Inter-Frame Space (IFS)-based Distributed Fair Queuing in IEEE 802.11 WLANs

Jeng Farn Lee^{1,3}, Wanjiun Liao^{1,2}, and Meng Chang Chen³

¹*Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan*

²*Graduate Institute of Communication Engineering, National Taiwan University, Taipei, Taiwan*

³*Institute of Information Science, Academia Sinica, Taipei, Taiwan*

E-mail: wjliao@ntu.edu.tw

Abstract- In this paper, we study fair queuing in the MAC layer of IEEE 802.11 with the Distributed Coordination Function (DCF). In particular, we propose an IFS-based Distributed Fair Queuing (IDFQ) mechanism to provide differentiated service in conformance with the 802.11 standard. IDFQ is designed to emulate Self-Clocked Fair Queuing (SCFQ) in a distributed manner. There is no backoff in IDFQ. Thus, it provides better stability and improved aggregate throughput, as compared to existing work. Simulation results show that IDFQ supports differentiated service for different flows in proportion to their weights. More importantly, it outperforms existing solutions in terms of fairness and stability, rendering IDFQ an excellent candidate to provide weighted fairness for IEEE 802.11 WLANs.

Keywords: distributed fair queuing, IEEE 802.11 WLANs

I. INTRODUCTION

IEEE 802.11 Wireless Local Area Network (WLAN) with the Distributed Coordination Function (DCF) [1] is the dominant wireless medium to access the Internet. In DCF, mobile stations contend for channel access. All stations operate independently and share the channel bandwidth equally. Since DCF provides best effort service only, the natural evolution is to provide differentiated service for traffic of different demands. There are many proposals to provide service differentiation for wireless LANs, but most are based on static priority assignment [2-4]. The typical approach is to tune one of three 802.11 MAC parameters to enable priority-based service: Contention Window (CW), Backoff Interval (BI), and Inter-Frame Space (IFS). The higher priority traffic is then assigned a smaller parameter value so as to reduce the waiting time in channel access. These fixed priority protocols, however, may starve low priority traffic. To solve this problem, fair queuing is required [5].

With fair queuing, different flows contending for a shared link can be allocated bandwidth in proportion to

their “weights.” The typical approach of fair queuing is to emulate the Generalized Processor Sharing (GPS) service discipline [6]. GPS is a fluid system in which the traffic is infinitely divisible and all traffic streams can receive service simultaneously. In GPS, every flow i is assigned a positive real number ϕ_i , which indicates its weight of sharing the channel capacity. Let $W_{i,GPS}(t_1, t_2)$ denote the amount of workload received by flow i in time interval $[t_1, t_2]$. A GPS server guarantees the following equation for each flow that is continuously backlogged over the interval $[t_1, t_2]$.

$$\frac{W_{i,GPS}(t_1, t_2)}{W_{j,GPS}(t_1, t_2)} \geq \frac{\phi_i}{\phi_j} \quad i, j=1, 2, \dots, n \quad (1)$$

A flow is *backlogged* if it has packets waiting for transmission in the queue or its packet is transmitting. Let $B(t)$ denote the set of the backlogged flows at time t , and C is the link capacity. The service rate $r_{GPS_i}(t)$ received by each backlogged flow i at time t is then expressed as follows.

$$r_{GPS_i}(t) = \frac{\phi_i}{\sum_{j \in B(t)} \phi_j} C \quad (2)$$

The challenge of providing fair queuing in WLANs is in that service provisioning must be fully distributed. This renders existing centralized mechanisms (e.g., [7] for wired networks and [8] for wireless networks in which base stations are involved) inappropriate. There have been many scheduling disciplines proposed for weighted fairness in the link or MAC layer of IEEE 802.11, including Distributed Fair Queuing (DFS) [9], Priority-based fair Medium Access Control (P-MAC) [10], and Distributed Deficit Round Robin (DDRR) [11]. Their typical approach is applying fair queuing to one of the three 802.11 MAC parameters (i.e., BI, CW, and IFS). In what follows, we first review 802.11 DCF and describe the related work. We then state the problem to be solved in this paper.

