Performance of Wireless LAN Access Methods in Multicell Environments

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***Abstract*— In this paper, we address the issue of evaluating performance of wireless LANs in multicell scenarios. We try to understand the complex behavior of the DCF (*Distributed Coordination Function*) access method defined in the IEEE 802.11 standard [1] and its modifications proposed for improving performance: *Slow Decrease* [2], *Asymptotically Optimal Backoff* [3], and *Idle Sense* [4]. We analyze the influence of overlapping cells and large multicell environments on their performance. Our results show that the IEEE 802.11 DCF and its two modifications (*Slow Decrease* and *AOB*) exhibit important unfairness between stations close to the access point and those near the border of a neighbor cell. *Idle Sense* performs much better: it provides much better fairness than the IEEE 802.11 DCF and its modifications. It also obtains the highest throughput when stations adapt their bit rate to channel conditions.**

I. INTRODUCTION

Wireless Local Area Networks (WLANs) are being increasingly deployed in many places to provide easy and tetherless access to the Internet. When the density of deployment becomes high, several cells may be found in a close vicinity and the question of coexistence arises: where to place an access point (AP) and how to choose the right frequency channel. These choices influence the performance of a wireless cell that strongly depends on the distance from neighbor cells and on the level of interference. Due to a small number of available channels in the public 2.4 GHz band, co-channel and adjacent channel interference are significant issues [5]. The situation becomes even more complex with the effect of overlapping cells in which stations of different cells operate in the coverage range of each other (the problem of *exposed stations*), which leads to considerable performance degradation [6]. The multicell scenarios that correspond to realistic conditions in densely deployed areas have received so far little attention in the literature, because usually the performance of wireless LANs is evaluated assuming one isolated cell.

In this paper, we address the issue of evaluating performance of wireless LANs in multicell scenarios. We try to understand the complex behavior of the DCF (*Distributed Coordination Function*) access method defined in the IEEE 802.11 standard [1] and its modifications proposed for improving performance: *Slow Decrease* [2], *Asymptotically Optimal Backoff* [3], and *Idle Sense* [4]. 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 study uses a discrete-event simulator that accurately models the physical and MAC layer of IEEE 802.11 DCF and chosen access methods. We analyze the influence of overlapping cells and large multicell environments on their performance. To the best of our knowledge, this study is the first evaluation of the access methods in such environments.

Our results show that exposed stations reduce their performance degradation when working under *Idle Sense* mechanism. Moreover, the IEEE 802.11 DCF and its two modifications (*Slow Decrease* and *AOB*) exhibit important unfairness between the stations close to the access point and those near the border of a neighbor cell. The former benefit from good channel conditions and take advantage of the situation by increasing their throughput at the cost of the stations near the border. The throughput difference of these two types of stations is much larger for the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*. *Slow Decrease* presents the largest discrimination by giving the highest throughput to the close stations while *Idle Sense* shows smaller throughput differences.

We also show that when stations use an *ideal bit rate adaptation scheme* to choose an optimal bit rate for a given error rate, they suffer from *performance anomaly* [7]: the bit rate of a slower station limits the throughput of a fast station. The IEEE 802.11 DCF obtains lower aggregate throughput than the other methods. *Idle Sense* solves this problem by scaling the contention window with respect to the chosen bit rate [4] and presents an aggregate throughput higher than the other three access methods. Moreover, for *Idle Sense* a cell contains the largest number of stations operating at higher rates.

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 overlapping cells and multicell scenarios. Finally, Section V summarizes the results and concludes the paper.

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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* [2], *Asymptotically Optimal Backoff* [3], and *Idle Sense* [4].

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 station 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. 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 exposed software has been employed in published papers [5], [8] and evaluates the access methods in terms of throughput and fairness. We have chosen the physical 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 [2]. $CW_{\min} = 16$ 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 assume that stations transmit at the highest available data rate (54 Mbps) unless stated otherwise 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 stations: they always have a frame to transmit.

