Promise and Perils of Dynamic Sensitivity Control in IEEE 802.11ax WLANs

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***Abstract*—Dynamic sensitivity control (DSC) is being discussed within the new IEEE 802.11ax task group as one of the potential techniques to improve the system performance for next generation Wi-Fi in high capacity and dense deployment environments, e.g. stadiums, conference venues, shopping malls, etc. However, there appears to be lack of consensus regarding the adoption of DSC within the group. This paper reports on investigations into the performance of the baseline DSC technique proposed in the IEEE 802.11ax task group under realistic scenarios defined by the task group. Simulations were carried out and the results suggest that compared with the default case (no DSC), the use of DSC may lead to mixed results in terms of throughput and fairness with the gain varying depending on factors like inter-AP distance, node distribution, node density and the DSC margin value. Further, we also highlight avenues for mitigating the shortcomings of DSC found in this study.**

I. Introduction

Wireless local area networks (WLANs, a.k.a WiFi or IEEE802.11) have achieved tremendous success thanks to the explosive growth of portable computing and communications devices. At the same time as the growth in the number of the aforementioned end devices, the WiFi networks themselves are getting more and more dense in order to meet the huge traffic demand. It has been challenging for the current WiFi networks to tackle problems due to high density, notably, the interference arising from overlapped basic service set (OBSS) deployments. It was agreed that after generations of evolution from 802.11b to 802.11ac, the WiFi network design targeting improvements in the peak data rate has to now focus on improving the overall system performance instead of peak data rate alone to tackle the OBSS problems. The IEEE 802.11ax task group was formed to design high efficiency WLAN systems for future high capacity and dense deployment environments, e.g. stadiums, conference venues, shopping malls, etc. Within this group, several physical and MAC layer techniques are being discussed and investigated with the aim to improve overall system performance. Amongst these, dynamic sensitivity control (DSC) is one of the techniques currently under discussion.

DSC aims to improve overall system performance by improving spatial reuse. DSC has been the subject of discussion within the 11ax group because of its simplicity and ease of implementation. The current IEEE 802.11 networks mostly use the legacy fixed clear channel assessment (CCA) scheme enforced through the use of a physical carrier sensing threshold (PCST) for all the devices which means all devices use the same sensitivity threshold[1]. The fixed CCA threshold is not an optimal solution for achieving high throughput [1] [2] which suggests that DSC is needed to optimize the performance.

Several mechanisms have been proposed to dynamically change the carrier sensing threshold with the promise of enabling significant gains (see [3] and the references therein). The most popular proposals are: manipulate the PCST e.g. v-MAC to enhance spatial reuse in virtual antenna array system [4], KAPCS, KAPCS2 in 802.11k [5], and several Ad-hoc based cooperative MAC designs [6] [7]. With DSC, dynamic access control strategy within MAC layer is used to judge whether the channel is idle or not for transmission and clients can adjust the sensitivity threshold in a distributed manner. Generally speaking, a client will choose a lower sensitivity threshold for carrier sensing based on the received signal strength indicator (RSSI) it hears from the AP. The lower the sensitivity threshold, the higher the possibility that the node will succeed in gaining access to the channel during the contention process.

Even though such a technique sounds promising, there appears to be a lack of consensus regarding the adoption of DSC within 11ax. There are arguments that the gain by using DSC might not be as much as expected when it is applied to practical scenarios [8–10]. Motivated by this, the work in this paper focuses on evaluation of the performance of DSC for the realistic system, specifically, for the scenario and system setup defined by the IEEE802.11ax group [11]. The DSC method widely discussed within the group [2] wherein the sensitivity level is obtained by adding a margin to RSSI heard from the AP subject to upper and lower limit is used as a baseline in this work. Different from the other research work in this area, the contribution of this paper is to provide some insights into the performance of the technique ([2]) and point to avenues for mitigating the shortcomings of this technique.

The rest of the paper is organised as follows: Section II describes the concept of DSC along with the implementation details. Section III elaborates on the simulation setup and presents findings from the performance evaluation. The paper finally concludes in Section IV highlighting the pros and cons of the DSC technique and pointing to avenues for future work.

