Channel Access Unfairness of Wireless LAN Access Methods

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***Abstract*— In this paper, we present an evaluation of chosen wireless LAN access methods involving stations with different bit error rates: $n-1$ stations in ideal transmission conditions (*BER* $= 0$) and 1 station with a given bit error rate (*BER* $\neq 0$). The simulation results show that the IEEE 802.11 DCF and its modifications (*Slow Decrease*, *AOB*) are very sensitive to transmission errors, whereas *Idle Sense* provides good channel access fairness: the value of the contention window is almost the same regardless of transmission errors, so that the throughput difference between stations subject to different bit error rates corresponds only to the proportion of lost frames.**

I. Introduction

An access method in a *Wireless Local Area Network* (WLAN) defines contention rules for stations that share a common radio channel. It needs to have many desired properties such as high throughput, good channel access fairness, and low collision overhead. Since the definition of the IEEE 802.11 DCF (*Distributed Coordination Function*) [1], many variants and modifications have been proposed to improve its performance. Usually, they are evaluated under ideal channel conditions, which means that transmission errors are not taken into account. In fact, transmission conditions strongly influence the performance of most WLAN access methods: as a station cannot distinguish between a failed transmission and a collision, it always applies the exponential backoff algorithm when it does not receive an ACK—it doubles the *Contention Window* (*CW*) from which random backoff intervals are chosen. This means that the station in bad transmission conditions may have less transmission opportunity than other stations.

Several authors have pointed out important performance problems of the IEEE 802.11 DCF under imperfect transmission conditions. The most significant example of such problems is the *physical layer capture* [2] that results in strong channel access unfairness between two stations transmitting to an access point with different signal strengths. The station with the stronger signal succeeds to transmit in case of a collision whereas the other one is penalized twice: it fails its transmission because of a collision and performs the exponential backoff that lowers its probability of channel access. Note that the capture effect may appear independently of transmission errors—Kochut *et al.* have analyzed the effect by assuming no channel errors for both stations.

In a previous work, we have evaluated several representative access methods in presence of transmission errors [3]. We have assumed one infrastructure *Basic Service Set* (BSS) and considered that all stations are subject to the same *Bit Error Rate* (BER). The results show that increased bit error rates degrade the throughput and the channel access fairness of the IEEE 802.11 DCF and its modifications (*Slow Decrease* [4] and *Asymptotically Optimal Backoff* [5]). The main reason of this degradation is again the exponential backoff applied after each frame loss. The only access method that does not suffer from adverse transmission conditions is the *Idle Sense* [6], because it does not use the exponential backoff and totally decouples contention control from dealing with frame losses.

In this paper, we push the investigation further by considering a more realistic scenario in which stations in a BSS may have different bit error rates: we assume that in a cell with n stations, 1 station experiences transmission errors with a given bit error rate (*BER* $\neq 0$) and all $n-1$ other stations benefit from perfect transmission conditions (*BER* $= 0$). In fact, this corresponds to a realistic situation in which stations at different spatial positions with respect to an access point may experience different transmission conditions: a station far away from the access point will have higher bit error rates than the stations in the closed vicinity of the access point. We will say that an access method is *sensitive to transmission errors*, if the stations do not obtain a similar level of performance for differing transmission conditions.

To perform our study, we consider four wireless LAN access methods: the original IEEE 802.11 DCF [1], *Slow Decrease* [4], *Asymptotically Optimal Backoff* (AOB) [5] and *Idle Sense* [6]. The three last mechanisms improve the performance of the IEEE 802.11 DCF, work in a fully distributed way and do not require an estimation of the number of active hosts, which distinguish them from other proposals that we have not considered in this study.

Our results show that for the IEEE 802.11 DCF and its modifications (*Slow Decrease* and *AOB*) the performance of the station with a higher bit error rate is much lower than for the other stations. We can thus say that these access methods are *sensitive to transmission errors*. *Idle Sense* performs much better, because the station with a higher bit error rate exhibits much lower performance degradation.

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The results of this paper provide quantitative evidence of *Idle Sense* fairness when stations experience imperfect transmission conditions.

