Taming the Densification Challenge in Next Generation Wireless LANs: An Investigation into the Use of Dynamic Sensitivity Control

Parag Kulkarni*, Fengming Cao*†
*Telecommunications Research Laboratory, Toshiba Research Europe Ltd., Bristol, UK
†Dept. Of Electrical & Electronic Engineering, University of Bristol, UK
Email: {parag.kulkarni, fengming.cao}@toshiba-trel.com

***Abstract*—The IEEE 802.11ax Working Group is aiming to devise ways to improve spectrum efficiency, in particular to enhance the system throughput in highly dense scenarios, frequently referred to as Overlapped Basic Service Set (OBSS). Several techniques are being considered to achieve these objectives. In this paper we explore receiver sensitivity adaptation, one of these techniques, as a potential lever for accomplishing the above mentioned objectives. In particular, we propose a practical method of adapting receiver sensitivity and highlight findings from a comprehensive simulation based study conducted using the network simulator ns3. Findings from this study indicate that the proposed method significantly outperforms the baseline technique currently being considered in the 11ax working group. The proposed method achieves this without requiring any changes to the hardware, the existing infrastructure and the WLAN standard. Moreover, STAs employing the proposed technique can co-exist with legacy devices that do not employ such adaptation. Findings also highlight that the traditional conservative approach of using a static CCA threshold (no sensitivity adaptation) may not always yield the best performance and that identifying the optimal CCA threshold at design time is a non-trivial problem.**

***Keywords*-IEEE 802.11ax; WiFi; WLAN; dense wireless; dynamic sensitivity control; dynamic sensitivity adaptation; DSC; CCA adaptation**

I. Background

Wireless networks, in particular, WLANs are getting denser in terms of an increase in concentration of the number of stations (STAs) as well as Access Points (APs) over a given area. Current efforts such as those from the IEEE 802.11ax Working Group are aiming to address challenges arising in such dense deployments. The goals of 11ax are slightly different from its predecessors (11n and 11ac) in that the aim is to improve not only the peak data rate but also the overall system throughput and the average per user throughput. One of the techniques which could potentially aid in accomplishing the aforementioned objectives and currently being discussed in the 11ax working group is Dynamic Sensitivity Control (DSC). STAs rely on the Clear Channel Assessment (CCA) threshold to aid them in the carrier sensing process so as to avoid engaging in overlapping transmissions. This CCA threshold is traditionally fixed thereby resulting in a roughly fixed carrier sensing range of the STA. In dense deployments wherein a number of WLAN networks may be operating in each other's vicinity on the same channel, transmissions in one network may result in suppression of transmissions in the other, e.g., when an STA in network A performs carrier sensing and finds the medium busy, in this case, due to an STA in network B who may be transmitting on the same frequency at the same time. In such a case, it may be meritorious for the STA(s) to curtail their CCA range (adapt their sensitivity) so as to go out of listening range of each other, in other words mitigate such an unnecessary link suppression effect. Since the topology and link conditions in such networks may be variable, the sensitivity of each STA should be adapted dynamically. How much and how often to adapt are open questions.

Thorpe et al. provide a detailed overview of adaptive carrier sensing approaches in [1]. As described in this paper, the work in this area has been motivated by the quest for identifying the optimum physical carrier sense threshold based on some form of theoretical modelling. The practicality of these schemes varies - e.g. some require infrastructure support whilst some require coordination between the nodes in the network. As the authors point out, there are several limitations with these, some of the fundamental ones being making unrealistic assumptions about topology (e.g. uniform node distributions), using simplified interference models, tuning the physical carrier sensing threshold by assuming a certain transmission rate (changing MCS can significantly impact performance) etc. all of which have an impact on the results obtained.

In the context of 11ax, the principle of Dynamic Sensitivity Control was first proposed in [2] as a potential way of mitigating interference issues in OBSS deployments. In the remainder of this paper this approach will be referred to as 'Baseline'. In general, whilst the principle behind dynamic sensitivity control appeals intuitively, the issue of when to adapt and by how much to adapt the sensitivity are open issues. The idea described in [2] involves changing the CCA threshold of the STA (by adding a fixed margin to the received signal strength from the AP) to minimise overhearing other STAs operating on the same channel in adjacent networks. Even though this is simple from an implementation perspective, it does not perform well as will be shown in the later part of this paper.