[1]For convenience, CCA threshold and PCST are used interchangeably in the paper

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II. Dynamic Sensitivity Control

A. Fixed Physical Carrier Sensing Threshold and Idle Channel Recognition

According to the IEEE 802.11 Distributed Coordination Function (DCF), nodes contend for the idle channel to obtain a transmit opportunity using the carrier sensing multiple access with collision avoidance (CSMA/CA) protocol. This requires a threshold to judge whether the channel is idle or not. In the classic Clear Channel Assessment (CCA) MAC, this threshold called the 'CCA threshold' is fixed and is also referred to as the 'Physical Carrier Sensing Threshold (PCST)'. The PCST value, if too low (too sensitive), may fail to fully utilize the channel. On the other hand, a value too high (low sensitivity), may fail to sense ongoing transmission on the link thereby leading to the node grabbing the medium to transmit when it is infact busy resulting in interference. When this threshold is chosen appropriately, it can bring benefits to the overall system performance with higher throughput and lower collisions. However, identifying such an optimum value is an open problem.

Successful idle channel recognition is related to several factors. The factors that can be manipulated by devices at hardware level are transmit power and sensitivity to interference. The manipulation of transmit power is termed as transmit power control (TPC). Whilst TPC at a node can avoid interfering the transmission of others, it also has a weakness: the lower power signal may be less robust to the interference in the wireless environment and therefore reduce probability of it being decoded successfully. As for the carrier sense sensitivity, the approach can be divided into two categories: fixed and dynamic. The fixed approach proposes optimal static CCA threshold based on theoretical analysis making some assumptions. As soon as the assumptions change, the choice of the threshold may not be optimal anymore. In contrast, the dynamic approach lets every node in the system determine and adjust its own sensitivity on the fly subject to changes in the operating condition.

B. Dynamic Sensitivity Control

As mentioned before, DSC allows clients to manipulate their own PCST in a distributed manner. The baseline mechanism (in [2]) used for clients to set up uplink PCST is shown below:

$$L_{DSC} = min(max(RSSI - Margin, L_{min}), L_{max}) \quad (1)$$

This threshold is obtained by using a predefined margin value. There is an upper limit L_{max} and a lower limit L_{min} to constrain the sensitivity. Fig.1 illustrates the dynamic sensitivity level assuming $L_{min} = -76dBm$ and $L_{max} = -30dBm$. We can see from this figure that the margin constrains the range of RSSI at the clients to update PCST and a client with higher RSSI will have higher chance to increase its CCA threshold. The value of the margin is an important factor affecting the performance of DSC, which will be confirmed by our simulation results as shown in the next section. Letting the CCA range represent the sensitivity level, the lower the sensitivity, if all the nodes use the same transmission power, the shorter range within which the transmission can be detected by a node as shown in Fig. 2. As shown in Fig. 2., client1 and client2 are connected to AP1, while client3 is connected to AP2. Both the APs operate on the same channel. When the sensitivity of client1 is updated according to DSC, the equivalent change of CCA range is shown as the red circle shrinking to the green circle. This shortened radius of the CCA range of client1 implies that a node transmitting outside the green circle will not cause the CSMA mechanism at client1 to report a busy channel. In this case, the unnecessary interference from AP2 and client3 can be avoided by client1.

