QoS-Guaranteed Slot Allocation Algorithm for Efficient Medium Access in HR-WPAN

Jung-Sik Sung, Hyunjeong Lee, Tae-Gyu Kang, and Jaedoo Huh

It is very important to provide a parameterized quality of service (QoS) using traffic specification (TSPEC), such as mean data rate, maximum burst size, and peak data rate, when packets from the application layer need to be transmitted with guaranteed services in a high-rate wireless personal area network (HR-WPAN). As medium resources are limited, the optimal medium time required for each device needs to be estimated to share the resources efficiently among devices. This paper proposes a variable-service interval-based resource allocation algorithm to efficiently make a reservation of medium resources based on a parameterized QoS. In other words, the proposed algorithm calculates the number of medium access slots (MASs) based on TSPEC, local resources, and local conditions and determines suitable locations for the MASs within a superframe to accommodate more devices. The simulation results show that the proposed algorithm can accommodate more devices and has greater than 10% resource allocation efficiency in an HR-WPAN compared to existing schemes.

Keywords: MAC resource allocation, MAS, DRP, QoS guarantee, traffic specification.

I. Introduction

Common solutions for scheduling time slot allocation fall into two main categories. One is a centralized resource management mechanism using a central controller, such as a piconet coordinator (PNC) [1]. In the PNC method, the channel time allocation for each device is calculated by a beacon, data are transmitted through the allocated channel time, and centralized media access control (MAC) protocols offer quality of service (QoS) guarantees for smaller networks because information is collected regarding the state of the network. The other is a distributed MAC protocol, where nodes are responsible for managing access to the medium on their own. Distributed protocols can also be easily scaled to arbitrarily large networks, but cannot provide strict QoS guarantees [2].

There are two methods for providing end-to-end QoS — parameterized QoS and prioritized QoS. Each method gains access to media using a distributed reservation protocol (DRP) and priority contention access (PCA) for the purpose of reserving time slots [3]–[8]. The DRP scheme is similar to time division multiple access (TDMA) [9]. It is responsible for reserving a time in which to transfer data. PCA is similar to enhanced distributed channel access, of IEEE 802.11e, and uses a contention-based method that utilizes the remaining time after a DRP reservation or the non-used time. The authors of [10] and [11] describe the performance of delay in the DRP scheme, and the authors of [12] and [13] do the same for PCA.

The efficient use of bandwidth satisfying QoS guarantees is a very important issue in high-rate wireless personal area networks (HR-WPANs). It is necessary to consider the characteristics of the data in the reservation process, and isochronous data transmissions are achieved by reserving the