Our goal is to analyze the performance of different MAC access methods when multiple cells coexist in a given area. We consider the following scenarios:

1) *overlapping cells*: there are 2 infrastructure *Basic Service Sets* (BSS), each one with a station suffering from the overlapping cell problem: the station is in the coverage area of a station belonging to the other cell. All stations transmit in ideal channel conditions (we assume no transmission errors) and we vary the number of stations per cell;
2) *multiple cells*: there are a large number of BSS, each one composed of 10 stations uniformly distributed over the coverage area (we simulate 100 BSS covering a rectangular area with 36 cells in the middle considered for computing statistics). We use a validated propagation model for IEEE 802.11 devices operating at 2.4 GHz in outdoor environments [10]. We consider independent errors occurring during transmission with an upper bound on the frame error probability under the assumption of binary convolutional coding and hard-decision Viterbi decoding with independent errors [11].

IV. SYSTEM PERFORMANCE

A. Overlapping BSS

We analyze the overlapping BSS scenario to evaluate the performance of non-exposed and exposed stations for different access methods. Table I shows a comparison of throughput per station for each access method. We can observe that for any access method, an exposed station (the one in the overlapping BSS) strongly suffers from the degradation of throughput, because it hears the signal from both BSS. However, the throughput difference is much smaller for *Idle Sense* than for the other methods, e.g. it is 9.12% for 10 stations compared to 24.86% for the IEEE 802.11 DCF, 36.21% for *Slow Decrease*, and 33.12% for *AOB*. The gain for the exposed station is significant when it uses *Idle Sense*: its throughput is increased by 21.32% for 10 stations compared to the results observed under the IEEE 802.11 DCF.

Another aspect is channel access fairness that we evaluate by means of the *Jain fairness index* [12] (we normalize the window size with respect to the number of stations and

TABLE I

OVERLAPPING CELLS, THROUGHPUT (MBPS) COMPARISON FOR DIFFERENT ACCESS METHODS

Number of stations per BSS	2	4	10	15	20	25
IEEE 802.11 DCF, station in non-overlapping BSS	21.46	8.30	2.87	1.83	1.33	1.04
IEEE 802.11 DCF, station in overlapping BSS	9.35	5.17	2.30	1.55	1.19	0.95
difference	129.50%	60.47%	24.86%	17.86%	11.84%	9.56%
Slow Decrease, station in non-overlapping BSS	23.74	8.92	3.13	2.01	1.48	1.16
Slow Decrease, station in overlapping BSS	9.26	5.04	2.30	1.68	1.32	1.10
difference	156.35%	77.07%	36.21%	19.93%	12.09%	6.19%
AOB, station in non-overlapping BSS	21.61	8.57	3.14	2.06	1.54	1.23
AOB, station in overlapping BSS	9.31	5.12	2.36	1.79	1.34	1.07
difference	132.07%	67.52%	33.12%	15.03%	14.89%	14.45%
Idle Sense, station in non-overlapping BSS	20.59	8.11	3.04	2.01	1.51	1.21
Idle Sense, station in overlapping BSS	9.61	5.84	2.79	1.91	1.46	1.18
Throughput difference	114.17%	38.98%	9.12%	5.23%	3.43%	2.34%

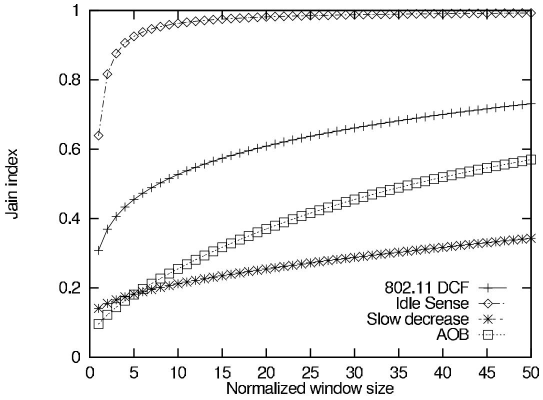

Fig. 1. Channel access fairness comparison in an overlapping BSS with 25 stations

