A New per-Class Flow Fixed Proportional Differentiated Service for Multi-Service Wireless LAN*

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Abstract. In this paper, we propose a new per-CLAss Flow fixed proportional differentiated service model (CLAF) and a companion medium access control scheme for multi-service wireless LANs (WLANs). The scheme is based on the IEEE 802.11 framework. Different from conventional relative differentiated service, in CLAF, a fixed bandwidth quality ratio is guaranteed on per-class per-flow basis regardless of the traffic load of each service class. Specifically, each service class is assigned a number of separate coordination periods, proportional to the policy-based bandwidth quality ratio for class isolation. Each class is associated with its own contention window size which is dynamically adjusted in accordance with the number of flows in the class in such a way to minimize collision probability between flows of the same class. Simulations results of the CLAF performance as well as a comparison with IEEE 802.11e EDCF including the support of QoS-sensitive VoIP applications are presented. The results show that the proposed scheme outperforms EDCF and achieves better resource utilization efficiency. It can provide users a more predictive, affirmative service guarantees than conventional relative differentiated service like IEEE 802.11e EDCF.

1 Introduction

Wireless LANs (WLANs) are gaining significantly in popularity and being deployed at a rapid rate. The beauty of WLANs is that they are scalable with low entry cost. As IEEE 802.11–based WLAN penetrates further, its Quality of Service (QoS) support for multimedia applications such as VoIP and video streaming is important and critical to the success of wireless communications, especially to produce profitable business. In the past, several QoS mechanisms based on the IEEE 802.11 wireless LAN framework have been proposed. Most of them base their methods on tuning three different parameters: *a*) duration of the Interframe Space (IFS)[1][2][3][4]; *b*) length of the contention window (CW)[1][2][5][6][7][8]); and *c*) length of the backoff timer [3][9] to provide service differentiation among different service classes. The

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IEEE 802.11e EDCF [1] is an example that combines the first two approaches. The scheme provides a simple "*relative*" differentiation of bandwidth sharing between classes. The problems with such distributed priority-based approach are two folds. First, the channel bandwidth sharing ratio between classes is a function of total channel load and the number of active wireless stations in the network. Second, there is no traffic regulation and performance guarantees to flows within the same class. Third, the lower classes can experience starvation effects if no restriction is placed on the load of higher classes.

Schemes [4][7][9] were also proposed to provide proportional channel bandwidth sharing between multiple service classes. Better than 802.11e EDCF, these schemes have the merit of preventing lower priority traffic from access starvation. But in all these schemes, the contention probability increases as more flows requesting the same class of service. Other related works include some relative differentiated service models proposed for wired networks, such as strict prioritization[10], price differentiation[11] and capacity differentiation[12][13][14]. As illustrated in [15], relative differentiated service can not provide consistent service differentiation, because resource allocated to each service class does not reflect actual class load variation.

In this paper, we propose a new service mode called *per-CLAss Flow fixed proportional differentiated service model* (CLAF) and its wireless medium access control scheme. Different from conventional relative differentiated service model [10][11][12][13][14], CLAF provides a fixed proportion on the bandwidth sharing between multi-class flows. Here, a *flow* is a unidirectional sequence of packets uniquely identified by the IP addresses and port numbers of the source and destination stations, as well as the IP protocol type. For example, suppose there are two service classes. Class 1 has one flow and Class 2 has two flows. In the case that the per-class flow bandwidth quality ratio policy is 2:1, according to the CLAF service model, the Class 1 flow will receive 1/2 of the channel capacity and each Class 2 flow will receive 1/4 of the channel capacity. The bandwidth share ratio of Class 1 flow and Class 2 flow is 2:1.