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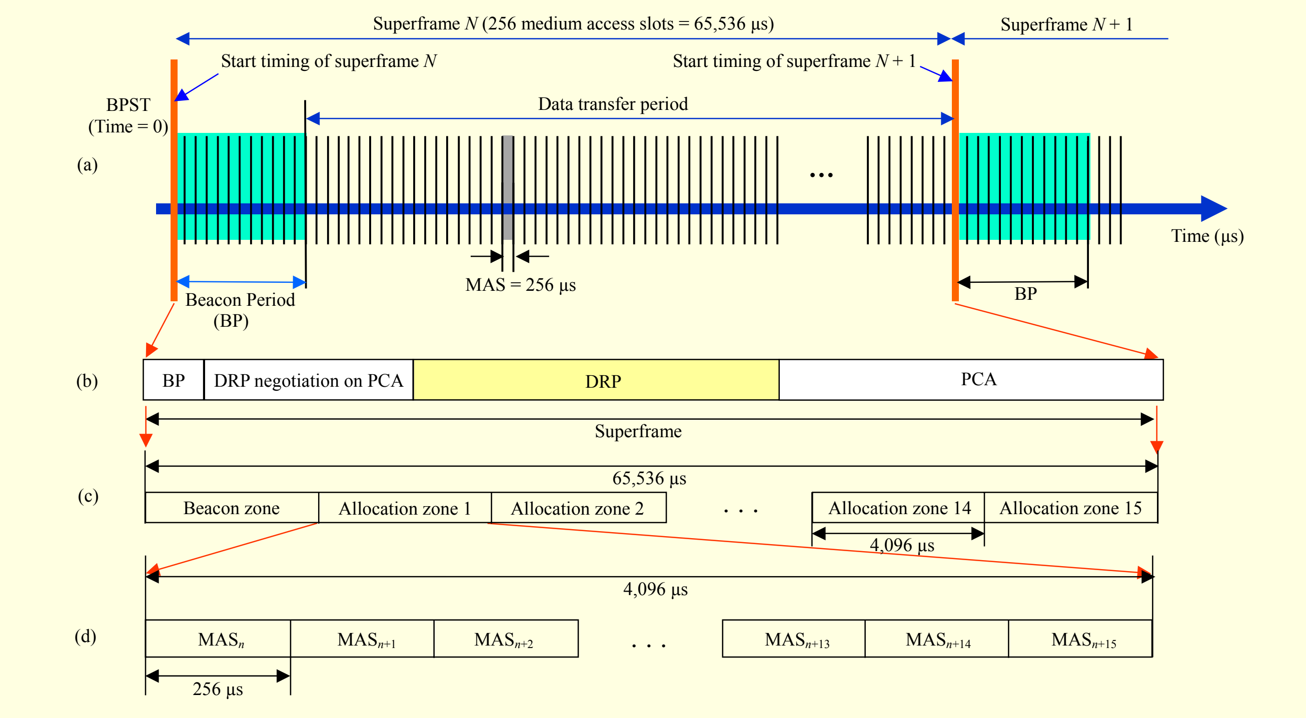


Fig. 1. Structure of superframe.

same slots at regular intervals [8]. An isochronous data transmission requires a guarantee of the service rate with a specific service interval. This paper proposes an algorithm for MAC resource allocation to efficiently use a restricted channel time. The suggested algorithm uses a parameterized QoS method, and assigns a basis position according to the number of allocation zones. If a channel allocation fails in the first allocation zone, then the channel is reallocated in rotating neighbor zones for the purpose of gaining a high rate of channel time allocation by reducing the number of idle zones.

The remainder of this paper is organized as follows. Section II illustrates the ISO-zone service interval–based MAS allocation (SIMA) algorithm [14] and existing schemes. In Section III, this paper shows that each reserved zone is uniformly distributed using the suggested algorithm for strictly limiting a service interval, and discusses in detail the algorithm for efficiently allocating a time slot. In Section IV, the simulation environment for evaluating the performance is described. In addition, the results of the simulation are shown. The resource-allocation efficiency of the proposed algorithm is proven in a multiple-node environment and an HR-WPAN. Finally, conclusions and future works are discussed in Section V.

II. Related Works

In an HR WPAN environment, all devices transferring data share the resources of the superframes. Figure 1 shows the structure of a superframe. How efficiently the resources are allocated is important. For this, an HR WPAN supports a parameterized QoS method using traffic specification (TSPEC) — the mean data rate, maximum burst size, and peak data rate — to ensure the required service rates of the application layer.

There has been some research conducted on parameterized QoS approaches. The SIMA algorithm [13], a kind of parameterized QoS, is used to allocate the medium access slots (MASs) of a superframe using TSPEC from the application layer. Each ISO-zone is identified by an ISO index (ranging from 0 to 3) and has a $2^{4-i} \times 4{,}096$ ms regular service interval according to index i.

The authors in [15] proposed an improved SIMA algorithm to increase the bandwidth utilization. However, the method in [15] does not overcome the inefficiency originating from a predetermined reservation order.

The authors in [5] and [6] proposed two heuristic reservation algorithms — a best-fit algorithm and a cross-ISO-zone-fit algorithm — to meet application QoS requirements and ensure an efficient channel utilization. To increase the channel utilization, the best-fit algorithm uses the PCA after transferring a certain amount of data in the DRP. However, this leads to a delay bound. The cross-ISO-zone-fit algorithm uses higher ISO-zones recursively, but still has a utilization inefficiency.

