Achieving Fair Bandwidth Sharing for Downlink and Uplink Traffic in an Infrastructure WLAN

Chih-Heng Ke[1] , Chih-Ang Huang[2*],and Kawuu W. Lin[3]

[1]Department of Computer Science and Information Engineering, National Quemoy University, Kinmen, Taiwan, R.O.C.

[2,3]Department of Computer Science and Information Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan, R.O.C.

ABSTRACT

The current IEEE Standard 802.11 for the distributed coordination function (DCF), which provides equal medium access probability to all transmitters, suffers from downlink and uplink unfairness problem when operating in the infrastructure mode. Therefore, this paper proposes a Modified High-performance Distributed Coordination Function (MHDCF) to solve this unfairness problem. In MHDCF, the current transmitting station selects the access point (AP) with a high probability and the wireless stations with a low probability as the next transmitter to improve the downlink saturation throughput. Furthermore, when the channel error rate is high and the number of contending station is large, the saturation throughput of High-performance Distributed Coordination Function (HDCF) degrades sharply. Accordingly, this paper also modifies the HDCF in the contending mode. The MHDCF adopts a modified exponential increase exponential decrease backoff algorithm (MEIED) to resolve the aforementioned problem. Results show that MHDCF not only provides fair bandwidth sharing for downlink and uplink traffic but also yields a significant improvement in the network throughput even when the medium is very noisy.

Keywords: downlink and uplink unfairness problem, infrastructure, IEEE 802.11

增強高效能分散式協調機制－用於解決基礎架構無線區域網路下載與上傳傳輸頻寬不公平之問題

柯志亨[1]　黃志昂[2*]　林威成[3]

[1]國立金門大學資訊工程學系

[2,3]國立高雄應用科技大學資訊工程學系

摘　要

在 IEEE 802.11 基礎架構無線區域網路，利用分散式協調機制(DCF)來確保工作站或基地台在無線傳輸媒介中享有相同存取權，卻造成上傳和下載傳輸頻寬不公平之問題。因此，本文提出增強高效能分散式協調機制(MHDCF)，用於解決此傳輸頻寬不公平的問題。在 MHDCF 中，基地台有較高的機率被傳輸中的節點選為下一個傳輸者，而行動工作站則以較低的機率被傳輸中的節點選為下一個傳輸者，以有效改善下載的飽和吞吐量。另外，當無線傳輸媒介錯誤率很高時，且競爭節點很多時，高效能分散式協調機制(HDCF)的傳輸吞吐量就會嚴重地降低。因此，本文採用了改良式指數增加指數減少倒退演算法(MEIED)來解決上述的問題。經由模擬實驗的結果，可以證明本文所提出的 MHDCF 方法除了確保下載與上傳傳輸頻寬公平性外，即使在無線傳輸媒介訊號很差的時候，其整體系統傳輸吞吐量也可以有顯著的改善。

關鍵詞：下載與上傳傳輸頻寬不公平之問題，基礎架構，IEEE 802.11

文稿收件日期 100.5.6;文稿修正後接受日期 102.1.8; *通訊作者
Manuscript received May 6, 2011; revised January 8, 2013; *Corresponding author

Ⅰ. INTRODUCTION

IEEE 802.11[1] provides two operating modes: one is in the infrastructure mode and the other is in the ad hoc mode. In the infrastructure mode, the access point (AP) plays a coordinating role for wireless stations. The AP forwards downlink traffic to the corresponding wireless station and passes all uplink traffic to their respective destinations. Therefore, the AP usually requires more channel access time for delivering traffic than wireless stations. However, the Distributed Coordination Function (DCF) used in the infrastructure mode provides equal medium access probability to all transmitters, including AP and wireless stations. Consequently, the AP only gains approximately $1/(n+1)$ channel access probability to deliver downlink traffic while all the wireless stations can earn $n/(n+1)$ access chance to upload the traffic with the assumption of n transmitting wireless stations in the same basic service set. This asymmetric bandwidth sharing makes the AP become the bottleneck and causes so-called downlink and uplink unfairness problem [2].

