Improved Abstraction for Clear Channel Assessment in ns-3 802.11 WLAN Model

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ABSTRACT

An important challenge for ns-3 is to enable efficient performance evaluation of increasingly dense and heterogeneous networks, cognizant of cross-layer (specifically, Layers 1 & 2) interactions. In this work (a continuation of U. Washington efforts), we present improved physical layer abstractions for a key component underlying all 802.11 WLAN MAC performance evaluation - the Clear Channel Assessment (CCA) procedure central to CSMA/CA - for implementation in the ns-3 simulator. We model the preamble correlation process as typically implemented in 802.11 radio and represent the resulting probability of detection as a look-up table with a parameterized correlation threshold for different receive sensitivity strategies. Further, we also added a new carrier sense threshold adjustment mechanism to allow nodes to enable bypassing the default (and to date, fixed) -82dBm threshold. Such a capability aligns ns-3 for performance evaluation of dense networks equipped with new spatial reuse mechanisms. We demonstrate this via simulation of spatial reuse gains from dynamic sensitivity control (DSC) that are verified against IEEE 802.11ax standards group contributions. Using simulation results from a fixed rate multi-BSS network, we then identify valuable design guidelines to maximize the aggregate throughput with DSC.

CCS CONCEPTS

• **Computing methodologies** → **Discrete-event simulation**; *Modeling methodologies*; • **Networks** → Network simulations.

KEYWORDS

Wi-Fi, Network Simulator 3 (ns-3), Carrier sense

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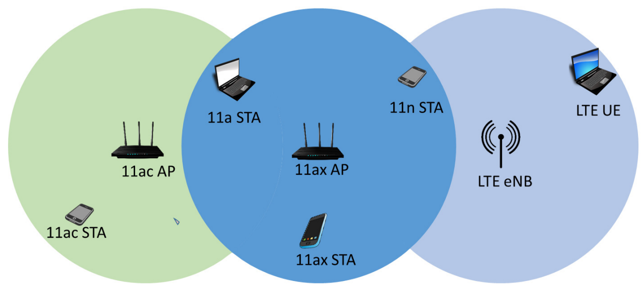

Figure 1: WiFi - LTE Network Coexistence

1 INTRODUCTION

IEEE 802.11 WLAN (Wi-Fi) is the dominant wireless infrastructure for broadband access. Based on carrier sense multiple access collision avoidance (CSMA-CA) concepts, the distributed contention function (DCF) MAC protocol allows multiple stations (STA) within a single network (or BSS per WLAN nomenclature) to time-share a single channel. While DCF is adequate for minimizing MAC collisions, in dense networking scenarios with overlapping BSS, packet losses due to PHY collisions (the so-called 'hidden' terminal problem) between transmissions in neighboring cells increase, thereby reducing aggregate network throughput. Since many emerging deployment scenarios involve dense hotspots (such as stadiums, malls, congested urban living and enterprises), network performance evaluation for such use-cases is a focus of very topical research interest. For example, the latest WLAN amendment 802.11ax includes enhanced spatial reuse (SR) features to address the aforementioned network throughput reduction[2]. Other associated aspects of such dense deployments center on considerations of fairness caused by the new 802.11ax features against legacy BSS [9].

The main goal of the ns-3 modifications reported here is to improve existing Wi-Fi modules (based on WifiSpectrumPhy) fidelity for multi-BSS network performance evaluation, in the presence of mixed 802.11a/n/ac/ax clients such as those illustrated in Figure 1. Analytical models for such dense network performance for a mix of clients (legacy 802.11a/n/ac and 802.11ax in near future) as a function of the many network parameters/functions (Carrier Sense Threshold, Transmit Power, Rate Adaptation to name a few) are presently inadequate, and will continue to remain so for the foreseeable future due to the complexity of the problem involved.

This work represents an update regarding ongoing efforts at U. Washington (see [12] to improve the IEEE 802.11 module in ns-3 [5]. Our prior work [14] began the process of implementing more realistic abstractions for 802.11 packet reception over additive white Gaussian noise (AWGN) channel; specifically it modeled packet synchronization via detection of 802.11 preamble and further, described the need for a more fine-grained multi-stage approach to Clear Channel Assessment (CCA). Subsequently, [13] utilized a spectrum-aware PHY model class in ns-3: WifiSpectrumPhy to build accurate *link-to-system* mappings for various 802.11 MCS (modulation and coding schemes) combinations.[1] While it is possible to perform a rudimentary multi-BSS study through these improvements, additional PHY feature abstractions are necessary to incorporate effects unique to heterogeneous networks simulations. In [7], work in support of Wi-Fi coexistence and LAA has improved the ns-3 attributes around CCA, becoming the precursor to the further CCA improvements proposed in this work. For instance, an 802.11ac device must first detect whether an incoming signal is a supported 802.11 PHY protocol data unit (PPDU) (i.e. 802.11a/n/ac), before it can decide whether the channel is busy or idle. Aside from not having the PPDU dependent state machine in handling the PPDU reception (it treats all packets as 802.11a PPDUs), the lack of a preamble *correlation* based CCA PHY abstraction is a major limitation in the existing ns-3 Wi-Fi stack.