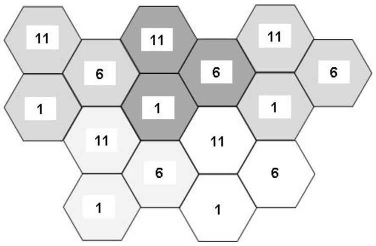

Fig. 2. Multiple cells with clusters of 3 cells

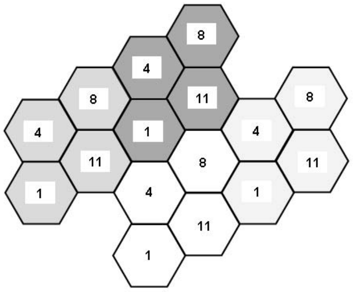

Fig. 3. Multiple cells with clusters of 4 cells

provide the Jain fairness index for the window sizes which are multiples of the number of stations). Figure 1 shows the Jain fairness index for an overlapping BSS with 25 stations. We can see that *Idle Sense* provides much better fairness than IEEE 802.11 DCF and its modifications. The result comes from the fact that *Idle Sense* does not perform the exponential backoff, which leads to higher fairness and an increased performance of exposed nodes.

B. Multiple cells

In this part, we investigate the performance of different wireless LAN access methods in large multicell environments. We consider a rectangular area covered with access points operating on channels chosen according to a *Fixed Channel Allocation* (FCA) scheme. We consider each BSS composed of 10 stations distributed randomly over the coverage area. At first, we assume that stations do not use any mechanism for bit rate adaptation such as *Automatic Rate Fallback* (ARF) [13], we relax this assumption later on.

We have simulated two cases:

1) *clusters of 3 cells*: we assign three non-interfering channels 1, 6, and 11 of the 2.4 GHz band (cf. Figure 2). Channels are not overlapped, but it is more difficult to cover the whole area, because the reuse distance is small and consequently the interference level is higher. Note that the reuse distance is $d = R \cdot \sqrt{3K}$, where R is the cell radius and K is the cluster size;
2) *clusters of 4 cells*: we assign four channels 1, 4, 8, and 11 of the 2.4 GHz band (cf. Figure 3). In this case, channels are partially overlapped with some adjacent-channel interference factors [14], but it is easier to cover the area—the reuse distance is higher in this case.

In both considered cases, 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 error rates than the stations in the closed vicinity of it. Moreover, stations at the border of neighbor cells may suffer from the exposed station problem, because they receive the signal from both BSS.