The proposed medium access control scheme for CLAF complies with the IEEE 802.11 framework. To achieve per-class flow fixed bandwidth share proportion in a multi-service wireless LANs, *separate* number of coordination periods are allocated to different service classes to achieve class isolation in channel access. Second, the number of coordination period allotted to a service class is proportional to the class's bandwidth share defined in the policy-specified bandwidth quality ratio. During the coordination period, both upstream and downstream flows of the same class contend for packet transmission. Third, each service class is associated with a different class contention window size whose value is adaptive to the number of flows in the class. Distributed flows of the same class will follow the baseline CSMA/CA protocol to resolve contention. Under the scheme, flows of different service classes access the wireless channel in a distributed, coordinated way. The advantages of CLAF include class isolation, prevention of lower priority traffic from access starvation, and the adaptation of channel resource allocation to different service classes based on their actual traffic load.

A common problem with the IEEE 802.11 CSMA/CA-based medium access control scheme is that the scheme does not provide access point (AP) the capability in channel access that reflects the traffic load at the AP. This is especially crucial for many APs serving as Internet gateways as well as for networks with asymmetric uplink and downlink traffic pattern. In these environments, AP usually carries many more downlink flows than any other wireless station. It often results inefficient resource utilization and low overall channel throughput. In our proposed per-class flow fixed proportional differentiated service, this problem is resolved by allocating channel resources on per-class, per-flow basis. Moreover, such allocation is in accordance with the actual number of flows in the network.

The paper is organized as follows. In Section 2, the proposed *per-CLAss Flow fixed proportional differentiated service model* (CLAF) is presented. In Section 3, the medium access control scheme is described in detail. In Section 4, the simulation results of the CLAF performance are presented. Then, we compare the results with IEEE 802.11e EDCF, including the support of QoS-sensitive VoIP applications. Section 5 gives the conclusion.

2 CLAF - The per-CLAss Flow fixed proportional differentiated Service Model

In this section, we present the per-CLAss Flow fixed proportional differentiated service model for wireless local area networks. Different from conventional relative differentiated service model, CLAF provides fixed bandwidth share proportion to individual flow of different service classes. How bandwidth share between flows is defined in a system parameter called *bandwidth quality ratio* which is set by the network administrator as a resource management policy.

The CLAF service model is formulated as follows. Consider a wireless local area network supporting K service classes. Let j_k be the target bandwidth quality ratio parameter; and w_k be the target throughput measurement of a class k flow. The model imposes constrains of the following form for all classes:

$$w_1 : w_2 : ... : w_K = j_1 : j_2 : ... : j_K \tag{1}$$

where $j_1 > j_2 > ... > j_K$. The higher classes have the larger bandwidth shares. Let the total number of flows in service class k is N_k, k=1, …, K. Given the invariant bandwidth quality ratio, the aggregate throughput of each service class changes as the number of flows admitted to the class varies. We have the aggregate bandwidth quality ratio of the K service classes, denoted as $\{B_k\}$, as follows.

$$B_1 : B_2 : ... : B_K = N_1 \times j_1 : N_2 \times j_2 : \ldots : N_K \times j_K \tag{2}$$

For example, consider a wireless network supporting two service classes with $j_1 : j_2 = 4:1$. The policy says that every Class 1 flow would be guaranteed four times as much the bandwidth share as of a Class 2 flow. If there are two Class 1 flows and three Class 2 flows in the network, the aggregate bandwidth share ratio would be 8:3.

3 The Medium Access Control Scheme

The medium access control scheme for the CLAF service model consists of three parts: *a*) the baseline channel access procedure for the contending flows of the same service class; *b*) the coordination of the channel access between different classes; and *c*) the protocol for the join and leave of a flow.

3.1 Baseline Intra-class Channel Access Procedure

In CLAF, the medium access control procedure for flows of the same class follows the basic backoff procedure as defined in the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol of the IEEE 802.11 Distributed Coordination Function (DCF) mechanism. When a station has a packet to transmit, it generates the random backoff timer from the range of 0 to the current *Contention Window-1*. The backoff timer is decremented while the wireless medium is sensed idle and is frozen when it is busy. When the backoff timer counts down to zero, the station transmits the packet. If two or more stations transmit at the same time, collision occurs. In our scheme, a collided station does *not* double contention window size for retransmission. The flow waits for the next coordination period of the class it belongs to retransmit the packet.