The paper is organized as follows. Section II presents the principles of chosen access methods. Section III describes the simulation environment. In Section IV, we analyze and compare the performance of the access methods for different bit error rates. Finally, Section V summarizes the results and concludes the paper.

II. Wireless LAN Access Methods

To realize our study, we have considered four wireless LAN access methods: the IEEE 802.11 *Distributed Coordination Function* (DCF) [1], *Slow Decrease* [4], *Asymptotically Optimal Backoff* [5] and *Idle Sense* [6].

The IEEE 802.11 DCF uses the *Carrier Sense Multiple Access/Collision Avoidance* (CSMA/CA) access method: before initiating a transmission, a station senses the state of the channel. If the medium is sensed busy, the station waits until the channel is free during a *Distributed Interframe Space* (DIFS) interval, afterwards, it waits for an additional random contention time. The station chooses a backoff time that is an integer number of time slots distributed uniformly in the contention window $[0, CW-1]$. The value of *CW* is set to $CW_{\min}$ for the first transmission attempt and it is increased in integer powers of 2 at each failed transmission (collision or frame loss) up to $CW_{\max}$.

The *Slow Decrease* method aims at adapting the contention window of each station to the current network congestion level by performing a slow decrease of *CW* values. After each successful transmission, the new *CW* value is chosen as the maximum value between $CW_{\min}$ and $\delta * CW_{\text{old}}$. The constant decrease factor δ has a power of 2 form $\delta = 1/2^g$, where g is a positive integer greater than zero. $g = 1$ means $\delta = 1/2$, which is the slowest decrease for which the method achieves the best performance in terms of throughput.

In *AOB*, each station observes the number of slots in the backoff interval in which one or more stations attempt transmission and the total number of slots available for transmission in the backoff interval. In this way, each station is able to obtain the utilization rate of the slots observed on the channel (*Slot Utilization*). Each station computes the *Probability of Transmission* that depends on the *Slot Utilization* and evaluates the opportunity of either attempt or defer a scheduled transmission. If the transmission is rescheduled, a new backoff interval is computed.

Finally, in the *Idle Sense* method, each host estimates the number of consecutive idle slots between two transmission attempts and uses it to adjust its *CW* to the optimal value by means of the *Additive Increase Multiplicative Decrease* (AIMD) principle [7]. The *Idle Sense* proposal goes further beyond the IEEE 802.11 DCF: contending stations do not perform the exponential backoff algorithm after failed transmissions, rather they make their contention windows dynamically converge in a fully distributed way to similar values solely by tracking the number of idle slots between transmissions.

III. Simulation environment

To perform our evaluation, we have developed a discrete-event simulator that implements the standard IEEE 802.11 DCF method and all other considered access methods for different parameters of the physical and MAC layer. The simulation tool evaluates the access methods in terms of throughput and channel access fairness. It has been used in published papers [3], [8]. We have chosen the physical and MAC layer of IEEE 802.11g [9] for the study. We use the values of $CW_{\min} = 8$ and $CW_{\max} = 1024$ for the simulations of *Slow Decrease*, because the authors state that a small initial contention window value achieves higher throughput gain [4]. $CW_{\min} = 16$ and $CW_{\max} = 1024$ are the values defined in the IEEE 802.11g physical layer, so we use them for the IEEE 802.11 DCF and *AOB*, as well as for the initial values in *Idle Sense* simulations. To get our simulation results we have run a large number of independent simulations and obtained small confidence intervals, so that they are not shown in the figures.

We consider a scenario involving one infrastructure BSS. The stations transmit at the highest available data rate (54 Mbps) and send data frames with the maximum size used in practice, that is the Ethernet MTU of 1500 bytes. We consider the case of greedy hosts: they always have a frame to transmit. To study the effect of transmission errors on performance, we vary the number of stations in the cell and the bit error rate: we assume that in a cell with n stations, 1 station experiences transmission errors with a given bit error rate ($BER \neq 0$) and all $n-1$ other stations benefit from perfect transmission conditions ($BER = 0$). We consider independent errors occurring during transmission and simply compute the *Frame Error Rate* as $FER = 1 - (1 - BER)^l$, where l is the frame size in bits.