First, we have analyzed the influence of the distance from an

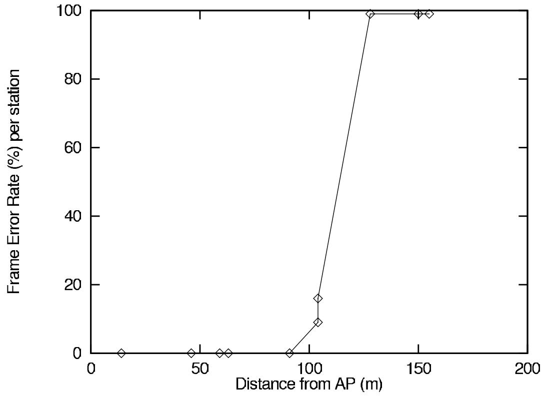

Fig. 4. Frame Error Rate (%) vs. distance from AP, clusters of 3 cells

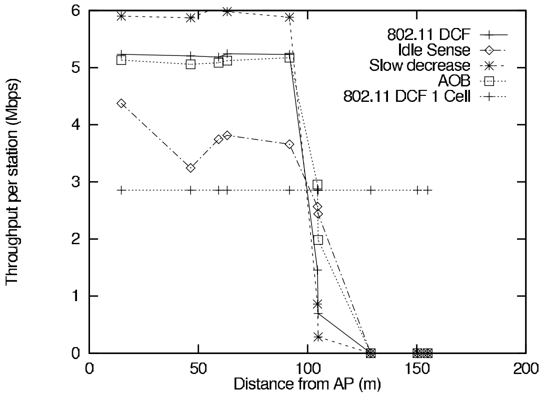

Fig. 6. Throughput per station vs. distance from AP, clusters of 3 cells

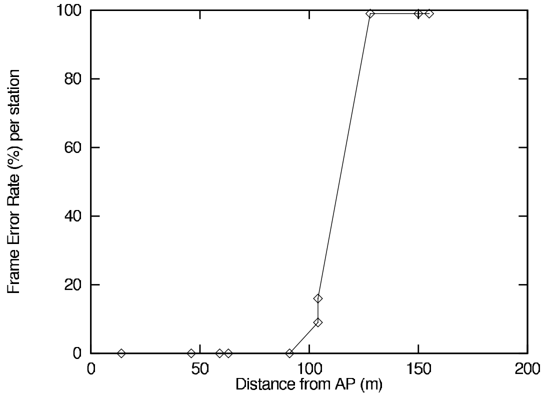

Fig. 5. Frame Error Rate (%) vs. distance from AP, clusters of 4 cells

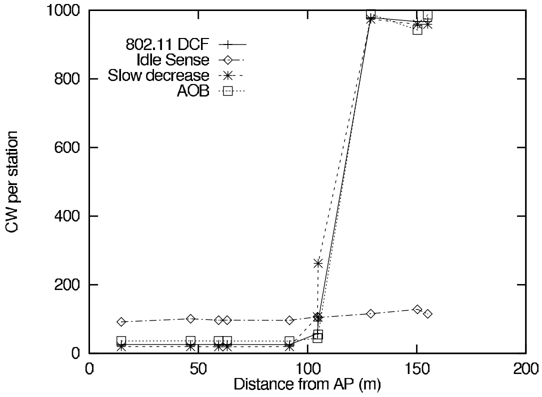

Fig. 7. Contention window vs. distance from AP, clusters of 3 cells

access point on transmission errors. Figures 4 and 5 show an important increase in the *Frame Error Rate* (FER) as stations approach the border of a cell. *FER* behaves slightly better in function of the distance for the clusters of 4 cells than for the clusters of 3 cells.

1) Clusters of 3 cells: Figure 6 presents throughput for different access methods in the case of the clusters of 3 cells. We can see that performance degrades with the distance. The stations nearest to the access point, which benefit from a good frame error rate, take advantage of the situation and increase their throughput compared to the throughput that can be attained in an isolated cell. The gain is done at the cost of the lower throughput of the stations near the border. We can observe that the throughput difference of these two types of stations is much larger for the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*. *Slow Decrease* presents the largest discrimination by giving the highest throughput to close stations, while *Idle Sense* shows smaller throughput differences. For the isolated cell case, we do not consider noise, so the results represent the ideal performance for an isolated cell. For multicell, we assume a noise level of -96 dBm and we take into account the interference generated by neighbor cells.

To get more insight into the behavior of the access methods, we have collected statistics on the contention window *CW* (cf. Figure 7). For the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*, the most distant stations from the access point, which suffer from *FER* values near 100%, considerably increase their *CW* compared to the stations close to the access point. This fact decreases their access probability so they suffer less from the effect of exposed stations. Consequently, stations close to the access point operate in an aggresive manner by using small values of *CW*. As *Idle Sense* does not use the exponential backoff, its *CW* values are almost equal for all the stations independently of their distance from the access point, and consequently, of their frame error rate, which is a desirable property. In this way, they also experience similar channel access probability, which equalizes the throughput of stations far away and close to the access point. The small variations in *CW* are due to the overlapping BSS problem: some stations work at the border of overlapping neighbor cells.

Figure 8 presents channel access fairness for the clusters of 3 cells. We can observe that *Idle Sense* provides much better fairness than any other access method.

2) Clusters of 4 cells: We analyze the same performance indices as above for the cluster of 4 cells. Figure 9 shows throughput for different access methods. In this case, the stations at the border obtain higher throughput due to a decreased level of interference, e.g. an IEEE 802.11 DCF

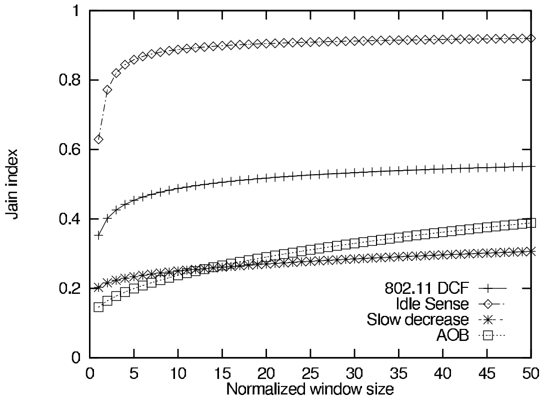

Fig. 8. Channel access fairness comparison for 10 competing stations, clusters of 3 cells