The authors in [8] suggested a compact allocation algorithm with a reservation-based MAC protocol to increase the channel-utilization efficiency for a multimedia data transmission. It uses a protocol that prioritizes a flow with large MASs and allows nodes to reserve fragmented slots without any QoS violation. However, it uses an ISO-zone scheme like that of existing approaches. An ISO-zone scheme has two problems in terms of efficiently allocating resources. One is that a service interval is not uniform according to the number of allocation zones joining an MAS reservation. Second, it cannot allocate MASs, even if the number of unreserved MASs is sufficient in a superframe to meet the QoS required by the application layer using TSPEC.

III. Proposed Algorithm: Distributed Resource Allocation

This paper proposes an algorithm to support a uniform service interval using an optimized base position, and to efficiently allocate MAS resources in a superframe. In the algorithm, the parameterized QoS scheme using the DRP reservation method is assumed to be utilized. The SIMA algorithm is based on the base position according to the number of allocation zones joining a reservation, and uses an ISO-zone with a higher priority first. Thus, the allocation zones may not be uniformly distributed in some cases, such as when the service intervals are unequal or when the service intervals increase in size. When a service requires a short service interval, the ratio of allocation failure becomes high when several devices share the media with this base position.

The proposed algorithm with a uniform distribution can designate the base position for each allocation zone by strictly limiting the service interval for the purpose of an even distribution of allocation zones joining a reservation. The proposed algorithm consists of two stages. In the first stage, the service rate is calculated based on TSPEC, and the number of MASs required by the application layer is counted considering the packet overhead. The service interval of a reservation is dependent on the number of allocation zones per superframe, which we denote by *k*; the service interval is then determined based on the value of *k*. In the second stage, the proposed algorithm is applied to allocate MASs using the results of the first stage. It allocates MASs rotating to a neighbor zone whenever MAS allocation fails, thereby increasing the coefficient of MAS utilization.

1. Number of MASs

The number of MASs in a superframe has to be allocated to satisfy the service requirements, such as the service rate of the stream, delay bound, and service interval. The service requirements can influence the required MAS number in certain cases. The service rate (g) for communication among devices can be obtained using a TSPEC suitable for the QoS requirements of the application layer. In this paper, the service rate is dependent upon three parameters — the mean data rate (r), maximum burst size (b), and peak data rate (p) — obtained by using the Token Bucket Model of [16]. In this model, the service rate for a traffic stream with traffic characteristics of r, b, and p is represented by the following formulae. The minimum buffer space needed is given by

$$\mathrm{buf} = \frac{p-g}{p-r} \times b. \tag{1}$$

To calculate the delay bound, consider the fact that the last bit of the fully loaded buffer is going to experience the maximum queuing delay, as that bit needs to wait for the entire buffer to be serviced. As the traffic stream is serviced at rate g, the delay bound, d_q, can be expressed as

$$d_\mathrm{q} = \frac{\mathrm{buf}}{g}. \tag{2}$$

From (1), it can be seen that the maximum queuing delay d_q is mathematically bounded by

$$d_\mathrm{q} = \frac{p-g}{g} \times \frac{b}{p-r}. \tag{3}$$

The service rate, the value used to guarantee the delay condition d_q for a traffic stream including TSPEC, is given by

$$g = \frac{p}{1 + d_\mathrm{q} \times \dfrac{p-r}{b}}. \tag{4}$$

The service rate required by the upper layer or TSPEC is the throughput of the data traffic; thus, it is difficult to directly gain the number of MASs using this rate. After the total transmission time per superframe is calculated by regarding the overhead

Table 1. Variables for producing number of MASs.

Variables	Description	Values
T_preamble	PLCP preamble duration	9.375 µs
T_header	PLCP header duration	3.75 µs
T_SYM	OFDM symbol interval	0.3125 µs
N_IBP6S	Number of information bits per 6 symbols	See [17]
MSDU	MSDU size	0 to 4,095 bytes
MIFS	Minimum interframe spacing	1.875 µs
SIFS	Short interframe spacing	10 µs
N_s	Number of frames per superframe	Reference equation (5)
RTS/CTS	Request/Clear to Send	13.125 µs
GT	Guard Time	12 µs

caused by the transmitted physical layer (PHY) protocol data unit (PDU) [PPDU], the number of MASs to reserve can be produced by estimating the required service rate using the PPDU parameters for the service capabilities and frame transmission. The overhead for the frame transmission is influenced by the PHY transmission data rate, Ack Policy, Preamble mode, and so on. The response modes are N (No)-Ack, B (Block)-Ack, and I (Immediate)-Ack. In N-Ack mode, a response is not generated. In B-Ack mode, the frames, defined to be as large as the buffer size, are continuously transferred without responses.