The legacy solutions to this unfairness problem can be simply classified into time domain and frequency domain methods. The time domain methods, such as [3][4], provide the AP with a greater transmission opportunity (TXOP) to send more data frames when it gets the right to access the channel. On the other hand, the frequency domain schemes adjust the contention window [5][6] or inter frame space [7] to give the AP higher transmission probability to send more times than the wireless station to improve the throughput of the downlink traffic. However, these solutions are fundamentally based on contention-based operation, and therefore they waste much time in resolving contention and retransmitting, especially when the number of competing stations is large. Accordingly, this paper proposes a Modified High-performance Distributed Coordination Function (MHDCF) to achieve fair bandwidth sharing for downlink and uplink traffic while keeping the system throughput high no matter how many stations are in an infrastructure WLAN. The MHDCF has two working modes, namely a contending mode and an active mode. In the proposed protocol, new stations join the network through the contending mode, but will switch to an active mode as soon as they have gained access to the channel. Having transmitted a data packet, the active node then select the next transmission station in accordance with a probability-based rule designed such that the AP receives a greater number of transmission opportunities than wireless stations. As a consequence, the throughput of downlink traffic is significantly improved. Moreover, when all wireless stations operate in active mode, no contention is needed and accordingly the collision can be avoided. The system throughput can be higher than the legacy contention-based methods.

The remainder of this paper is organized as follows. Section Ⅱ describes the background and related works, and our proposed Modified High-performance Distributed Coordination Function is introduced in section Ⅲ. Section Ⅳ validates our proposal through simulations and compares with some legacy solutions to downlink and uplink unfairness problem. Finally, Section Ⅴ presents some brief conclusions and future works.

Ⅱ.BACKGROUND AND RELATED WORK

2.1 High-performance Distributed Coordination Function

The MHDCF is the modified version of the high-performance distributed coordination function (HDCF) presented in [8] that was originally designed to achieve a high and more stable throughput, and simultaneously ensure a fair access to all the wireless stations. Therefore, before introducing the MHDCF, the HDCF has to be reviewed.

The HDCF is designed to solve the wasting time in contention resolution via classifying stations into active and contending ones. Each active station maintains an active list containing all the active stations that still have data frames to transmit. The transmitting station chooses randomly the next station to transmit from its own list of active users following a uniform distribution. In another word, each station in the active list has the same probability of being selected as the next transmission station. The selected station waits for an interval of one PIFS following the previous transmission and then sends out a packet of its own. Thus, in the active mode, all the stations are guaranteed to be contention free. In the contending mode, the HDCF protocol is identical with the original IEEE 802.11 distributed coordination function (DCF) protocol, i.e. the stations start transmitting as soon as the back-off and DIFS expire. However, fewer collisions occur in the HDCF protocol contending mode than in the original DCF protocol since only new transmission stations need to contend for the wireless channel. The new station can issue a jamming signal after the finish of the current active transmission plus one SIFS interval. Meantime, when the selected next transmission station detects a signal before the PIFS has elapsed, it stops its transmission to allow the new stations to contend for the channel access. If the idle time for the channel lasts for the duration of DIFS - SIFS plus back-off time, the new station can transmit its data frame. Furthermore, due to the channel errors or hidden terminal problem, the next selected station may not be able to start its transmission. In this case, all other active stations will switch back to DCF mode if they wait one more slot time after a PIFS period that is the operating gap between the active transmissions. Once the active transmissions are recovered, the active stations switch back to active mode again.

As a further exposition of the HDCF protocol, consider the example shown in Fig. 1. We assume that station A has three packets to transmit, station B has two packets to transmit, and station C has one packet to transmit. Initially, station A, station B, and station C use DCF to contend for channel access. Assuming that station B wins the contention, it transmits one packet, and adds itself to its active list. The packet sent by station B informs all the other stations in the network that station B still has packets to transmit. Moreover, the packet header indicates that the next transmission station is once again station B since no other stations currently exist in the active list. However, station A and station C subsequently interrupt station B by jamming for one slot SIFS after the ACK packet. Suppose that station A wins the contention. It waits for one slot and a random number of back-off (BO) slots, and then starts to transmit its first data frame and adds itself to its active list. Again, the station C interrupts the next transmission, sends out one packet, and informs all the other stations that it has no more data to transmit. Now the active list at each station contains station A and station B. Furthermore the packet header indicates that the next transmission station is station B, and so station B transmits PIFS after transmission of station C as no more stations are interrupting. Node B transmits while declaring that it has no more data and that station A is the next transmitter. In consequence, active list at all stations are updated to contain only station A. Station A transmits PIFS after the transmission of station B while declaring itself as the next transmitter, and it has more data to transmit. Finally, Station A transmits its last packet and then all three stations empty their active list.