IV. System performance

Initially, we have considered the following setup: $BER = 10^{-5}$ ($FER_{\text{DATA}} = 12\%, FER_{\text{ACK}} = 0.65\%$) for the host subject to $BER \neq 0$. Figure 1 presents the throughput performance for a host with ideal channel conditions ($BER = 0$) and Figure 2 shows the throughput for the station with $BER = 10^{-5}$. We can observe that in the first case, *Idle Sense* performs slightly worse than other access methods for a small number of stations. As the number of stations in the cell increases, so does the proportion of stations subject to $BER = 0$ and the performance of the access methods becomes similar. On the other hand, we can see from Figure 2 that the station subject to $BER = 10^{-5}$ performs better for any number of stations if it uses *Idle Sense*. For this station, *Idle Sense* achieves a throughput gain of 48.1% for a BSS composed of 10 stations and a gain of 69.6% for a cell with 25 stations compared to the results obtained by the IEEE 802.11 DCF. Moreover, we can observe that the throughput values of the station with $BER = 0$ and that with $BER = 10^{-5}$ are fairly close for the *Idle Sense* mechanism.

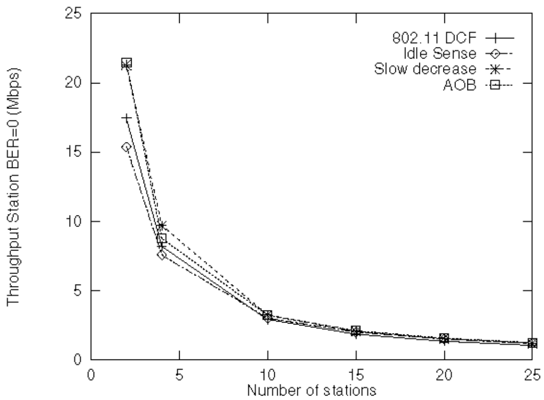

Fig. 1. Throughput for the station with $BER = 0$ vs. number of stations.

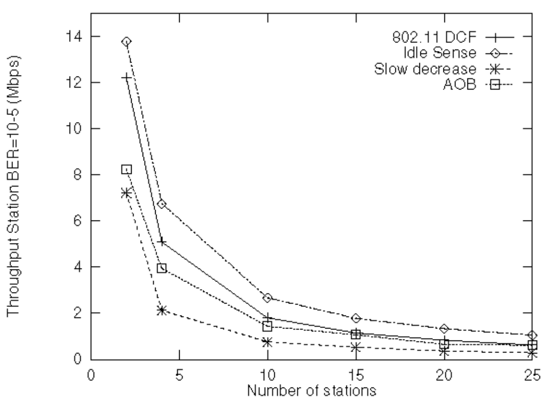

Fig. 2. Throughput for the station with $BER = 10^{-5}$ vs. number of stations.

Table I shows a comparison of throughput for each access method and stations with different transmission conditions. We can observe that for the first three access methods (IEEE 802.11 DCF, *Slow Decrease* and *AOB*) the station in adverse transmission conditions ($BER = 10^{-5}$) obtains much lower part of the throughput compared to the station in ideal transmission conditions: in a BSS composed of 10 stations the throughput difference is 61.87% for the IEEE 802.11 DCF, 324.09% for *Slow Decrease*, and 124.65% for *AOB*. *Idle Sense* performs the best with a slight reduction of the throughput around 11-14%.

The behavior of the access methods can be explained by examining the values of the contention window *CW* (cf. Table II). For the first three access methods (IEEE 802.11 DCF, *Slow Decrease* and *AOB*), large differences in throughput come from the corresponding large differences in the contention window that can be seen from Table II. In these access methods, stations perform the exponential backoff after a frame loss, which leads to an increase in the *CW* values for the station with a higher error rate, so it will experience lower access probability and lower throughput. For *Idle Sense*, the *CW* values for stations with different bit error rates are almost equal. The difference in throughput can be explained by a lower probability of successful transmission for the station in