A. Distributed Coordination Function (DCF) in 802.11

IEEE 802.11 DCF is based on Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA), similar to CSMA/CD for Ethernet but introducing the “inter frame space” (IFS) and a backoff interval to avoid collisions. Each mobile station wishing to transmit monitors the wireless channel. When the channel becomes idle, the station waits for a period of DCF IFS (DIFS) and a backoff process before a transmission. If the channel is still free, the station begins transmission; otherwise, the transmission is deferred.

Once the mobile station enters the backoff process, a Backoff Interval (BI), uniformly distributed in the interval $[0, CW]$, where CW (i.e., Contention Window) falls between the minimum ($CW_{\min}$) and maximum ($CW_{\max}$) contention windows, is selected. The backoff interval is decremented by one after each time slot over an idle medium. When the channel is busy, the backoff process is frozen, and resumed after the channel is idle again. Eventually, when the backoff counter reaches zero, the station starts transmission. A collision occurs if more than one mobile station transmits at the same slot. In this case, the CW s of the collided stations are doubled until $CW_{\max}$ is reached. CW is reset to $CW_{\min}$ after each successful transmission.

B. Related Work on Weighted Fair Scheduling in 802.11

1) DFS

DFS is designed to emulate Self-Clocked Fair Queuing (SCFQ) [7] in a distributed manner. In SCFQ, a virtual clock is maintained by the central coordinator in the system. Let $v(t)$ denote the virtual clock at real time t , P_i^k be the k^{th} packet of flow i , and A_i^k be the real arrival time of P_i^k . Let L_i^k denote the packet size of P_i^k and ϕ_i the assigned weight of flow i . A start tag S_i^k and a finish tag F_i^k are associated with each packet P_i^k , given by

$$\begin{aligned} S_i^k &= \max\{v(A_i^k), F_i^{k-1}\} \\ F_i^k &= S_i^k + \frac{L_i^k}{\phi_i} \end{aligned} \quad (3)$$

The system virtual clock is set to 0 initially, and is updated to the finish tag of the packet transmitted on the output link. In SCFQ, packets are transmitted in increasing order of the finish tags. Ties are broken arbitrarily.

To emulate SCFQ in which the frame with the smallest finish tag is transmitted first, each transmitted frame in DFS is stamped with a finish tag, based on which the BI for each competing mobile station is then chosen. The backoff interval BI_i for each mobile

station i is expressed as follows.

$$BI_i = \left\lceil \left\lfloor \text{Scaling_Factor} \times \frac{L_i}{\phi_i} \right\rfloor \times \rho \right\rceil \quad (4),$$

where L_i is the head of line frame size, ϕ_i is the assigned weight of mobile station i , and ρ is a random variable uniformly distributed in $[0.9, 1.1]$ to prevent collisions. In (4), the ratio between L_i and ϕ_i here is from the finish tag in (3), and the scaling factor allows the choice of an appropriate scale for the virtual time in DFS. DFS, however, requires a complicated backoff interval mapping scheme to improve its throughput performance as the duration of the backoff interval is inversely proportional to the weight of a station. This mapping scheme may cause many BI_i to be mapped to the same value, resulting in more collisions. Worse, the backoff process itself introduces randomness, causing throughput and delay variability.

2) P-MAC

In P-MAC, the weighted fairness is achieved by adjusting the contention window (CW) of each station j as follows:

$$CW_j = \frac{CW_1 - 1}{\phi_j} + 1, \quad (5)$$

where CW_j and ϕ_j are the CW and the weight of mobile stations of class j , respectively, assuming the weights of all mobile stations of class 1 are 1. CW_1 is an optimal value properly selected to reflect the number of stations contending for the wireless medium such that P-MAC can maximize the aggregate throughput. P-MAC, however, suffers from high variance of throughput and delay as it also uses backoff to avoid collisions.