An actually transmitted PPDU has an overhead by the PHY convergence protocol (PLCP) preamble, PLCP header, frame check sequence (FCS), tail bits, and pad bits, where the values are fixed independent of the floating MAC service data unit (MSDU). The transmit time per frame can be calculated the symbol interval of the PLCP sublayer defined in multiband orthogonal frequency-division multiplexing (OFDM) alliance (MBOA), and by the required number of symbols according to the transmit speed in the PHY. Table 1 shows the variables used in the production of the number of MASs.

Equation (5) below illustrates the total transmission time needed in a superframe in the case of N-Ack mode. The number of information bits per six symbols (N_{IBP6S}) is defined for each physical transmission speed [17], and the transmission time for the PLCP service data unit (PSDU) can be calculated using (6) below according to the length of the required MSDU, where the constant C represents the length in bits of the FCS and tail bits section. The overhead based on the length of MSDU used to transmit a fixed data size increases when the MSDU size is small. Namely, the MSDU size is inversely proportional to the number of frames. The range of the MSDU size is 0 bytes to 4,095 bytes. The number of frames per superframe can be gained using (7) below. The required number of MASs can be yielded by dividing 256 µs, the MAS time, after producing the total transmission time, T_{total}.

$$\begin{aligned} T_{\mathrm{total}} &= (T_{\mathrm{preamble}} + T_{\mathrm{header}} + T_{\mathrm{PSDU}}) \times N_{\mathrm{s}} + \mathrm{MIFS} \times (N_{\mathrm{s}} - 1) \\ &\quad + 3 \times \mathrm{SIFS} + \mathrm{RTS} + \mathrm{CTS} + \mathrm{GT}, \end{aligned} \tag{5}$$

$$T_{\mathrm{PSDU}} = T_{\mathrm{sym}} \times 6 \times \frac{8 \times \mathrm{MSDU} + C}{N_{\mathrm{IBP6S}}}, \tag{6}$$

$$N_{\mathrm{s}} = \mathrm{ceil}\left(\frac{g \times 65{,}536\,\mu\mathrm{s}}{\mathrm{MSDU} \times 8} \right). \tag{7}$$

2. Distributed Resource Allocation Algorithm

In the DRP method, the number of MASs to be allocated and their locations within the superframe both need to be determined to reserve network resources. In this section, the location of an MAS can be determined using the number of MASs produced in the previous stage and the MAS bitmap in the present superframe. The position of an MAS in a superframe is dependent on the number of produced MASs and the service interval required by the application layer.

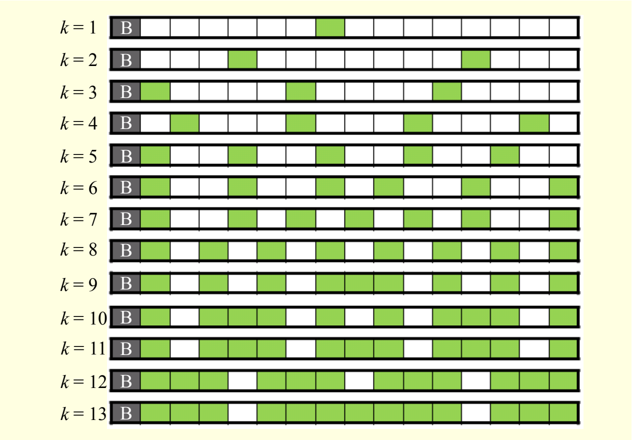


Fig. 2. Base positions based on number of allocation zones (k).

