이중 IEEE 802.11 WLAN에서 경성 실시간 통신을 위한 대역폭 할당

(A New Bandwidth Allocation Scheme for Hard Real-time Communication on Dual IEEE 802.11 WLANs)

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요 약 본 논문은 이중 IEEE 802.11 무선 근거리 통신망 상에서의 경성 실시간 통신을 위한 메시지 스케줄링 기법과 이에 따르는 대역폭 할당 기법을 제안하고 그 성능을 분석한다. 동일한 주기를 갖는 각 네트워크에서 슈퍼프레임이 서로 반주기의 편차를 갖고 진행되도록 함으로써 최대 대기시간을 반으로 감소시키고 비콘 지연 현상이 실시간 트래픽 스케줄링에 주는 영향을 최소화한다. 비콘 지연 현상의 영향이 오프라인시에 형식화되고 고려되어 라운드로빈 방식을 기반으로 PCF 구간의 폴링 스케줄을 결정한다. ns-2에의해 수행된 모의실험은 제안된 방식이 실험을 위해 생성된 메시지 집합에 있어서 동일한 대역폭과 MAC 방식을 갖는 이중 근거리 통신망에 비하여 실시간 메시지의 스케줄가능성을 36 % 향상시킬 수 있으며 비실시간 메시지들에게는 9%의 대역폭을 더 할당할 수 있음을 보인다.

키워드 : 실시간 통신, 이중 802.11 WLAN, 비콘 지연 현상, 대역폭 할당, 스케줄가능성

Abstract This paper proposes and analyzes a message scheduling scheme and corresponding bandwidth allocation method for the hard real-time communication on dual standard 802.11 Wireless LANs. By making the superframeof one network precede that of the other by half, the dual network architecture can minimize the effect of deferred beacon and reduce the worst case waiting timeby half. The effect of deferred beacon is formalized and directly considered to decide the polling schedule of PCF phase. Simulation results executed via ns-2 show that the proposed scheme can improve the schedulability by 36 % for real-time messages and give 9 % more bandwidth to non-real-time messages for the given stream sets, compared with the network whose bandwidth is just doubled with the same MAC.

Key words : Real-time communication, Dual 802.11 WLAN, Deferred beacon problem, Bandwidth allocation, schedulability

1. Introduction

Wireless communication technology is gaining a wide-spread acceptance for distributed systems and applications in recent years[1]. As both speed and capacity of wireless media such as WLAN (Wireless Local Area Network) increase, so does the demand for supporting time-sensitive high-bandwidth applications such as broadband VOD (Video On Demand) and interactive multimedia[2]. One of the promising application area of wireless technology is a wireless sensor network, where the periodically sampled data are delivered to the appropriate node within a reasonable deadline to produce timely data[3]. That is, the message has hard real-time constraints that it should be transmitted within its deadline (as long as there is no network error). Otherwise, the data is considered to be lost, and the loss of hard real-time data may jeopardize the correct execution of relevant application or the system operation itself. A real-time message needs the guarantee from the underlying network that its time constraints are

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always met in advance of the system operation.

The IEEE 802.11 was developed as a MAC standard for WLAN[4]. The standard consists of a basic DCF(Distributed Coordination Function) and an optional PCF(Point Coordination Function). The DCF uses CSMA/CA(Carrier Sense Multiple Access with Collision Avoidance) protocol for the transmission of asynchronous non-real-time messages, mainly aiming at improving their average delivery time and network utilization. However, a real-time guarantee can be provided only if a deterministic contention-free schedule is developed[5]. It is PCF that satisfies such a requirement based on a polling mechanism. Several MAC protocols have been proposed to support the hard real-time communication over a wireless channel, but they cannot be easily ported to the IEEE 802.11 WLAN standard, as they ignored the CSMA/CA part of WLAN or just aimed to enhance the ratio of timely delivery for soft multimedia applications[6].