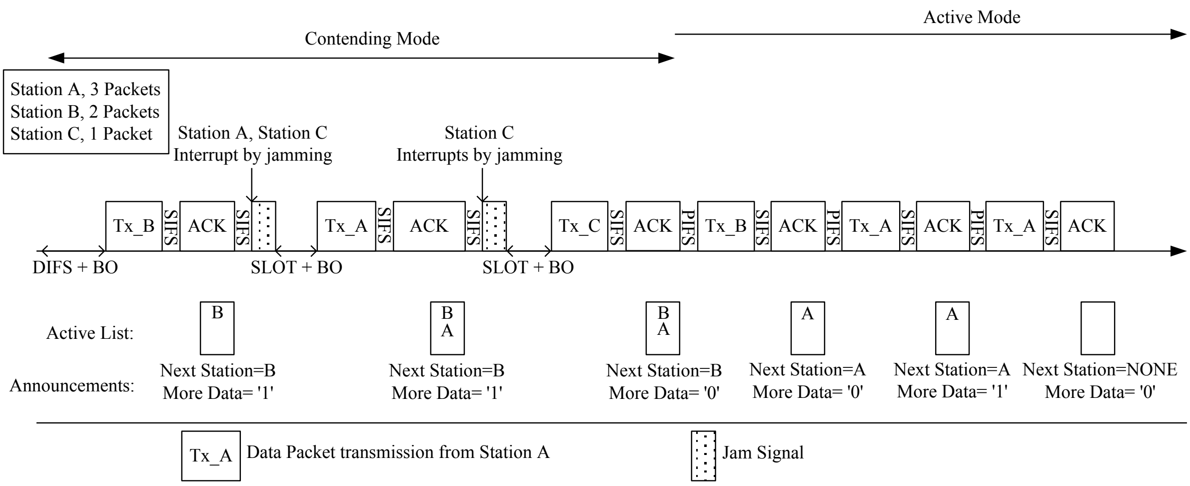

Fig. 1. An example of HDCF.

2.2 Other Methods for Solving Downlink and Uplink Unfairness Problem

The asymmetry problem makes the AP become a bottleneck in bi-direction communications. The delay of time-constraint applications such as VoIP, multimedia streaming may become unbearable. The delay may also incur acknowledgement timeout in some feedback based transport protocols like TCP and DCCP. The solutions to the asymmetric link problem in the MAC layer can be grouped into two types: time domain and frequency domain. In the time domain, the methods extend the transmission duration of the access point. The AP can then transmit more frames instead of only one frame each time the AP seizes the channel. The authors in [3] observe the number of downlink flows and number of transmitted frames during a TXOP. For example, if all wireless stations have *k* uplink flows and each flow needs to send *q* frames in a TXOP, the value of the TXOP in the AP should be adjusted as $k*q$ frames to get similar throughput to uplink flows. The operations of TXOP can be further illustrated in the following. Assume that there are one access point and two mobile stations. If an access point gets the right to access the channel, it can send two packets, but if a mobile station wins the channel access, it can only send one packet. For a long-term, the packets sent by access point and mobile station are very close. In [4], the authors measure the ratio between number of successful downlink and uplink transmissions and compare it with predefined utilization ratios. If the ratio is less than the predefined utilization ratio, the value of the TXOP is doubled to keep a similar throughput between downlink and uplink. The authors in [9] focus the delay balance instead of throughput between downlink and uplink. The authors measure the queue size in the access point (QAP) and other wireless stations (QNode) and allow the access point to transmit QAP/QNode packets using TXOP.

In frequency domain, the underlying concept is to provide the AP higher transmission probability than other stations when it contends for the channel access. Parameters such as size of contention window (cw) and Inter Frame Space (IFS) are often used to improve fairness and throughput. In [10], the authors adjust the parameters of Arbitration Inter-Frame Space (AIFS) and cw in 802.11e to improve fairness and throughput for voice traffic. In [11], the authors suppose that the access point use multiple independent backoff timers (MBT), each of which is combined with the downlink traffic flows for each client station. A packet in a given queue is transmitted when the backoff timer associated with that queue reaches zero. If the backoff times in two or more queues expire at the same time, a virtual collision resolution procedure is invoked and solved the inner collision.

These related works are all the contention-based methods for solving the downlink and uplink unfairness problem. Although these solutions can achieve the fairness, the performance of the total throughput is not good enough and can be improved.

Ⅲ. MODIFIED HIGH-PERFORMANCE COORDINATION FUNCTION

3.1 Selection-Rules

The MHDCF is the modified version of the high-performance distributed coordination function (HDCF) presented in [8] that was originally designed to achieve a high and more stable throughput, and simultaneously ensure a fair access to all the wireless stations.