In the ISO-zone scheme, allocation zones of a superframe excluding zone zero are further grouped into four subsets of allocation zones, called ISO-zones [15]. Each ISO-zone is identified by its index, called ISO-index (i), ranging from 0 through 3 inclusive. The service interval of each ISO-zone is 2^{4-i} ms. The service interval is guaranteed when the number of allocation zones is 1, 2, 4, and 8. But, in other cases, it cannot be guaranteed. For example, if three allocation zones are requested, then the 8th allocation zone of ISO-zone 0, and the 4th and 12th allocation zones of ISO-zone 1 are selected. In this case, the service intervals cannot be equally provided through all three zones.

In this paper, a uniform service interval is supported using a base position optimized by the number of allocation zones, k. Moreover, a uniform distribution resource allocation algorithm is proposed for efficient resource allocation by promoting MAS allocation in a superframe.

In addition, to uniformly distribute resources for each reservation block by limiting the service interval, the base position is designated per allocation zone to be reserved, as shown in Fig. 2. The allocation zone can be assigned according to k, the value satisfying the service interval needed by the application layer, after producing the number of MASs. The proposed algorithm supports a more evenly distributed service interval to that supported by the SIMA algorithm.

To increase the coefficient of MAS utilization, the proposed algorithm allocates an MAS rotating to a neighbor when the MAS allocation fails. In addition, the MAS is assigned to move down a line at a failed location. The proposed algorithm

```
determine $k_{min}$ with service interval;
consider MAS block size within an Allocation zone;
if($k_{min} > k_{max}$)
    perform Row Reservation;
while($k_{min} < k_{max}$) {
    Determine Allocation zones from $k_{min}$;
    rotate = $(16 – k_{min})/k_{min}$;
RT:  while(rotate--) {
         if(available MAS in superframe) {
           Allocate MAS;
           Return MAS bitmap; }
         else
           if(block size > c)
             Perform rotation
                 else
                   Perform down allocation
           }
       if (possible a step down) {
         Perform a step down;
         goto RT; }
       else
         $k_{min}$ ++;
}
```

Fig. 3. Proposed algorithm.

Table 2. Comparison of ISO-zone scheme and proposed algorithm.

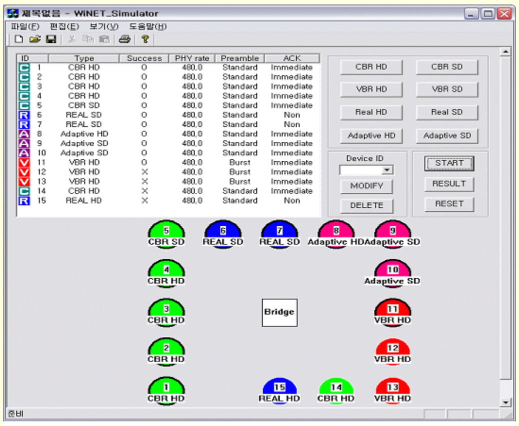
		ISO-zone scheme	Proposed algorithm
Service interval	$k = 3$	8 × 4,096 ms	6 × 4,096 ms
	$k = 6$ or 7	4 × 4,096 ms	3 × 4,096 ms
MAS allocation	Location	Predefined “ISO zone”	Optimized based on “service interval”
	Allocation failure	Down allocation	Consider block size, rotation or down allocation

can increase the rate of MAS allocation compared with a fixed ISO-zone scheme because MASs are allocated again using a rotation mechanism for every next row.

When an MAS cannot be allocated after rotating the neighbor zone and moving down a line, k is increased by one and the mechanism described above is applied again. This is because if k is increased, then the delay of traffic is reduced. Figure 3 shows the uniform distributed resource algorithm proposed in this paper. In addition, Table 2 compares the MAS allocation methodology between the ISO-zone scheme and the proposed algorithm.

IV. Simulations and Performance Evaluation

For the simulation, we implemented the SIMA algorithm, a compact allocation [8], and the proposed algorithm. We also implemented a simulator to evaluate the MAS allocation performance using video traffic similar to that actually used. The TSPEC is received from the application layer because the algorithm uses a parameterized QoS using DRP resource allocation. Thus, TSEC information, such as the mean data rate, the peak data rate, the max burst size, the max packet size, the service rate, and the slack term, can be determined as illustrated in Table 3.



