{K_{total}} \frac{d_{j,n}}{K_{total}}. \end{aligned} \qquad (9)$$

Fig. 8 shows the numerical result of average delay from (9) as K_{total} increases in a beacon group. Fig. 9 presents the simulation result of average delay, in which a new TS requests the same TSPEC service of Table 4 in a randomly chosen device in the network topology of Fig. 4 every two seconds and the new TS is provided with a service rate in three methods. From these figures, it can be shown that Max_QoS achieves the best performance in terms of average delay. Its average delay maintains 0 ms until K_{total} reaches 24. However, as shown in Fig. 10, Max_QoS achieves poor performance in terms of delay fairness. STD of $d_{j,n}$ in Max_QoS increases extremely when K_{total} exceeds the limit of the maximum K_{cur}, 24. It is because Max_QoS provides the maximum QoS for K_{cur} TSs, but it cannot allocate any service rate to the blocked $(K_{total} - K_{cur})$ TSs, which causes an undeterministic delay to the $(K_{total} - K_{cur})$ TSs. From Figs. 8–10, it can be shown that Min_QoS shows the worst performance in terms of delay while it achieves fair QoS provisioning. It is because it always offers TSs the minimum service rates which guarantee only the maximum allowable delay. However, allocating the minimum service rate to a TS does not mean providing the guaranteed QoS all the time. Fundamentally, the wireless link is unstable due to high bit error rate and high sensitivity to changes in radio circumstances. Thus, it can frequently occur to retransmit some parts of a TS when the parts

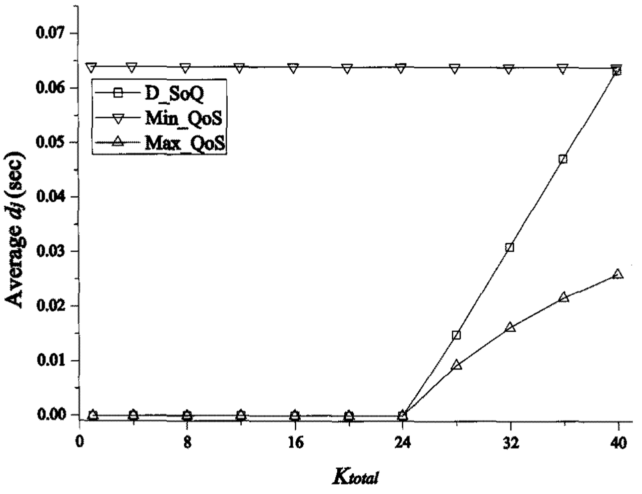


Fig. 8. Average delay for K_{total} TSs.

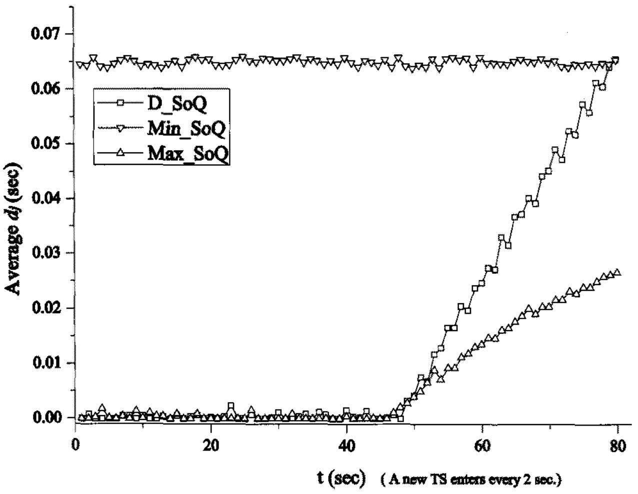


Fig. 9. Simulation result of Average delay for K_{total} TSs.

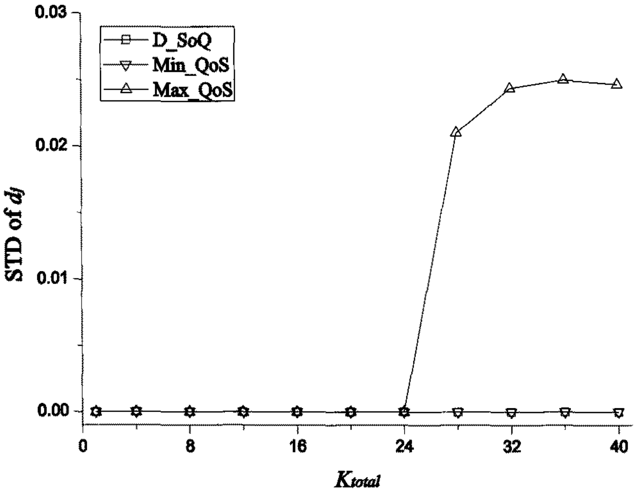


Fig. 10. Standard deviation of d_j for K_{total} TSs.

is corrupted. Accordingly, the TS experiences additional and unexpected delay, which causes encroachments on guaranteed QoS of the TS. From the simulation result of Fig. 9, it is observed that average delays of TSs at some superframes exceed the maximum allowable delay, 64 ms in the Min_QoS. Thus, a TS should be provided with a service rate higher than the minimum service rate if possible. On the other hand, as shown in Figs. 8 and 9, D_SoQ always guarantees that all K_{total} TSs experience a lower delay than maximum allowable delay, $d_{j,max}$, until K_{total} reaches the maximum number of TSs which BW can admit. Also, D_SoQ shows good performance in terms of fairness in Fig. 10.

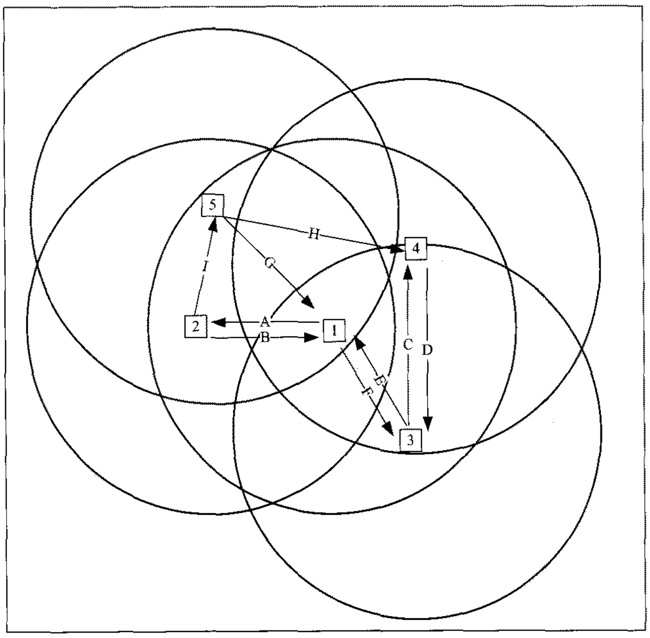


Fig. 11. Simulation Topology.

B. Case of Multiple TSPEC Traffic Characteristics

In this section, we simulate D_SoQ in a scenario where several TSs with different token bucket TSPEC characteristics are considered. As shown in Fig. 11, there are five devices (DEV1–5) in the beacon group of DEV1, each arrow corresponds to a TS, and a circle around a device presents the communication range of the device. Table 6 shows the range of service rates to guarantee QoS of each TS. In simulation results, the nine TSs (A–I) are sequentially created and request guaranteed QoS to the MAC entity every ten seconds. Accordingly, each DEV allocates proper service rates to its TSs using D_SoQ. As shown in Table 6, $SoQ_{j,n}$ of each TS is calculated at 1 until the 954th superframe, 60 sec, that means all six TSs (A–F) are provided with peak service rates, PR_j. Whenever each new TS (G–I) continuously requests is service respectively at the 953th, 1093th, and 1265th superframes, service rates allocated to existing TSs are adjusted to lower service rates to accommodate the new TS according to $SoQ_{F,n}$. Accordingly, $SoQ_{j,n}$ of each TS also decreases from 1 to 0.3 while each TS obtains the same and fair $SoQ_{j,n}$ value as shown in Table 6. Table 5 shows the variation of $SoQ_{F,n}$ and $SR_{j,n}$ in devices of the beacon group whenever a new TS requests its service. Fig. 12 shows the simulation results which measures actual throughput of each TS transmitted in its reserved MAS blocks, $SR_{j,n}$, for fair QoS provisioning

Table 5. Variation of SoQ_F at each device whenever the traffic load changes.

	$SoQ_{F,953}$	$SoQ_{F,954}$	$SoQ_{F,955}$	$SoQ_{F,1094}$	$SoQ_{F,1095}$	$SoQ_{F,1266}$	$SoQ_{F,1267}$
DEV1	1	0.629	0.629	0.4545	0.4545	0.3	0.3
DEV2	1	1	0.629	1	0.4545	0.875	0.3
DEV3	1	1	0.629	0.4545	0.4545	0.4545	0.3
DEV4	1	1	0.629	0.4545	0.4545	0.4545	0.3
DEV5	1	1	0.629	1	0.4545	0.875	0.3

Table 6. QoS parameters of TSs and the variation of $SoQ_{j,n}$ and $SR_{j,n}$.

TS	MR_j	PR_j	$SoQ_{j,954}$	$SR_{j,954}$	$SoQ_{j,955}$	$SR_{j,955}$	$SoQ_{j,1095}$	$SR_{j,1095}$	$SoQ_{j,1267}$	$SR_{j,1267}$
A	30Mbps	50Mbps	1	50Mbps	0.6296	42.59Mbps	0.4545	39.09Mbps	0.3	36Mbps
B	50Mbps	70Mbps	1	70Mbps	0.6296	62.59Mbps	0.4545	59.09Mbps	0.3	56Mbps
C	60Mbps	70Mbps	1	70Mbps	0.6296	66.29Mbps	0.4545	64.54Mbps	0.3	63Mbps
D	20Mbps	50Mbps	1	50Mbps	0.6296	38.88Mbps	0.4545	33.63Mbps	0.3	29Mbps
E	35Mbps	60Mbps	1	60Mbps	0.6296	50.74Mbps	0.4545	46.36Mbps	0.3	42Mbps
F	50Mbps	60Mbps	1	60Mbps	0.6296	56.29Mbps	0.4545	54.54Mbps	0.3	53Mbps
G	30Mbps	50Mbps	-	-	0.6296	42.59Mbps	0.4545	39.09Mbps	0.3	36Mbps
H	10Mbps	40Mbps	-	-	-	-	0.4545	23.63Mbps	0.3	19Mbps
I	15Mbps	50Mbps	-	-	-	-	-	-	0.3	25Mbps

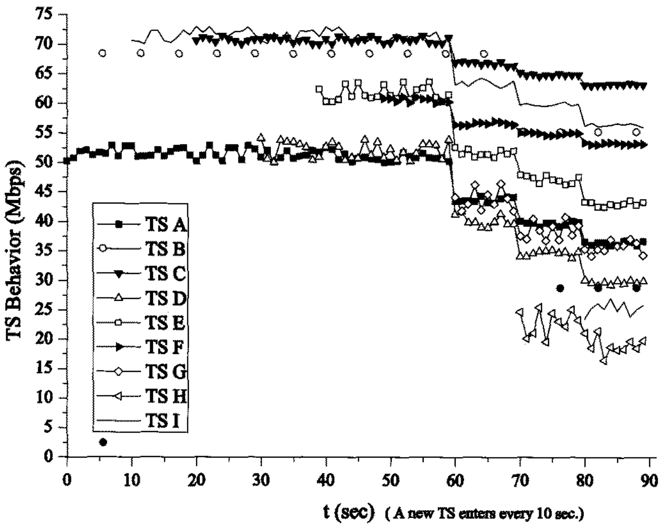


Fig. 12. Measurement of TSs' Throughput Behavior in D_SoQ.

according to D_SoQ under varying traffic conditions.

V. CONCLUSION

In this paper, we propose a fair distributed resource allocation method (D_SoQ) for the WiMedia MAC to guarantee a required QoS to each traffic stream in a beacon group. D_SoQ provides a fair and maximized QoS for all TSs according to the current traffic load condition in a fully distributed manner. D_SoQ offers a fair and maximum QoS to all TSs so that each TS is serviced faster and more robustly under light traffic load whereas it fairly provides TSs with a relatively lower QoS to ensure high TS capacity under heavy traffic load. To make these operations work in a fully distributed manner, we define a new QoS IE, which needs a minor addition to the current WiMedia MAC specification. From the numerical and simulation results, it is proved that the proposed method improves TS capacity while it achieves fairness in terms of QoS. For future work, it is necessary to study the differentiated resource allocation method to support TSs with DiffServ QoS priorities.

REFERENCES

[1] P. Pavon, N. S. Shankar, V. Gaddam, K. Challapali, and C.-T. Chou, "The MBOA-WiMedia specification for ultra wideband distributed networks," *IEEE Commun. Mag.*, vol. 44, no. 6, pp. 128–134, June 2006.

[2] IEEE 802.15.3. (2003). Wireless medium access control and physical layer specification for high rate wireless personal area networks. [Online]. Available: http://standards.ieee.org /reading /ieee /std /lanman /restricted / 802.15.3-2003.pdf

[3] V. M. Vishnevsky, A. I. Lyakhov, A. A. Safonov, S. S. Mo, and A. D. Gelman, "Study of beaconing in multi-hop wireless PAN with distributed control," *IEEE Trans. Mobile Comput.*, vol. 7, no. 1, pp. 113–126, Jan. 2008.

[4] WiMedia alliance. (2006, Dec. 15). WiMedia MAC Release Spec. 1.01. Distributed medium access control for wireless networks. [Online]. Available: http://www.wimedia.org/en/index.asp

[5] H.-T. Chou, P. Pavon, and N. S. Shankar, "Mobility support enhancements for the WiMedia UWB MAC protocol," in *Proc. IEEE BROADNETS*, vol. 2, Oct. 2005, pp. 136–142.

[6] WiMedia alliance. (2007, Aug. 13). WiMedia logical link layer control protocol spec. Approved Draft 1.0. [Online]. Available: http://www.wimedia.org/en/index.asp

[7] J. Wroclawski. (1997, Sept.). RFC 2211 - Specification of the controlled-load network element service. [Online]. Available: http://www.faqs.org/rfcs/rfc2211.html

[8] S. Shenker, C. Partridege, and R. Guerin. (1997. Sept.). RFC 2212 - Specification of the guaranteed quality of service. [Online]. Available: http://www.faqs.org/rfcs/rfc2212.html

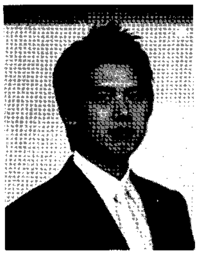
[9] S. Shenker and J. Wroclawski. (1997, Sept.). RFC 2215 - General characterization parameters for integrated service network elements. [Online]. Available: http://www.faqs.org/rfcs/rfc2215.html

[10] H. Zhai, "QoS support over UWB mesh networks," in *Proc. IEEE WCNC*, pp. 2283–2288, Apr. 2008.

[11] W.-K. Kuo and C.-Y. Wu, "Supporting real-time VBR video transport on WiMedia-based wireless personal area networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1965–1971, May 2009.

[12] Y. Xu, Q. Guan, J. Zhang; G. Wei, Q. Ding, and H. Zhang, "Service interval based channel time allocation in wireless UWB networks," in *Proc. IEEE ICCS*, Nov. 2008, pp. 1550–1554.

[13] Information sciences institute. (2005). The network simulator ns-2. [Online]. Available: http://www.isi.edu/nsnam/ns



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