Hard real-time guarantee depends strongly on the underlying polling policy, that is, how polling interval starts, how the coordinator selects the node to be polled, and how long a node transmits on each poll. According to the WLAN standard, these issues are left to the implementor. As an example, weighted round robin scheme makes the coordinator poll each node one by one, and the polled node transmits its message for a time duration, or weight, decided by its traffic characteristics. While this scheme makes the guarantee mechanism simple and efficient, it suffers from poor utilization due to polling overhead, extended waiting time, and *deferred beacon problem*[7]. Deferred beacon problem means a situation that a non-real-time message prevents a CFP from starting at the regular interval. Though the maximum amount of deferment is bounded, it seriously degrades the schedulability of real-time messages.

In order to overcome this poor schedulability, we are to propose a network architecture and corresponding network access mechanism based on the dual wireless LANs. The dual link system can enhance the schedulability for the real-time traffic because it can reduce the worst case waiting time for each stream to access the network as well as save the network access that may be lost due to deferred beacons. Moreover, efficient bandwidth allocation can also offer more network bandwidth to the non-real-time traffic. As the wireless channel supports multiple frequency bands, it is not unusual for a group of components belonging to a common control loop to be linked by two networks. Specifically, infrastructure mode WLAN exploits two frequency channels, one for uplink and the other for downlink. This architecture can be modified into the dual networks with two shared mediums. In addition, the model of fading error in dual wireless mediums has been analyzed[8].

This paper is organized as follows: After issuing the problem in Section 1, Section 2 introduces the related works and backgrounds on real-time communications on the wireless medium, operation of 802.11 WLAN protocol, and real-time message model. Then Section 3proposes the bandwidth allocation scheme for PCF of IEEE 802.11 WLAN based on the round-robin polling policy, and this scheme also is extended to the dual networks. Section 4 shows and discusses performance measurement results and then Section 5 finally concludes this paper with a brief summarization and the description of future works.

2. Related Works and Background

2.1 Related works on real-time communication on wireless LAN

Several MAC protocols have been proposed to provide bounded delays for real-time messages while providing a reasonable performance for a non-real-time data over a wireless channel. However, these protocols are typically based on a framestructured access which consists of a contention part and reservation part, necessitating time synchronization between the nodes on a network, so they make it impossible or unrealistic to apply to the IEEE 802.11 WLAN. For example, Choi and Shin suggested a unified protocol for real-time and non-real-time communications in wireless networks[6]. A BS(Base Station) polls a real-time mobile according to the non-preemptive EDF(Earliest Deadline First) policy. The BS also polls the non-real-time message according to the modified round-robin scheme rather than a standard CSMA/CA protocol to eliminate message collision.

M. Caccamo and et. al have proposed a MAC that supports deterministic real-time scheduling via the implementation of TDMA(Time Division Multiple Access), where the time axis is divided into fixed-size slots[5]. Referred as *implicit contention*, their scheme makes each node concurrently run the common real-time scheduling algorithm to determine which message can access the medium. Each message implicitly contends for the medium through the scheduling algorithm, for example, with priorities, rather than explicitly on the physical medium. However, for this implicit contention, every node must schedule all messages in the network, making it difficult to scale to large networks. Above protocols didn't consider the DCF that is defined as mandatory in WLAN standard, so the deferred beacon problem may make their guarantee policy unavailable.

Most works that conform to the IEEE standard are aiming at just enhancing the ratio of timely delivery for soft multimedia applications, rather than providing a hard real-time guarantee. DBASE (Distributed Bandwidth Allocation/Sharing/Extension) is a protocol that supports both synchronous and multimedia traffics over IEEE 802.11 *ad hoc* WLAN[2]. The basic concept is that each time a real-time station transmits a packet it will also declare and reserve the bandwidth demanded at the next CFP. Every station collects this information and then calculates its actual bandwidth at the next cycle. This scheme can be ported to WLAN standard, but it does not provide a hard real-time guarantee as it does not directly consider the maximum bandwidth request.