ID		Type	Success	PHY rate	Preamble	ACK
C	1	CBR HD	O	480.0	Standard	Immediate
C	2	CBR HD	O	480.0	Standard	Immediate
C	3	CBR HD	O	480.0	Standard	Immediate
C	4	CBR HD	O	480.0	Standard	Immediate
C	5	CBR SD	O	480.0	Standard	Immediate
R	6	REAL SD	O	480.0	Standard	Non
R	7	REAL SD	O	480.0	Standard	Non
A	8	Adaptive HD	O	480.0	Standard	Immediate
A	9	Adaptive SD	O	480.0	Standard	Immediate
A	10	Adaptive SD	O	480.0	Standard	Immediate
V	11	VBR HD	O	480.0	Burst	Immediate
V	12	VBR HD	X	480.0	Burst	Immediate
V	13	VBR HD	X	480.0	Burst	Immediate
C	14	CBR HD	X	480.0	Standard	Immediate
R	15	REAL HD	X	480.0	Standard	Non

Fig. 4. Example behavior of simulator in initial state.

In addition, the information required by the physical and MAC layers, such as the transmission rate, preamble mode, and response mode, can be set. The simulator is supposed to have eight traffic types, and users can select one of them, apply it to the MAS allocation algorithm, and thereby recognize the assigned form of superframe and some other information. In Table 3, the information for each traffic type in the simulation is shown. In the simulation, a real-time multimedia streaming service is chosen because the service interval is important for the service. In addition, the device types are defined by eight multimedia transmission (compression format) types and the image quality. The transmission types include a constant bit rate (CBR), variable bit rate (VBR), real, and adaptive, and the image quality is high definition (HD) or standard definition (SD). Users can select the traffic using eight buttons at the top-right of the simulator, and allocate the devices that use the traffic. The traffic information, such as TSPEC, the transmission speed of the physical layer, the preamble mode, and the acknowledge mode, can be set by clicking the traffic button. In addition, the device list is shown at the upper-left. After pressing the “START” button, the results of the allocation are displayed in the success column by an “O” or “X.” Moreover, each device is arranged at the bottom, yet only those devices that are successfully allocated are clearly displayed. Figure 4 illustrates an example of the behavior in the initial state. All simulation results presented in this paper are the

Table 3. Eight types of TSPECs used for simulation.

	CBR HD	VBR HD	Real HD	Adaptive HD	CBR SD	VBR SD	Real SD	Adaptive SD
Mean data rate (Mbps)	20	20	20	20	6	6	6	6
Peak data rate (Mbps)	20	50	40	40	6	50	20	20
Max burst size (Bytes)	16,380	16,380	16,380	16,380	16,380	16,380	16,380	16,380
Max packet size (Bytes)	4,095	4,095	4,095	4,095	4,095	4,095	4,095	4,095
Service rate (Mbps)	20	20	35	25	6	6	17.5	13.5
Slack term (ms)	40	40	40	65.536	40	40	40	65.536
PHY rate (Mbps)	53.3–480	53.3–480	53.3–480	53.3–480	53.3–480	53.3–480	53.3–480	53.3–480
ACK mode	N/IB/I	N/IB/I	N/IB/I	N/IB/I	N/IB/I	N/IB/I	N/IB/I	N/IB/I
Preamble mode	Std/Burst	Std/Burst	Std/Burst	Std/Burst	Std/Burst	Std/Burst	Std/Burst	Std/Burst

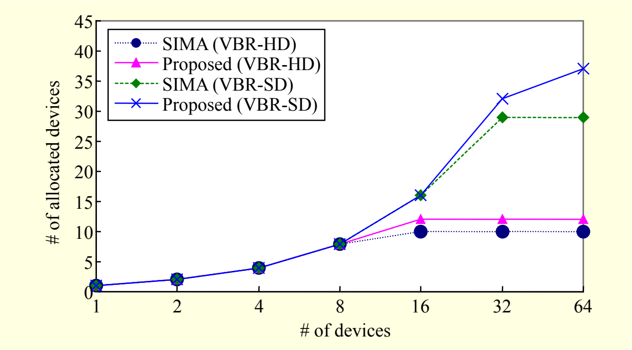


Fig. 5. Performance comparison for VBR-HD and VBR-SD traffic types.