The main difference between MHDCF and HDCF is the selection rule. In the HDCF protocol, each wireless station has an equal opportunity to be selected as the next transmission station while in the MHDCF protocol, the AP has always one half probability to transmit a packet. The remaining probability is equally shared by active wireless stations.

The selection rules are listed as follows:

Case 1: If both AP and MS have data packets to send.

- $P_{AP}=1/2$……Downlink (Probability of channel access for AP)
- ? $P_{MS}=1/2n$……Uplink (Probability of channel access for MS)

Case 2: If AP has no data packets to send.

- ? $P_{MS}=1/n$ ⋯ ⋯ Uplink (Probability of channel access for MS)

n : number of active mobile stations.

3.2 A Modified Exponential Increase Exponential Decrease Backoff Algorithm (MEIED)

The second difference between MHDCF and HDCF is that we adopts a modified exponential increase exponential decrease backoff algorithm (MEIED), which is based on [12], in the contending mode. When the channel error rate is high, transmission easily gets failure and all stations need to switch from active mode to contending mode. The performance of HDCF will be worse than DCF. Because in DCF, only the node of successful transmission will reset the contention window to CW_{min} while others keep their respective CW values. But in legacy HDCF mode, when one transmission succeeds and all stations switch back to active mode, the CW of all stations will be reset to CW_{min}. As a consequence, when the channel error rate is high and the number of contending stations is large, the stations have to spend more time getting larger CW to resolve contention. Furthermore, the difference between EIED and MEIED is that when the transmission is successful, all nodes with MHDCF will switch back to active mode. In active mode the current transmitting node can decide the next node and there will be no collision. Therefore, there is no need to use collision resolution. On the contrary, the EIED always use its backoff algorithm to resolve the collision regardless of successful or failed transmission.

So the MHDCF adopts a modified exponential increase exponential decrease backoff algorithm (MEIED) to solve this situation. The pseudo code is shown as follows:

```
if (counter = = N)
{
the CW of all stations are set to CWmin;
}
else
{
     if (successful transmission)
     {
         cw[i]/=2;
         if (cw[i]<cwmin)
              cw[i]=cwmin;
         all nodes switch back to active mode
         while keeping their respective CW
         values.
     }
     else if (failed transmission)
     {
          cw[i]*=2;
          if(cw[i]>cwmax)
               cw[i]= cwmax;
     }
}
```

When the transmission failed, all nodes switch back to contending mode. If the transmission consecutively fails, the participating node will double their corresponding CW values. If the transmission is successful, the participating node will halve its CW value and all nodes switch back to active mode while keeping their respective CW values. However, when there are N consecutive successful transmissions, the channel is assumed to get better or the number of contending stations is supposed to be less. Accordingly, the CW of all stations will be reset to CW_{min} to prevent large transmission delay.

3.3 An Illustrative Example

Consider the example shown in Fig. 2. Initially, station A, station B, and AP use DCF to contend for channel access. Assuming that station B wins the contention, it transmits one packet, and adds itself to its active list. The packet sent by station B informs all the other stations and AP in the network that station B still has packets to transmit. Furthermore, the packet header indicates that the next transmission station is once again station B since no other stations currently exist in the active list. However, station A and AP subsequently interrupt station B by jamming for one slot SIFS after the ACK packet. Suppose that station A wins the contention. It waits for one slot and a random number of back-off (BO) slots, and then starts to transmit its first data frame and adds itself to its active list. Again, the AP interrupts the next transmission, sends out one packet, and adds itself to its active list. After the AP and wireless stations are all in the active list, they don't need to contend for channel access. The AP gets 1/2 while station A or B gets 1/4 probability to be selected as the next transmitter.

