A Distributed Transmission Control Method for Weighted Fairness in IEEE 802.11 WLANs

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Abstract: In wireless networks, a medium access control (MAC) protocol is sought to coordinate the transmissions of all nodes for the efficient utilization of the limited channel reception capability. When designing a MAC protocol, fair allocation of bandwidth is an important issue. However, achieving the design goal is difficult, especially for the IEEE 802.11 wireless local area networks (WLANs). In this paper, we propose a method that can properly control the transmission probability to reflect the relative weights among data traffic flows for the fair share. A closed-form expression of system throughput is derived for each class in a WLAN and numerically evaluated with different simulation scenarios. The results show that the proposed method can achieve the design goal of weighted fairness under the multi-class environment.

Key–Words: Quality of Service, Weighted Fairness, Multiple Classes, IEEE 802.11 DCF, Performance Analysis.

1 Introduction

The main objective of the next-generation broadband wireless networks is to provide suitable levels of Quality of Service (QoS) over IP-based wireless access networks. As one of the most successful MAC protocols for these networks, IEEE 802.11 DCF [1], however, pays no attention to the QoS provision, such as throughput guarantees, among traffic connections of different priorities. In fact, the above missed in DCF, has been identified as the most important issue when designing the wireless card of next-generation. Thus, in this paper we study the challenging problem to achieve the weighted fairness for data communications in WLANs. To this end, the ideal weighted fairness should be defined at first. Assume that there are \( N \) different priority classes. Each class \( i \) is characterized by a positive weight, \( \psi_i \), with the assumption of \( 1 = \psi_1 > \psi_2, \ldots, > \psi_n > 0 \). Assume further that each node carries only one traffic flow. The set of nodes carrying class \( i \) traffic is denoted by \( J_i \). Let \( w_i(t_h, t_e) \) be the amount of class \( i \) traffic during the time interval \([t_h, t_e]\). In order to achieve fair share to all traffic flow, it requires

\[
\frac{w_i(t_h, t_e)}{\psi_i} = \frac{w_j(t_h, t_e)}{\psi_j}, \quad \forall i, j \in \{1, \ldots, N\}
\] (1)

As shown above, the ideal weighted fairness cannot be actually achieved since data transmitted on a real network is packetized. However, when considered with IEEE 802.11 WLANs, each data packet in the higher layer is fragmented into smaller MAC frames for transmission, which provides a reasonable assumption that each data flow has the same MAC frame size. Let \( P_{i,i} \) be the probability that a MAC frame is transmitted from a node in class \( i \) and successful. With this, it is considered that all the traffic flows within a WLAN would fairly share the wireless medium and the weighted fairness in the WLAN is achieved, in a probabilistic sense, if the following condition holds

\[
\frac{P_{i,i}}{\psi_i} = \frac{P_{j,j}}{\psi_j}, \quad \forall i, j \in \{1, \ldots, N\}
\] (2)

The remaining parts of this paper are organized as follows. In Section 2, we briefly summarize the P-IEEE 802.11 DCF adopted. Following that, a Markov chain analysis for the P-IEEE 802.11 DCF in multi-class environment is given in Section 3. According to this model, the transmission probability to achieve the weighted fairness is derived in Section 4. The analytical results are examined with the experiments in Section 5. The related works are summarized in Section 6 as reference. Finally, conclusions are drawn in Section 7.

2 P-IEEE 802.11 DCF

To deal with the weighted fairness problem and fulfill the design objective mentioned previously, we choose
to extend the capability of P-IEEE 802.11 DCF protocol in [2] that does comply with the legacy 802.11 DCF and require no changes in the existing frame formats and access procedures. As shown in Fig. 1, the P-IEEE protocol uses a separate layer between the standard access scheme and the physical layer to calculate the transmission opportunity for a node. When carried out, each node filters its transmission attempt based on the decision made in this layer. If the decision is positive, the frame under transmission is delivered by the normal DCF. Otherwise, the frame is deferred with a new back-off interval, just as that it encounters a collision in the legacy MAC.