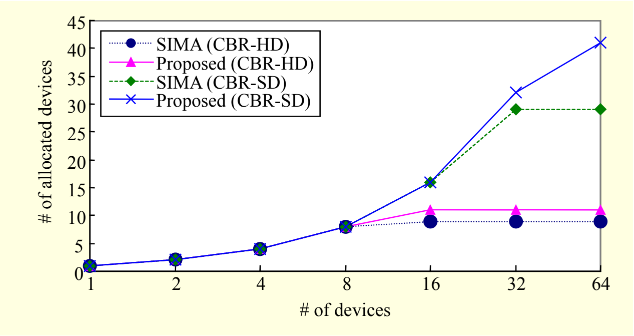


Fig. 6. Performance comparison for CBR-HD and CBR-SD traffic types.

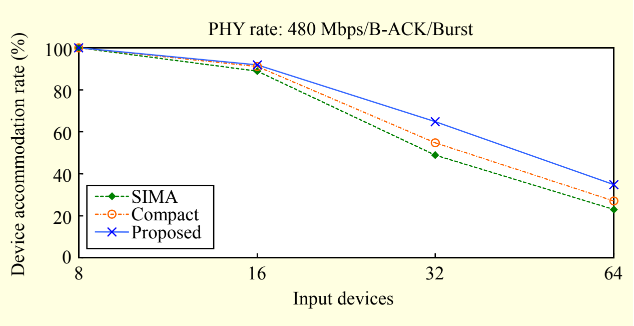


Fig. 7. Device accommodation rate for random traffic.

average of 300 runs.

Figure 5 shows the number of allocated devices with a 480 Mbps physical layer, N-ACK, and standard preamble mode for the cases of VBR-HD and VBR-SD. For VBR-HD, all devices can be allocated MASs when there are eight devices because the MAC channel time can accommodate the required traffic. When the number of devices is more than 16, the MAC channel time cannot use a MAC policy because the traffic increases. Thus, an efficient MAS allocation is needed in this case to admit the maximum number of devices.

In Fig. 5, the proposed algorithm is more efficient in allocation than SIMA; thus, it can accommodate more devices. In the case of VBR-HD, the proposed algorithm is slightly more efficient than SIMA when the number of devices is greater than 16 because VBR-HD traffic from more than 16 devices goes beyond the capability of the MAC resources. However, the proposed algorithm can assign devices more efficiently for more than 16 devices in the case of VBR-SD. All 32 devices are accommodated when 32 devices generate VBR-SD traffic, as shown in Fig. 5. In the case of 64 devices, the proposed algorithm can accept 41 of the devices, whereas SIMA can accept 29. Figure 5 shows that the accommodating capability of the proposed algorithm is superior to SIMA by about 20% for VBR-SD. Figure 6 shows the number of successfully allocated devices for CBR-HD and CBR-SD with 480 Mbps, I-ACK, and standard preamble mode. In addition,

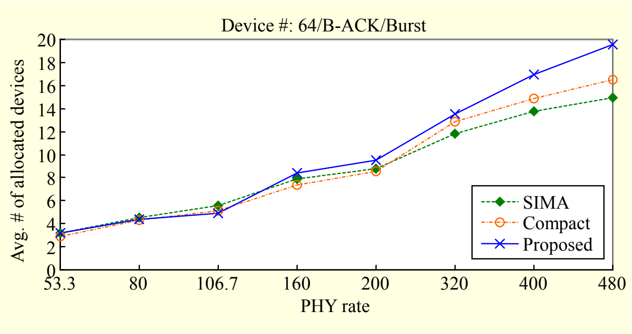


Fig. 8. Average no. of allocated devices according to increase in PHY rate.

