Resolving the Unfairness Limitations of the IEEE 802.11 DCF

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Abstract—In this paper, we propose a new solution to cope with the unfairness limitations of the Distributed Coordination Function (DCF) algorithm. Indeed, in current widely deployed IEEE 802.11b wireless local area networks (WLAN), the performance of all the competing access nodes are dramatically affected once the bit rate of one station degrades. This anomaly is due to the unfairness behavior of the DCF algorithm. To avoid this, our solution is based on multiple backoff windows principle. We demonstrate through simulations the efficiency of our proposal. Our results show that the proposed algorithm enables fair bandwidth sharing and increases significantly the total network throughput.

1. Introduction

IEEE 802.11 wireless local area network (WLAN) is now ubiquitous in access networks. The WLAN hotspots are widely deployed in residence, enterprise and public areas. In such networks the main concern of operators is ensuring fair sharing of the common bandwidth among competing access nodes while maximizing the network throughput.

Actually, access is arbitrated by the use of the distributed coordination function (DCF) algorithm, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. This non centralized algorithm (i.e. DCF) strongly participates in the success of IEEE 802.11b thanks to its simplicity. Nevertheless, this basic concept presents two main drawbacks. First, DCF algorithm is unsuitable for Quality of Service (QoS) aware applications. In view of this, the IEEE 802.11 IETF Working Group is currently defining a new supplement to the existing legacy 802.11 MAC sub-layer in order to support QoS feature. The new 802.11e MAC [1] will therefore expand the 802.11 application domain by enabling new applications such as voice and video services.

The second drawback behind DCF algorithm is its throughput unfairness issues. This issue is known in literature as the 802.11b anomaly [2][3]. Accordingly, the throughput of each contending access nodes is drastically reduced once a station transmission bit rate decreases due to physical radio properties. Specifically, a node that is relatively far from the access point (AP) is subject to important signal fading and interference leading to repeated unsuccessful frame transmission. As a result, the current deployed IEEE 802.11b reacts by degrading the station bit rate from the nominal 11Mbit/s rate to 5.5, 2 or 1Mbit/s. Doing so, the station throughput as well as all the contending access nodes throughput are degraded due to the unfairness limitations of the CSMA/CA-based DCF algorithm. In other words, all the stations are penalized due to the position of one station. Indeed, the basic CSMA/CA scheme allows a fair access to the shared channel. In this regard, a station with a relatively low bit rate (e.g. 1Mbit/s) captures the channel a longer period with respect to the remaining stations transmitting at 11Mbit/s. This leads to a degradation of all the access nodes' throughput.

To alleviate this problem, we advise a new strategy based on multiple backoff windows concept. We refer to this technique as the DCF-MB (DCF Multiple Backoff). Considering our scheme, access nodes are classified into different sets according to their physical transmission bit rate (11, 5.5 or 1Mbit/s). Moreover, each set will be characterized by each own backoff window.

The rest of this paper is organized as follows. In section II, we revise the related works presented in the literature, pointing out our position relative to these works. Section III analyses the DCF anomaly through simulation illustrations. In section IV, we describe our proposed solution. Then, in section V, we present simulation results to evaluate the fairness introduced by our scheme as well as its impact on the total network throughput. Finally, conclusions are drawn in section VI.

2. Related Work

In the wireless literature, several studies dealt with the analysis of the unfairness behavior of the DCF protocol due to the basic CSMA/CA algorithm [2][3]. These works studied this concern without providing particular solutions. Specifically, the work in [2] analyzed theoretically the DCF anomaly by deriving simple expressions of the useful throughput. Furthermore, in [3], authors focus on the short-term unfairness of CSMA-based medium access protocol. They evaluated the short-term fairness degree through experimental and analytical methods.

On the other hand, unfairness engendered by the TCP utilization in IEEE 802.11 WLAN was extensively addressed in [4][5][6]. Nonetheless, the proposed solutions are TCP-specific and are not adapted to our case of study.

Recently, some service differentiation schemes have been proposed for the IEEE 802.11 DCF to support QoS feature [1][7][8]. The basic idea consists in providing a priority scheme for the DCF. The differentiation is simply achieved through varying the amount of time a station would sense the channel to be idle and the length of the contention window for a backoff. Such methods give an access priority for the shared medium to hosts with stringent QoS requirements but without resolving the above-mentioned unfairness issue.