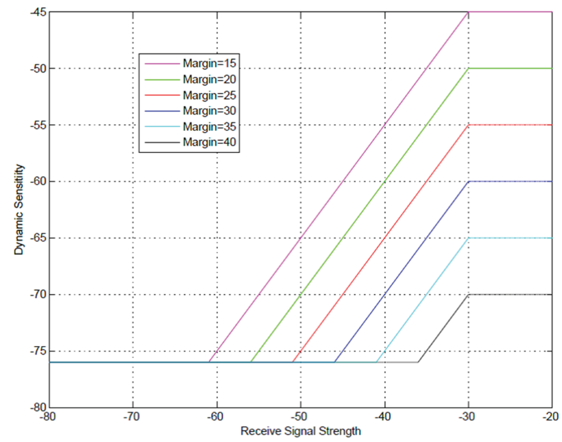

Fig. 1. Manipulation of PCST by DSC

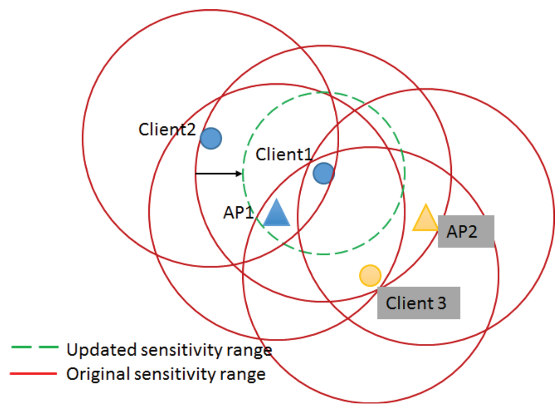

Fig. 2. A scenario illustrating DSC

C. Limitation of DSC

DSC provides not only interference-avoidance ability to every eligible node, but also gives the nodes who receive higher RSSI an even stronger advantage in channel contention. This benefit for users with geographic advantage may be a threat to other nodes in relatively weaker positions. In Fig. 2, the transmission of client2 should have client1 to suspend its transmission if the legacy PCST is in use. DSC threshold however allows client1 to pretend to be deaf to this transmission and therefore grab the medium for transmission.

The transmission from client1 may collide at AP1 when it is receiving the packet of client2 which will waste time and channel resource. Similarly, AP2 may also be interfered by client1 when receiving the data frame transmission from client3. This phenomenon may increase collision probability and also cause fairness issues among the clients. High unfairness among clients means nodes at advantaged positions will win the contention more often. The proportion of the privileged nodes decides how well the performance of the system will be, and the large proportion of insensitive nodes may even cause interference among the privileged nodes. Again, these are closely related to the value of the margin and the selection of margin is certainly of great importance.

According to the analysis above, the performance of DSC may vary according to the margin, the network topology, modulation and coding scheme etc. Also, the fairness in the DSC system may be lower than that in the legacy fixed PCST system. In the next section, we elaborate on numerical simulations to confirm the above hypothesis.

III. Performance Evaluation

A. Simulation scenario

The topology used in the simulations is shown in Fig. 3. This is based on scenario 3 described in the IEEE 802.11ax task group simulation scenario document [11]. The numbers in each cell indicate the cell index. In the simulations, six different inter-cell distances (ICD, unit used is metre) were employed. During the simulation, the locations of APs was fixed but the clients were dropped randomly in each cell. In each simulation case, DSC and fixed PCST (fixed CCA threshold) performance was simulated individually. There are 3 non-overlapping channels and channel reuse with reuse factor of 3 was deployed as shown in Fig. 3. Margin used for DSC was fixed at 20, 25, 30, 35 respectively during each set of simulations (one with and the other without DSC). The simulation parameters and their values used in this work are listed in the Table I. These values are consistent with IEEE802.11ac system parameters, but without the MIMO feature.

The achievable rate was calculated by a look-up table II, which was derived through link-level simulation and the performance metrics used were overall throughput, individual node throughput, number of collisions and fairness index.

B. Simulation Results

The overall throughput in each iteration (2 second/iteration, 30 iterations in total) is shown in Fig. 4. From the figure, we can see DSC with different margins has similar throughput when the ICD is high (ICD=60.65) in which nodes are loosely distributed around the AP. In the case of ICD=52, the performance of DSC with different margins starts to change. DSC with a margin of 20 and 30 (DSCM20, DSCM30) performs better than the one with fixed PCST (FPCST), while DSC with a margin of 25, 35 appears to deliver worse performance. When ICD is reduced to 43.35 and 34.70, DSC with all different types of margin tends to deliver better overall throughput than FPCST. DSCM25 catches up with DSCM20 from ICD=43.5 and outperforms other DSC margins in ICD=34.7 case. In very dense scenarios, the last two ICD cases, DSCM25 continuously delivers best overall throughput while throughput for DSCM20 is lower than that of FPCST. The results show that DSC with ‘proper’ margin outperforms fixed CCA threshold MAC (FPCST) in dense scenarios. In an environment with loosely deployed clients, DSC and FPCST are likely to end in a draw. The averaged overall throughputs