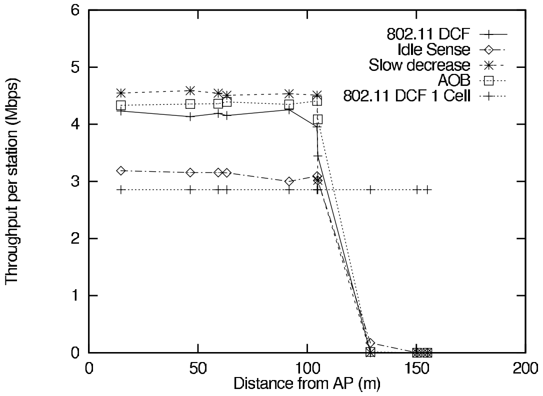

Fig. 9. Throughput per station vs. distance from AP, clusters of 4 cells

station at 110 m from the access point obtains almost 3.5 Mbps compared to 1.4 Mbps for the cluster of 3 cells. The throughput increase of the stations at the border is compensated by a small throughput decrease of the stations near the access point. We can also observe that *Idle Sense* still provides the smallest throughput differences.

As above, we also evaluate channel access fairness for the cluster of 4 cells. We can see from Figure 10 that *Idle Sense* provides better fairness than the other access methods. Moreover, as the problem of exposed nodes is reduced, *Idle Sense* improves its fairness with respect to the level observed in Figure 8. The other three access methods increase also their fairness: the problem of overlapping BSS is reduced and error rates are decreased.

3) Impact of bit rate adaptation: Stations far from the access point experience high error rates. At some threshold frame error rate, a station may lower its bit rate to obtain better throughput—transmission at the lower bit rate uses more robust modulation schemes that decrease the frame error rate (e.g. the IEEE 802.11g [9] and IEEE 802.11a [15] standards define several bit rates ranging from 6 to 54 Mb/s). Obviously, transmission takes longer, but a station expects this to be compensated by a decrease in the frame error rate, which globally results in better throughput. Let us consider a single station transmitting at the higher bit rate (lower bit rate) r_h (respectively r_l). When switching to the lower bit rate, we expect to lower the frame error rate from e_h to e_l. A simple analysis shows that [4]:

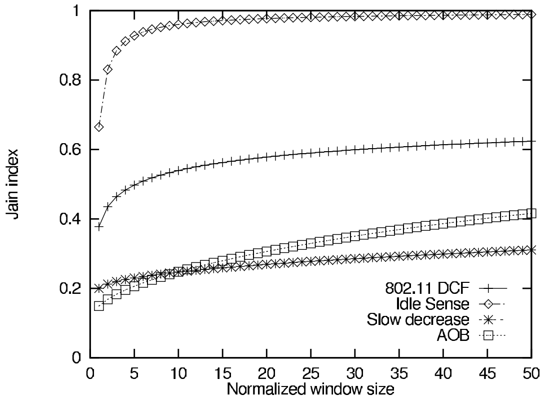

Fig. 10. Channel access fairness comparison for 10 competing stations, clusters of 4 cells

TABLE II

AGGREGATE THROUGHPUT (MBPS), BIT RATE ADAPTATION

Single Cell, IEEE 802.11 DCF	28.55
Single Cell, Slow Decrease	29.75
Single Cell, AOB	30.66
Single Cell, Idle Sense	30.16

Cluster of	*3 cells*	*4 cells*
Multicell, IEEE 802.11 DCF	24.71	21.85
Multicell, Slow Decrease	26.42	24.11
Multicell, AOB	26.63	25.17
Multicell, Idle Sense	27.70	27.35

$$e_\mathrm{h} \cong 1 - \frac{r_\mathrm{l}}{r_\mathrm{h}} \tag{1}$$

This means that for IEEE 802.11b, we need to switch from 11 Mb/s to 5.5 Mb/s when the frame error rate exceeds 50%.