3.2 Inter-Class Channel Access Scheme

3.2.1 The Size of the Class Contention Window

A new distributed coordination algorithm is used to regulate the channel access between classes. First, each service class is associated with a *class contention window*, denoted as $CW_k(t)$ whose size is determined based on the number of flows in the class at time t as follows:

$$CW_k(t) = CW_0^e(N_k(t)) \tag{3}$$

CW_0^e is the base contention window function, where e is the target maximum collision probability in a coordination period and $N_k(t)$ is the number of flows in class k at time t. Flows belonging to the same service class use the same class contention window size in their backoff timer computation. An example of CW_0^e specification is given in Table 1.

Table 1. An example of the base contention window function CW_0^e

Number of flows	1	2	3	4	5
$CW_0^{0.25}$	1	4	8	11	15
Number of flows	6	7	8	9	10
$CW_0^{0.25}$	18	22	25	29	32

3.2.2 The Class Frames and Coordination Periods

EQ(3) only specifies the range of the backoff time for flows of the same class. To achieve per-class flow fixed bandwidth quality ratio, two structures - *Class Frames* and *Coordination Periods* - are used. First, the channel access time axis is divided into a sequence of *superframe*. Each superframe consists of K class frames, one for each service class. A superframe always begins with the class frame of the highest priority class. For the k^{th} service class, its class frame will consist of j_k coordination periods. In the case that a service class has zero flow, its class contention window size will be set to zero. It results in zero duration of the corresponding class frame. In other words, the channel access will immediately continue to the next lower service class without waste of channel capacity. Within a class coordination period, flows of the corresponding class follow the basic intra-class channel access backoff procedure for packet transmission. Fig. 1 depicts the inter-class channel access structure.

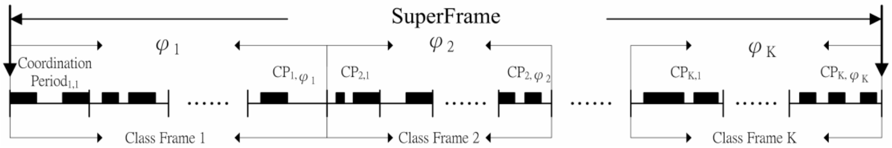

Fig. 1. The inter-class channel access structure assuming K service classes

3.3 Channel Access and Packet Scheduling at a Station

At the beginning of a superframe, the QoS AP broadcasts a Beacon message, including a list of the current class contention window sizes to use by wireless stations. The packet scheduling algorithm used at a wireless station is given in Fig. 2. In the algorithm, a backlogged flow makes one single channel access attempt in each coordination period of its associated class's Class Frame. Fig. 3 shows a possible implementation of the packet scheduling algorithm in the embedded kernel. The scheduler picks out the next packet from the flow with the minimum remaining backoff time to transmit in the currently-served service class and forwards the packet to the MAC layer. In the embedded kernel, software can be designed to effectively manage per-flow FIFO queueing and the associated backoff timers.

Station_ Packet _Scheduling_and_Channel_Access_ Algorithm
/* used by a wireless station to determine packet scheduling sequence of flows of multiple classes in each superframe */

On receiving the Beacon Message {
  for (i =1 to K) { /* For each Class Frame *i* */
    for (j = 1 to j_i) { /* for each Coordination Period of Class *i* */
      $b_{prev} = 0$; /* previous backoff timer */
      $\Gamma = f$; /* initialize un-served backlogged flow set */
      if ($B_i \neq f$) /* B_i : the set of locally backlogged flows of Class *i*. */
        Generate a different random backoff time for each flow in B_i,

i.e. $\Gamma = \{b_{i,m}\} \quad \forall m \in B_i$ /* $b_{i,m}$: backoff timer of flow *m* of class *i* */
stationBackOffTime = 0; /* initialize station's backoff timer */
while ($\Gamma \neq f$) {
Select a flow *x* such that $b_{i,x} = \min\{b_{i,m} \mid b_{i,m} \in \Gamma\}$;
stationBackOffTime = ($b_{i,x} - b_{prev}$);
Follow the baseline channel access procedure;
When stationBackOffTime counts down to zero {
Transmit the head-of-line packet from flow *x* to the network;
/* remove flow from un-served backlogged flow set */
$\Gamma = \Gamma \setminus \{b_{i,x}\}$;
$b_{prev} = b_{i,x}$;
} /* end of when */
} /* end of while */
/* All backlogged class *i* flow have been served. */
stationBackOffTime = $CW_i - b_{prev}$;/* remaining coordination period */
Follow the baseline channel access procedure;
Count down stationBackOffTime to zero;
} /* end of j
} /* end of i
}

Fig. 2. The packet scheduling algorithm for channel access at a wireless station

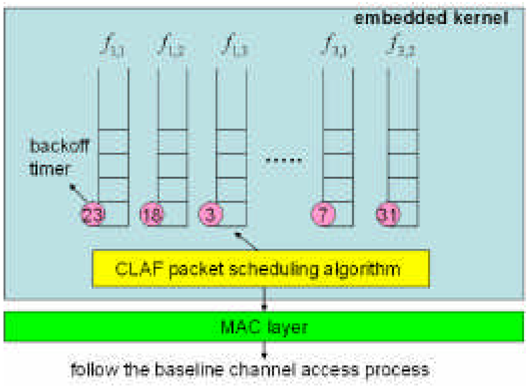

Fig. 3. The implementation architecture of the packet scheduling and queueing at a wireless station in the CLAP service model

Fig. 4 is an example that illustrates the proposed scheme in intra- and inter-class channel access. There are two service classes with $j_1 : j_2 = 3:1$. There are two stations - A and B. Station A has two Class 1 flows ($f_{1,1}^{A}$ and $f_{1,2}^{A}$), and one Class 2 flow ($f_{2,1}^{A}$); and Station B has a flow of each service class ($f_{1,1}^{B}$ and $f_{2,1}^{B}$). Using the base contention window specification in Table 1, we have the Class 1 and 2 contention window size as CW_1=8 and CW_2=4, respectively. The backoff times of these flows at both stations are given in Table 2. Note that in this case the Class 1 contention window size is eight. Therefore, each Class 1 coordination period spans eight idle time slot duration to coordinate the start and end of a coordination period of a service class. This is necessary because in wireless LAN, each station does not know the actual number of backlogged flows of each service class in the other stations but individual class contention window sizes. Even though they know, if there is a collision, it is difficult to infer how many stations were involved in the collision. Therefore, the contention window size in terms of number of idle time slots is used for distributed coordination period synchronization. All stations monitor the channel events and count the number of idle slots to execute the proposed CLAF channel access scheme in a distributed and coordinated fashion.

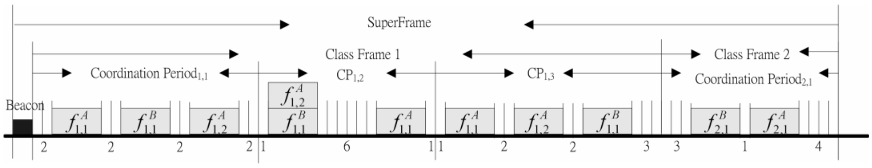

Fig. 4. The packet scheduling sequence and channel access events

Table 2. Backoff times of the example in Fig. 4.

Station	A			B	
Class	Class 1		Class 2	Class 1	Class 2
Flow Index	$f_{1,1}^{A}$	$f_{1,2}^{A}$	$f_{2,1}^{A}$	$f_{1,1}^{B}$	$f_{2,1}^{B}$
Backoff Time	2	6	4	4	3
	7	1	-	1	-
	1	3	-	5	-

In a coordination period, if a collision occurs (as occurred in $CP_{1,2}$ in Fig. 4), all collided flows will retransmit their packets in the next coordination period. If the collision takes place in the last coordination period of a Class Frame, retransmission will be deferred to the next superframe. Hence, in CLAF, there is *no* exponential backoff time computation for packet retransmission.