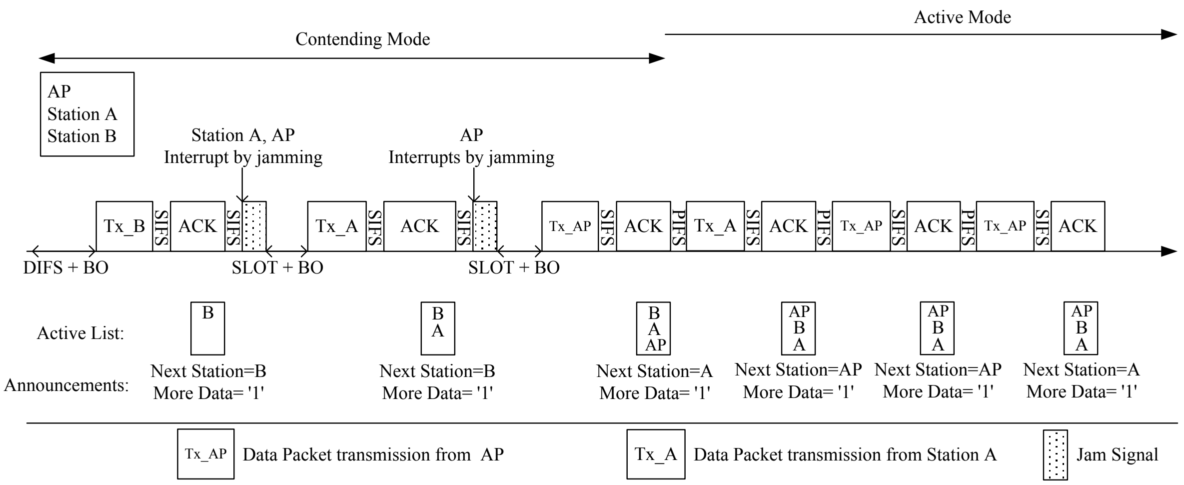

Fig. 2. An example of MHDCF.

As a consequence, in a long run the bandwidth can be equally shared by downlink and uplink traffic.

3.4 The Upper Bound of Throughput

If the contending period in the initial stage is ignored, and the channel is assumed to be error-free, the upper bound of throughput can be formulated as

$$S_{MHDCF} = \frac{E[L]}{PIFS + E[T_{data}] + SIFS + T_{ack}}$$

where E[L] is the average packet size, E[Tdata] is the average time needed to send one data packet, and Tack is the time needed to send an ACK. Comparing legacy contention-based solutions with the MHDCF, the MHDCF does not require a back-off interval when all wireless stations are in active mode, and therefore it has a higher throughput.

Ⅳ. SIMULATION RESULTS

This section commences by comparing the achievable saturation throughput of the proposed MHDCF protocol with the standard DCF, MBT [11], TXOP[3] and HDCF[8], and then compares the downlink and uplink throughput through simulations. Finally, we compare the normalized saturation throughput of DCF and MHDCF when the wireless channel is noisy. The simulation programs were written in C++. The simulation environment is an IEEE 802.11b infrastructure WLAN setup with basic access transmission. The parameter settings are shown in Table 1. The number of mobile stations was set from 10 to 50 with 5 intervals. To simplify the problem, suppose that the AP and wireless stations have always data packets to send.

Table 1. PHY and MAC parameters

Parameter	**Value**
Packet Payload（bytes）	1000
MAC Overhead	28 Bytes for DCF,MBT,TXOP※1 34 Bytes for HDCF,EHDCF※2
PLCP Overhead	192μs
MAC ACK Size	14Bytes
Slot time	20μs
SIFS	10μs
PIFS	30μs
DIFS	50μs
CW_{min}	32
CW_{max}	1024
Data Rate	11Mbps
Control Rate	1Mbps

※1 only the address 1, address 2 and address 3 are used.
※2 an overhead of 6 bytes is the next station's MAC address.

Fig. 3 presents the variation of the achievable saturation throughput with the number of active stations for the proposed MHDCF, DCF, MBT, TXOP and HDCF scheme. Here, we compare the normalized saturation throughput of MHDCF with DCF and MBT for 1000bytes as a function of the contending stations, which changes from 10 to 50. The gain ranges from 20% to 40%. Moreover, when we compare the normalized saturation throughput of MHDCF with TXOP, the gain goes from 10% to 20%. However, the simulated throughputs of MHDCF and HDCF are similar due to the same operations except the selection rule.

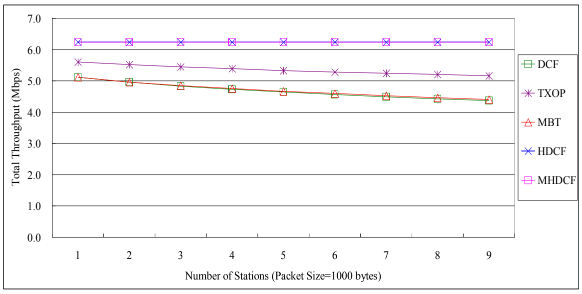

Fig. 3. The total throughput.