In this study, we adapt these priority mechanisms to achieve fairness. As a key distinguishing feature from existing literature, we provide an effective solution to the unfairness concern with minor changes in the DCF algorithm.

3. IEEE 802.11 DCF ANOMALY

The IEEE 802.11b standard defines two access methods: the DCF technique, which is based on the CSMA/CA protocol, and the centralized Point Coordination Function (PCF). Unlike DCF, the PCF method provides free collision access via a central arbitration by a Point Coordinator, which resides in the AP. Even though, the PCF method is barely implemented in today's products due to its complexity. In contrast, DCF thanks to its simplicity is the main reason of the tremendous growth in IEEE 802.11 installation.

As stated before, the DCF access method is based on the CSMA/CA principle. Accordingly, a host wishing to transmit a frame senses the channel activity until an idle period equal to Distributed Inter Frame Space (DIFS) is detected. Then, the station waits for a random backoff interval before transmitting. The backoff time counter is decremented in term of slot time as long as the channel is sensed free. The counter is suspended once a transmission is detected on the channel. It resumes with the old remaining backoff interval when the channel is sensed idle again for a DIFS period. The station transmits its frame when the backoff time becomes zero.

If the frame is correctly received, the receiving host sends an acknowledgement (ACK) frame after a Short Inter Frame Space (SIFS). If the sending host does not receive this ACK frame, a collision is assumed to have occurred. In this case, the sending host attempts to send the frame again when the channel is free for a DIFS period augmented by the new backoff calculated as follows.

For each new transmission attempt, the backoff interval is uniformly chosen from the range $[0, CW]$ in term of slot of times. At the first transmission attempt of a frame, CW equals the initial backoff window size $CW_{\min}$. Following to each unsuccessful transmission, CW is doubled until a maximum backoff windows size value $CW_{\max}$ is reached. Once the frame is successfully transmitted, the CW value is reset to $CW_{\min}$. Figure 1 illustrates the DCF mechanism.

In essence, the DCF algorithm ensures equal access to the shared medium among all the contending stations. However, equal access probability does not guarantee a fair medium occupancy among all the hosts. Specifically, a station moving away from the AP may result in the degradation of its nominal bit rate to 1Mbit/s. In this case, it captures the channel for a period 11 times longer than the period required by a station close to the AP to transmit the same frame. In this regard, this kind of access policy may not be desired since it is extremely penalizing for all the stations. In addition, this issue affects the total network throughput.

To illustrate this anomaly, we consider the simple example of 3 station-access network. The 3 contending access stations are situated at different distances from the AP. Accordingly, the first station, which is the closest node to the AP, transmits at a bit rate equal to 11Mbit/s. The second station transmits at 5.5Mbit/s and the third station at 1Mbit/s. We assume that packets arrive with the same rate at each station buffer level according to a Poisson process. In this example, the arrival rate is set high enough, so that, there is always at least one frame in each host buffer.

Moreover, in our simulation, station 2 is activated at t_1=10s and station 3 is activated at t_2=40s. This scenario enables us to check the network throughput evolution. We note that the DCF parameter settings used in our simulations are depicted in Table1.

As depicted in Fig. 2, during the first 10s, only station 1 is activated. Its useful throughput is maximal and attains 6.41Mbit/s, which represents nearly 60% of its transmission bit rate (11Mbit/s). This difference is mainly due the backoff delay, SIFS and DIFS periods left on the medium for each frame transmission.

Once the station 2 is activated, the first station throughput logically reduces. But, this reduction is dramatic since the new useful throughput 2.42 Mbit/s is less than the half of the old throughput (6.41Mbit/s). Moreover, we point out that both stations present the same throughput although their different bit rates. Indeed, the throughput of the first station is decelerated due the relatively low bit rate of station 2. This is typically due to the CSMA/CA policy, which allows fair access probability between both stations but does not ensure a fair medium occupancy in term of time. In this case, station 2 occupies the channel twice more time than the first station. As a result, station 1 is unfairly penalized as well as the total network throughput, which significantly decreases as it passes from 6.41Mbit/s to 4.84Mbit/s.