3.4 Procedure for Flow Join and Leave

In CLAF, the class contention window size is dynamically adjusted based on the number of flows of the service classes. To keep track of the number of flows, a control frame is used. As shown in Fig. 5, each superframe is followed by a control frame in which stations send Re-association Requests to the QoS AP specifying the number of new flows to join and the number of flows to leave for each service class. The QoS AP will reply a Re-association Response to the station with a status code indicating whether the join request is accepted or not. Based on the results, the QoS

AP computes new class contention window sizes, if necessary and updates all wireless stations in the next Beacon message.

No stations are allowed to send Association and Re-association messages in a superframe. During the control frame, stations use a separate contention window size denoted as $ControlFrameContenetionWindow_{min}$ to randomize channel access backoff times when submitting the join/leave requests.

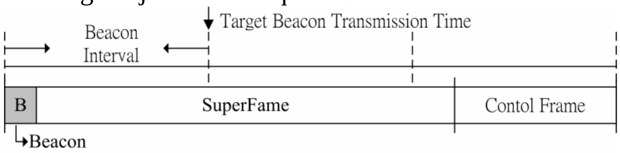

Fig. 5. A channel access round consists of a superframe for multi-class packet transfer plus a control frame for notifying flow join and leave

3.5 Base Contention Window Function

Given the number of flows of a service class, we want to find the contention window size ($CW_0^e(n)$) such that the probability of colliding flows is upper bounded by a small value e in a coordination period. The computation is based on the *Inclusion-Exclusion Principle* and is summarized as follows:

Step 1: Compute the mean collision number by using $n \times e$

Step 2: Compute the expected number of collided flows $E_n^{CW}[Coll] = \sum_{i=0, i \neq 1}^{n} p_n^{CW}(i) * i$ under different pair (CW, n), where $CW \geq n$. Here,

$$p_n^{CW}(i) = \begin{cases} \dfrac{F(CW, n)}{CW^n}, & i = n, \quad i \neq 1 \\ \dfrac{C_k^n C_k^{CW} k!(F(CW-k, n-k))}{CW^n}, & 2 \leq i \leq n-1, \quad k = n-i, \quad n \geq 3 \end{cases} \tag{4}$$

and

$$F(CW, n) = CW^n - \sum_{i=1}^{n} (-1)^{i-1} C_i^n C_i^{CW} i!(CW-i)^{n-i} \tag{5}$$

Step 3: To get $CW_0^e(n)$, we can find smallest w that satisfies $E_n^{CW}[Coll] < n \times e$ from a sequences of { $E_n^{CW}[Coll]$ }. Then $CW_0^e(n) = w$.

4 Performance Evaluations

In this section, we provide a performance evaluation of the proposed per-CLAss Flow fixed proportional differentiated service model (CLAF) and its medium access control scheme via simulations. The simulator is implemented in C[16]. The parameter values of the baseline Intra-class Channel Access procedure used in the simulations are the same as those in 802.11 (see Table 3) in ns-2[17] configuration. Consider N wireless stations and a QoS AP. All communication between stations must be forwarded by the QoS AP. Packets are fixed of length 1K bytes.

Table 3. IEEE 802.11 PHY/MAC parameters used in sumulation

SIFS	10 µs	Slot_time	20 µs
DIFS	50 µs	ACK Size	14 bytes
MAC Header	28 bytes	PreambleLength	144 bits
PLCP Header Length	48 bits	Rate	11 Mbps

4.1 Fixed Proportional Bandwidth Differentiation

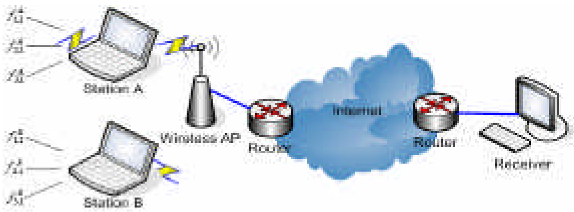

Fig. 6. The network configuration of Fig.7.

Fig. 7 shows the fixed bandwidth sharing proportion is enforced between per-class flows regardless of the traffic load of individual classes. Fig. 6 is the simulation configuration. There are three service classes with $j_1 : j_2 : j_3 = 3:2:1$. Initially, the bandwidth quality ratio between Class 1 flow and Class 3 flow is approximately 3:1. The throughputs of flows of the same class are closely equal. At time 50, two Class 2 flows join the network. The resulting bandwidth sharing ratio changes to 3:2:1, while the actual throughput received by per-class flow is reduced due to the new flows. When the new flows leave, the throughput share restores to the initial state. The aggregate throughput of each service class is shown in Fig. 8, as the product of the class' s bandwidth share proportion and the number of admitted flows in the class.

4.2 Performance Comparison with IEEE 802.11e EDCF

To illustrate the performance difference between CLAF and EDCF, previous experimental scenario is repeated for EDCF using ns-2. The minimum contention window sizes for the Class 1, 2 and 3 are 16, 32 and 48, respectively. Fig. 9 shows the throughputs of flows of different classes. The throughput proportion is non-deterministic and has no direct relationship with the minimum contention window size. Moreover, throughput performance of individual flow fluctuates heavily. Comparing the result with Fig. 7, CLAF can guarantee a fixed bandwidth proportion to individual flow of different service classes and achieve more stable throughput performance at both the flow and class levels. Furthermore, the aggregate throughput of the EDCF is lower than that of the CLAF as shown in Fig. 10. It shows that CLAF is more efficient in the resource utilization.

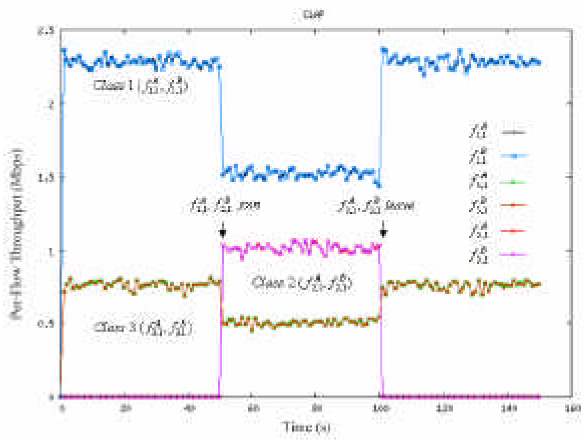

Fig. 7. The per-class flow throughput performance using CLAF ($j_1 : j_2 : j_3 = 3:2:1$)

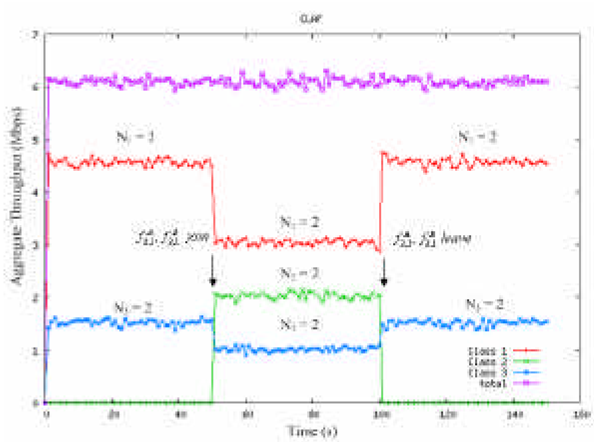

Fig. 8. The per-class aggregate throughput performance of Fig.7.

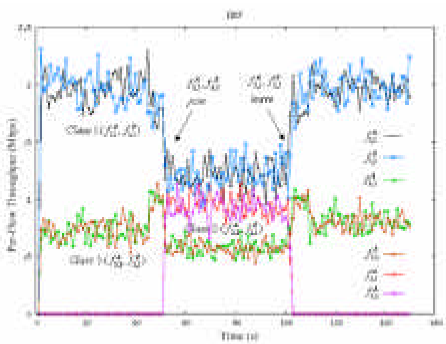

Fig. 9. The per-class flow throughput performance using EDCF

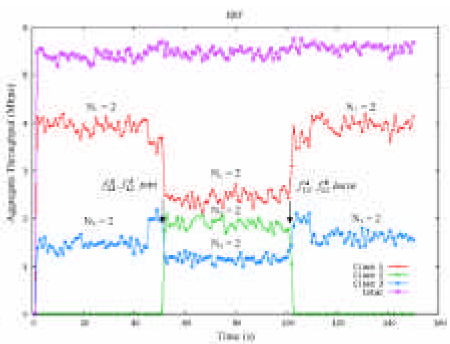

Fig. 10. The per-class aggregate throughput performance of Fig.9.