In our prior work, any STA hears all other STAs regardless of whether they are from the same BSS or not - due to the intrinsically large carrier sense (CS) range setting.[2] It is well-known that while a large carrier sensing range is effective in reducing hidden terminals, it leads to increased exposed terminals[3] - the suppression of transmissions (due to the unnecessarily large carrier sense range) that would have been successful had it been allowed. As was recognized early in [10], a key to optimizing multi-BSS networks is via the choice of a suitable CS range (i.e. dynamic sensitivity control), a concept that has now been embraced in 802.11ax.

The rest of the manuscript is structured as follows. In Section 2, we give a brief review of the ns-3 CCA implementation when this work was started. In Section 3, we detail the proposed modifications to improve the ns-3 CCA. We then demonstrate the capabilities of the new ns-3 CCA model by evaluating the performance of a multi-BSS simulation scenario. We then conclude the paper in Section 5.

2 CLEAR CHANNEL ASSESSMENT IN NS-3: BRIEF REVIEW

CCA is the mechanism used by 802.11 STAs to determine whether the channel is busy or idle. An idle state (CCA-IDLE) means that the STA can continue to decrement its CSMA/CA backoff counter until it reaches 0, whereupon it transmits. A busy state (CCA-BUSY) on the other hand means that the STA must freeze its backoff counter for the duration of channel being detected busy. The CCA mechanism has two flavors: the first is a signal detect (SD) which uses correlation for the 802.11 PHY preamble. As such, CCA-SD only works in detecting (in-network) 802.11 transmissions. For non-802.11 transmissions, the second method uses energy detect (ED). In CCA-ED, the STA simply computes the ambient power on the channel and thresholds it to decide whether the channel is busy. The standard requires all STAs to accurately detect the presence of 802.11 signals with at least -82 dBm of receive power using CCA-SD and non 802.11 signals with at least -62 dBm of receive power.[3] It is worth noting that the thresholds of -82dBm for CCA-SD and -62dBm for CCA-ED applies only to 20MHz bandwidth signals. For signals with $BW > 20MHz$ bandwidth, the standard increases the threshold by $10 \log \frac{BW}{20MHz}$ dB. Hence for 40MHz signals, the CCA-SD and CCA-ED thresholds are -79dBm and -59dBm respectively, while for 80MHz signals, the thresholds are -76dBm and -56dBm respectively.

Originally, the ns-3 Wi-Fi stack already had a crude implementation of the CCA-SD and CCA-ED mechanisms. The CCA-SD threshold is referred to as *EnergyDetectionThreshold* while the CCA-ED threshold is referred to as *CcaMode1Threshold*. These thresholds were set to an extremely high sensitivity of -99 dBm and -96dBm respectively.[4] Aside from the unrealistic default thresholds, a number of problems in the existing implementation arose from the fact that it doesn't have a real concept of preambles and PHY headers. In a realistic model, a CCA window of 4µs allows the system to lock on the strongest arriving signal within the window. In the existing model however, the receiver locks on the first signal regardless of how strong an immediately following signal is impairing its ability to do physical layer capture.

Once the preamble is detected, a realistic model will detect the PHY header followed by the DATA symbols. Over the years, the Wi-Fi preamble and PHY header has evolved from a single SIG field symbol to multiple SIG field symbols as the 802.11 standard support new PPDU formats. This is shown in Figure 2 with SIG field symbols in light shade and DATA symbols in darker shade. For all PPDU formats, the SIG fields are preceded by the L-STF and L-LTF symbols which are necessary for the initial frame synchronization and channel estimation respectively. The SIG fields on the other hand contain the duration, and other information necessary for the STA to decode the DATA symbols.

Another problem with the current ns-3 implementation is that the PPDU duration is known *a priori* instead of being a detected value from the SIG fields. Hence, any signal with a power exceeding *CcaMode1Threshold*, the CCA-BUSY state is triggered for the exact PPDU duration as shown in Figure 3. Also, STAs will defer for the exact PPDU duration (unless an optional frame capture model has been added) regardless of a successful header decode outcome. In a realistic model, should the detection of the SIG fields fail, the receiver can stop the decode process and reset the PHY back to CCA-IDLE allowing it to access the channel sooner.

It is worth noting that our multi-stage reception proposal in [14] solves the *a priori* duration problem but only for 802.11a PPDUs. In

[1] This introduced appropriate time-frequency signal representations to Wi-Fi in ns-3, enabling evaluation of performance over frequency selective and interference channels - i.e. different technologies on the same channel.

[2] The carrier sense range in a WLAN network represents the region wherein no two transmissions may occur simultaneously; this is enforced by requiring each STA desiring channel access to conduct prior channel sensing or CCA.

[3] The standard does not directly specify false alarm limits for CCA. Instead, it requires STAs to successfully detect packets with a packet error rate of less than 10%. Too many false alarms would make the STA fail this requirement.

[4] Based on ns-3 release 3.29 and lower

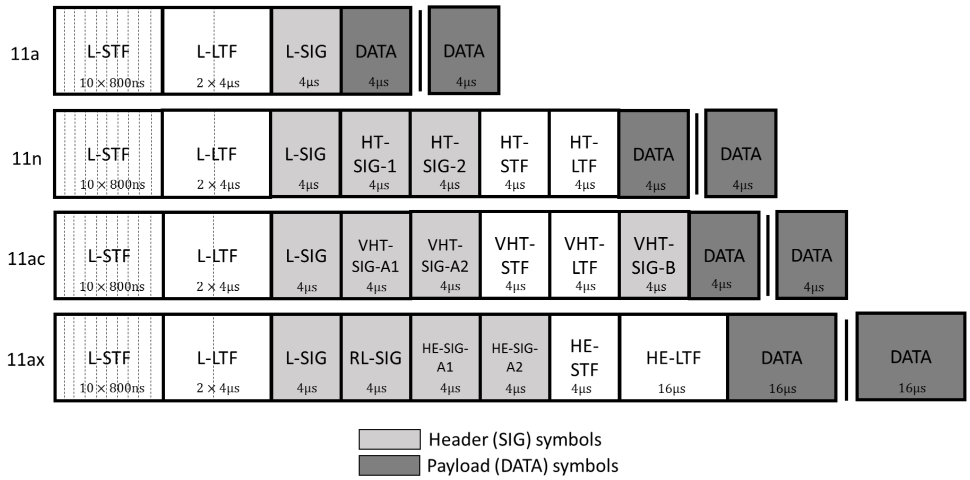

Figure 2: Evolution of 802.11 PPDU Frame Format

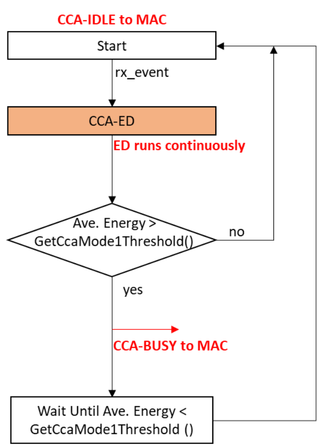

Figure 3: Existing CCA Flowchart for ns-3

this work, we extend the multi-stage reception to all PPDU formats as will be detailed in the next section.

3 IMPROVED PHY ABSTRACTION FOR CCA IN NS-3

The proposed CCA flowchart for ns-3 is illustrated in Figure 4, improving the existing ns-3 CCA by adding a correlation based CCA-SD mechanism as well as multi-stage reception for all supported PPDU formats. During CCA-IDLE, a receiver runs CCA-SD and CCA-ED concurrently with the default thresholds of -82dBm and -62dBm respectively. Thus, a valid 802.11 signal will trigger CCA-BUSY via CCA-SD, traversing the left side of the flowchart where multi-stage reception is performed. A non 802.11 signal on the other hand will only trigger CCA-BUSY through the CCA-ED if it exceeds the high threshold. In the next subsections, we explain in

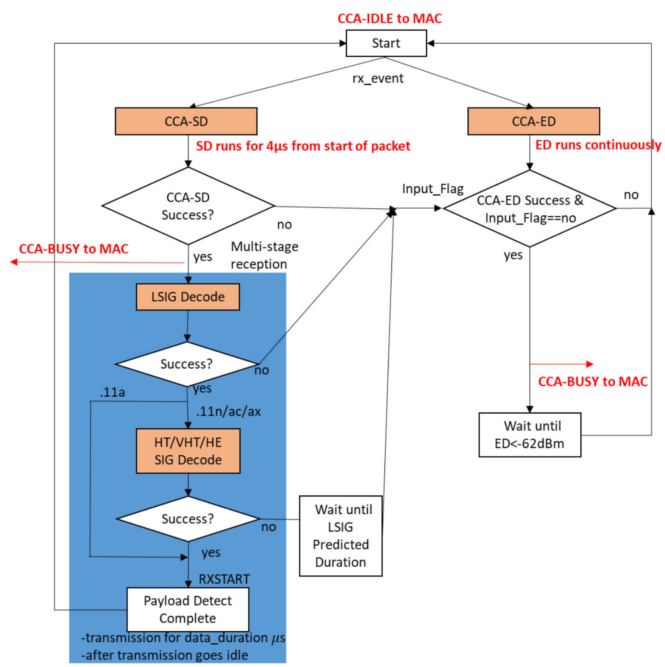

Figure 4: Proposed CCA Flowchart for ns-3

detail CCA-SD, CCA-ED, and multi-stage reception that make up the proposed CCA PHY abstraction.

3.1 CCA-SD

In this paper, we implemented the CCA-SD PHY abstraction in accordance to the correlation based preamble detection (PD) module in the Matlab WLAN toolbox [15]. This PD module is based on [8]

Table 1: Success Probability P_{SD} of CCA-SD. Noise Floor = -94dBm

RSSI [dBm]	≤-100	-99	-98	-97	-96	-95	-94	-93	-92	-91	-90	-89	-88	-87	≥ -86
α = 0.3	0	0.012	0.019	0.050	0.196	0.465	0.781	0.981	0.999	1	1	1	1	1	1
α = 0.5	0	0	0	0	0	0.002	0.013	0.052	0.242	0.711	0.971	1	1	1	1
α = 0.7	0	0	0	0	0	0	0	0	0	0	0.010	0.076	0.481	0.931	1

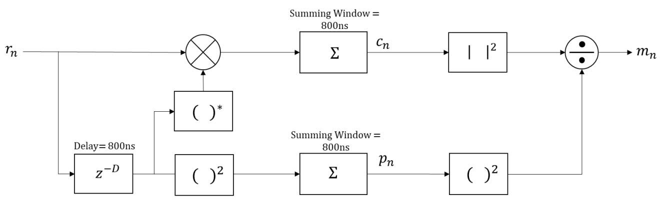

Figure 5: Preamble Normalized Correlation Block

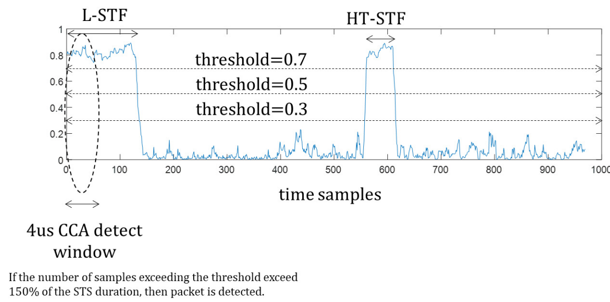

Figure 6: Normalized Correlation of 802.11 Preamble

and is illustrated in Figure 5. First, the received signal $r(n)$ is auto-correlated with a delayed version of itself. The delay is denoted by D which equals 800ns, the length of the standard cyclic prefix duration in 802.11a PPDUs. The resulting magnitude-squared correlation signal $|c_n|^2$ is then normalized by the signal power p_n^2 to yield m_n (i.e. $0 \leq m_n \leq 1$) and tested against a threshold which can be varied to provide a robust statistic, i.e.

$$c_n = \sum_{l=1}^{N_R}\sum_{k=0}^{D-1} r_{n+k,l} r^*_{n+k+D,l} \tag{1}$$

$$p_n = \sum_{l=1}^{N_R}\sum_{k=0}^{D-1} \left|r_{n+k+D,l}\right|^2 \tag{2}$$

$$m_n = \frac{|c_n|^2}{p_n^2} \tag{3}$$

where N_R is the number of receiver antennas. For the purposes of this paper, N_R is assumed to be 1.

Figure 6 shows a typical plot of m_n for a valid 802.11n signal at a signal to noise power ratio (SNR) of 10 dB and a noise floor level of -94 dBm. An m_n value near unity denotes a very high probability that an 802.11 signal is present. One can see that high levels of correlation are detected for the L-STF and HT-STF portions of the frame, since both contain the same sequences. However, due to the 4µs latency budget for CCA-SD set by the standard, we can only use the first half of the L-STF correlation to decide whether a valid 802.11 signal exists. With CCA-IDLE flag set, a timer keeps track of the durations when the normalized correlation exceeds the threshold. [8] recommends a threshold value of 0.5 to balance out false alarms with missed detections but this can be adjusted to make the receiver more or less sensitive. We chose the decision rule by requiring the duration of the normalized correlation exceeding the threshold to be at least 1.2µs (i.e. 150% of the STS duration) for declaring 802.11 PPDU presence. The methodology described is achieved using a lookup table parameterized by the received signal strength indicator (RSSI), and correlation threshold α. The CCA-SD success probability $P_{SD}(\alpha)$ vs the RSSI is summarized in Table 1 for thresholds α=0.3, 0.5 and 0.7. As can be observed, the P_{SD} values increase as RSSI increases and the threshold is increased from 0.3 to 0.5 to 0.7. Moreover, the table form an approximate diagonal matrix of P_{SD} values for the 3 thresholds given. To simplify the implementation in ns-3, we use $P_{SD}(\alpha = 0.5)$ as the reference lookup table denoted as $\hat{P}_{SD}$) and use translation to generate the other $P_{SD}(\alpha)$ lookup tables, i.e.,

Table 2: Success Probability P_{ED} of CCA-ED. Noise Floor = -94dBm

RSSI [dBm]	≤-63	-62	-61	≥ -60
γ=-62dBm	0	0.452	0.998	1

$$P_{SD}(\alpha, RSSI) = \hat{P}_{SD}[RSSI + 10(\alpha - 0.5)] \tag{4}$$

For the default $\alpha = 0.5$, one can see that the correlation method has an effective sensitivity of -90dBm, as opposed to the target value of -82dBm set in the 802.11 standard. In order to artificially reduce the sensitivity to match any desired CCA-SD threshold (e.g. the default -82dBm), we introduce another parameter β. The modified CCA-SD success probability can be expressed as

$$P'_{SD}(\alpha, RSSI, \beta) = P_{SD}(\alpha, RSSI)\ \mathcal{I}(RSSI > \beta) \tag{5}$$

where $\mathcal{I}$ is the Indicator function, i.e.,

$$\mathcal{I}(RSSI > \beta) = \begin{cases} 1 & \text{if } RSSI > \beta \\ 0 & \text{if } RSSI \leq \beta \end{cases} \tag{6}$$

3.2 CCA-ED

CCA-ED is functionally implemented as in Figure 7 that represents power averaging of the receive signal and conversion to dB. Due to lack of in-band interference/noise filtering capability of the CCA-ED mechanism, the standard only requires STAs to have a sensitivity of -62dBm with CCA-ED (i.e. that is 20dB lower than the corresponding CCA-SD threshold) and is kept running at all times.

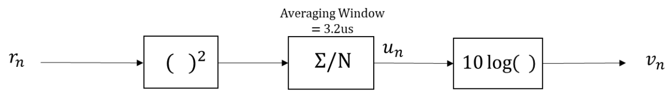

Figure 7: Energy Detect Block

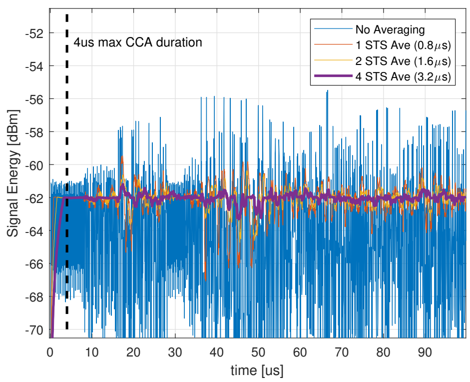

Figure 8: Average Signal Energy of 802.11 Signal

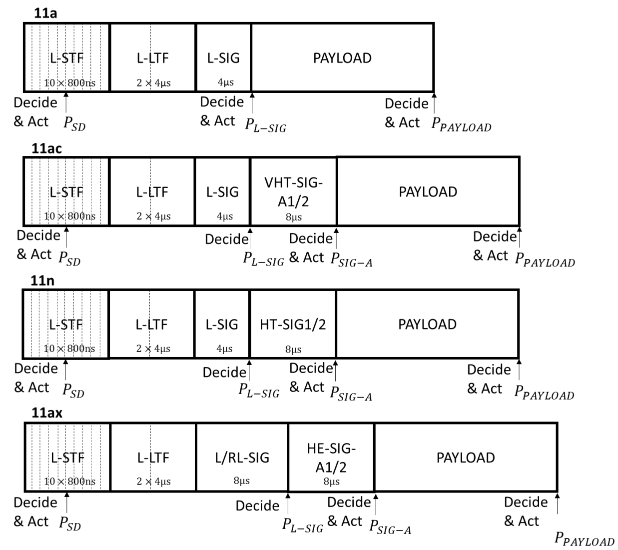

Figure 9: Decision Timeline for Different PPDU Formats

In order to reduce the estimation error due to the high peak to average power of 802.11 signals, a suitable amount of averaging must be done to estimate the signal power. Like CCA-SD, CCA-ED is governed by the 4μs CCA window to flag CCA-BUSY for any received signal greater than the CCA-ED threshold. The averaged instantaneous energy of a -62dBm signal is shown in Figure 8 for varying averaging duration and a noise floor of -94dBm. The step-size for the averaging is set to match the STS duration of 800ns which results in a smoother average when the preamble is present. Up to 4 STS duration (i.e. 3.2μs) of averaging can be done to improve the accuracy of the estimate; note that the fluctuations of the averaged signal energy is reduced to within 1dB as a result.

The CCA-ED success probability is shown in Table 2 for a threshold of $\gamma = -62$dBm. Due to the high CCA-ED threshold, equivalent to an SNR of 32dB without interference, the success probability is almost a step function and can be modeled in ns-3 as a simple binary switch, i.e.

$$P_{ED}(\gamma, RSSI) = \begin{cases} 1 & \text{if } RSSI > \gamma \\ 0 & \text{if } RSSI \leq \gamma \end{cases} \tag{7}$$

3.3 Multi-stage Reception

For multi-stage reception, we extend our work in [14] which only considered 802.11a PPDUs - by adding appropriate decisions rules for 802.11n/ac/ax PPDUs as illustrated in Figure 4. The corresponding decision timelines are shown in Figure 9. For 802.11a PPDUs which has a single L-SIG symbol, multi-stage reception is made possible by the parity bit contained in the L-SIG . A correct parity bit validates the L-SIG decoded information (probability indicated as P_{L-SIG} in Figure 9) and allows it to proceed with DATA symbol decoding.

For 802.11n/ac/ax PPDUs on the other hand, the next step after a successful L-SIG detection is to decode and validate their 2 remaining SIG field symbols (HT-SIG1/2 for 11n, VHT-SIG-A1/2 for 11ax and HE-SIG-A1/2 for 11ax).[5] We refer to these symbols collectively as SIG-A symbols due to their having similar lengths, modulation, and field location in their respective PPDU. These SIG-A symbols are validated using the 8 bit cyclic redundancy check (CRC) field they contain (probability indicated as P_{SIG-A} in Figure 9). Only when the L-SIG and SIG-A are both detected successfully can the receiver proceed with the DATA reception. Otherwise, the STA will reset the CCA state into CCA-IDLE avoiding unnecessary attempts at reception of the DATA symbols.[6]

The probability P_{L-SIG} and P_{SIG-A} are shown in Table 3 for an AWGN channel. The almost 50% L-SIG success rate even for extremely low SNR values are due to false alarms caused by the single parity bit validation. This is why in Figure 9, for PPDUs with SIG-A symbols, any decision after the L-SIG detection is not accompanied by an immediate action; instead, the action is postponed until the result of the SIG-A detection decision becomes available.

4 NS-3 SIMULATION RESULTS

We demonstrate the capabilities of the improved PHY abstractions described via simulations of multiple BSS networks that employ dynamic sensitivity control (DSC), i.e. whereby STAs independently adapt their respective CCA thresholds as enabled in 802.11ax (instead of using the legacy fixed CCA thresholds defined by the standard) so as to enhance aggregate network throughput. All MATLAB

[5]For the purposes of this paper, we ignore the repeated L-SIG (RL-SIG) symbol used in long range applications as well as the VHT-SIG-B symbol used for multi-user applications.
[6]When only the L-SIG or SIG-A is in error, the STA can still estimate the duration of the current signal. In this case, it has to defer until this predicted duration.

Table 3: Success Probability P_{LSIG} and P_{SIGA}. Noise Floor = -94dBm

SINR [dBm]	≤-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	≥ 4
P_{LSIG}	0.444	0.535	0.560	0.495	0.495	0.412	0.526	0.550	0.568	0.802	0.873	0.963	0.989	0.999	1
P_{SIGA}	0	0	0	0	0	0	0	0.018	0.094	0.335	0.686	0.882	0.969	0.992	1

Table 4: PHY and MAC Simulation Parameters

Bandwidth	5GHz (CH 36, 5180), 80MHz static
Shadowing	No Shadowing
PPDU format	IEEE 802.11ac VHT
STA TX power	15dBm
AP TX power	20dBm
Antennas	1x1 (SISO)
CCA-SD (β)	-56/-76dBm @ 80MHz
CCA-ED (γ)	-56dBm @ 80MHz
Link adaptation	Fixed MCS = 5 (234 Mbps)
Path loss model	LogDistancePathLossModel $d = \{1, 10, 30\}$, $e = \{2, 3.5, 3.5\}$, $PL_0 = -47.5$dBm
Access protocol	EDCA, Default AC_BE parameters
Traffic type	UDP constant 200Mbps bit rate
Traffic direction	Uplink only
MPDU size	1538 bytes
Aggregation	64 MPDUs with Block ACK
Simulation time	10s
No. of simulation iterations	10

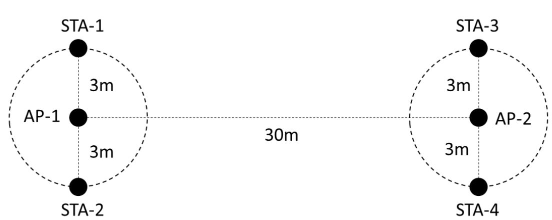

Figure 10: Dual BSS Calibration Scenario

and ns-3 codes, and instructions for reproducing results in this section are publicly available in [1].

4.1 Calibration Scenario

A useful first test-case is the two BSS scenario shown in Figure 10. This was used as a calibration scenario during 802.11ax standardization in order to align simulations from different vendors[11]. Each BSS consists of two STAs separated by 3m from their respective AP and 30m from their OBSS counterparts. For this scenario, we fixed the CCA-ED threshold to -56dBm (equivalent to the default -62dBm threshold adjusted for 80 MHz bandwidth) whereas the CCA-SD threshold is set to two values, -56dBm and -76dBm to test the effect of DSC. The rest of the simulation parameters are summarized in Table 4.

Table 5: DSC Calibration SR Gain Results[7]

CCA -SD		MTK	UPC	SON	WIL	NTT	**This work**
-76	BSS1	98.7	100.7	102.8	107.1	97.5	**96.6**
	BSS2	105.8	99.8	101.9	108.9	96.0	**98.5**
	Sum	204.5	200.5	204.7	216.0	193.5	**195.1**
-56	BSS1	201.6	201.7	193.2	191.1	186.4	**190.0**
	BSS2	201.6	201.4	191.1	192.2	186.7	**189.0**
	Sum	399.2	400.3	384.4	383.3	373.1	**379.0**
	S	1.97	2.01	1.88	1.78	1.93	**1.94**

It is clear that in Figure 10, a maximum of two concurrent transmissions (i.e. one per BSS) is possible depending on the value of CCA-SD threshold applied. To illustrate this, we assume without loss of generality that STA-1 is performing CCA. There are then 5 possible STAs including the APs that it can hear signals from. Based on the three log-distance path loss propagation model[4], the receive powers from all the other STAs are expected to be

(1) AP-1 = -42dBm
(2) STA-2 = -48dBm
(3) AP-2 = -69.3dBm
(4) STA-3 = -69.2dBm
(5) STA-4 = -69.5dBm

To enable two concurrent transmissions, STA-1 needs to set a CCA-SD threshold that would allow it to sense transmissions from STA-2 and AP-1 as they belong to the same BSS but ignore transmissions from AP-2, STA-3 and STA-4 as they belong to the other BSS. From the receive powers given above, a good CCA-SD threshold is therefore any value in range (-69.3dBm, -48dBm). It thus follows that a CCA-SD threshold of -56dBm will result in two concurrent transmissions while a CCA-SD threshold of -76dBm is expected to result in a single transmission. The goal of any DSC algorithm is to increase the aggregate throughput in a specific multi-BSS scenario by controlling the number of concurrent transmissions via the CCA-SD threshold. For a specific CCA-SD threshold β, we define the SR gain as the ratio of the resulting aggregate throughput $T(\beta)$ and the aggregate throughput when the reference threshold of -76dBm is used, i.e.