This anomaly is more pertinent when station 3 is activated. In this case, the useful throughput of each station is limited to only 0.57Mbit/s and the total throughput becomes 1.71Mbit/s.

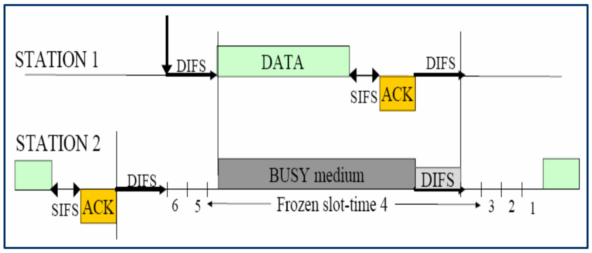

Fig. 1. IEEE 802.11 CSMA/CA-based DCF.

Table.1 : Parameter of IEEE 802.11 b

PLCP Preamble	18 bytes
PLCP Header	6 bytes
Class bit rate	1 ; 5,5 ; 11 Mbit/s
DIFS	50 µs
SIFS	10 µs
Backoff-Slot Time	20 µs
CWmin	31
ACK	14 bytes

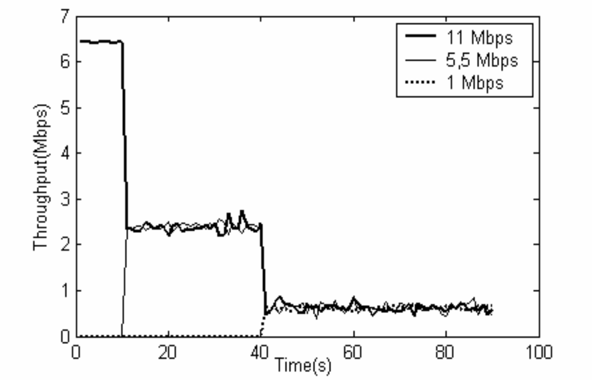

Fig. 2. Throughput of each node according to its class bit rate: DCF case.

4. THE DCF-MB SOLUTION

To relieve this issue, we advise a method that ensures a fair channel sharing in term of time occupancy among the contending nodes instead of ensuring fair access probability. To achieve this, we give different access priority to different hosts according to their transmission bit rate classes (11, 5.5 or 1Mbit/s). Let us revisit the example of section III. As stated before, thanks to its relatively high transmission bit rate (i.e. 11Mbit/s), station 1 sends the same frame 2 times faster than station 2 and 11 times faster than station 3. In view of this, station 1 has to access the channel 2 more times than station 2 and 11 more times than station 3 in order to obtain a fair occupancy of the medium.

This aim can be simply accomplished with centralized systems such as the PCF technique by allocating more time to the high-priority classes. Nonetheless, such centralized methods are not deployed due to their complexity. On the other side, one possible solution to achieve this, while keeping the DCF algorithm, is to use a priority scheme. Such a scheme can be easily designated with minor changes in DCF.

The key idea behind our proposal is to provide each class bit rate C_i with its associated initial contention windows size $CW_{\min}(i)$ for backoff procedures. Specifically, $CW_{\min}(1)$ associated to class C_1 (i.e. 11Mbit/s) is set equal to 31 as specified in the standard. Moreover $CW_{\min}(i)$ of class C_i is derived as follows:

$$CW_{\min}(i) = CW_{\min}(1)\frac{\text{bit rate of class } C_1}{\text{bit rate of class } C_i} \qquad (1)$$

Specifically, in our study, we assume 3 classes of stations. According to (1), we get $CW_{\min}(1) = 31$, $CW_{\min}(2) = 60$ and $CW_{\min}(3) = 330$, which are the window sizes of classes C_1 (11Mbit/s), C_2 (5.5Mbit/s) and C_3 (1 Mbit/s), respectively.