TABLE I
PARAMETERS USED IN SIMULATIONS

Parameter	Value
SIFS	16μs
Slot time	9μs
DIFS	SIFS + 2*Slot time (34μs)
Propagation delay	1μs
RTS/CTS	Disabled
ACK Timeout	300μs
Carrier Sense threshold	-76dBm
Data header	272 bits
CW backoff index	[5, 10] equivalent to CW [31,1023]
ACK size	(2+2+6+4)bytes = 112bits
Payload	Varies, fixed data transmission time
Data Rate	Constrained Shannon Capacity function
Constant transmit power	70mW
Number of Channels	3 (channel 3,7,11)
Operating frequency	2.4GHz
Antenna gain	0dBi
Path loss model	$PL(d) = 40.05 + 20 * log10(fc/2.4) + 20 * log10(min(d, 10) + 35 * log10(d/10)(d > 10)$ $PL(d) = 40.05 + 20 * log10(fc/2.4) + 20 * log10(min(d, 10)(d < 10)$
Clients	10 per cell, 190 in total
APs	19
Noise Figure	7
Traffic model	Full Buffer
Bandwidth	20MHz

TABLE II
PHY LOOK-UP TABLE VALUES USED IN SIMULATIONS

SNR(dB)	Rate(Mbps)	SNR(dB)	Rate(Mbps)
-0.5	6.5	15.4	52
2.6	13	16.6	58.5
5.1	19.5	18.4	65
8	26	22	78
11.3	39		

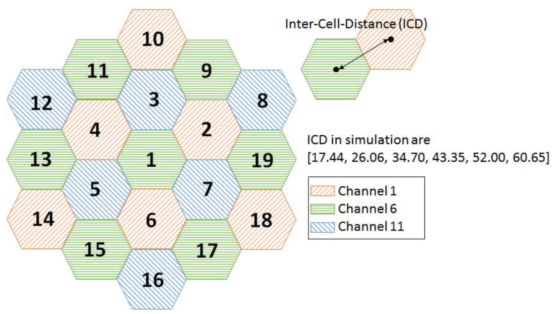

Fig. 3. Topology used in simulations

in Fig. 5 further confirms the observations above. From Fig. 4 and Fig. 5, a simple conclusion can be drawn: DSC can surpass FPCST when a proper margin is chosen in different type of client density/distribution/deployment.