A proposal by Coffey et al. [3] suggests a protocol which uses number of successful consecutive transmissions at an STA to notify neighbours (that can overhear this STA) of the CCA threshold they might want to choose to avoid overhearing this STA. This approach is also simple from an implementation perspective, however, it relies on “tell others to change” philosophy which may not always be practical, especially if the nodes being notified do not implement any sort of adaptation / are legacy nodes. Moreover, based on the insight gathered through number of successful transmissions, the STA does not update/adapt its own sensitivity values.

Ever since the first DSC contribution was presented at the 11ax meetings in June 2014 by Smith et al. [2], there has been a lot of activity with several contributions following in the subsequent 11ax meetings (see [4] [5] [6] [7] [8] [9]). The focus of these have been on evaluating the efficacy of the Baseline approach in different topologies, different scenarios (such as co-channel / non-overlapping channel assignments), for different values of margin, coexistence issues between legacy and DSC enabled STAs etc. These studies show that different sensitivity levels lead to different performance in different circumstances depending on the topology and network conditions. However, as mentioned earlier, the adaptation process itself has been left open. It has also been shown that the use of DSC can lead to mixed results, i.e. performance improvements in some cases and degradation in some others. The objective of the work in this paper is to come up with a new dynamic sensitivity control technique, explore its behaviour in terms of how well it adapts and compare its performance quantitatively against the Baseline scenario as well as the traditional approach of using fixed CCA threshold. A salient feature of the proposed method is that it does not require any changes to the hardware, the existing infrastructure and the WLAN standard. Moreover, STAs that employ the proposed technique can coexist with legacy devices that do not employ such adaptation.

The rest of the paper is organized as follows: Section II outlines the proposed dynamic sensitivity control technique following which section III analyses the behaviour of the proposed algorithms through comprehensive simulations carried out using the network simulator ns3 in different scenarios. The paper finally concludes in section IV pointing to potential future directions.

II. Proposed Algorithm

Figure 1 embodies the concept of DSC. As evident from this figure, the conventional approach of employing static sensitivity values leads to manifestation of link suppression effects - STAs C1 and C2 being able to hear each other on the same channel which means when one is transmitting, the other will keep silent even though both of them are communicating with different APs. On the other hand, when DSC is used, the CCA threshold adaptation mitigates the interference effect by curtailing the carrier sense range thereby eliminating the link suppression effect.

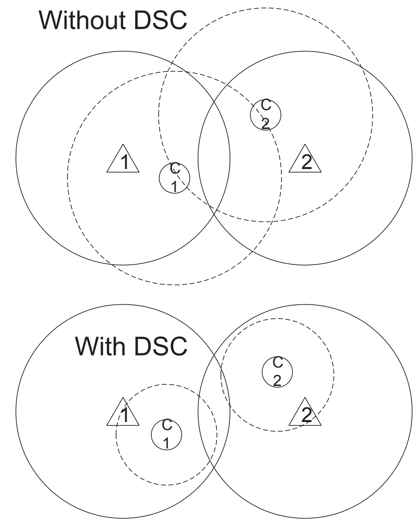


Figure 1. DSC concept

Algorithm 1 embodies the proposed DSC technique. This algorithm would typically run on an STA. The key principle underlying the proposed algorithm is for the STA to keep track of the status of the most recent ‘N’ transmissions and subsequently use this information to guide the sensitivity adaptation (in a step-wise manner). The proposed algorithm works as follows: Each STA starts with the highest sensitivity supported by the wireless network interface card. The STA also stores the signal strength recorded upon reception of frames from the access point. Instead of relying on instantaneous values which may fluctuate, the STA computes a smoothing average over the values recorded and stores the smoothed value hereinafter referred to as $RSSI_{AP}$. After each transmission, if an ACK is received, the number of successful transmission count is increased. In the absence of an ACK, failure statistics are updated such as the number of failed transmissions and the loss rate. There are two variants of the proposed algorithm.

- **Proposed V1:** In this variant, the overall loss rate based on cumulative number of successes and failures is used in the adaptation process. In particular, the loss rate is computed at the end of each window of ‘N’ transmission attempts based on the cumulative success, failure counter values, i.e. cumulative failures / cumulative(success + failures). The overall loss rate at the end of the most recent window is compared against the overall loss rate at the end of the preceding window and this feeds into the sensitivity adaptation process.
- **Proposed V2:** In this variant, the loss rate over a window of ‘N’ transmissions is computed at the end of each ‘N’ transmission attempts based on statistics over the window under consideration, i.e. number of

Algorithm 1 Proposed DSC algorithm

Initialisation
Default sensitivity setting of the network interface
$RST_{min} = -82dBm$
Maximum permissible CCA threshold value
$DSC_{limit} = -30dBm$
Start with the most conservative value
$CCA_t = -82dBm$
Adapt CCA_t after every $winSize$ transmission attempts
$winSize = 50$
Adapt CCA_t by $stepSize = 5dBm$
Number of successful, failed transmissions (window)
$succ_{win} = 0, fail_{win} = 0$
Number of successful, failed transmissions (cumulative)
$succ_{cumul} = 0, fail_{cumul} = 0$
Initialise $numTx = 0$, $lossRate_{prev} = 0$

Begin Loop – Transmit packet to the AP
$numTx++$
if ACK received **then**
  $succ_{win}++, succ_{cumul}++$
else
  $fail_{win}++, fail_{cumul}++$
end if
if $numTx == winSize$ **then**
  Compute loss rate
  $numTx = 0, succ_{win} = 0, fail_{win} = 0$
  if $lossRate_{curr} <= lossRate_{prev}$ **then**
    Decrease Sensitivity ($CCA_t += stepSize$)
  else
    Increase Sensitivity ($CCA_t -= stepSize$)
  end if
  $lossRate_{prev} = lossRate_{curr}$
else
  Go back to Begin Loop
end if

failed attempts over the window / N. This is unlike the previous variant wherein cumulative success/failure statistics are employed. Subsequent to computation of the loss rate over the most recent window, this is then compared against the loss rate at the end of the preceding window. The result from this comparison guides the adaptation process.

In both the variants, if the loss rate over the most recent window is lower than the loss rate over the preceding window, a decision is taken to reduce the sensitivity (curtail carrier sensing range). The rationale behind this decision is that if the number of losses has gone down, then the STA should continue to explore whether the next more aggressive CCA threshold (current CCA threshold plus the step size) would yield any further benefit. On the other

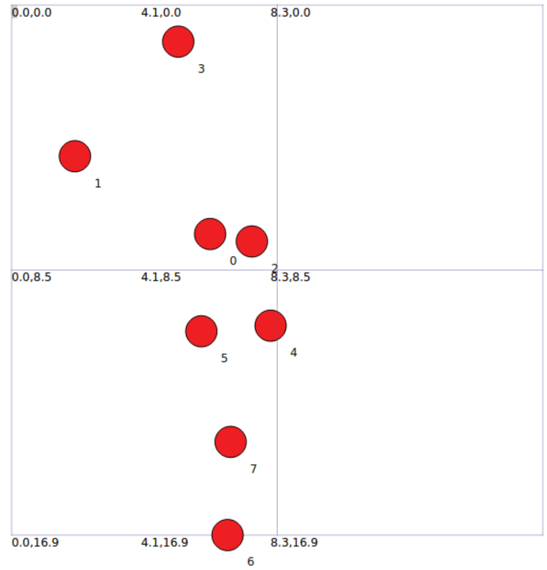


Figure 2. An example topology with 2 cells

hand, if the number of losses has gone up (the inherent assumption being that losses are due to collisions), this suggests that the STA should be a bit more conservative in its approach and therefore increase its sensitivity thereby increasing its carrier sensing range. In reality losses may be due to either collisions or deterioration in the underlying channel. Ideally, it would be highly desirable to have the ability to distinguish the cause of loss and act accordingly. However, this is currently out of scope of this work and could provide an interesting avenue for further work. Even though the proposed algorithm cannot differentiate between the types of losses, its adaptive approach ensures that it does not get stuck with a particular threshold, e.g. if the algorithm increases sensitivity amidst an increased loss rate and if the increase was due to a temporary degradation in the channel, the loss rate statistics might subsequently improve when the channel improves thereby leading the algorithm to potentially lead to decreasing sensitivity. Any decrease (increase) in sensitivity is carried out by adding (subtracting) 'step size' to the existing CCA threshold. As an example, Algorithm 1 shows the value of step size being 5dBm. Whilst this is merely to illustrate the concept, the value of step size can be varied to make the adaptation process fine/coarse grained. In terms of the actual increase/decrease in sensitivity decision, the following should be noted:

- The CCA threshold is decreased by step size only if the signal level received by the STA from its serving AP is less than the value that would result after the decrease. Otherwise, the existing threshold is retained. This is to ensure that the STA continues to be within range of the serving AP.
- Similarly, the CCA threshold is increased by a step size

only if the value resulting from the increase does not fall below the minimum receiver sensitivity supported by the wireless network interface card. Otherwise, the CCA threshold is set to the default minimum receiver sensitivity value supported by the wireless network interface card of the STA.

A key benefit of the proposed method is that it does not require any changes to the hardware, the existing infrastructure and the standard. Moreover, STAs that employ the proposed technique can co-exist with legacy devices that do not employ such adaptation. In fact, STAs using the proposed algorithm that are just about within range of the serving AP (also referred to as 'cell-edge users') will not adapt their sensitivity as this may lead to their going out of coverage of the serving AP. One can look at such STAs as behaving similar to 'legacy STAs' that don't adapt their sensitivity.

III. Performance Evaluation

The proposed algorithms along with the baseline technique (with 5dBm margin value) were implemented in the network simulator ns3 and their performance was studied through simulations in a number of different scenarios. The traditional approach of using a fixed CCA threshold was also considered in this performance evaluation. Towards the same goal, several experiments were carried out for different values of the CCA threshold (-82dBm, -72dBm, -62dBm, -52dBm) each of which was fixed during an experiment. System throughput, user throughput and Jain's fairness index [10] were used as metrics to assess the performance of the different methods.

Experiments were carried out in the IEEE 802.11 infrastructure mode using a log distance propagation loss model (using default values) for a number of different combinations of the relevant parameters such as number of cells (each cell containing a single AP), channel allocation strategy (neighbouring APs use same or different channels) and the technique under consideration (fixed CCA threshold, baseline and the proposed algorithms). Five repetitions were carried out with different seed values for each combination and the results reported are an average over these five runs. The size of each cell was set to 10x10 m^2 with the AP and STA locations being randomly chosen within this area. The AP and STA locations were fixed throughout an experiment. Each STA was configured to transmit thousand packets per second with each packet being thousand bytes long. Each experiment was run for thirty seconds.

A. Performance benchmarking with Baseline

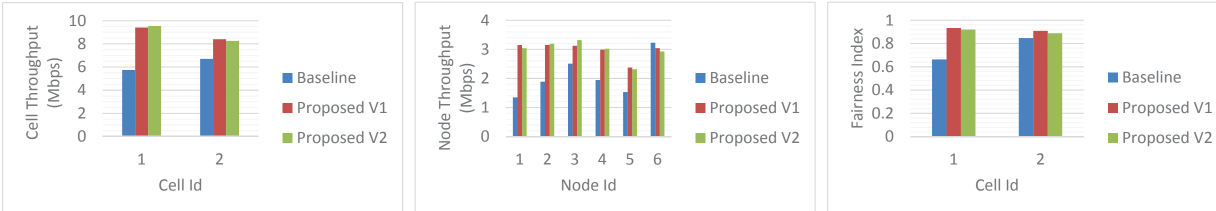
Figure 2 depicts an example topology used in one of the experimental combinations. In this topology, there are two cells located next to each other with three STAs per each cell. Node 0 and Node 4 are the APs in cell 0 and cell 1 respectively while nodes (1,2,3) and (5,6,7) are the STAs in the two respective cells. The main objective here is to gain a better insight into the behaviour of the proposed algorithm in a simple setup.

Figure 3 shows the findings for the scenario where both the cells use the same frequency. As evident from this figure, the proposed algorithms outperform the baseline achieving 30% to 50% higher system throughput and 20% to 100% higher user throughput at the same time achieving better fairness than the baseline. The gain can be explained in terms of the proposed algorithms adaptive approach. As an example, we'll look into the behaviour of node 1 in more detail. Figure 4 shows the CCA threshold and loss rate of this node over time. As per the baseline approach, the node sets its CCA threshold to $RSSI_{AP}$ + $Margin$. Observe that the loss rate of the node fluctuates (with the overall loss rate around 0.64) but there is no measure in place to react to this. In contrast to this, the CCA threshold of the same node when using the proposed algorithms (as shown in Figure 5) continues to react to changes in the loss rate. To start with the node adopts a conservative approach and starts at the lowest CCA threshold and adapts in a stepwise manner - step-up if loss goes down and step-down if loss goes up during each window. Even though the loss rate fluctuates in this case too, it is much lower (around 0.32 which is almost half) as compared to the baseline case for identical topology and traffic conditions.

To study the performance in a dense deployment, we considered a 25 AP setup with 5 nodes in each AP's cell (an example topology shown in Figure 6). Results averaged over five runs shown in Figure 7 and 8 indicate that we observe similar trends as those in the 2 cell setup. Barring a handful of cells, the proposed algorithm outperforms baseline in the vast majority of the cells (21 out of the 25 cells) achieving better fairness performance. The improvement in throughput observed varies from 10% to 50%. There appears to be a general consensus in the 11ax working group that the gains from DSC are topology dependent. For example, a deployment with nodes clustered around the AP with the AP being sufficiently away from other neighbouring APs is more likely to show greater benefits from using DSC than a deployment scenario with nodes spread far apart from the AP. In the latter case, nodes that are on the cell edge, are more likely to use conservative CCA thresholds and therefore resemble legacy nodes that do not employ DSC. The findings from the above experiments are therefore in unison with the discussion in the 11ax group.

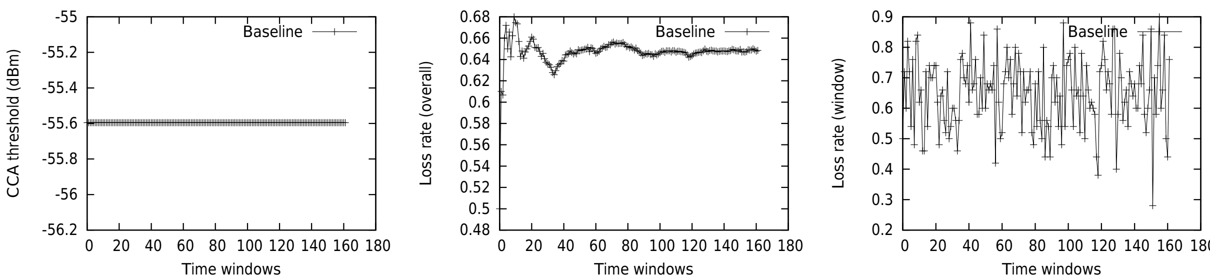
B. Performance benchmarking with fixed threshold approach

We also repeated experiments for the same topology and traffic conditions as above but with using fixed CCA thresholds. Figure 9 and 10 show the findings from these experiments. As seen from these figures, different fixed CCA thresholds attain different levels of performance. In the 2 cell



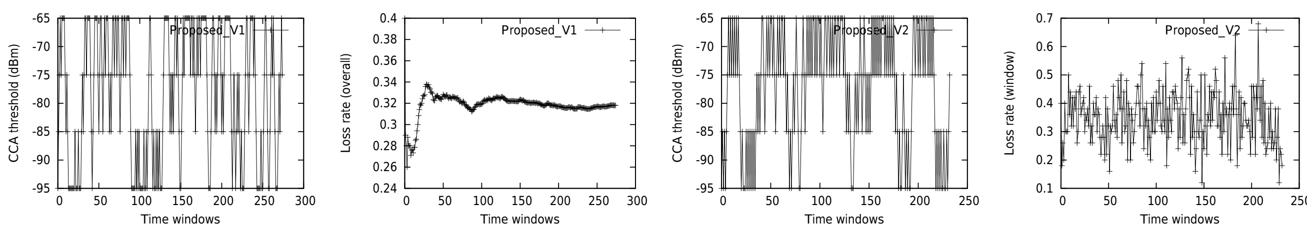
(a) Cell Throughput (b) Node Throughput (c) Fairness Index

Figure 3. Findings from the 2 cell topology



(a) CCA Threshold (b) Loss rate (overall) (c) Loss rate (window)

Figure 4. Behaviour of node 1 in the 2 cell topology using the Baseline approach



(a) Proposed V1 (b) Proposed V1 (c) Proposed V2 (d) Proposed V2

Figure 5. Behaviour of node 1 in the 2 cell topology using the proposed algorithms V1 and V2

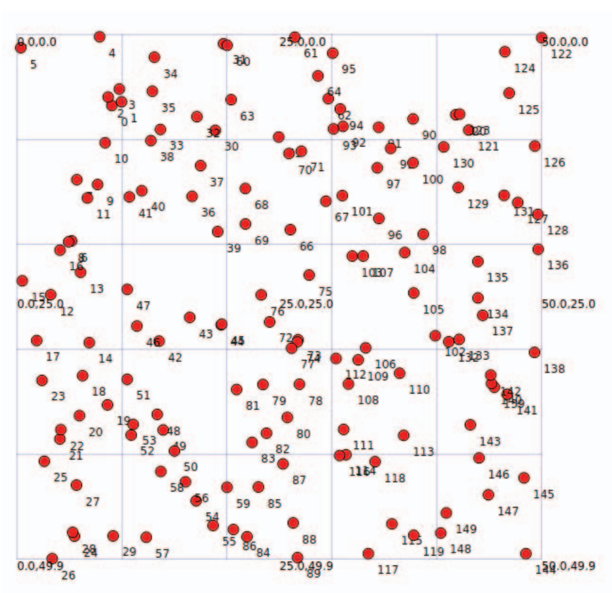


Figure 6. An example topology with 25 cells

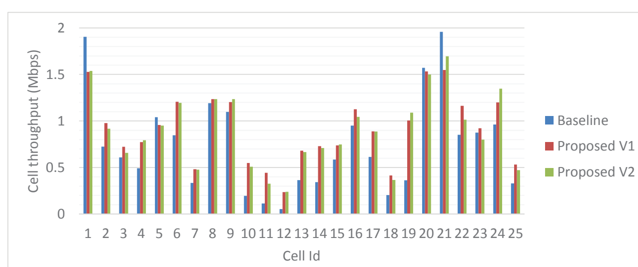


Figure 7. Cell throughput attained in the 25 cell topology

scenario, the fixed threshold approaches (especially lower values such as -82 dBm and -72 dBm) appear to attain better performance than the baseline and the proposed methods. On the other hand, in the 25 cell scenario the results are mixed with the proposed algorithm doing well in some cells and not so well in others.

As mentioned earlier, the suitability of a particular thresh-

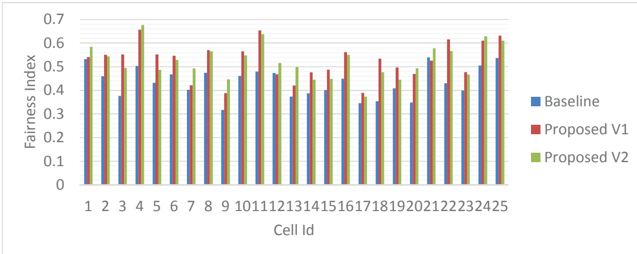


Figure 8. Fairness index observed in the 25 cell topology

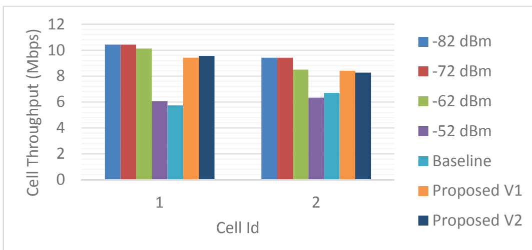


Figure 9. Performance in the 2 cell topology using baseline, proposed and fixed CCA approaches

old depends on the underlying topology. For nodes closely clustered around the AP, a lower value of fixed CCA threshold is likely to bring benefits in terms of better spatial reuse. On the other hand, for a deployment with nodes scattered all around the AP in all directions, the same lower fixed threshold may lead to nodes within the cell going out of carrier sense range of each other thereby increasing the number of collisions and therefore lowering the throughput.

The other open problem is, it is practically difficult to identify a threshold that will work best in any situation and therefore an adaptive approach is desirable. Because of the probing mechanism adopted by the proposed approach, it can choose more aggressive thresholds in favourable conditions (when losses go down) and more conservative thresholds in less favourable conditions (when losses go up). However, the probing process being reactive, is likely to make mistakes as a result of which there may be a performance penalty. Despite this, we observe that in situations where the proposed approach falls short it still comes close to achieving performance as that of the conservative

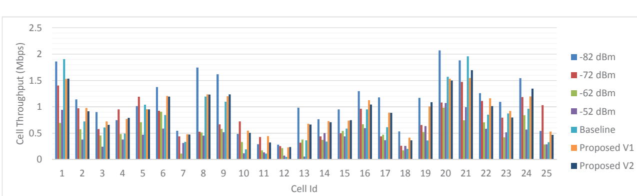


Figure 10. Performance in the 25 cell topology using baseline, proposed and fixed CCA approaches

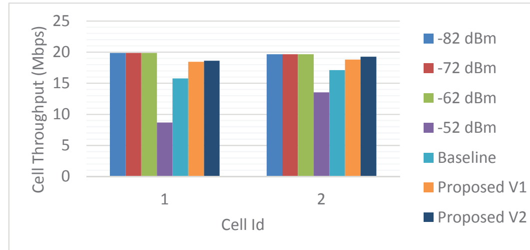


Figure 11. Performance in the 2 cell topology with channel selection enabled

approach (i.e. using a fixed CCA threshold of -82dBm).

This suggests that adopting a conservative approach (a fixed CCA threshold of -82 dBm in this case) may not always be the best thing, that having different thresholds in different situations is desirable and knowing the best threshold beforehand is a challenging problem. Thus, a stepwise adaptation approach like the one proposed in this work might come in handy as it improves performance where possible (outperforms the fixed approach in some cases) and in situations where it can't, its performance approaches that of the conservative fixed CCA approach.

C. Performance with channel selection enabled

In the experiments described above, all the APs were configured to operate on the same channel as this is the type of scenario where there is a greater need for improving spatial reuse. Having examined performance in this setup, it is also of interest how the performance varies if some of the neighbour APs were configured to use different channels. The results detailed in this section are therefore based on such a setup where most APs were configured to use a channel such that at least one or more of their neighbours was not using the same channel. There were cells of course, where it was impossible to totally avoid conflicting allocations between immediate neighbours.

Figure 11 and 12 show the findings for this scenario. We observe similar trends as seen previously except that the throughput almost doubles compared to the scenario where all APs use the same channels. The throughput in the channel selection enabled scenario is significantly better in both the cases with and without DSC as compared to the scenario where all APs operate on the same channel. This indicates that combining DSC with channel selection has the ability to significantly improve performance.

In summary, the findings indicate that the choice of the optimal CCA threshold is dependent on the topology and network conditions. Therefore one threshold may not be ideal in all circumstances. Even if one wants to, it is practically difficult, to identify the best value of the CCA threshold beforehand. This calls for devising an adaptive regime for tailoring the CCA threshold in response to changes in the underlying topology/network conditions. As shown by findings

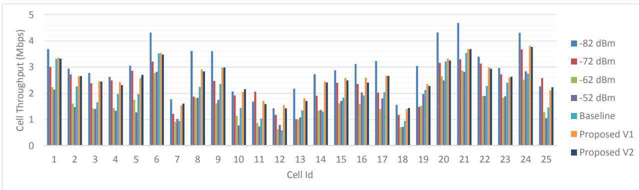


Figure 12. Performance in the 25 cell topology with channel selection enabled

from this study, the proposed adaptive approach significantly outperforms the baseline approach. The use of the baseline approach is currently being considered in the 11ax working group. The legacy approach of using a conservative CCA threshold does not yield benefits in all situations. In some situations more aggressive CCA thresholds are required to improve spatial reuse. However, since it is difficult to know what the topology/network conditions will be before hand, choosing an aggressive threshold in a static manner at design time is not advisable/practical. This is confirmed by findings from the simulation where the aggressive thresholds lead to dramatic degradation in performance in different cells. Finally, whilst the proposed approach yields significant performance improvements in some scenarios, its performance comes close to that of the traditional approach of using fixed conservative CCA threshold in other scenarios.

IV. Conclusion

The IEEE Working Group '11ax' has been focusing on identifying and addressing issues in dense WiFi deployments. Unlike its predecessors, where the objective was solely to increase the peak data rates, the major goals of 11ax are to improve spectral efficiency, in particular, improve the area throughput and the average user throughput. Several techniques are being considered to realise these objectives. One of the techniques being actively debated as of this writing is Dynamic Sensitivity Control (DSC).

This paper elaborated on the traditional fixed CCA approach and the principle underlying DSC. Details of an adaptive scheme were also presented along with a simulation based performance evaluation. Findings from this study indicate that the traditional approach of using a fixed CCA threshold may not always yield the best performance, that identifying an optimal CCA threshold at design time is a non-trivial problem and therefore CCA adaptation has merit. However, employing DSC may not automatically translate to benefits. The magnitude of the gains are dependent on the underlying topology, in particular the node distribution around the APs, distance between neighbouring cells and the presence of 'cell-edge' nodes. The proposed approach was shown to significantly outperform the baseline technique currently being considered in the 11ax working group. It was also observed that in some cases the traditional approach of using a fixed conservative CCA threshold performed better than the proposed approach. This is quite normal as using a conservative threshold should lead to lower overall collisions and therefore better throughput. However, this approach fails to capitalise in circumstances, e.g., in scenarios where nodes are clustered around the AP, where using a more aggressive threshold is likely to kick users in neighbouring cells out of carrier sensing range thereby avoiding unnecessary link suppression and therefore significantly improving throughput. Because of the probing mechanism adopted by the proposed approach, it can choose more aggressive thresholds in favourable conditions (when losses go down) and more conservative thresholds in less favourable conditions (when losses go up). However, the probing process is likely to make mistakes as a result of which there may be a performance penalty. Despite this, we observe that in situations where the proposed approach falls short, it still comes close to achieving performance as that of the conservative approach.

Such a mixed outcome seems to suggest that there is still great potential for research in this area. In particular, devising adaptive mechanisms that could potentially predict the cause of losses and factor them in the CCA threshold adaptation decision, employing some form of coordination between the nodes (AP-STA, AP-AP coordination) to identify upper/lower limits beyond which CCA threshold should not be adapted and exploring effects of joint transmit power control, link adaptation and sensitivity adaptation are interesting avenues for further work. Finally, it would be also interesting to explore the effect of such lower layer optimisations on higher layer performance, e.g., studying the impact of decisions made at the MAC layer on the performance of transport protocols such as TCP.

References

[1] C. Thorpe and L. Murphy, "A survey of adaptive carrier sensing mechanisms for ieee 802.11 wireless networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 3, pp. 1266–1293, Third 2014.

[2] G. Smith, "Dynamic sensitivity control for hew sg," IEEE doc. 802.11-13/1290r0, Nov 2013.

[3] S. Coffey, D. Liu, B. Hart, and G. Hiertz, "A protocol framework for dynamic cca," IEEE doc. 802.11-14/0872r0, July 2014.

[4] G. Smith, "Dynamic sensitivity control channel selection and legacy sharing," IEEE doc. 802.11-14/0294r1, March 2014.

[5] J. Soder, F. Mestanov, L. Wilhelmsson, H. Persson, K. Agardh, W. Carney, K. Sakoda, and S. Coffey, "Ul & dl dsc and tpc mac simulations," IEEE doc. 802.11-14/0868r0, July 2014.

[6] W. Carney, Y. Morioka, K. Sakoda, M. Mori, T. Itagaki, B. Hart, T. Adachi, S. Coffey, and G. Hiertz, "Dsc and legacy coexistence," IEEE doc. 802.11-14/0854r0, July 2014.

[7] F. Sita, P. Xia, J. Levy, and R. Murias, “Residential scenario sensitivity and transmit power control simulation results,” IEEE doc. 802.11-14/0833r0, July 2014.

[8] S. Choudhury, A. Cavalcante, F. Chaves, E. Almeida, F. Abinader, E. Tuomaala, K. Doppler, and J. Kneckt, “Impact of cca adaptation on spatial reuse in dense residential scenario,” IEEE doc. 802.11-14/0861r0, July 2014.

[9] M. S. Afaqui, E. Garcia-Villegas, E. Lopez-Aguilera, G. Smith, and D. Camps, “Evaluation of dynamic sensitivity control algorithm for ieee802.11ax,” in *IEEE WCNC, New Orleans, USA*, March 2015.

[10] R. Jain, D. Chiu, and W. Hawe, “A quantitative measure of fairness and discrimination for resource allocation in shared computer systems,” DEC Research Report TR-301, Sept 1984.