Therefore, with this protocol a node can manipulatively control its transmission flow. However, it is still unknown that if a node in a certain priority class can decide the controlled p-persistent transmission probability for its transmission flow to cooperatively achieve the weighted fairness with other flows from different classes in the WLAN. For solving this problem, the controlled probability, called $P_{i,j,k}$, should be represented with a form that is analytically tractable in the multi-class environment. In this work, it is done with a simple non-uniform increasing function that can reasonably reflect the channel contention level sensed by a node in class $j$ and back-off stage $k$. More precisely, with $\phi_i$ as the transmission factor for class $i$, the probability is represented by

$$P_{i,j,k}^t = 1 - \phi_i^{j+1}$$ (3)

### 3 Throughput of P-IEEE 802.11 Protocol in Multi-Class Environment

For the throughput calculation in the multi-class environment, we first let the conditional collision probability of class $i$ be $P_i$ (as $P$ in [3]). Given that, the successful transmission probability of a node can then be represented by $(1 - P_i) \cdot P_{i,j}^t$. With this probability, a node will reset its back-off timer to a value within $W_{i,j}$ (the minimum window size of class $i$). On the other hand, the failure transmission probability of a node can be given by $1 - (1 - P_i) \cdot P_{i,j}^t$. In this case, a node will defer its transmission to the next back-off stage, choosing a new back-off timer with a value within the window size of the stage. Besides, other non-null probabilities include the probability of 1 with which a back-off timer should decrease by 1 when the channel is sensed idle, and the probability of 1 with which a node should reset its contention window to $W_{i,j}$ when the maximum back-off stage $m_i$ is encountered.

More precisely, for a node in class $i \in [1, N]$, let $b(i, t)$ be the stochastic process representing the back-off timer $k \in [0, W_{i,j} - 1]$, and $s(i, t)$ be the process representing the back-off stage $j \in [0, m_i]$. Thus, at time $t$, the state of a node in class $i$ can be modeled with a discrete-time Markov chain $\{b(i, t), s(i, t)\}$, and fully determined by $\{i, j, k\}$, as shown in Fig. 2. With the Markov chain, the non-null probabilities considered in above can be represented by

$$P(i, 0, k, i, j, 0) = \frac{k \in (0, W_{i,j}, j \in [0, m_i])}{(1 - P_i) \cdot P_{i,j}^t}$$
$$P(i, 0, k, i, j, 0) = \frac{k \in (0, W_{i,j}, j \in [0, m_i])}{(1 - P_i) \cdot P_{i,j}^t}$$

$$P(i, 0, k, i, j, 1, 0) = \frac{1}{(1 - P_i) \cdot P_{i,j}^t} \cdot \frac{k \in (0, W_{i,j}, j \in [1, m_i])}{W_{i,j}}$$

With some manipulations, we can lead to the above to the stationary probability, $b_{i,j,k}$, for a node in class $i$ with its back-off stage in $j$ and back-off timer in $k$,

$$b_{i,j,k} = \frac{W_{i,j} - k}{W_{i,j}}$$ \cdot \frac{1}{(1 - P_i) \cdot P_{i,j}^t} \cdot \prod_{l=0}^{m_i-1} (1 - P_i) \prod_{j=0}^{m_i-1} b_{i,j,l+1} \cdot b_{i,j,l+1}$$

Finally, the probability $\tau_i$ that a node transmits a frame in a randomly chosen time and the probability $P_i$ that a node in the back-off stage senses the channel busy, both for class $i$, constitute a nonlinear system of equations as follow

$$\tau_i = \sum_{j=0}^{m_i} b_{i,j,0} \cdot P_{i,j,0} \cdot P_i = 1 - (1 - \tau_i) \cdot \prod_{j=m_i}^{N} \left(1 - \tau_j\right)^{n_{i,j}}$$

where $n_{i,j}$ denotes the number of nodes in class $i$. Not that because there are $N$ classes, the system totally has $2N$ unknowns $\tau_i$ and $P_i$, to be solved numerically.