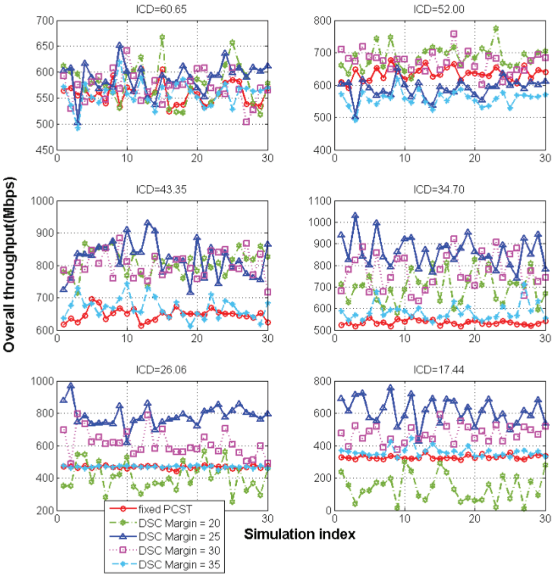

Fig. 4. Overall throughput for different ICD

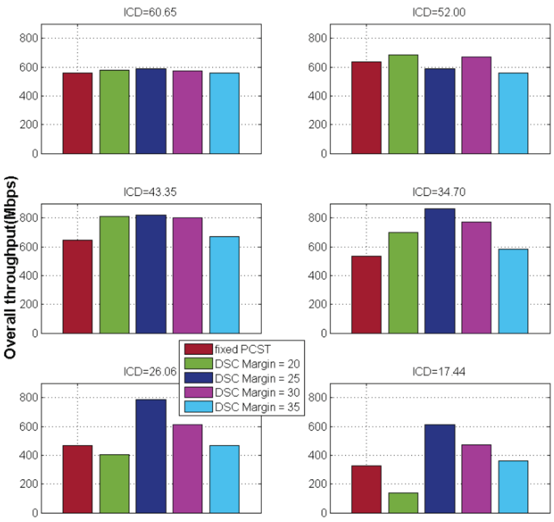

Fig. 5. Average overall throughput for different ICD

Fig. 6 depicts collisions during the simulations which vary a lot in comparison to the scenario employing FPCST. This suggests that the performance of DSC can vary according to the distribution of clients since this is the only variable factor in every iteration of simulation. The variation in the number of collisions is closely related to the choice of the value for the DSC margin: use of a higher margin implies less sensitive nodes.

It should be noted that the collision shown in Fig. 6 is recorded on a per node basis, which means one collision (unsuccessful Tx/Rx) may involves several transmitting nodes,

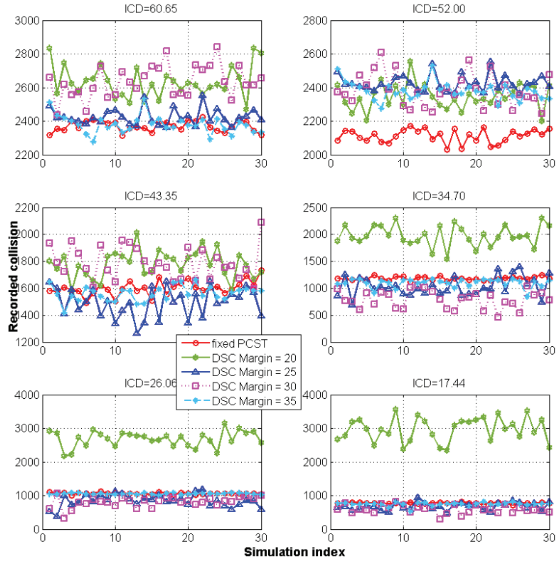

Fig. 6. Collisions recorded for different ICD

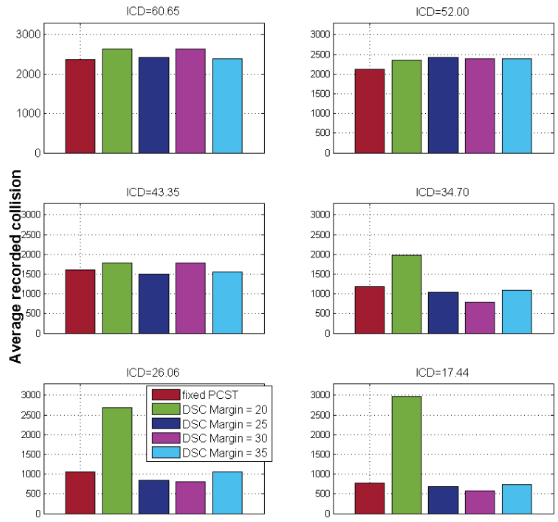

Fig. 7. Average number of collisions

e.g. two or more nodes transmission interfering each other. From the figure, we can also see that the collision in DSC system is generally higher than that in PCST system in first two ICD (60.65 and 52) cases. This could potentially be due to the ‘edge user’ transmission being interrupted by the ‘centre user’ with the high throughput of DSC coming from the advantaged centre users at the cost of edge users performance. When ICD reduces, the number of collisions start to show a difference: take FPCST as benchmark, DSCM25 and DSCM30 see less collisions than the FPCST, whilst DSCM20 and DSCM35 show more collisions than FPCST in the case of ICD=43.35. With ICD shrinking further, DSCM20 system exhibits distinctively high rate of recorded collisions than other DSC experiments with different margins. All the other DSC experiments with higher margin value exhibit fewer collisions similar to FPCST. High collision rate of DSCM20 explains its low overall throughput performance (as evident from Fig. 5). Similarly the average collisions in Fig. 7 are consistent with our observations. The figures show that DSC with proper margin yields fewer collisions and higher throughput in dense scenarios.