$(j_1 : j_2 : j_3 = 3:2:1)$

4.3 VoIP over wireless LAN

In this experiment, we want to show the merit of CLAF in the support of real-time multimedia applications. There are two kinds of VoIP calls - G.711 (Class 1) and G.729 (Class 2). Each call is between a wireless station and a wired host connected to a LAN on the other interface of the QoS AP. Hence, each VoIP call generates an uplink and a downlink flow in the wireless LAN, one for each direction. The offered loads of the G.711 and G.729 VoIP flow are 100.8Kbps and 44.8Kbps, respectively (including RTP/UDP/IP/MAC packet header overhead). Hence, the bandwidth quality ratio is set to 9:4. In EDCF, both G.711 and G.729 flows belong to the same access category 3 (AC3), and the minimum and maximum contention window is 7 and 15 respectively.

Fig. 11 compares the average throughput of a VoIP flow between CLAF and EDCF under different numbers of VoIP calls. One can see that the throughput performance of both G.711 and G.729 flows are well protected under CLAF regardless the number of VoIP calls. For EDCF, the VoIP throughput performance is acceptable when there is no congestion within the class (i.e. less than ten calls). For CLAF, the maximum number of calls in this case is fourteen calls (i.e. 28 flows), more than ten calls for EDCF. CLAF can not only provide individual flow QoS but also achieves higher overall throughput performance.

5 Conclusions

In this paper, we have presented a new per-CLAss Flow fixed proportional differentiated service model (CLAF) and its medium access control scheme for multi-service wireless local area networks. Different from conventional differentiated services, CLAF provides a) policy-based fixed proportional differentiated service; b) such fixed proportional service differentiation is on per-class flow basis; and c) each class contention window size is adjusted to reflect the actual traffic load of the class. The simulation results show that the proposed scheme successfully provides per-flow fixed proportional differentiated service between multiple service classes. Second, we compare throughput performance between CLAF and IEEE 802.11e EDCF. The proposed scheme outperforms EDCF in terms of providing fixed proportional bandwidth share to individual flows of different service classes. It also achieves higher channel throughput. In the VoIP simulation runs, the scheme can as well better support real-time applications with QoS constraints. In summary, CLAF provides users a more predictive, affirmative service guarantees than conventional relative differentiated service like IEEE 802.11e EDCF.

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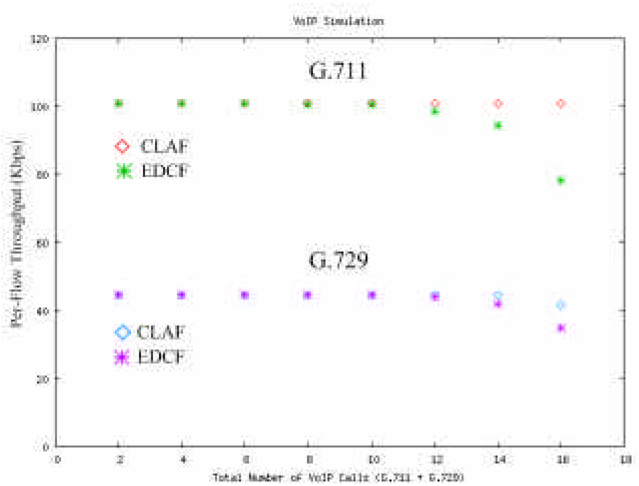

Fig. 11. The average throughput performance for VoIP using CLAF and EDCF