2.2 IEEE 802.11 WLAN

The wireless LAN operates on both CP(Contention Period) and CFP(Contention Free Period) phases alternatively in BSS (Basic Service Set) as shown in Figure 1. A superframe consists of an instance of CFP and CP. It is mandatory that a superframe includes a CP of minimum length that allows at least one data packet delivery under DCF[4]. PC (Point Coordinator) node, typically AP, sequentially polls each node during CFP one by one, and only the polled node is given the right to transmit its message up to a predefined time interval. Even in the *ad hoc* mode, it is possible to make a specific node play a role of PC[9].

The PC regularly tries to initiate CFP by broadcasting a *Beacon* at the rate specified in *CFPRate*. It polls the stations in a round-robin fashion in CFP, and a polled station always responds to a poll immediately whether it has a pending message or not. Every node is polled once per a polling round, and a polling round may be either completed within a superframe or spread over more than one superframe. If the CFP terminates before all nodes have been completely polled, the polling list is resumed at the next node in the following CFP cycle. In case of an unsuccessful transmission, the station retransmits the frame during the next contention period or when it receives the next poll.

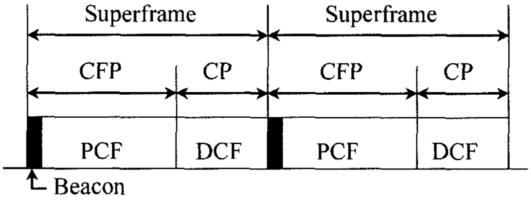


Figure 1 Time axis of wireless LAN

The network manages operation phases by exchanging control frames, for example, the broadcast of beacon by the coordinator initiates the CFP and thus a new superframe. This control frame should have the precedence over normal data packets and the WLAN supports the prioritized network access via IFS(InterFrame Space) mechanism. Every packet has its own IFS according to its priority and it should wait for IFS after sensing the medium idle. Then the station begins the transmission procedure according to the protocol. The SIFS(Short IFS) is assigned to the top priority frames such as acknowledgement and beacon. The PIFS(Priority IFS) is used by real-time frames, while DIFS(DCF IFS), the longest IFS, is used by non-real-time frames. The delivery of a beacon frame can get delayed even if it has higher priority due to the non-preemptive nature of packet transmission[2]. Provided that another packet has already occupied the network when the coordinator is to send a beacon, coordinator should wait until the medium becomes free. In that case, the start of

CPF may be delayed as shown in Figure 2. This situation is referred as deferred beacon problem, and maydisable the timely delivery of hard real-time messages scheduled at the deferred CFP. As can be inferred in Figure 2, the maximum amount of deferment coincides with the maximum length of non-real-time packet.

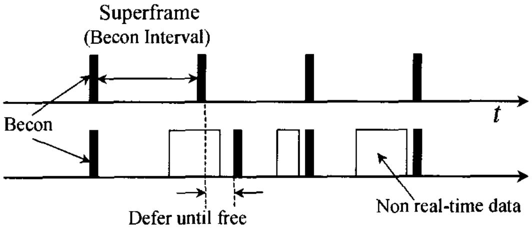


Figure 2 Deferred beacon problem

2.3 Message model

In real-time communication literature, the term real-time traffic typically means *isochronous* (or synchronous) traffic, consisting of message streams that are generated by their sources on a continuing basis and delivered to their respective destinations also on a continuing basis[10]. The stream set is fixed and known in advance of system operation, and the most important traffic characteristics of each stream are its period and message size. In case of a change in the stream set, bandwidth is reallocated or network schedule mode is changed. If we assume that there are n real-time streams, namely, $S_1, S_2, ..., S_n$, each stream can be modeled as follows: A message arrives at the beginning of its period and it must be transmitted by the end of period. The period of stream, S_i, is denoted as P_i, and the maximum length of a message as C_i. The first message of each stream arrives at time 0. The destination of message can be either within a cell or outside a cell, and the outbound messages are first sent to the router node such as AP and then forwarded to the final destination[11]. A proper routing and reservation protocol can provide an end-to-end delay guarantee. As is the case of other works, we assume that each stream has only one stream, and this assumption can be generalized with virtual station concept[10].

3. Bandwidth Allocation

3.1 Basic assumption

By allocation, we mean the procedure of determining capacity vector, $\{H_i\}$, for the given superframe time, F, and message stream set described as $\{S_i\ (P_i,\ C_i)\}$[12]. H_i limits the maximum amount of time during which S_i can send on its turn. A polling round may spread across more than one superframe. However, for simplicity, we assume that a polling round completes within a single superframe without the loss of generality, and then the assumption will be eliminated. Additionally, the PC tries to initiate the CFP at fixed time interval of F, though a non-real-time message may defer some initiations. First of all, though there are many issues one needs to consider in wireless networks such as *error control*, we mainly focus on a significant performance issue, that is, timeliness[2,5,6]. It is true that wireless environment is prone to communication errors due to interference from outer sources, absorption, scattering, and fading. Error control issues are not considered in this paper, but some related researches can be incorporated[13].

If a node has no pending message when it receives a poll, it responds with a null frame containing no payload. The unused time may be reclaimed by such technique as FRASH(FRAme SHaring) to improve network utilization[5]. The reclaimed time is used for error control purpose or transmission of a non-real-time message, but not for the other real-time messages.Otherwise, for a certain node, the poll moves ahead, while its next poll remains unchanged, enlarging the maximum gap between the two adjacent polls. This may further cut down the worst case network access time for a period. Finally, It is desirable that the superframe time is a hyperperiod of the set and it is known that a message set can be made harmonic by reducing message periods by at most half[1]. So we assume that the superframe time is also given in priori, focusing on the determination of capacity vector.

3.2 Allocation Procedure

Allocation procedure determines capacity vector, $\{H_i\}$, for the given superframe time and message stream set. Figure 3 illustrates that the slot size is not fixed, namely, $H_i \neq H_j$ for different i and j. It is natural that more network bandwidth is assigned to the stream with more utilization. At this figure, a message of size C_i is generated and buffered at each start of P_i, and then transmitted by H_i every time the node receives poll from PC.

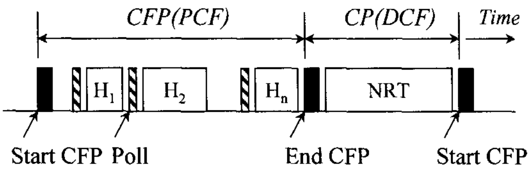


Figure 3 Polling procedure and capacity vector

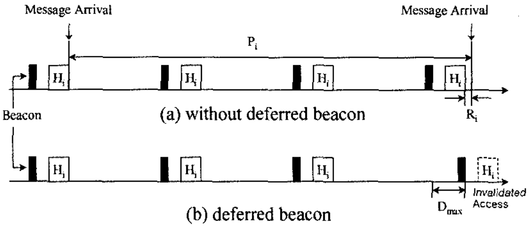
To begin with, let δ denote the total overhead of a superframe including polling latency, IFS, exchange of beacon frame, and the like, while D_{max} the maximum length of non-real-time data packets. For a minimal requirement, F should be sufficiently large enough to make the polling overhead insignificant. In addition, if we let P_{min} be the smallest of set $\{P_i\}$, F should be less than P_{min} so that every stream can meet at least one superframe within its period. For each superframe, not only the start of CFP can be deferred by up to D_{max}, but also at least a time amount as large as D_{max}, should be reserved for a data packet so as to be compatible with WLAN standard. After all, the requirement for the superframe time, F, can be summarized as follows:

$$\sum H_i + \delta + 2 \cdot D_{\max} \le F \le P_{\min} \tag{1}$$

The number of polls a stream meets is different for each period. Meeting hard real-time constraints for a node means that even in the period which meets the smallest number of poll, the node can transmit message within its deadline. Figure 4 analyzes the worst case available time for S_i. In this figure, a series of superframes are contained in P_i and each period can start at any instant from the start of superframe. Intuitively, the stream is likely to meet the smallest number of polls in the period which starts just after it releases its slot time.

In this figure, R_i is the residual obtained by dividing P_i by F, namely, $R_i = P_i - \left\lfloor \frac{P_i}{F} \right\rfloor \cdot F$. Without the deferred beacon, the CFP starts regularly at each time interval of F. In that case, for S_i, the least bound of network access within P_i is $\left\lfloor \frac{P_i}{F} \right\rfloor$, as illustrated in Figure 4(a). On the contrary, if we consider the deferred beacon, the deferred start of the last superframe may deprive S_i of one access when R_i is less than D_{max}, as shown in Figure 4(b). If R_i is greater than D_{max}, the number of available time slots is not affected by the delayed start of superframe. It doesn't matter whether the intermediate superframes are deferred or not. Figure 4(b) describes that S_i can be affected by the deferred beacon only if R_i is less than D_{max}. As a result, the minimum value of available transmission time, X_i is calculated as Eq. (2). Namely,

$$X_i = \left(\left\lfloor \frac{P_i}{F} \right\rfloor - 1 \right) \cdot H_i \qquad \text{if } R_i \le D_{\max}$$
$$X_i = \left(\left\lfloor \frac{P_i}{F} \right\rfloor \right) \cdot H_i \qquad \text{Otherwise} \tag{2}$$



(a) without deferred beacon

(b) deferred beacon

Figure 4 Worst case analysis

For each message stream, X_i should be greater than or equal to $C_i (X_i \ge C_i)$. By substituting Eq. (2) for this condition, we can obtain the least bound of H_i that can meet the time constraint of S_i.

$$H_i = \frac{C_i}{\left(\left\lfloor \frac{P_i}{F} \right\rfloor - 1 \right)} \qquad \text{if } R_i \le D_{\max}$$
$$H_i = \frac{C_i}{\left\lfloor \frac{P_i}{F} \right\rfloor} \qquad \text{Otherwise} \tag{3}$$

The allocation vector calculated by Eq. (3) is a feasible schedule if the vector meets Ineq. (1). By this, we can determine the length of CFP, T_{CFP}, and that of CP, T_{CP}, as follows:

$$T_{CFP} = \sum H_i + \delta, \quad T_{CP} = F - T_{CFP} \ge D_{\max} \tag{4}$$

This calculation is easily fulfilled with simple arithmetic operations. In addition, the size of time slot is different for each stream, so the proposed scheme can expect the efficient use of network bandwidth compared to other schemes based on fixed size slots. Finally, as this allocation scheme generates a larger T_{CP} for the given F, the network can deliver more non-real-time messages.

In case a polling round spreads into more than one superframe, say k superframes, each one can be marked as F_1, F_2, ..., F_k. The size of each superframe is F, while each includes its own CP duration and performs only a part of polling round. S_i eceives poll once a $k \cdot F$ and the worst case can be calculated by replacing F with $k \cdot F$ in Eq. (2). But the condition remains intact which checks whether a stream will be influenced by a deferred beacon. After all, Eq. (2) can be rewritten as follows:

$$X_i = \left(\left\lfloor \frac{P_i}{k \cdot F} \right\rfloor - 1 \right) \cdot H_i \qquad \text{if } R_i \le D_{\max}$$

$$X_i = \left\lfloor \frac{P_i}{k \cdot F} \right\rfloor \cdot H_i \qquad \text{Otherwise} \qquad (5)$$

3.3 Dual wireless networks

The poor utilization of PCF arises from the fact that a message cannot be transmitted on demand, as there is no way for a node to request a immediate poll to the coordinator. The node should wait up to one superframe time at the worst case. However, dual network architecture can reduce this waiting time by half in round-round style network. The dual networks are analogous to the dual processor system, as both network and processor can be considered to be an active resource. The jobs or messages are scheduled on two equivalent processors or networks. Priority-driven scheduling on multiple resources induces scheduling anomaly that less tasks can meet their deadlines even with more resources. In addition, it is known that off-line scheduling for this environment is a NP-hard problem[10]. Contrary to priority-driven scheduling, the transmission control scheme proposed in the previous sections can easily calculate the feasible and efficient schedule for the dual resource systems.