Subsequently, it is clearly shown that the number of stations has small effect on the performance of MHDCF. On the contrary, the performance of DCF, MBT and TXOP degrades as the number of station gets larger since the probability of collisions increases exponentially when the number of stations increases.

Also from Table 2, we can see that the switching time for all stations from contending mode to active mode is very short, i.e. shorter than 0.1 seconds. After switching to active mode, there is no contention and collision. Therefore, the throughput of MHDCF is better than other schemes and keeps stable no matter how many stations are in the same basic service set.

In Fig. 4, we compare the normalized saturation throughput of MHDCF, DCF, MBT, TXOP and HDCF as a function of packet size. Here, the number of contending stations is fixed at 50. Simulation results show that the normalized saturation of MHDCF is better than DCF and MBT by 22%, and better than TXOP by 13% when the packet size is 2000 bytes.

Table 2. The contention time of MHDCF (Unit：second)

Number of Stations \ Packet Sizes	1000 Bytes
10	0.014016
15	0.024483
20	0.035060
25	0.040309
30	0.056394
35	0.063801
40	0.076617
45	0.086545
50	0.094352

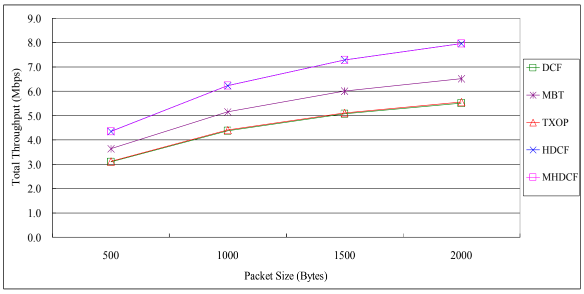

Fig. 4. The total throughput.
(contending stations = 50)

Fig. 5 shows the normalized saturation throughput for downlink and uplink traffic with different schemes. Firstly, the normalized saturation throughput for downlink traffic in standard DCF and HDCF without asymmetric link consideration obtain only around $1/(n+1)$ resources while the normalized saturation throughput for uplink traffic in standard DCF and HDCF can earn $n/(n+1)$ resources. This asymmetric bandwidth sharing makes a lot of difference between the downlink and uplink traffic. For example, the packet size is fixed at 1000bytes and the number of stations is fixed at 30 stations. Simulation results show that the normalized saturation throughput for uplink traffic of DCF and HDCF is about 96.7% and the normalized saturation throughput for downlink traffic of DCF and HDCF is about 3.3%. This simulation result is very closed to the above theory result. Therefore, due to this asymmetric bandwidth sharing, the DCF and HDCF schemes can not resolve the downlink and uplink unfairness problem.

Secondly, in contrast to the DCF and HDCF approach, the proposed MHDCF and the MBT, TXOP schemes share equally the channel resource by extending the transmission duration of the AP, or providing the AP higher transmission probability. When we compare the downlink and uplink normalized saturation throughput of the MBT and TXOP schemes, the results are similar and the performance is worse than the MHDCF. Because they are all contention-based solutions, the downlink and uplink performance degrades under larger network sizes and higher loads due to higher contention and higher collision rates.

Moreover, take a closer look at the Fig. 5, the throughput of downlink and uplink for the MHDCF scheme is better compared to the TXOP and MBT methods, since the MHDCF is contention-free in the active mode, and the throughput doesn't degrade as the number of station gets larger.

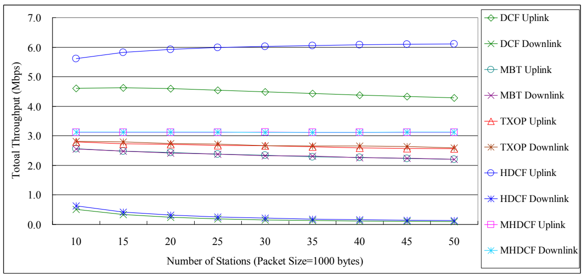

Fig. 5. The total throughput for the downlink and uplink traffic.

Fig. 6, Fig. 7 and Fig. 8 show the throughput of DCF, HDCF, and EHDCH with different N values when the wireless channel is noisy. The simulation environment is the same as Table 1 and the channel error rate are assumed to be 10^{-4}, 10^{-5}, and 10^{-6} respectively. In addition, the MHDCF (counter=N) is meant to be the throughput for MHDCF when N is the number of consecutive successful transmissions. In one special case for N=0, i.e. MHDCF (counter=0), means that MSETL is not adopted in MHDCF and the CW will be reset to CW_{min} for all stations each time when the working mode is changed from contending to active.