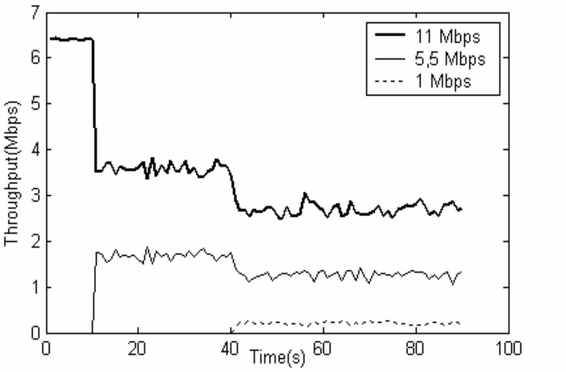

Fig. 3. Throughput of each node according to its class bit rate: DCF-MB case.

Doing so, we guarantee, for instance, that the average backoff counter timer of class C_1 is the half of that of class C_2 (5.5Mbit/s). Hence, we ensure that class C_1 stations access the medium twice time more than C_2 stations

Finally, we underline that the main advantage of this method is its simplicity. It requires minor modifications in the existing DCF. Indeed, each station modulates its contention window size according to its current physical bit rate. This decision is taken locally, at the station level, without requiring any extra communications with the AP, keeping thus the simplicity and the distributed feature of DCF.

5. Performance Evaluation

In order to assess the efficiency of our proposal, we apply our DCF-MB scheme using the same scenario of section III and the results are reported in Fig. 3. This figure shows that the initial useful throughput of station 1 (i.e. 6.41 Mbit/s) is divided by 2 when station 2 is activated and is divided by 3 when station 3 joins the network. Unlike the classical DCF, thanks to our method, the performance of station 1 only depends on the number of sharing access stations and no more on their relative positions with respect to the AP. In other word, the fact that station 2 transmits at 5.5Mbit/s or more or less does not really affect the station 1 throughput. According to our scheme, the utilization time of the medium is equally shared among the different stations. Moreover, each station uses its proportion of time according to its transmission bit rate. In this regard, using a low bit rate, the station will transmit less without penalizing the remaining contending stations. Based on Fig. 3, we can observe that the useful throughput of station 1 is the double of the station 2 throughput and 11 times the station 3 throughput.

In what follows, we evaluate the performance of our scheme under different simulation scenarios. Throughout this section, we compare our method to the classical DCF scheme. To do so, we study the impact of our scheme on the total network throughput and the collision probability.

As explained before, one of the major concerns with DCF is the drastic degradation of the total network throughput due to the relatively far away stations with respect to the AP. Figure 4 confirms this issue, where the total throughput significantly degrades once station 2 and 3 join the network. Figure 4 also shows that our DCF-MB scheme alleviates this issue. Indeed, the increase of sharing nodes degrades less significantly the total network throughput when using DCF-MB. Specifically, when the number of sharing nodes is 3, the throughput obtained thanks to our DCF-MB is 4.21Mbit/s whereas it is limited to 1.71Mbit/s with the classical DCF.

Note that the slight decrease of the total throughput with DCF-MB when station 2 and 3 are activated is due two main reasons. First, station 2 and 3 transmit at relatively low bit rates with respect to station 1 during their utilization of the medium, which reduces the total network throughput. Moreover, increasing the number of access stations increases the collision probability among different nodes' frames, leading thus to increasing bandwidth waste.

In this context, Fig 5 shows the total network throughput evolution with the network density. We refer by the network density as the number of access nodes composing each bit rate class (11, 5.5 and 1Mbit/s). In this case, the network density varies from 1 to 7, that is, the total number of access nodes varies from 3 to 21. Again, Fig. 5 shows that the total network throughput decreases with the increase of access nodes for both cases (DCF and DCF-MB). Moreover, this figure exhibits once more the significant gain introduced by our method.

Figures 6 and 7 show the average useful throughput of each class bit rate for the DCF and DCF-MB cases, respectively. Figure 6 shows that, using the classical DCF, all the access stations have the same useful throughput although their different transmitting bit rates. Moreover, the useful throughput of each class is very low (less than 0.6Mbit/s). This is typically due to the limitations of the classical DCF.