It is desirable for the two networks to have a common coordinator that schedules and synchronizes them. A node sends its message on any poll from either network. If we make a superframe progress simultaneously or randomly as shown in Figure 5(a), S_i may simultaneously lose one access on each network, two in total. This case is analogous to the case when network bandwidth is just doubled. So X_i is formalized as in Eq. (6).

$$X_i = 2 \cdot \left\lfloor \frac{P_i}{F} \right\rfloor \cdot H_i \qquad \text{if } (R_i \ge D_{\max})$$

$$X_i = 2 \cdot \left(\left\lfloor \frac{P_i}{F} \right\rfloor - 1 \right) \cdot H_i \qquad \text{Otherwise} \qquad (6)$$

On the contrary, if we make one network precede the other by $\frac{F}{2}$ as illustrated in Figure 5(b), one loss can be saved, improving the worst case behavior. Namely, F is reduced by half, so Xi can be calculated by replacing F in Eq. (2) with $\frac{F}{2}$. However, though D_{max} cannot exceed F, it can be larger than $\frac{F}{2}$, though it seems quite unrealistic. In that case, the last access at the second network can be also omitted. So X_i is formalized as in Eq. (7).

$$X_i = \left\lfloor \frac{2 \cdot P_i}{F} \right\rfloor \cdot H_i \qquad \text{if } (R_i \ge D_{\max})$$

$$X_i = \left(\left\lfloor \frac{2 \cdot P_i}{F} \right\rfloor - 1 \right) \cdot H_i \qquad \text{if } \left(R_i \le D_{\max} \le R_i + \frac{F}{2} \right)$$

$$X_i = \left(\left\lfloor \frac{2 \cdot P_i}{F} \right\rfloor - 2 \right) \cdot H_i \qquad \text{if } \left(\left(R_i + \frac{F}{2} \right) \le D_{\max} \right) \qquad (7)$$

4. Performance Measurement

Only TDMA-base schemes can be competitors, because they can provide hard real-time guarantee.

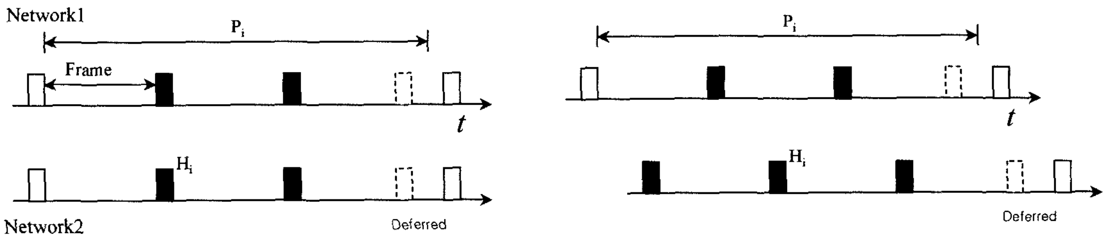


Figure 5 Dual wireless LAN time axis

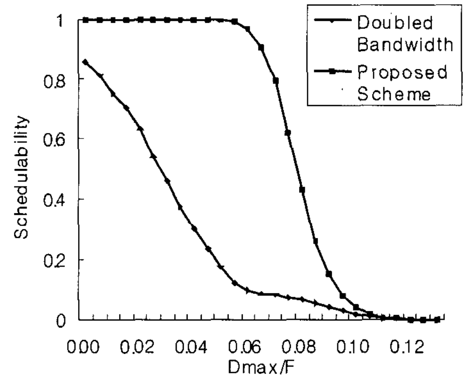


Figure 6 Schedulability vs. D_{max}

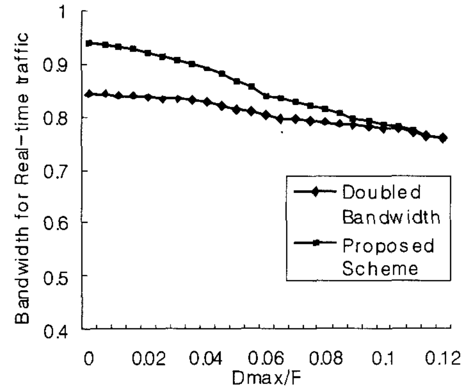


Figure 7 NRT bandwidth vs. D_{max}

However, a comparison with TDMA is almost infeasible because it essentially requires so many assumptions on slot size, superframe operation, way of dealing with deferred beacon, and so on.

We measured the performance of the proposed scheme in the view of schedulability and non-real-time bandwidth via simulation using ns-2[14]. In the experiments, every time variable is aligned to the superframe time, and an initiation of superframe is deferred by from 0 to D_{max} exponentially. By normalized utilization, we mean the average utilization assigned to one network. For example, if a set has total utilization of 2.4 and there are 3 networks, thenormalized utilization is 0.8. Without any other protocol overhead, the network can schedule the stream set whose utilization is $1.0 - \frac{2 \cdot D_{max}}{F}$, achievable throughput. For the first experiment on schedulability, we have generated 2000 stream sets whose utilization ranges from 0.68 to 0.70. The number of streams in a set is chosen randomly between 5 and 15. The period of each stream ranges from $5.0F$ to $10.0F$, while its message length from $0.3F$ to $5.0F$. We measured the schedulability, the ratio of schedulable stream sets to total generated sets, changing D_{max} from $0.0F$ to $0.14F$. Figure 6 plots schedulability of proposed dual network architecture comparing with that of the network whose bandwidth is just doubled. The schedulability begins to drop abruptly at a certain point for each curve. The breakdown point moves to the right (closer to the achievable throughput), minimizing the protocol overhead of round-robin polling mechanism. The final guarantee ratio is 0.60 while that of doubled bandwidth network stays at 0.24.

Figure 7 shows how much bandwidth is assigned to non-real-time messages. For this experiment, message sets schedulable by all schemes (including doubled bandwidth) are selected first and their T_{CP} values are averaged. We address that our scheme provides tighter and smaller H_i's, as Eq. (7) is significantly weaker constraint than Eq. (6). According to the increment of D_{max}, more bandwidth is assigned to non-real-time traffic, because D_{max} is its minimum bound. As shown in the figure, proposed scheme is able to assign more bandwidth to non-real-time messages and we can expect more improvement with more networks. The maximum improvements are $0.09F$.

5. Conclusion

This paper has proposed and evaluated a bandwidth allocation scheme that enhances the schedulability of hard real-time streams via dual wireless network architecture, strictly observing IEEE 802.11 WLAN standard. By exploiting the round robin style polling mechanism, network schedule and bandwidth allocation become much simpler, and they can check efficiently whether a stream is affected by deferred beacons. Additionally, by differentiating the start times of both networks by $\frac{F}{2}$ under the control of common coordinator, the proposed scheme improves the least bound of network access time for each message stream.

Simulation results show that the capacity vector decided by the proposed scheme schedules more stream sets than the network whose bandwidth is just doubled, and that it can invite more non-real-time message to occupy the network, for the given experiment parameters.

As a future work, we consider a message scheduling scheme on dual networks combined with an error control mechanism to cope with the potential instability of wireless communication environment. We believe that the proposed method can be adapted to distributed scheduling and bandwidth allocation schemes, so research to devise the distributed scheme is on the way.

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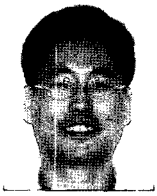

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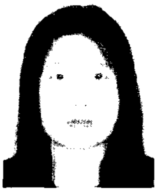

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