In Fig. 6, it is clearly shown that the throughputs of MHDCF (counter=0) and HDCF degrade more aggressively than that of DCF. In MHDCF (counter=0) and HDCF, when a transmission fails, all stations switch to contending mode and the CW are all set to CW_{min}. If one transmission (data and ack packet) is successfully finished, all stations switch back to active mode again. In contending mode of MHDCF (counter =0) or HDCF, all stations contend for channel access with the same initial vaule, i.e. CW_{min}. However in DCF, only the node that has successful transmission will set the contention window to CW_{min} while other stations keep their respective CW values. Therefore, when channel error is high and there are many stations contending for channel access, the MHDCF (counter =0) and HDCF will take longer time than DCF to resolve contention and that is the reason why the throughputs of MHDCF (counter=0) and HDCF is worse than that of DCF in 10^{-4} BER environment.

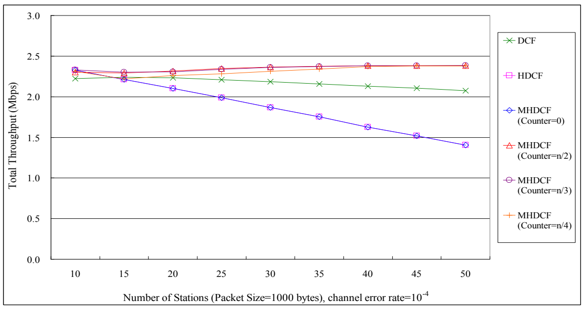

Fig. 6. The throughput for channel error 10^{-4}.

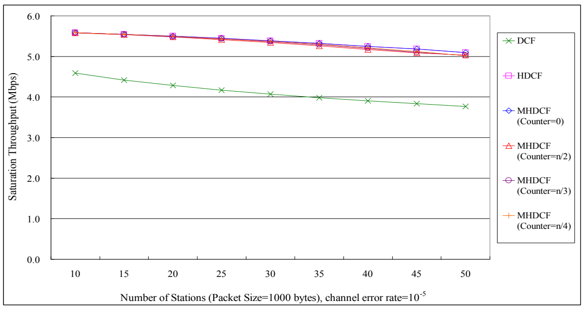

Fig. 7. The throughput for channel error 10^{-5}.

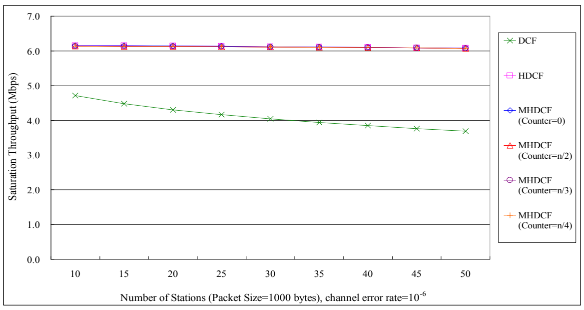

Fig. 8. The throughput for channel error 10^{-6}.

For this reason, the MSTEL backoff algorithm is adopted in MHDCF to solve this situation. The simulation results in Fig. 6 show that the total throughputs of MHDCF (counter=n/2), MHDCF (counter=n/3), and MHDCF (counter=n/4) are better than those of HDCF, MHDCF (counter=0) and DCF. That means that no matter what counter value is set, the results are similar and the performance will be better than DCF, HDCF and MHDCF (counter=0).

In Fig. 7 and Fig. 8, we compare the throughputs of MHDCF, HDCF and DCF when the channel error rate is 10^{-5}or 10^{-6}. Since the channel error rate is mild and the probability for a packet to be erroneous would be less than that of channel error rate 10^{-4}. As a result, the AP and mobile stations are mostly in active mode and can achieve better performance compared with that of DCF. And the difference among HDCF and MHDCF with different N values is small.