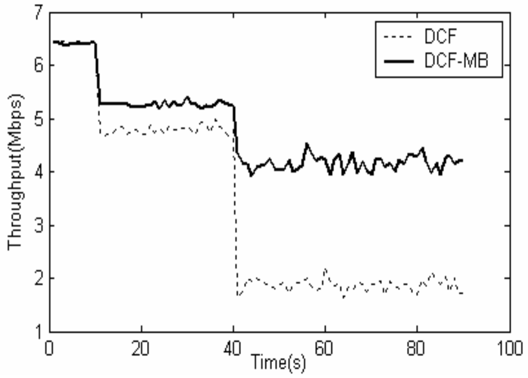

Fig. 4. Evolution of the total useful throughput of the network.

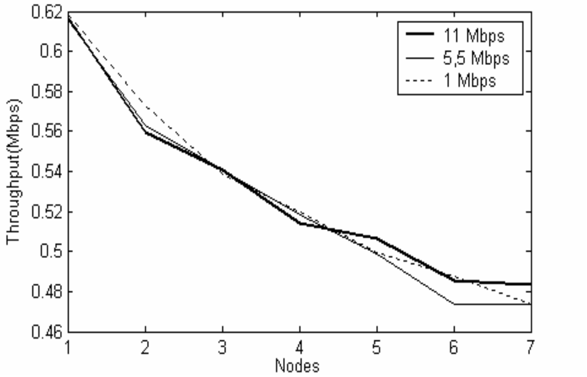

Fig. 6. Impact of the network density on the useful throughput of each class bit rate: DCF case.

On the other hand, enabling our DCF-MB scheme, this issue is alleviated. Figure 7 shows that the throughput is fairly distributed among different classes. In addition, the throughput per class significantly increases. Specifically, when density is equal to 1, a station belonging to class C_1 benefits from a throughput around 2.5Mbit/s, whereas the same station has a throughput less than 0.6Mbit/s when DCF-MB is disabled.

In Fig. 8 the network density is set equal to 1. In other words, the network is composed of 3 stations belonging to classes C_1, C_2 and C_3. Figure 8 depicts the evolution of the total network throughput with the arrival rate of frames. Recall that the frames arrive to each node level according to a Poisson process. Figure 8 shows that both DCF and DCF-MB behaves similarly when the network load is low. On the other side, increasing the arrival rate, a network using the classical DCF is rapidly saturated with a maximal network throughput of 1.71Mbit/s. In contrast, enabling DCF-MB, the network throughput attains 4.21 Mbit/s.

Finally, we conclude this section by studying the impact of our scheme on the collision in the network. In such network, a collision between two stations occurs when their associated backoff counters expire at the same time. Figure 9 depicts the collision probability according both DCF and DCF-MB schemes. To achieve this, we use the same scenario used in section III. According to Fig. 9, we can observe that the collision probability reduces when DCF-MB is enabled. This is a direct result of the utilization of different contention windows for the different classes of stations.

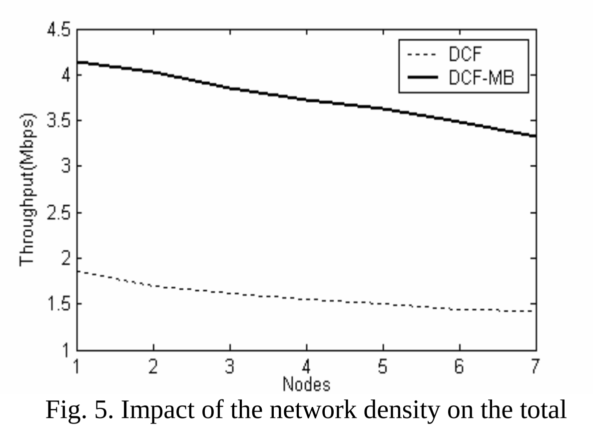

Fig. 5. Impact of the network density on the total network throughput.

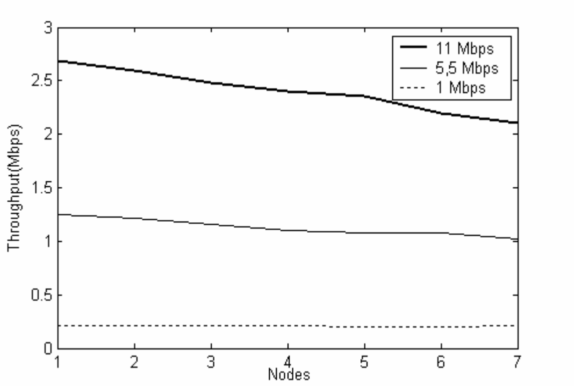

Fig. 7. Impact of the network density on the useful throughput of each class bit rate: DCF-MB case.