Further, for the throughput calculation, we let $P_i$ be the probability of at least one transmission in a slot.
time. Similarly, let $P_{s,i}$ be the probability of a transmission that is successful for a node in class $i$ (as defined previously), and $P_S$ be the probability that a successful transmission occurs in a slot time. In terms of $\tau_i$, these probabilities can be represented by

$$P_{tr} = 1 - \prod_{h=1}^{N} (1 - \tau_h)^{n_h}$$ (7)

$$P_{s,i} = \tau_i \cdot (1 - \tau_i)^{n_{i-1}} \cdot \prod_{h=1, h \neq i}^{N} (1 - \tau_h)^{n_h}$$ (8)

$$P_S = \sum_{i=1}^{N} n_i \cdot P_{s,i} = \sum_{i=1}^{N} \frac{n_i \cdot \tau_i}{1 - \tau_i} \cdot (1 - P_{tr})$$ (9)

With these probabilities, we can express the throughput for a node in class $i$, $S_i$, and the overall system throughput, $S$, as the following ratios

$$S_i = \frac{P_{s,i} \cdot E[P]}{(1 - P_{tr}) \cdot \sigma + P_S \cdot T_s + (P_{tr} - P_S) \cdot T_c}$$ (10)

$$S = \frac{P_S \cdot E[P]}{(1 - P_{tr}) \cdot \sigma + P_S \cdot T_s + (P_{tr} - P_S) \cdot T_c}$$ (11)

where $E[P]$ denotes the average frame length, $\sigma$ the duration of an empty slot time, and $T_s$ and $T_c$ the average times that the channel is sensed busy due to a successful transmission or a collision, respectively. For the values of these parameters, one may refer to [3].

4 Weighted Fairness with P-IEEE 802.11 DCF

In this section, we introduce a method to obtain weighted fairness among data traffic in different priority classes. For doing so, we take $P_{s,i}$ in (8) into the weighted fairness in (2), and after some simple manipulations, we have

$$\frac{\tau_i \cdot (1 - \tau_j)^{n_{i-1}} \cdot (1 - \tau_j)^{n_j}}{\psi_j \cdot (1 - \tau_j)^{n_{i-1}} \cdot (1 - \tau_i)^{n_i}}, \forall i, j \in \{1, ..., N\}$$ (12)

Further, without loss of generality, we let $\tau_i = \tau_1$, which leads to

$$\tau_j = \frac{\psi_j \cdot \tau_1 \cdot (1 - \tau_j)^{n_{j-1}}}{\psi_1 \cdot (1 - \tau_1)^{n_1} + \psi_j \cdot \tau_1 \cdot (1 - \tau_1)^{n_{j-1}}} = \frac{\psi_j \cdot \tau_1}{\psi_1 - \psi_1 \cdot \tau_1 + \psi_j \cdot \tau_1}$$ (13)

In other words, any $\tau_j, j \neq 1$ can be represented in terms of $\psi_j$, $\psi_1$, and $\tau_1$. Thus, if the transmission probability of class 1, $\tau_1$, can be given, the transmission probabilities of the other classes, $\tau_j$s, can then be obtained with $\tau_1$ and the weights $\psi_j$s.

5 Performance Evaluation

In this section, we report on experiments made in order to verify the theoretical results derived previously.
In the experiments, we implement P-IEEE with multiple classes on the Pythagor simulator [4] and let all nodes with IEEE 802.11a PHY be uniformly distributed in the WLAN. Each node has a flow with 2000-bytes of UDP packets toward a randomly chosen destination, resulting in the saturated throughput as required. With the assumption of no hidden terminal problem, P-IEEE and IEEE 802.11 MAC are both taken into account for the throughput weighted fairness, with different scenarios. However, we show only the results of 6 Mbps data rate in IEEE 802.11a PHY, due to space limitations. Other results with different data rates have the same trend, and can be represented by that of 6 Mbps.