3) DDDR

DDRR is based on Deficit Round Robin (DRR) [12] to translate user requirements into the IFS parameter of 802.11 MAC. Each mobile station i is allocated a service quantum Q bits every T_i seconds such that Q/T_i is the desired throughput. The Deficit Counter (DC) of each station i (denoted as DC_i) is increased at a rate of Q bits every T_i seconds, and is decreased by the size of the frame when a frame is transmitted. The deficit counter value is then mapped to an appropriate IFS value at each station. At time t , the IFS for mobile station i is calculated as:

$$IFS_i = DIFS - \alpha \frac{DC_i(t)}{Q} * \text{random}(1.0, \beta) \quad (6)$$

where α is a scaling factor to ensure IFS_i fall between PIFS and DIFS, and β is a number larger than 1. In DDDR, no backoff algorithm as in DFS and P-MAC is employed. Collisions are avoided by using a random number between 1 and β . Thus, it eliminates the throughput and delay variability suffered by DFS

and P-MAC. DRRR, however, has a potential fairness problem. This happens when a station which has accumulated a high DC value (due to transmitting at a rate lower than the desired throughput) starts transmission at a high rate. As a result, the system may fail to provide the required service to other stations. Moreover, when the deficit counters of all stations become zero, the stations will share the link equally. This further degrades the fairness among flows. Improper settings of parameters may also cause performance problem with DRRR.

C. Problem Specification

In this paper, we study fair queuing in the MAC layer for IEEE 802.11 WLANs with DCF. In particular, we propose an IFS-based Distributed Fair Queuing (IDFQ) mechanism for providing differentiated service in conformance with the 802.11 standard. To emulate SCFQ [7] in a distributed manner, each head of line frame is stamped with a finish tag. The QoS metrics translated from user requirements are then mapped to the IFS of 802.11 DCF. A smaller finish tag is mapped to a smaller IFS value, and thus the frame with the smallest tag is transmitted first. There is no backoff mechanism in IDFQ, and hence no throughput fluctuation problem as in DFS and P-MAC. The collisions are avoided by randomizing each IFS. Moreover, the proposed mechanism eliminates the requirement of backoff mapping schemes as in DFS. The aggregate throughput is improved by better design of IFS. Finally, IDFQ is designed to be a scale mechanism, thus it works efficiently even in a wireless network with many nodes.

The rest of the paper is organized as follows. In Sec. II, the proposed mechanism for distributed fair queuing in 802.11 MAC is described. In Sec. III, the performance of the proposed IDFQ is compared with the existing distributed fair queuing disciplines for 802.11 via the ns-2 simulator. Finally, the paper is concluded in Sec. IV.

II. IDFQ: AN IFS-BASED DISTRIBUTED FAIR

QUEUEING MECHANISM IN IEEE 802.11 WLAN

In this section, we describe the proposed IFS-based Distributed Fair Queuing (IDFQ) for IEEE 802.11 MAC. IDFQ chooses an appropriate IFS value in proportion to the finish tag of the head-of-line frame. Note that the description of IDFQ in this paper is based on the parameters of 802.11b. It can be easily extended to other 802.11 variations (e.g., 802.11a/g).

In IDFQ, each station i maintains a local virtual clock $v_i(t)$ as a function of real time t , where $v_i(0) = 0$. Each transmitted frame is stamped with a finish tag. The calculation of the tag is also based on (3), except that the tag is calculated when the frame is at the head of line, instead of at the arrival time to the system.

The virtual clock is updated when station i transmits or hears¹ a data or ACK frame with finish tag F , say, at time t , and $v_i(t) = \max\{v_i(t), F\}$. As such, the virtual clock is ensured to grow monotonically as frames with larger finish tags may be transmitted before those with smallest finish tag due to randomization adopted in IDFQ described below. Note that since all mobile stations are associated with the same access point, their local virtual clocks should be equal. Therefore, the global clock in the system can be maintained.

The finish tag is then mapped to the IFS parameter of 802.11. A smaller finish tag is mapped to a smaller IFS value, so that the frame with the smallest tag could be transmitted first due to the smallest waiting time. To be compatible with the 802.11 MAC protocol, IFS is maintained in a range between PIFS (e.g., 30us in 802.11b) and DIFS (50us in 802.11b). Let F_i be the finish tag of the head of line frame for mobile station i , $L_{\max}$ and $\phi_{\min}$ be the maximum frame size and minimum weight in the system, respectively. The IFS of mobile station i is expressed as

$$IFS_i = \begin{cases} 40(\mu s) + \frac{\text{random}(0,1)}{\alpha} \times \beta, & F_i - v_i(t) = 0 \\ 40(\mu s) + \frac{F_i - v_i(t)}{\alpha} \times \beta, & \text{otherwise} \end{cases} \quad (7)$$

where $\alpha = L_{\max} / \phi_{\min}$, which is the maximum value of $F_i - v_i(t)$; the positive random number β is introduced to prevent collisions. In Theorem 1, we will show that if β is uniformly distributed over the interval $[0, 10]$, IFS_i is bounded between PIFS and DIFS.

Note that while the frame with the smallest finish tag is usually transmitted when the network is ready for service, a frame with a larger finish tag may be transmitted earlier as we use a random factor β to avoid collision in the distributed environment. When this happens, the value of $F_i - v_i(t)$ may be less than 0. We will show below that even so, the value of $|F_i - v_i(t)|$ is less than or equal to α . Consequently, $(F_i - v_i(t)) / \alpha$ stays between -1 and 1; thus the value of IFS is bounded between PIFS and DIFS, ensuring IDFQ is backwards compatible with IEEE 802.11.

Lemma 1: If $F_i - v_i(t) \geq 0$, then $F_i - v_i(t) \leq \frac{L_{\max}}{\phi_{\min}}$.

Proof:

Let t_i be the time when the frame of mobile station i reaches the head of queue and let L_i be the frame size; thus F_i is equal to $v_i(t_i) + L_i / \phi_i$ at t_i according

¹ The access point or mobile stations will attach the finish tag of the received frame on the ACK frame to help to maintain the system virtual clock.

to (3), and

$$F_i - v_i(t_i) = v_i(t_i) + \frac{L_i}{\phi_i} - v_i(t_i) = \frac{L_i}{\phi_i} \quad (8)$$

Let t' denote the time that the system is ready for transmitting the next frame after t_i . Since the virtual clock grows non-decreasingly, we have $v_i(t') \geq v_i(t_i)$. Thus, the value of $F_i - v_i(t)$ after t_i is:

$$\begin{aligned} F_i &= v_i(t_i) + \frac{L_i}{\phi_i} - v_i(t') \\ &\leq v_i(t_i) + \frac{L_i}{\phi_i} - v_i(t_i) \\ &= \frac{L_i}{\phi_i} \end{aligned} \quad (9)$$

Therefore, if $F_i - v_i(t) \geq 0$, the maximum value of $F_i - v_i(t)$ is $L_{\max} / \phi_{\min}$.

Lemma 2: If $F_i - v_i(t) < 0$, then $v_i(t) - F_i \leq \frac{L_{\max}}{\phi_{\min}}$.

Proof: Let P_i be the head of line frame of station i . $F_i - v_i(t) < 0$ because DIFS uses β to avoid collisions and thus the head of line frame P_i with finish tag F_i is transmitted after another frame, say, P_j with a larger finish tag F_j . As a result, $v_i(t)$, which is the finish tag of station j after P_j is transmitted, will be larger than F_i . Therefore, we would like to obtain the maximum value of $F_j - F_i$ that satisfies:

$$\begin{cases} \frac{F_i - v_i(t)}{\alpha} \times \beta_1 > \frac{F_j - v_i(t)}{\alpha} \times \beta_2 \\ F_i < F_j \end{cases} \quad (10)$$

$$F_i < F_j \quad (11)$$

Since $F_j - F_i$ has the maximum value when $\beta_1 \geq \beta_2$, from (10), we have

$$\begin{aligned} \frac{F_i - v_i(t)}{\alpha} \times \beta_1 &> \frac{F_j - v_i(t)}{\alpha} \times \beta_2 \\ \Rightarrow (F_i - v_i(t)) &> \frac{\beta_2}{\beta_1} (F_j - v_i(t)) \end{aligned} \quad (12)$$

From (11) and (12), we have

$$F_j - v_i(t) > (F_i - v_i(t)) > \frac{\beta_2}{\beta_1} (F_j - v_i(t)) \quad (13)$$

Subtracted $F_j - v_i(t)$ on the both sides of (13) and according to Lemma 1, we have

$$\begin{aligned} 0 < F_j - F_i &< \frac{\beta_1 - \beta_2}{\beta_1} (F_j - v_i(t)) \\ &\leq \frac{\beta_1 - \beta_2}{\beta_1} \frac{L_{\max}}{\phi_{\min}} \leq \frac{L_{\max}}{\phi_{\min}} \end{aligned} \quad (14)$$

Consequently, if $F_i - v_i(t) < 0$, the maximum value of

$$v_i(t) - F_i \text{ is } \frac{L_{\max}}{\phi_{\min}}. \blacksquare$$

Theorem 1: The value of IFS_i for each station i in IDFQ is bounded by PIFS and DIFS.

Proof: The value of $|F_i - v_i(t)|$ is less than or equal to $L_{\max} / \phi_{\min}$ according to Lemmas 1 and 2. Thus, $(F_i - v_i(t)) / \alpha$ is between -1 and 1, and then IFS_i varies between PIFS and DIFS if β is uniformly distributed over the interval $[0, 10]$. The value of IFS_i bounded by PIFS and DIFS ensures that IDFQ is backwards compatible to IEEE 802.11. $\square$

Fig. 1 shows the overall process of the successful transmission of a single frame in IDFQ chronologically. The total transmission time is comprised of the frame transmission time t_{tr} , the header transmission time t_{pr} , the MAC ACK transmission time t_{ack} , and a constant overhead t_{ov} , which is the sum of an IFS_i , an SIFS, and the Physical Layer Convergence Protocol (PLCP) preamble. The goodput of IDFQ is then

$$\frac{t_{tr}}{IFS_i + 2t_{pr} + t_{tr} + SIFS + t_{ack}} \times \frac{L}{L + D} \times C \quad (15)$$

where C is the link rate, L is the data size, and D is the MAC header of the frame. For example, if the average IFS_i value is $40\mu s$, and $t_{pr} = 192\mu s$ (i.e., long PLCP preamble). IDFQ over an 11Mbps radio channel and with a data size of 1520 bytes can achieve the theoretical aggregate throughput of 7.722 Mbps.

Figure 1. Successful transmission of a single frame

Note that while the value of IFS_i , bounded by PIFS and DIFS, ensures IDFQ to be backwards compatible to IEEE 802.11, the limited range limits the number of nodes supportable by the system because the time granularity is determined by the physical layer implementation that is equal to the minimum carrier sensing time period plus the transmission/receiving turnaround time period. If the range of IFS_i is set to a very large value, the channel might be idle for a long time before a station begins to transmit. The tradeoff in selecting the ranges of IFS_i is the fundamental problem for IFS-based mechanisms to provide service differentiation.

III. PERFORMANCE EVALUATION

In this section, we conduct simulations based on ns-2 [13] to evaluate the performance of four different fair

queuing mechanisms at the MAC layer for IEEE 802.11 WLANs, including DRRR, DFS, P-MAC, and IDFQ. Fig. 2 gives the simulation topology. The wireless link rate is 11Mbps, and the link capacity between the AP and the router is set to 100Mbps. Each mobile sender generates CBR UDP traffic at a rate of 8Mbps to the corresponding receiver in the wired network. The packet including the IP header is 1520 bytes in length. There are 5 mobile senders with weights 1:1:2:4:4, corresponding to S1, S2, S3, S4, and S5, respectively. Note that when DRRR is used, the target rates of the mobile senders are set to 0.5Mbps, 0.5Mbps, 1Mbps, 2Mbps, and 2Mbps for S1, S2, S3, S4, and S5, respectively.

Figure 2. Simulation topology

The performance metrics to be measured are the fairness and stability. The fairness is measured with respect to the fairness index FI defined in [10]. Let R_i and ϕ_i be the throughput and the weight of flow i . Thus,

$$FI = \frac{\mu\left(\frac{R_i}{\phi_i}\right)}{\mu\left(\frac{R_i}{\phi_i}\right) + \sigma\left(\frac{R_i}{\phi_i}\right)} \quad (16)$$

where μ and σ are the mean and the standard deviation of R_i / ϕ_i over all data flows. The fairness index is a real value between 0 and 1. The closer to 1 the fairness index, the fairer. The stability is defined as the fluctuation degree of the throughput of each flow in a scheduling discipline.

We first compare the fairness of different scheduling disciplines. Fig. 3 shows the throughput and fairness of each flow for each scheduling discipline. We see that all four mechanisms provide service differentiation for flows with different weights. Of these four mechanisms, IDFQ provides the best stability and fairness (i.e., 0.999). DRRR has the worst fairness index (i.e., 0.836), due to all stations sharing the link equally when their deficit counters become zero. IDFQ also works well with different frame sizes. Fig. 4 shows that when the frame size is uniformly distributed from 64 to 1500 bytes, the fairness index of IDFQ is still as high as 0.999.

Additionally, in another simulation, we set the weights of all mobile stations equal, and plot the results in Fig. 5. All four mechanisms improve the stability of

the original IEEE 802.11b. Besides, scheduling disciplines based on backoff mechanisms such as P-MAC and DFS cause more fluctuations in throughputs among flows. Typically, the backoff mechanism selects a random backoff interval from a uniform distribution over the interval $[0, CW]$ to avoid collisions, which results in a larger variance in the values of backoff intervals than IFS-based mechanisms. Thus, DRRR and IDFQ both provide more stable services to the system. IDFQ behaves more stably than DRRR.

(a) DRRR ($FI = 0.836$)

(b) DFS ($FI = 0.965$)

(c) P-MAC ($FI = 0.905$)

(d) IDFQ ($FI = 0.999$)

(c) DRR

Figure 3. The throughput and fairness index of four schemes.

Figure 4. IDFQ with different frame sizes

(a) The original IEEE 802.11b

(d) DFS

(e) P-MAC

Figure 5. The stability of different MAC mechanisms

(b) IDFQ

(a) DRR

(b) IDFQ

(c) DFS

(d) P-MAC

Figure 6. Throughputs when sending rates change.

We then compare the robustness of the four mechanisms with respect to network load changes. Fig. 6 shows the simulation results that when S3 changes its sending rate from 8Mbps to 0.5Mbps at time 17 and 0.5Mbps to 6Mbps at time 23. Fig. 6(a) shows that stations S1 and S2 fail to receive their desired service share when DRR is used since DRR maintains the deficit count locally and does not have a global clock in the system. Figs. 6(c) and 6(d) depict that DFS and P-MAC can only provide fair service to a limited extent (with some fluctuations in each curve). Fig. 6(b) shows that with IDFQ, all stations share the link capacity according to their weights with excellent fairness and stability. Thus, IDFQ is most robust to network load

changes among these four schemes.

Finally, we study the performance anomaly in 802.11 reported by Heusse et al. in [14]. The performance anomaly occurs when some mobile stations operate at lower rates than others due to signal fading and interference, and the throughputs of all stations are considerably degraded. For example, if a mobile station transmits at 2Mbps, the throughput of all stations in the system will degrade to 2Mbps. This anomaly results from the fact that 802.11 DCF guarantees an equal access probability for all stations in the long term. Consequently, when one station operates at a lower bit rate, it tends to capture the channel for a longer time. This behavior causes stations with higher rates to transmit at a lower rate, which is undesirable in practice. This anomaly can be remedied if we provide a weighted fair service discipline in the system and set the weight of mobile stations according to their bit rates. Fig. 7 plots the simulation result with the setting that S1 operates at a rate of 2Mbps, and the others at a rate of 11Mbps. We see that the original 802.11 DCF does suffer from the performance anomaly, while the proposed IDFQ is immune to this problem, and still provides each flow its demand.

(a) 802.11b DCF

(b) IDFQ

Figure 7. Throughput of flows when sending rates of stations are different

IV. CONCLUSION

In this paper, we have proposed an IFS-based Distributed Fair Queuing (IDFQ) mechanism for IEEE 802.11 WLANs. Unlike existing work based on backoff intervals for collision resolutions, the proposed mechanism chooses appropriate IFS values for flows with different weights, and applies some randomization to avoid collisions. Thus, there are no backoff intervals, and thus no throughput variability but improved aggregate throughput. We compare IDFQ with several existing distributed service disciplines through simulations. The results show that the proposed mechanism outperforms other service disciplines significantly in terms of fairness, stability, scalability, and aggregate throughput. More importantly, it is compatible with the IEEE 802.11 Standard.

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