Ⅴ. CONCLUSIONS AND FUTURE WORKS

The Distributed Coordination Function (DCF) used in the infrastructure mode provides equal medium access to all transmitters, including AP and wireless stations. Consequently, the AP only gains approximately 1/(n+1) channel access probability to deliver downlink traffic while all the wireless stations can earn n/(n+1) access chance to upload the traffic with the assumption of n transmitting wireless stations in the same basic service set. This asymmetric bandwidth sharing makes the AP become the bottleneck and causes so-called downlink and uplink unfairness problem. Therefore, in this paper we propose a Modified High-performance Distributed Coordination Function (MHDCF), which is based on HDCF, to mitigate this downlink and uplink unfairness problem in an infrastructure WLAN, and to keep the total throughput high no matter how many stations are in WLANs at the same time. Unlike other contention-based resolutions for solving the asymmetric bandwidth sharing problems in an infrastructure WLAN, the proposed MHDCF uses a probability-based selection rule that makes the AP receive a greater number of transmission opportunities than wireless stations to be selected as the next transmitter to send out its packets. As a result, the throughput of downlink can be increased. The simulation results show that the MHDCF is a simple and efficient method to achieve fair bandwidth sharing for downlink and uplink traffic in an infrastructure WLAN. The results also show that the proposed MHDCF can obtain higher throughput than legacy contention-based solutions no matter how many stations in the same basic service set.

Furthermore, when the channel error rate is high, e.g. 10^{-4} BER (bit error rate) and there are a lot of contending stations, the throughput of HDCF degrades aggressively. Accordingly, the MHDCF has to be different from HDCF in the contending mode. It adopts a modified exponential increase exponential decrease backoff algorithm (MEIED) to resolve this problem. MEIED will not reset the contention window (CW) to CW_{min} until there are N consecutive successful transmissions. Results show that the MHDCF can mitigate the throughput degradation problem even when the channel error rate is high and there are a lot of contending stations.

Future works will include the considerations of the STA working in the power saving mode, flow fair sharing with asymmetric traffic and multi-rate WLAN for the design of the proposed MHDCF scheme and develop a mathematical formula to model the MHDCF downlink and uplink throughput.

REFERENCES

[1] IEEE stand for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, ISO/IEC 802-11:1999(E), 1999.
[2] Gao, D., Cai, J., Foh, C. H., Lau, C. T., and Ngan, K. N., “Improving WLAN VoIP Capacity Through Service Differentiation,” IEEE Transactions on Vehicular Technology, vol. 57, issue 1, pp. 465-474, 2008.
[3] Freitag, J., Fonseca, N. L. S. da, and Rezende, J. F. de, “Tuning of 802.11e network parameters,” IEEE Communications Letters, vol. 10, no.8, pp.611-613, 2006.

[4] Keceli, F., Inan, I., and Ayanoglu, E., "Weighted Fair Uplink/Downlink Access Provisioning in IEEE 802.11e WLANs," IEEE International Conference on Communications ICC'08, pp. 2473-2479, 2008.
[5] Abeysekera, B. A. H. S., Matsuda, T., and Takine, T., "Dynamic Contention Window Control Mechanism to Achieve Fairness between Uplink and Downlink Flows in IEEE 802.11 Wireless LANs," IEEE Transactions on Wireless Communications, vol. 7, issue 9, pp. 3517-3525, 2008.
[6] Lopez-Aguilera, E., Heusse, M., Grunenberger, Y., Rousseau, F., Duda, A., and Casademont, J., "An Asymmetric Access Point for Solving the Unfairness Problem in WLANs," IEEE Transactions on Mobile Computing, vol. 7, no. 10, pp. 1213-1227, 2008.
[7] Kim, S. W., Kim, B. S., and Fang, Y., "Downlink and Uplink Resource Allocation in IEEE 802.11 Wireless LANs," IEEE Transactions on Vehicular Technology, vol. 54, no. 1, pp. 320-327, 2005.
[8] Al-Mefleh, H. and Chang, J. M.,"High Performance Distributed Coordination Function for Wireless LANs," Proceedings of IFIP Networking, Singapore, 2008.
[9] Shin, S. and Schulzrinne, H., "Balancing Uplink and Downlink Delay of VoIP Traffic in WLANs using Adaptive Priority Control (APC)," The Third International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, 2006.
[10] Casetti, C. and Chiasserini, C. F., "Improving fairness and throughput for voice traffic in 802.11e EDCA," 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, vol. 1, pp. 525-530, 2004.
[11] Siwamogsatham, S., "Achieving Uplink / Downlink Fairness in WLANs via Multiple Backoff Timers," The International Conference on Advanced Communication Technology, ICACT 2008, pp. 1794-1797, 2008.
[12] Song, N., Kwak, B., Song, J., and Miller, L. E., "Enhancement of IEEE 802.11 distributed coordination function with exponential increase exponential decrease backoff algorithm," The 57th IEEE Semiannual Spring VTC, vol. 4, 2003.