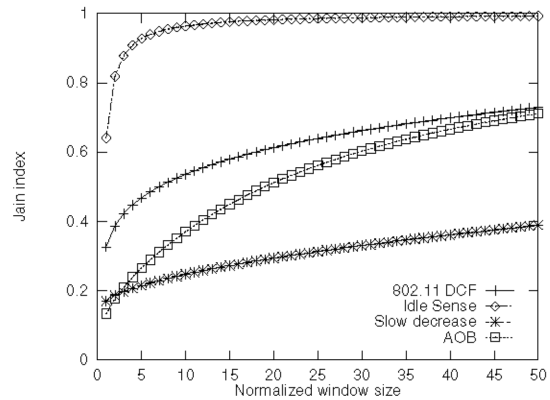

Fig. 3. Channel access fairness comparison for 25 competing stations, 1 station subject to $BER = 10^{-5}$ and 24 stations to $BER = 0$.

adverse transmission conditions ($BER = 10^{-5}$). As CW does not depend on the bit error rate for *Idle Sense*, we can say that this access method is *insensitive to transmission errors*.

After analyzing throughput, we evaluate channel access fairness. We use the sliding window method that considers the patterns of transmissions and computes the average *Jain fairness index* in a window of an increasing size [10]. It is defined as follows: consider n stations in the system and let γ_i be the fraction of transmissions performed by host i during window w; the fairness index is the following:

$$F_J(w) = \frac{(\sum_{i=1}^{n} \gamma_i)^2}{n \sum_{i=1}^{n} \gamma_i^2}. \tag{1}$$

Perfect fairness is achieved for $F_J(w) = 1$ and perfect unfairness for $F_J(w) = 1/n$.

We normalize the window size with respect to the number of hosts and compute the *Jain index* for the window sizes which are multiples of n: we call m such that $w = m \times n, m = 0, 1, 2, ...$, a *normalized window size*. Thus, the *Jain index* is computed as $F_J(m)$. We can see from Figure 3 that *Idle Sense* presents much better fairness than the IEEE 802.11 DCF, *Slow Decrease*, and *AOB* regardless of the time scale over which fairness is computed.

Another aspect that we want to investigate is the influence of higher error rates: one station in a cell is subject to $BER = 10^{-4}$ ($FER_{\text{DATA}} = 72\%, FER_{\text{ACK}} = 6.4\%$). Figure 4 presents throughput of a station in ideal transmission conditions ($BER = 0$), whereas Figure 5 gives the results for the station with $BER = 10^{-4}$. We can observe that, the throughput of the station with $BER = 0$ for *Idle Sense* is similar to the one shown in Figure 1. The station with $BER = 10^{-4}$ obtains a lower throughput, however it is still much larger than the observed for the other methods. Stations in ideal transmission conditions for the IEEE 802.11 DCF, *Slow Decrease*, and *AOB* increase their throughput, but the station in adverse transmission conditions sees its throughput almost reduced to zero, especially for a larger number of stations. Consequently, this station will need to switch to a lower transmission rate to be able to operate. On the opposite,

TABLE I

THROUGHPUT (IN MBPS) COMPARISON FOR EACH ACCESS METHOD AND DIFFERENT TRANSMISSION CONDITIONS

Number of stations	2	4	10	15	20	25
IEEE 802.11 DCF, $BER = 0$	17.44	8.22	2.92	1.85	1.34	1.05
IEEE 802.11 DCF, $BER = 10^{-5}$	12.22	5.10	1.80	1.15	0.83	0.62
Difference	42.74%	60.92%	61.87%	61.08%	60.95%	68.25%
Slow Decrease, $BER = 0$	24.28	9.68	3.24	2.06	1.51	1.18
Slow Decrease, $BER = 10^{-5}$	7.21	2.13	0.76	0.53	0.37	0.29
Difference	236.65%	354.74%	324.09%	289.96%	311.03%	311.44%
AOB, $BER = 0$	21.46	8.76	3.22	2.10	1.57	1.24
AOB, $BER = 10^{-5}$	8.25	3.95	1.43	1.07	0.66	0.61
Difference	160.28%	121.77%	124.65%	96.66%	139.37%	102.44%
Idle Sense, $BER = 0$	15.38	7.57	3.01	2.01	1.51	1.21
Idle Sense, $BER = 10^{-5}$	13.77	6.74	2.67	1.78	1.33	1.06
Difference	11.64%	12.28%	12.78%	12.74%	13.13%	13.96%

TABLE II

COMPARISON OF THE CONTENTION WINDOW *CW* FOR EACH ACCESS METHOD AND DIFFERENT TRANSMISSION CONDITIONS

Number of stations	2	4	10	15	20	25
IEEE 802.11 DCF, $BER = 0$	17.71	22.25	36.55	47.01	56.36	65.74
IEEE 802.11 DCF, $BER = 10^{-5}$	22.16	30.70	51.93	64.88	80.14	96.34
Difference	25.15%	38.01%	42.09%	38.01%	42.19%	46.54%
Slow Decrease, $BER = 0$	9.21	16.09	36.48	52.63	66.48	82.23
Slow Decrease, $BER = 10^{-5}$	23.47	57.05	124.52	164.63	205.75	264.23
Difference	154.77%	254.56%	241.37%	212.78%	209.48%	221.33%
AOB, $BER = 0$	19.11	30.95	55.92	70.95	81.75	95.34
AOB, $BER = 10^{-5}$	33.38	51.13	91.77	109.02	137.49	148.79
Difference	74.66%	65.21%	64.12%	53.65%	68.18%	56.06%
Idle Sense, $BER = 0$	29.23	54.80	122.17	169.87	213.22	256.74
Idle Sense, $BER = 10^{-5}$	29.28	54.37	121.92	170.11	213.68	257.23
Difference	0.16%	0.79%	0.21%	0.14%	0.22%	0.19%

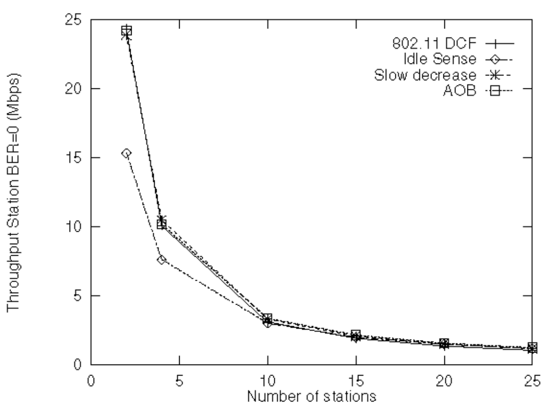

Fig. 4. Throughput for the station with $BER = 0$ vs. number of stations.

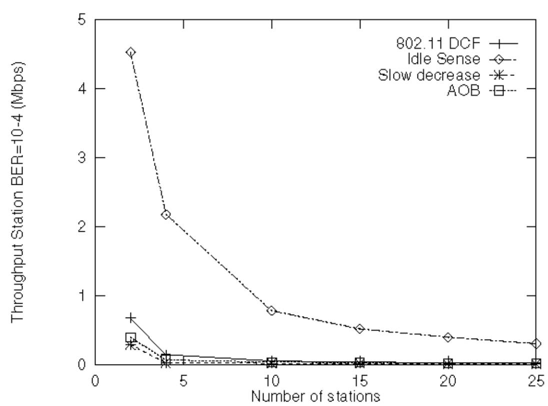

Fig. 5. Throughput for the station with $BER = 10^{-4}$ vs. number of stations.

stations using *Idle Sense* will reach this situation for error rates higher than $BER = 10^{-4}$. *Idle Sense* is thus more robust with regard to transmission errors, what allows stations to operate at higher bit rates.

The much better throughput performance of *Idle Sense* for the station subject to $BER = 10^{-4}$ can be explained by the fact that contending stations do not perform the exponential backoff. Figure 6 shows the *CW* values for the station with $BER = 0$ and Figure 7 presents corresponding results for the station with $BER = 10^{-4}$. We can see that the *CW* values are very different for these two types of stations while using the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*. The extent of the difference is even much larger than the results presented in Table II. The three access methods perform the exponential backoff after a collision or a frame loss. As the bit error rate increases, the exponential backoff results in a larger increase in the *CW* values (Figure 7), which become far from the optimal value derived for *Idle Sense* [6] leading to lower throughput performance. Figures 6 and 7 show that *Idle Sense* obtains *CW* values similar to the ones presented in Table II: this

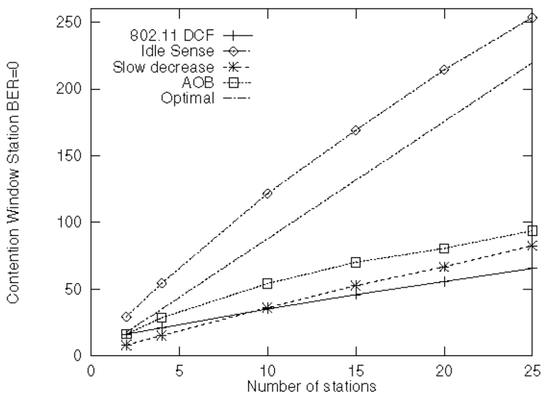

Fig. 6. *CW* for the station with $BER = 0$ vs. number of stations.

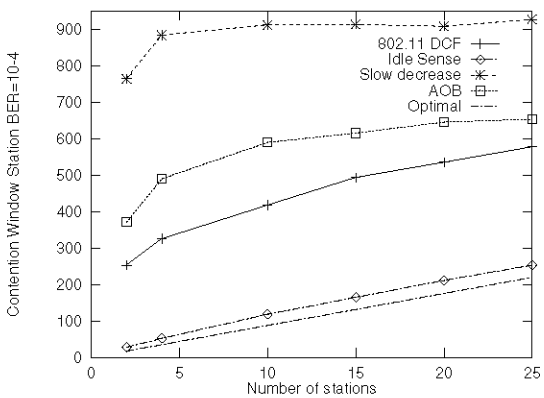

Fig. 7. *CW* for the station with $BER = 10^{-4}$ vs. number of stations.

access method uses the *CW* values close to the optimal one independently of channel conditions. Therefore, we can say that *Idle Sense* is *insensitive to transmission errors.*

As above, we also evaluate channel access fairness for the higher error rate. Figure 8 shows that *Idle Sense* presents much better fairness than the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*.

V. Conclusions

In this paper, we have presented an evaluation of chosen wireless LAN access methods involving stations under different transmission conditions. The results of simulations show that throughput and channel access fairness for the IEEE 802.11 DCF and its modifications (*Slow Decrease*, *AOB*) do not provide sufficient independence of transmission conditions. In fact, these methods penalize the station in adverse transmission conditions to a large extent: for bit error rates higher or equal to $BER = 10^{-4}$, its throughput may be almost reduced to zero. The main reason of this effect is the exponential backoff performed after a frame loss, which leads to an increase in the contention window for the station with higher error rates, so it will experience lower access probability and lower throughput. Unlike these access methods, *Idle Sense* is *insensitive to transmission errors*: the value of the contention

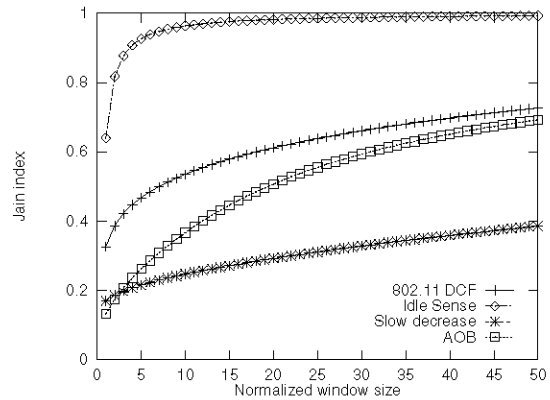

Fig. 8. Channel access fairness comparison for 25 competing stations, 1 station subject to $BER = 10^{-4}$ and 24 stations subject to $BER = 0$.

window is almost the same for both types of stations, so that the difference in throughput is only due to experienced transmission errors. The main reason is that *Idle Sense* does not perform exponential backoff. By using the *AIMD* principle to adjust the contention windows of stations, it makes them converge to values close to the optimal independently of bit error rates. This fact leads to more robust behavior in presence of transmission errors and allows stations subject to adverse channel conditions to work at higher transmission rates.

Acknowledgments

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