$$S(\beta) = \frac{T(\beta)}{T(-76dBm)} \tag{8}$$

For the calibration scenario in Figure 10, the aggregate throughput results for $\beta = \{-56dBm, -76dBm\}$ are summarized in Table 5. The first 5 simulation result columns were reported during 802.11ax standardization meetings while the last column are results from

[7]Simulation results in columns 1 to 5 are from Mediatek Inc., Technical University of Catalonia, Sony Inc., Wilus Inc., and NTT inc. respectively. Values are in Mbps except in the last row

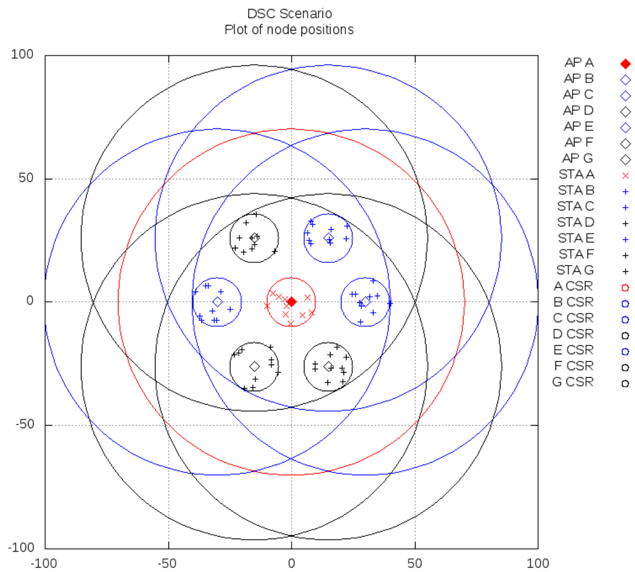

Figure 11: 7 BSS DSC Scenario

this work [6]. Using (8), the computed SR gain for the -56dBm threshold is shown at the bottom row. As seen in the table, the aggregate throughputs and SR gains reported have differences caused by different assumptions within the respective simulators. It is worthwhile noting that while the individual SR gains reported vary from 1.78 to 2.01, our result (1.94) is close to the average (1.91) of the various reference results.

4.2 Hexagonal BSS Scenario

With the aforementioned validation (our work produces throughput results that matches well with 802.11ax task group), we then test the simulator for more general scenarios consisting of 7 co-channel BSSes as shown in Figure 11, with the usual hexagonal cellular deployment. STAs are dropped randomly with a uniform distribution around a disc of radius 10m centered at the AP. The outermost circle indicated as the carrier sense range (CSR) refers to the distance from the AP where the presence of a transmitting STA will result in an RSSI of -76dBm. Note that with inter-AP distance of 30m, the CSR at each AP covers the entire network resulting in a fully overlapped network. Figure 12 presents the SR gain comparison with a) network simulation where duration is known *a priori* and b) this work where duration is detected from the PHY header.[8] As seen in the figure, the SR gain when the duration is already known is significantly lower compared to the one where the duration is detected, affirming the need for the improved abstractions in ns-3 proposed here. The higher SR gain for the latter can also be explained by the fact that a correct detection of the duration only happens when STAs observe the preamble. If for some some

[8]We emulated a system with known *a priori* duration using our modified code by setting the CCA-ED threshold equal to CCA-SD threshold.

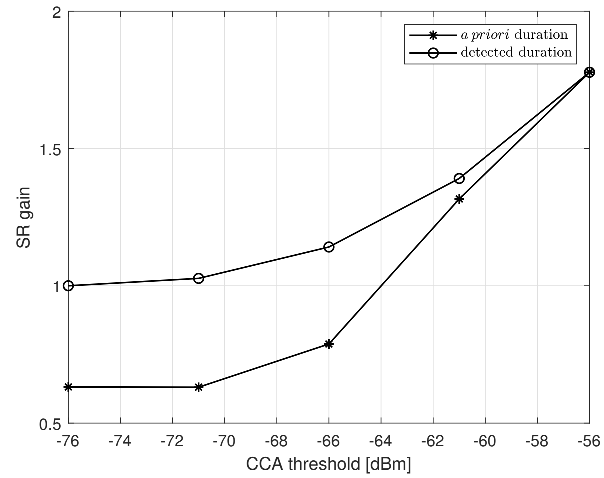

Figure 12: SR Gain Comparisons

Table 6: Best Aggregate Throughput/MCS per CCA-SD Threshold

CCA-SD [dBm]	-76	-71	-66	-61	-56
Best Agg. Tput [Mbps]	236	236	256	358	700
Best MCS	4	4	4	9	9