We have evaluated the performance of the chosen access methods for stations adapting the bit rate to the channel conditions. We have assumed that stations implement an *ideal bit rate adaptation scheme*: a station is always able to choose an optimal bit rate for a given error rate so that it obtains the best performance. We do not use the existing schemes such as *Auto Rate Fallback* (ARF) [13] nor the proposed ones such as *Receiver Based Auto Rate* (RBAR) [16], because they present some important performance drawbacks or implementation problems. In this way, we can compare different access methods so that none of them is penalized by the bit rate adaptation scheme.

Table II presents a comparison of the aggregate throughput obtained by stations operating at the bit rate adapted to the channel conditions in a multicell environment. Moreover, we compare these results with the aggregate throughput achieved in an isolated cell with stations transmitting at the maximal bit rate—54 Mbps. We present the results for 10 stations per BSS. When stations use lower bit rates, they suffer from *performance anomaly* [7]: the bit rate of a slower station limits

TABLE III

ASSIGNMENT OF BIT RATES (MBPS) FOR CLUSTERS OF 3 CELLS

Station	IEEE 802.11 DCF	Slow Decrease	AOB	Idle Sense
1	54	54	54	54
2	54	54	54	54
3	54	54	54	54
4	54	54	54	54
5	54	54	54	54
6	36	36	36	54
7	36	36	36	48
8	36	36	36	36
9	18	18	18	36
10	18	18	18	24

TABLE IV

ASSIGNMENT OF BIT RATES (MBPS) FOR CLUSTERS OF 4 CELLS

Station	IEEE 802.11 DCF	Slow Decrease	AOB	Idle Sense
1	54	54	54	54
2	54	54	54	54
3	54	54	54	54
4	54	54	54	54
5	48	48	48	54
6	48	48	48	54
7	48	48	48	54
8	24	24	24	36
9	24	24	24	36
10	24	24	24	36

the throughput of a fast station. We can see from the table that the IEEE 802.11 DCF obtains lower aggregate throughput than the other methods. *Idle Sense* solves the performance anomaly problem by scaling the contention window with respect to the chosen bit rate [4]. In this way, it presents an aggregate throughput closer to the value obtained in an isolated cell and much higher than the other three access methods.

Moreover, stations in a cell are able to operate at higher transmission rates when they use *Idle Sense*, because it is more robust in presence of transmission errors [8]. Tables III and IV show the assignment of bit rates that leads to the best throughput for each access method. *Station 1* is the closest one to the access point and *Station 10* is the farthest one. In this way, for *Idle Sense* and clusters of 3 cells, we obtain 6 stations transmitting at 54 Mbps compared to 5 stations at 54 Mbps for the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*. Moreover, the two most distant stations from the access point are able to operate at 36 and 24 Mbps, respectively when they use *Idle Sense*, whereas they need to transmit at 18 Mbps for the three other access methods. For clusters of 4 cells and stations using *Idle Sense*, we obtain 7 stations operating at 54 Mbps compared to 4 stations for the IEEE 802.11 DCF, *Slow Decrease*, and *AOB*. Finally, the three most distant stations are able to transmit at 36 Mbps when they use *Idle Sense*, whereas the three other access methods need to operate at 24 Mbps.

V. CONCLUSIONS

In this paper, we have presented an evaluation of chosen access methods in various multicell scenarios. We have taken into account more realistic wireless environments than those studied in the literature: stations experience transmission errors and the influence of overlapping or neighbor cells. Our results show that exposed stations limit their performance degradation when they use *Idle Sense*. Moreover, the IEEE 802.11 DCF and its two modifications (*Slow Decrease* and *AOB*) present important unfairness between the stations close to the access point and those near the border of a neighbor cell. They exhibit much larger throughput differences for these two types of stations. For *Slow Decrease* the differences are particularly considerable, while *Idle Sense* shows smaller throughput differences. We also show that when stations adapt their bit rate to channel conditions, the IEEE 802.11 DCF obtains lower aggregate throughput than the other methods. *Idle Sense* presents in this case the highest aggregate throughput. Moreover, stations that use *Idle Sense* are able to operate at higher transmission rates.

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