When a small margin is used among the clients who are densely distributed around the APs, most of them will be able to set their PCST to a high value. One of the worst case scenario is that high density nodes with low sensitivity will be deaf to each others transmissions, grab the medium more often (thinking it is free) and resulting in persistent collisions (interrupting each others transmission). The other possible undesirable scenario is that wherein one or more dominant nodes (closer to the AP) will be able to grab the medium more often interrupting transmission of the other neighbor nodes who may be in relatively disadvantaged position. This not only implies that the performance of DSC is highly related to the distribution/location of clients but also that such aggressive behaviour may lead to fairness issues in accessing the medium. A popular metric for capturing the fairness issue

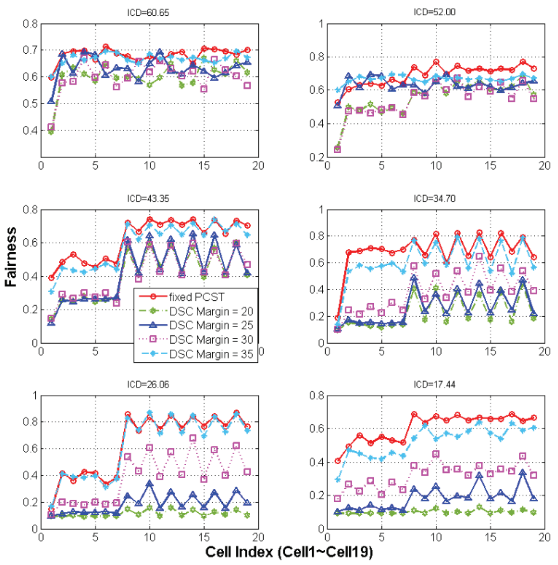

Fig. 8. Intra-cell fairness for different ICD

is Jains fairness index [12] and CDF of node throughput. Fig. 8 and Fig. 9 show the intra cell fairness index and system fairness index respectively. The intra cell fairness is calculated using the node throughput in every individual cell whereas the system fairness is calculated by using the cell throughput of each cell in the system. From Fig.8, it can be seen that the intra cell fairness of FPCST is higher than DSC which is inline with the behaviour noted earlier - privileged nodes in DSC interrupting the transmission and occupying more resources causing lower fairness. The fairness in dense scenarios decreases with higher number of privileged nodes (caused by the decrement of Margin) in the DSC based setup. In the first two cases (loose client deployment), both DSCM25 and DSCM35 have higher fairness in a few cells. However, this is not accompanied by overall throughput improvement

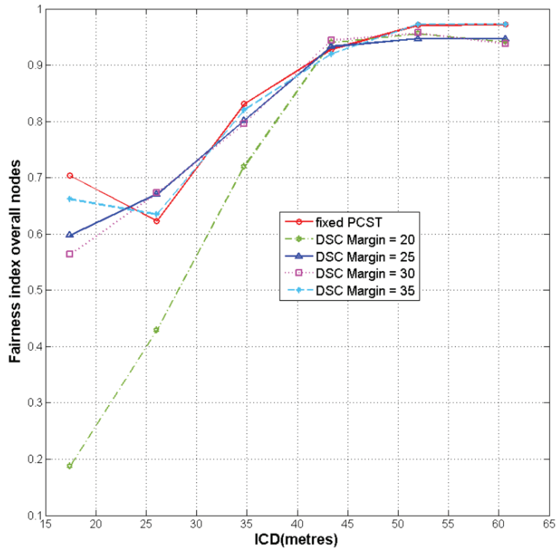

Fig. 9. System level fairness

according to Fig. 5. This could be explained by edge users avoiding interference from other nodes and winning contention to transmit, these transmissions further happening at lower MCS which facilitates robustness against interference. In such cases, the intra cell fairness actually improves. The system fairness shown in Fig.9 demonstrates that most cases with DSC can achieve similar fairness among the cell throughput except the case with low margin and short ICD.

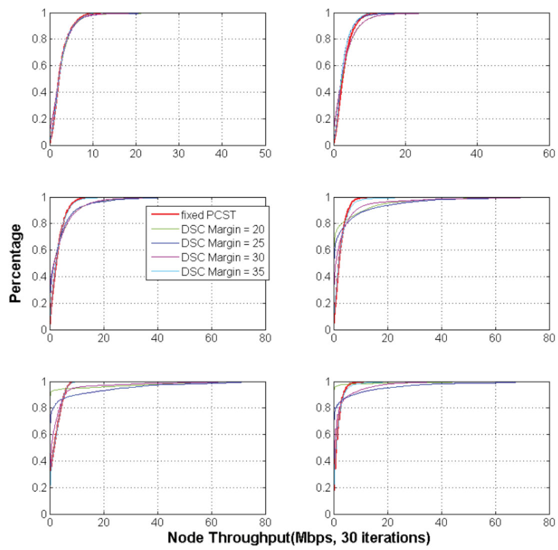

Fig. 10. CDF of per node throughput for different ICD

In Fig. 10, CDFs of individual node throughput with different ICD were plotted to understand the fairness behaviour for the topology used in simulations. Low throughput nodes and high throughput ones dominating the resources can be distinguished from the CDF plots. From the simulations, it can be seen that in all the scenarios, the trends are similar: use of the DSC proposal [2] does not improve fairness in comparison to the use of the legacy approach of using a fixed PCST and the unfairness increases with the ICD shrinking, especially in the extreme case of ICD=17.44m. The transmissions from nodes which attain a relatively low throughput, gradually reduce in setups where DSC is used with low margin. The high collisions experienced by nodes (in the low margin DSC setup as seen in Fig 7) in extremely dense scenario is the most likely reason for high proportion of nodes attaining low/zero throughput. From Fig 7, 9 and 10, it can be inferred that the high collision rate in low margin DSC eliminates its spatial reuse advantage.

On the whole, it can be concluded that performance of the DSC scheme ([2]) varies with its margin value, client distribution/location and inter cell distances. Given that one may not have much control over the latter two aspects (i.e., node distribution and inter cell distances), future DSC proposals should investigate different ways of dynamically updating the margin value so as to avoid the pitfalls of the proposal in [2]. In particular, any potential DSC proposal should aim to avoid the problem of nodes in a cell pushing other nodes within the same cell out of carrier sensing range of each other as this may negate the benefits attainable from the use of DSC. Devising such a solution would help to realise the promise of DSC at the same time ensuring that the benefits of DSC do not come at the cost of the performance that can be attained by nodes in relatively disadvantaged positions.

IV. Conclusion

Dynamic Sensitivity control, promises to improve spatial reuse by adapting the physical carrier sensing threshold (PCST) and is a hot topic currently being discussed in 802.11ax task group. In this paper, we investigated the effect of enabling DSC in comparison to the traditional approach of using a fixed carrier sensing threshold under realistic scenarios defined by the 802.11ax group through a simulation based study. Results from this study show that DSC with proper margin can outperform fixed PCST on overall throughput, but this gain varies highly with respect to topology (node distribution) and node density. Further, the degree of fairness in accessing the medium also varies. Improper margin leads to high collisions and neutralizes the advantages that DSC brings. As it stands, such semi-static DSC proposals are most likely to bring benefits in limited set of scenarios such as high capacity nodes clustered closely around AP (with no edge nodes) with higher inter AP distance/ICD. If there are edge nodes in the aforementioned setup, they are likely to experience degraded performance from a lack of transmission opportunities. Based on these findings, we conclude that performance gains from DSC through enabling better spatial reuse can be achieved by setting proper margin. However, mechanisms are needed that could adapt the margin in response to changes in operating conditions. Whilst the current approach being discussed at the 11ax meetings (adding a fixed margin to the AP RSSI) is a simple approach, devising an algorithm that can dynamically tune the PCST taking into a change in performance is an interesting avenue for further work and is currently under exploration as a part of our ongoing work.

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