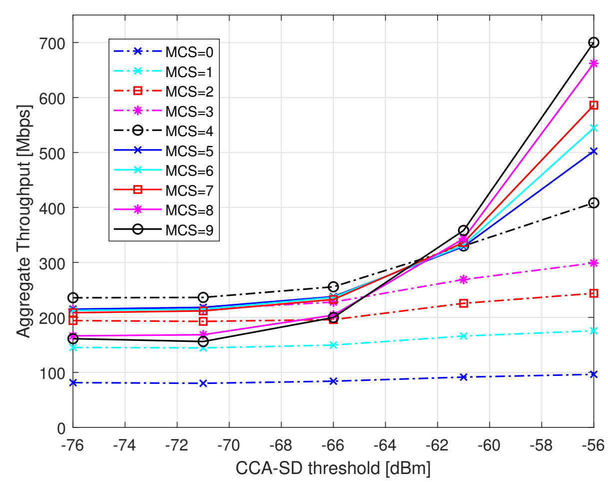

Figure 13: Aggregate Throughput With DSC

reason, a contending STA misses the preamble of the currently transmitting STA, it will signal CCA-IDLE which may allow it to transmit concurrently with an already transmitting STA.

Finally, in Figs 13 and Figs 14, the aggregate throughput and SR gain results are shown using the average of 10 independent STA realizations, for all supported MCSes in 80 MHz bandwidth. First in Figure 13, we see that MCS 4 achieves the best aggregate throughput of 236 Mbps for the CCA-SD threshold of -76dBm compared

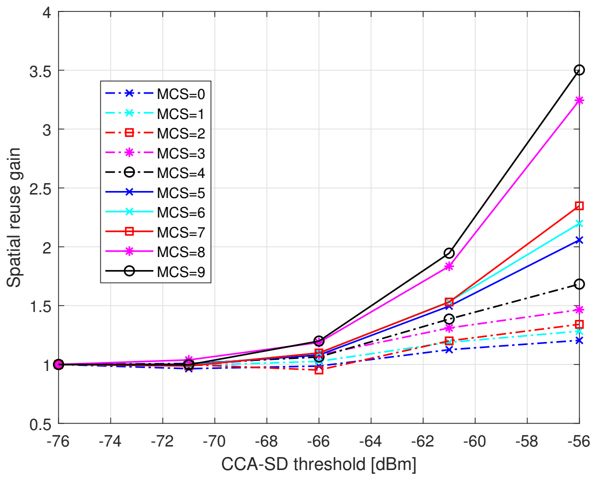

Figure 14: SR Gain With DSC

to 161 Mbps for MCS 9. For the maximum CCA-SD threshold of -56dBm, the MCS 9 aggregate throughput increases dramatically to 700 Mbps compared to only 408 Mbps for MCS 4. At -63dBm, a crossover point can be seen for the maximum aggregate throughput of MCS 4 and 9 indicating that the aggregate throughput is sensitive not only to the MCS of choice but also to the CCA-SD threshold. Table 6 summarizes the best MCS to use in terms of aggregate throughput for each CCA-SD threshold. The crossover point can be explained by the fact that at low CCA-SD thresholds, both exposed terminal problem and hidden terminal problem impact high MCS transmissions the most due to their high data rate and high required SINR margins. When the CCA-SD threshold is increased, the reduction of the exposed terminal problem alone allows high MCS transmissions to show their large aggregate throughput potential.

It can be confirmed from Figure 14 that the SR gain increases monotonically with increasing MCS values. At the highest CCA-SD threshold of -56dBm, MCS 9 has an SR gain of 4.3 compared to SR gain of 1.7 for MCS 4 and 1.2 for MCS 0. Using these simulation results, one can conclude that regardless of the MCS, an increase of the aggregate throughput will result by increasing the CCA-SD threshold. It is noteworthy to mention that while not directly investigated in this work, unfairness issues against legacy STAs (i.e. not supporting DSC) can be inferred from Figs 13 and Figs 14.

5 CONCLUSION AND FUTURE WORK

In this paper, we have detailed a new PHY abstraction that was implemented in the ns-3 simulator focusing on accurate CCA modeling and multi-stage reception. The improved CCA model now supports the correlation based CCA-SD mechanism which is shown to have a non-trivial effect on the aggregate network throughput. To verify our work, the new modules were shown to produce consistent simulation results compared to those presented during the 802.11ax standardization meetings. Sample simulation study for a use case of interest with 7 BSS deployment scenario quantified the SR gain of DSC as a function of MCS. The following design guidelines to enhance the multi-BSS aggregate throughput emerged from this study:

(1) Higher CCA-SD thresholds in DSC result in higher aggregate throughput.
(2) Higher MCS transmissions get higher SR gains from DSC.

The core PHY abstraction improvements such as CCA and multi-stage reception have been pushed to the ns-3-dev mainline and is available in [1]. A test suite called *WifiPhyReceptionTestSuite* can be used for unit testing the said improvements. Other remaining features will soon follow to support more advanced SR enhancements in IEEE 802.11ax. The actual simulation scripts used in this paper can be found in the *dsc_test* branch of the repo.

Additional work is needed to model the CCA involved for dynamic channel bonding as well as physical layer capture model. A dynamically changing bandwidth transmission will require a third CCA mechanism which is designed specifically to detect 802.11 signals on a STA's non-primary channels.

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