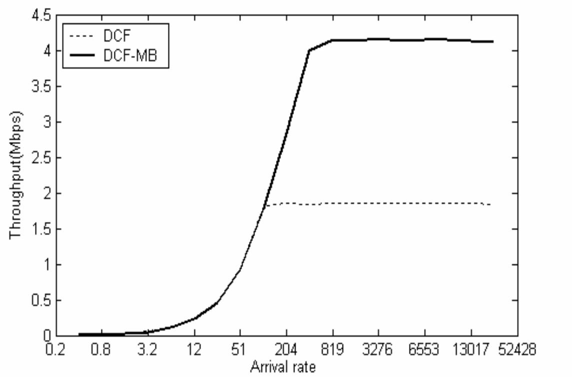

Fig. 8. Evolution of the total network throughput as a function of the arrival rate $\left(\times 10^{-6}\right)$.

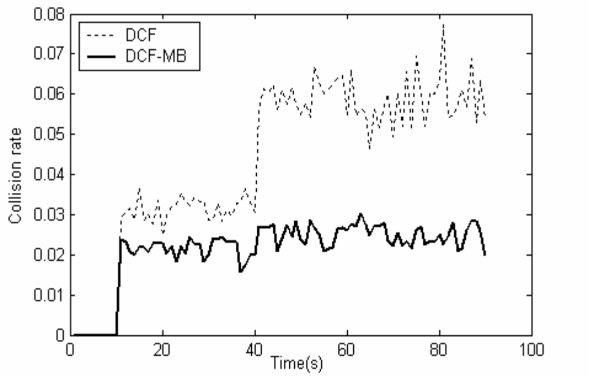

Fig. 9. Comparison between DCF and DCF-MB collision rate.

6. CONCLUSIONS

In this paper, we proposed an improvement of the existing DCF scheme in order to cope with its unfairness limitations. We advised the introduction of relative priorities among different access stations according to their physical transmission bit rate. To achieve this, we used different contention window sizes for each class of bit rate. Finally, we motivated the use of the proposed scheme since it allows achieving fairness among contending access nodes while improving the total network throughput.

References

[1] IEEE Std 802.11e/D13.0, *Part 11: Wireless LAN Medium Access Control (MAC) and physical Layer (PHY) Specifications: Amendment: Medium Access Control (MAC) Quality of Service (QoS) Enhancements*, Jan 2005.

[2] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, *Performance anomaly of 802.11b*, IEEE Infocom’03, San Francisco, USA, Mar. 2003

[3] C. Koksal et al, *An analysis of short-term fairness in wireless media access protocols*, Proceedings of ACM SIGMETRICS, 2000.

[4] G. Holland and N. H. Vaidya, *Analysis of TCP performance over mobile ad hoc networks*, IEEE/ACM MobiCom’99, August 1999, pp. 219–230.

[5] K. Tang, M. Correa, and M. Gerla, *Effects of ad hoc MAC layer medium access mechanisms under TCP*, ACM/Bal MONET, vol. 6, no. 4, pp. 317–329, 2001.

[6] C. L. Barrett, M.V. Marathe, D. C. Engelhart, and A. Sivasubramaniam, *Analyzing the short-term fairness of IEEE 802.11 in wireless multihop radio networks*, MASCOTS’02, Fort Worth, TX, USA, Oct. 2002.

[7] S. Choi, J. del Prado, S. Shankar, S. Mangold, *IEEE 802.11e Contention-Based Channel Access (EDCF) Performance Evaluation.*, Proceedings of IEE ICC 03, Anchorage, Alaska, USA, May 2003.

[8] I. Aad and C. Castelluccia, *Differentiation mechanisms for IEEE 802.11*, IEEE Infocom’01, Anchorage, AK, USA, Apr. 2001.