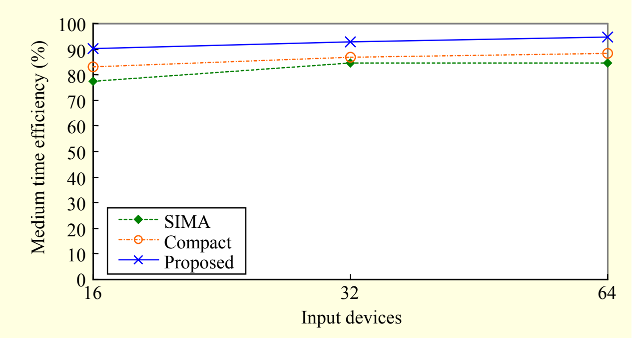


Fig. 9. Comparison of MAS allocation efficiency.

the proposed algorithm is better than SIMA for VBR traffic in which the traffic is too large to allocate MAC channel resources (for CBR-HD, the number of devices is more than 8, and for CBR-SD, the number of devices is more than 16).

Figure 7 shows the device accommodation rate for random traffic with 480 Mbps, B-ACK, and burst preamble mode. The simulator can generate random traffic for a device when the user assigns a number of input devices to simulate. The random traffic type of the device is one of eight types, as show in Table 3. At under a 480 Mbps physical speed rate, all devices can be allocated MASs when the number of devices is eight, as shown in Fig. 7. Thus, we compared the device accommodation rate for more than eight devices. Input traffic of the devices is randomly generated from eight types of traffic. When increasing the number of input devices, the proposed algorithm accommodates more devices supporting QoS guarantees than SIMA and compact allocation [8]. In particular, when the number of devices to send random traffic is 32, the accommodating rate of the devices of the proposed method is 65%, and is 49% for SIMA and 55% for compact allocation.

Figure 8 shows the average number of allocated devices when increasing the physical speed rate for 64 input devices and a random type of input traffic. The average numbers of allocated devices of the SIMA and compact allocation algorithms look very similar to the proposed method at a low physical speed between 53.3 Mbps and 106.7 Mbps. At over 160 Mbps, the proposed algorithm is even better. This result indicates that the proposed algorithm is more suitable to support QoS guarantee in an HR-WPAN. The results independent of ACK mode and preamble mode are the same as those shown in Fig. 8, where B-ACK mode and burst preamble mode are used.

The effectiveness of the three MAS allocation algorithms for eight types of traffic is compared in Fig. 9. The performance of the proposed algorithm is comparable with SIMA and compact allocation for eight devices because the MAC channel time is sufficient to accommodate the required traffic. However, the proposed algorithm is excellent as a MAS allocation scheme when the number of devices is greater than eight. The medium time efficiency of the proposed algorithm is always beyond 90%, which is superior to SIMA and compact allocation by about 10%.

V. Conclusion

As short-range wireless communications is continuously being demanded, high-rate WPANs and Wi-Fi are emerging as next-generation wireless technologies for a more efficient use of a limited frequency. To support wireless multimedia services for PCs, digital video equipment, mobile devices, home appliances, and so on, it is necessary to efficiently use channel time resources while satisfying the service speed, service intervals, and delay conditions. This paper proposed a uniform distribution rotation-service interval-based resource allocation algorithm, which supports equal service intervals using optimized allocation criteria for each allocation zone in a high-rate WPAN MAC superframe, and efficiently allocates MAS resources in a superframe. In addition, the performance of the algorithm is compared with the ISO-zone scheme algorithms through a simulation. As a result of the performance comparison with various types of media frames in multiple devices, the suggested algorithm is about 10% to 20% greater than ISO-zone scheme algorithms for a greater number of connected devices, and a higher transmission speed in the physical layer.

The application may support a class-based queue algorithm to accommodate Class I services, which requests QoS guarantees, and Class II services, which do not require QoS guarantees in multimedia networks [18]. Class I services match the resource reservation slots, while Class II services match congestion access slots. According to [19], the resource allocation mechanism in which some slots run in a congestion access slot and others run in a resource reservation slot, performs worse the channel utilization efficiency than in a pure congestion access slot or pure resource reservation slot. A study on exchanging the congestion access model using our reservation mechanism to provide a better channel time efficiency will be planned. For future work on IoT, a MAC layer algorithm is one of the major evolutions for sensor devices populating IoT networks.

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