Specifically, we let the number of priority classes be 3 as an example of the multi-class environment. With that, we investigate the impact of the number of nodes in each priority class on the weighted fairness, and perform 18 different simulation experiments to verify the corresponding theoretical results. Each of these experiments is carried out using a different set of \((n_1; n_2; n_3)\), where \(n_i\) denotes the number of nodes in priority class \(i\) with \(n_1 = 2, 5, 10, n_2 = 5, 10\) and \(n_3 = 5, 10, 20\), and will be referred to as experiment 1 to 18. All these experiments are carried out with \(\psi_1 = 1, \psi_2 = 0.5\) and \(\psi_3 = 0.1\), which reasonably represents the possible setting of \(\psi\).

In addition to the above, we conduct these experiments with two different fairness metrics to quantitatively evaluate these MACs. The first metric is the direct ratio between the performance metrics from these classes. More precisely, we consider the throughput ratio as \(\frac{S_i}{S_f}\). The second metric is the so-called fairness index in [5]. In this metric, \(S_f\) denotes the throughput of traffic flow \(f\), and \(\psi_f\) denotes the associated weight. The throughput fairness index, \(F_s\), is then defined as

\[
F_s = \frac{\mu(S_f/\psi_f)}{\mu(S_f/\psi_f) + \alpha(S_f/\psi_f)}
\]

where \(\mu\) and \(\alpha\) denote, respectively, the mean and the standard deviation of \(S_f/\psi_f\) over all the active data traffic flows.

Figure 3(a) shows the throughput results, with lines denoting the theory’s and symbols denoting the simulation’s. From this figure, we have the following points of observation. First, the simulation results well match those of theory. This indicates that our analysis can correctly evaluate these methods. Second, the throughput of class 1 is almost 2 times (10 times) that of class 2 (class 3) in all scenarios. The fair share is expected and can be further confirmed in Fig. 3(b), in which the direct ratio between class 1 and 2 (class 1 and 3) is about 2 (10) and the fairness index is about 1 despite the scenarios. Both indicate the same results on the fairness. However the former represents the desired fair share between these two classes while the latter shows the fairness in the sense that the weighted share is nearly identical for each traffic flow with few variations. All the above indicates that the design goal, achieving weighted fairness, can be actually obtained with our method based on the P-IEEE protocol.

6 Related Works

Since IEEE 802.11 becomes the de facto standard for WLANs, there are quite a lot of related works proposed either for obtaining its theoretical limits or for improving its performances. Specifically, many related works have been done to develop scheduling algorithms for wireless networks to achieve weighted fairness.
fairness. However, most of them are centralized or polling-based protocols. Recently, with the distributed EDCF in IEEE 802.11e, some works have also been done for service differentiation by using different priority schemes based on, for example, setting different IFS, CW, or back-off parameters specified in the MAC. Recently, [6] proposes a method to achieve weighted fairness in IEEE 802.11e. However, it considers only 2 classes, and provides no general solution when the number of classes larger than 2. [7] attempts to deal with this problem in a multi-hop wireless network subject to a minimum fairness guarantee, which is different from the issues we address on the WLANs. [5] provides a so-called P-MAC that modifies the DCF to achieve the design goal, but it uses a constant contention window and requires modifications to the DCF. [8] extends the work in [9], and derives a value for each class to ensure a user-specified utilization ratio. However, unlike ours, this work adopts another modeling scheme that determines the back-off interval with a p-persistent transmission probability sampling from a geometric distribution.

7 Conclusion

In this paper, we use a p-persistent transmission control protocol to enhance the legacy IEEE 802.11 DCF with the capability of achieving weighted fairness among data traffic in different priority classes in WLANs. Experiment results indicate that with our method, the p-persistent enhanced MAC can actually achieve the weighted share, which is a hard task for IEEE 802.11 WLANs even not impossible.

When compared with other complex or incompatible modifications to the IEEE 802.11 MAC, the proposed method has the characteristics of simplicity and complete distribution, and requires no extra messages to be shared among cooperating neighbor nodes. As a result, this method is considered as a more convenient alternate that can properly provide differential services in the WLANs, with the p-persistent transmission probability, $P_T$, as a parameter that can comply with the legacy DCF.

References:


