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More WiFi for everyone: Increasing spectral efficiency in WiFi6 networks using a distributed OBSS/PD mechanism

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Abstract: In this paper, we propose a distributed algorithm that determines effective Overlapping Basic Service Set/Preamble Detection (OBSS/PD) threshold levels in each WiFi6 device to maximize the total throughput by increasing the spectral efficiency. Within WiFi6 standard, OBSS/PD mechanism is introduced to increase the overall efficiency of WiFi networks by tuning the receiver sensitivity as well as the transmission power. In a nutshell, the proposed algorithm, RACEBOT, tunes the hearing (i.e. reception) and speaking (i.e. transmission) parameters of each WiFi device individually for the betterment of the WiFi experience of all WiFi networks in a neighborhood. WiFi experience is not only affected by the spectral efficiency but also by the so-called rate selection algorithms that aims to select the ideal modulation and coding levels according to the ever-changing channel conditions. For higher flexibility, the proposed algorithm works agnostically to the selected rate selection mechanism. Moreover, RACEBOT is a distributed algorithm working independently in all WiFi devices in a given environment. We have conducted extensive simulations in NS3 to evaluate the performance of our proposed algorithm and compare its results with other prominent carrier sensitivity threshold algorithms, both pre-WiFi6 and post-WiFi6. Our results show that RACEBOT outperforms its competitors the RTOT and DSC algorithms in terms of aggregate throughput by 10%-20% in dense networks and 5%-10% in sparse networks considering modern rate selection algorithms such as Thompson.

Key words: WiFi, 802.11ax, OBSS/PD, spectral efficiency

1. Introduction

Through the last two decades, WiFi has been transformed from a fledgling technology (a wireless alternative to Ethernet networks) to one of the most widely used last hop Internet connectivity solutions around the world. This resulting widespread usage demanded higher network capacities which had been addressed in 2009 with IEEE 802.11n/WiFi4 and in 2013 with IEEE 802.11ac/WiFi5. These standards introduced numerous key features of WiFi: higher level modulation and coding schemes (MCS), multiple input multiple output (MIMO) capabilities, increased channel bandwidth, and transmission opportunity concept to name a few.

As WiFi network capacities increase, more and more WiFi networks have been deployed, especially in residential and commercial areas. Due to the density of such locations, these networks are often times deployed with overlapping wireless footprints. Since the medium access control (MAC) layer of IEEE 802.11 is based on a random access scheme, namely the carrier sense multiple access/ collision avoidance (CSMA/CA), such overlaps force multiple WiFi networks in close proximity to basically share the same spectrum leading to an

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overall low spectral efficiency for WiFi. This becomes especially prevalent in 2.4 GHz band WiFi channels since out of the available 13 channels only three of them are nonoverlapping. As for the 5 GHz band, in order to utilize WiFi to its fullest network capacity and choose an 80 or 160 MHz channel bandwidth, a WiFi network is limited to five or two channels respectively.

To address this reduction in spectral efficiency, solutions have been proposed in the literature while being compliant with the base IEEE 802.11 channel access mechanism. IEEE 802.11h has introduced transmit power control (TPC) mechanism which enables WiFi devices to reduce their transmission powers when there are other WiFi networks nearby. Then, a multitude of adaptive carrier sensitivity threshold-based solutions have been proposed by various works [1–4]. These methods go one more step than the TPC mechanism and try to reduce the carrier sensitivity threshold of the CSMA/CA mechanism to enable multiple networks to operate on the same channel at the same time. Although these methods are useful in some scenarios, none of them are adaptive enough to cover a multitude of WiFi scenarios. Moreover, by trying to be less disruptive to other WiFi networks, these methods also decrease the WiFi quality of their own networks.

This spectral efficiency issue had been decided, by IEEE 802.11ax task group (TGax), to be one of the key issues to address in the next main iteration of the WiFi standard, the IEEE802.11ax/WiFi6[1] [5]. Utilizing the basic service set (BSS) color mechanism from IEEE 802.11ah, WiFi6 has introduced two key concepts: the two network allocation vector (NAV) system and the Overlapping BSS/Preamble Detection (OBSS/PD) mechanism. Leveraging these mechanisms, a WiFi6 device can apply different transmission power and carrier sensitivity threshold pairs for transmissions from its own and other WiFi networks. Moreover, these parameters can be adjusted during the device's operation as the WiFi spectral usage changes. This versatility is expected to increase the spectral efficiency of WiFi networks, especially in environments with more than a few overlapping WiFi networks.

However, the IEEE 802.11ax standard does not suggest any particular mechanism on how and when to tune these parameters and it is left unstandardized. Although there are some OBSS/PD parameter tuning algorithms proposed in the literature, these algorithms focus on scenarios where the MCS levels of each transmission link is static, which limits their applicability in many real-life scenarios. In this paper, we propose a Rate Adaptive inter-bss Carrier Elimination-Based OBSS/PD Threshold (RACEBOT) mechanism that tunes the OBSS/PD parameter of each WiFi device dynamically to increase the spectral efficiency of a given WiFi channel in a given area. RACEBOT works in conjunction with the rate selection algorithm utilized in the WiFi device to consider more realistic WiFi scenarios. We extend the WiFi module of the NS3 simulator with appropriate functionalities and rate selection algorithms to evaluate the performance of the proposed mechanism.

In this work, the main contributions are as follows:

- We develop an OBSS/PD threshold algorithm that is adaptive to the changes in data rate and interference. The algorithm works in a distributed fashion in each WiFi device separately.

- We present a random topology generator that creates topologies based on TGax outdoor box5 scenario.

- We evaluate the performance of the proposed OBSS/PD algorithm with rate selection algorithms.

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[1] WiFi6 is the name of the Wi-Fi Alliance certification program for IEEE 802.11ax standard compliance. We will use these two terms, IEEE 802.11ax, and WiFi6, interchangeably throughout this manuscript.

2. Channel access techniques and rate selection algorithms in IEEE 802.11

At its core, the OBSS/PD mechanism is built on top of the classical CSMA/CA mechanism of the IEEE 802.11 protocol. Although the CSMA/CA mechanism is quite an efficient and lightweight channel access mechanism, there are scenarios where it falls short in terms of performance. Over the last decade, numerous CSMA/CA variations have been proposed to alleviate such issues with varying degrees of success. Moreover, a WiFi device chooses a modulation and coding scheme (MCS) level among a set of predefined MCS levels when transmitting a message. While each MCS level has a particular throughput value, they also have different channel access requirements. Therefore, the selection of the MCS level is interlinked with the overall channel access mechanism.

2.1. Channel access techniques in IEEE 802.11

The channel access part of the CSMA/CA mechanism is mainly divided into two complementary parts: the physical carrier sensing and the virtual carrier sensing.

The physical carrier sensing mechanism is mainly conducted via a joint thresholding and preamble detection method. First, thresholding is applied over the energy of the incoming signal to distinguish the energy from the thermal noise. Afterwards, Rx-Sensitivity threshold is applied. If the received signal strength indicator (RSSI) of the signal is lower than the Rx-Sensitivity threshold, the signal is considered thermal noise and the channel is considered as IDLE. Otherwise, the receiver moves to preamble detection. In this second stage, if a WiFi preamble is detected in the signal the frame is decoded and the channel is considered as BUSY until the end of the frame. If a WiFi preamble is not detected, in case of non-WiFi signals, a second threshold called the clear channel assessment/energy detection (CCA/ED) threshold is applied. If the RSSI of the signal is greater than CCA/ED, then the channel is considered as BUSY, otherwise, it is IDLE.

The virtual carrier sensing takes place if a WiFi preamble is detected but based on the frame header it is observed that this device is not the intended destination of this WiFi frame. In this case, the length of the frame is read from the frame header and a special value called the network allocation vector (NAV) is set according to this value. As long as NAV has a nonzero value, the receiver defers from conducting carrier sense and considers the medium as BUSY.

For the collision avoidance part of the CSMA/CA mechanism, when the channel is detected as IDLE and the transmitter has frames to send, first the transmitter waits for a certain period of time called inter-frame spacing (IFS). Here, different IFS values (e.g., short IFS (SIFS), arbitration IFS (AIFS)) are used for different type of frames to provide a prioritization between frames of different importance. Then, to avoid collision between multiple potential transmissions of the same level of importance, a randomization-based mechanism called the contention window mechanism is used. In contention window mechanism, basically, each transmitter selects a random number and waits for that amount of time before sending their frames. Since the selection of this random number is not centralized, there is a chance of multiple transmitters selecting the same number which leads to a collision which is again handled by the contention window and retransmission mechanisms.

2.2. Common problems of the CSMA/CA mechanism

There are scenarios where the CSMA/CA mechanism falls short and yields collisions or underutilization. The most critical of such scenarios are the “Hidden Node Problem” and the “Exposed Node Problem”. Although the Hidden Node Problem is mainly solved by the request to send/ clear to send (RTS/CTS) mechanism of the IEEE 802.11 standard, no such reliable solution has been proposed for the Exposed Node Problem.

Mechanisms proposed to mitigate the exposed node problem are generally based on modifying the core RTS/CTS mechanism. Shukla et al. propose a mechanism that detects RTS frames and corresponding source-destination addresses by WiFi client station (STA) [6]. In the classical RTS/CTS mechanism, CTS must be heard after RTS frames. If no CTS frames are heard after RTS frame and instead a data frame is heard from another STA, that means there is an exposed node problem. In this mechanism, a node, after noticing that it is an exposed node, does not use RTS/CTS frames and transmits its frames without initiating RTS/CTS. One additional requirement of this mechanism is the need for synchronization between the exposed and transmitting nodes, which may be infeasible in some cases.

Effective solutions to exposed node problems require central coordination. Another group of works considers the coordination of multiple WiFi access points (APs) in the same vicinity to mitigate the exposed node problem. Nishide et al., propose a mechanism where each AP collects information of uplink traffic coming from the associated STAs and keeps them in a database [7]. This AP cooperation system analyzes the received frames from the STA and detects the hidden and exposed node problems. A similar approach is used in [8] and the exposed nodes are detected via offline training and then using the coordination of exposed links via newly introduced request-to-send-simultaneously (RTSS) and clear-to-send-simultaneously (CTSS) frames.

2.3. Rate selection algorithms

WiFi devices have access to a multitude of MCS levels depending on the IEEE 802.11 substandard. Each MCS level requires a minimum signal-to-interference and noise ratio (SINR) and a maximum bit error rate (BER) to be used depending on the channel bandwidth value (e.g., the latest IEEE 802.11ax substandard supports 11 MCS levels with varying minimum SINR values between -52 and -82 dBm). Due to their stringent minimum SINR and maximum BER requirements, higher MCS rates can only be used if the channel conditions are very good (i.e. low interference, close range to the receiver). On the other hand, while lower MCS levels can be used in all channel conditions, they can lead to underutilization of the spectrum if the channel is in a good state. Since the quality of WiFi channels is time-varying, specialized dynamic rate selection algorithms are needed to find the ideal MCS level optimizing requirements and spectrum utilization.

One of the most commonly used rate selection algorithms in the field is the Minstrel algorithm [9]. Introduced for Linux wireless drivers, Minstrel algorithm is based on transmission statistics. During its run-time, the algorithm keeps the successful and unsuccessful transmissions for each MCS level and constructs a decision table called retry chain. The throughput value of each MCS level is calculated via exponential weighted moving average (EWMA) and recorded in a table. To prevent being stuck on an MCS level, the algorithm also tries random MCS levels. So, the algorithm transmits 90% of transmissions as regular transmission and 10% of transmissions as “lookaround transmissions” to find MCS levels with better performances.

Although Minstrel has its strengths, it is known that in certain scenarios, Minstrel is unable to cope with the changes in the wireless medium and does not choose the ideal rate in some cases [10]. One of the best known recent rate selection algorithms that surpasses Minstrel in terms of overall performance is the Thompson algorithm [11]. The algorithm is based on the solution of the multi arm bandit problem by selecting the ideal slot machine to obtain more gain with limited resources. In Thompson, instead of the slot machines, the most efficient MCS level is tried. To that end, at each trial, the transmission is recorded whether successful or not. Then, by using the beta distribution, the success probabilities of each data rate is estimated. The shape of the beta distribution is determined by the recorded transmission. According to the success and failure rates, success probability of each rate is calculated, then the rate that has the maximum success probability is selected.

3. Channel access in IEEE 802.11ax with the OBSS/PD mechanism

When we look at the exposed terminal problem, and in a more general sense the spectral efficiency of WiFi networks in the same environment; another approach would be for each WiFi device adjusting its transmission powers according to the topology to maximize the overall spectral efficiency. In Figure 1, we consider a simple scenario consisting of two partially overlapping WiFi networks operating in the same WiFi channel. Here the dotted lines represent the range of the STAs if they use the default WiFi Rx-Sensitivity thresholds. In that case, STA_1 and STA_2 should take turns when sending information to their respective APs which leads to a considerable reduction in spectral efficiency.

The efficiency reduction can be mitigated by adjusting the Rx-sensitivity threshold of both devices as depicted by the dashed lines. In this case, STA_2 shall not be able to hear the active transmission between STA_1 and AP_1 and it will transmit its own traffic to AP_2 simultaneously leading to a higher total throughput.

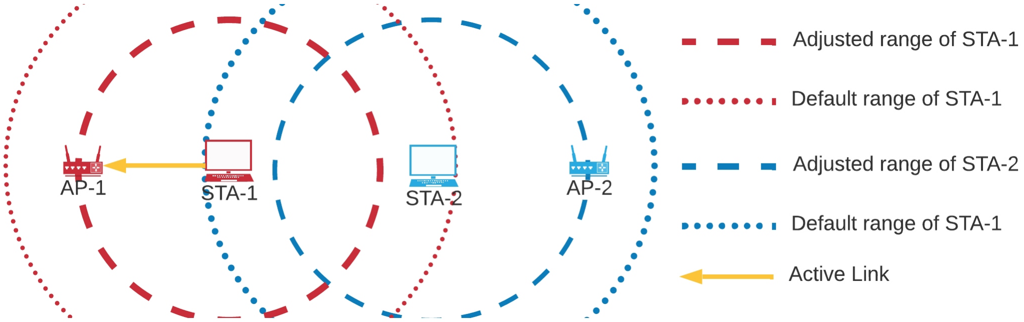

Figure 1. An example of spectral efficiency problem.

3.1. OBSS/PD mechanism in IEEE 802.11ax

Based on this premise, WiFi6 introduced the OBSS/PD mechanism: a dynamic Rx-sensitivity threshold mechanism that aims to increase the spectral efficiency of WiFi networks by adjusting the Rx-sensitivity threshold and accordingly the transmission power of each device.

As shown in Figure 2, OBSS/PD mechanism is built on top of the legacy CSMA/CA carrier sensitivity mechanism. In the OBSS/PD mechanism, when a WiFi preamble is detected, instead of simply stating that the channel is BUSY, a special frame header field called the color is utilized. If the color of the frame is equal to the color of this node, then the frame belongs to the same BSS and the channel is considered as BUSY. However, if the color of the frame is different than this node's color (i.e. the frame belongs to an OBSS) the RSSI level is compared to a third threshold, the OBSS/PD threshold. If it is greater than OBSS/PD threshold, the channel is considered as BUSY. Otherwise, the channel is considered as IDLE. The OBSS/PD threshold can be set to any value between a minimum (i.e. $OBSS/PD_{Min}$) and a maximum (i.e. $OBSS/PD_{Max}$) depending on the channel bandwidth.

However, simply reducing the Rx-sensitivity threshold via the OBSS/PD value shall lead to higher co-channel interference (CCI) to transmissions belonging to OBSSs. To achieve an overall higher spectral efficiency the multiplication of transmission power and Rx-sensing threshold should be a constant value [12]. Therefore, as the OBSS/PD threshold changes so does the transmission power. If the RSSI level of transmissions belonging to OBSSs is low, then the OBSS/PD threshold should be set to lower levels and with respect to this, transmission power should be adjusted to a high level. On the other hand, if the RSSI level of transmissions belonging to OBSSs are high, then OBSS/PD threshold should be adjusted to higher levels and the transmission power should be reduced. If the OBSS/PD mechanism is used, nodes adjust the OBSS/PD threshold and the transmission power together, and the relationship between the OBSS/PD threshold and the transmission power is given as

$$OBSS/PD = OBSS/PD_{Min} + (P_{Tx}^{Ref} - P_{Tx}) \tag{1}$$

where $OBSS/PD_{Min}$ is the minimum allowed OBSS/PD threshold, P_{Tx}^{Ref} is the maximum allowed transmission power, and P_{Tx} is the current transmission power. The default values of these parameters depend on the channel bandwidth (e.g., $OBSS/PD_{Min} = -82dBm$, $OBSS/PD_{Max} = -62dBm$, and $P_{Tx}^{Ref} = 21dBm$ for a 20 MHz channel bandwidth).

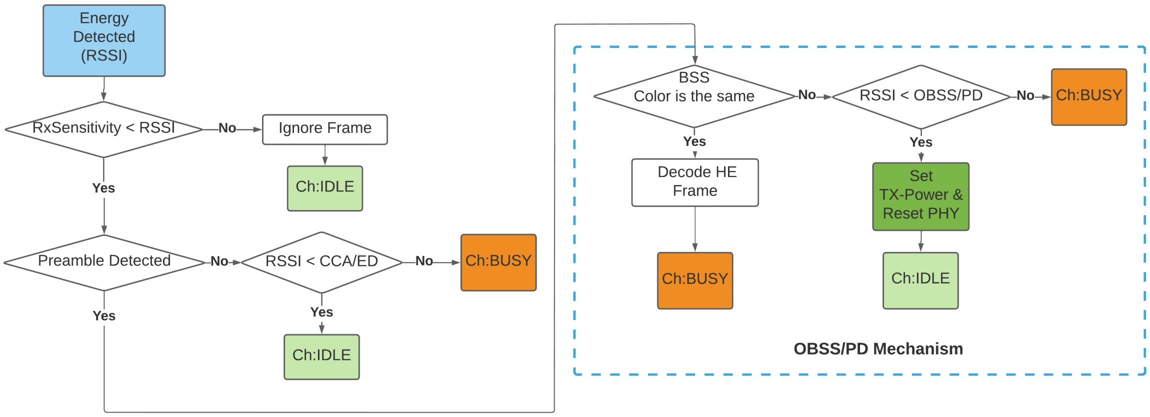

Figure 2. Carrier sensitivity mechanism with OBSS/PD in IEEE 802.11ax.

Consider a system that consists of two BSSs operating with a channel bandwidth of 20 MHz each having one AP and one STA as in the Figure 1 again. The dotted lines represent the case where OBSS/PD threshold values of STA_1 and STA_2 are both set to $OBSS/PD_{Min}$, and dashed lines represent the case where the OBSS/PD thresholds set to reduced values. In the initial case since both STAs are in range of each other, only one of them can transmit at the same time. If the OBSS/PD thresholds of STA_1 and STA_2 are set to higher levels respectively, the transmission of STA_1 can not be heard by STA_2 and vice versa and both transmissions can occur concurrently. Note that, in this scenario since OBSS/PD thresholds of both STAs are increased, their transmission powers are also decreased by the same margin.

3.2. Dynamic OBSS/PD threshold selection algorithms

Although IEEE 802.11ax defines the general OBSS/PD mechanism, its relationship with the maximum allowed transmission power, and numerical limits depending on the channel bandwidth; the standard does not specify any particular algorithm on how to select the OBSS/PD thresholds whether in a static or dynamic fashion and left it unstandardized. Since changing the OBSS/PD threshold directly affects the transmission power, and each MCS level has a minimum RSSI requirement to be used such an algorithm should take the RSSI requirements of available MCS levels into consideration. Otherwise, the wrong selection of OBSS-PD threshold may lead to lower MCS levels, hence the performance degradation. In the previous scenario depicted in Figure 3, STA_1 can reduce its OBSS/PD threshold up to 10 dBm otherwise it will become unable to connect to its AP. However, decreasing the threshold by 10 dBm results in the use of MCS 0 to communicate with its AP. Instead, if a reduction of 5 dBm puts him outside of the range of STA_2, this would be a better choice since then it will be able to use MCS levels of 0, 1, and 2 to communicate with its AP resulting in higher throughput values.

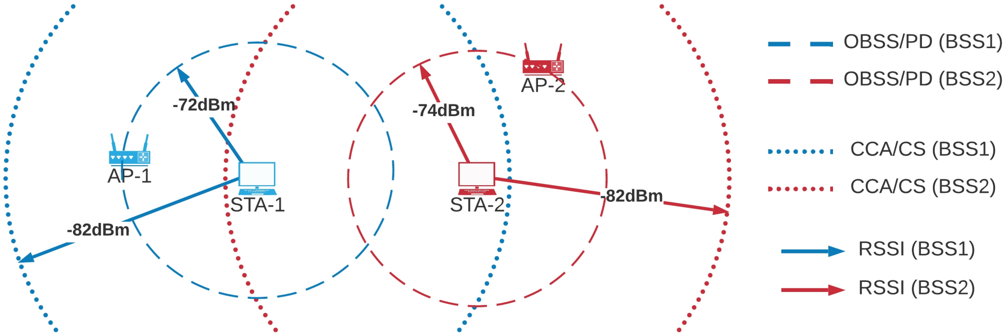

Figure 3. A simple scenario for OBSS/PD mechanism.

3.2.1. Pre-IEEE 802.11ax carrier sensitivity threshold algorithms

Initial work on such algorithms focused on finding optimal carrier sensitivity threshold for homogeneous networks [1], keeping the SINR in the operable range [2], increasing IEEE 802.11 hotspot capacity again based on SINR values [3].

A different work based on knowing the locations of each device in the network is introduced in [4]. In this work, a controller that has a camera detects the location of nodes and manages the APs and STAs in the vicinity. Then, the controller calculates the estimated carrier sensitivity thresholds from the information and adjusts them for all nodes. Since the controller knows the whole topology, the path loss and interference ranges can be calculated theoretically and then the carrier sensitivity threshold can be optimized.

During the TGax meetings, a mechanism called dynamic sensitivity control (DSC) algorithm was proposed focusing on RSSI based dynamic carrier sensitivity threshold algorithm for the uplink direction [13]. In this algorithm, beacon frame RSSI values are collected and a moving average of these RSSIs is calculated dynamically where the last value is of the greatest importance. The average RSSI is not applied directly as a carrier sensitivity threshold: a “Margin” value is subtracted from the average RSSI. This value is used as a safety interval, in the case of the existence of any disturbances in the channel or obstacles in between STA and AP. The instant energy drop may terminate the ongoing transmission and “Margin” value helps to keep the communication alive. After subtracting the “Margin” value, the resulting value is set as an OBSS/PD threshold. The beacon RSSI information is always collected and at each update period, the OBSS/PD value is updated by the same calculation.

In [14], the results show that DSC algorithm enhances the aggregated throughput, and keeps the fairness among the nodes. Since the original DSC algorithm only works for STAs and the uplink direction, as a complementary work, the same authors proposed a new mechanism that is built on top DSC algorithm that can be used for APs as well [15]. Although DSC had been suggested to be part of the IEEE 802.11ax protocol, eventually it is left outside of the standard.

Besides changing the carrier sensitivity threshold, some algorithms also change the transmission power as well. As an example of this approach, ax-Tech algorithm adjusts the transmission power with respect to the carrier sensitivity threshold to be as linearly dependent [16]. One algorithm called power and rate control (PRC) adjusts transmission power and data rate while keeping the carrier sensitivity threshold fixed [17].

3.2.2. OBSS/PD mechanism compatible algorithms

When we look at OBSS/PD mechanism compatible solutions, one such solution uses a metric called expected transmission count (ETX) to set the OBSS/PD threshold [18]. Here, ETX is defined as the number of successful transmissions expected to perform successful data delivery to the target. This solution, called ETX to power (ETP), converts ETX to the transmission power according to Equation (2) where a and b are the tuning variables of the algorithm,

$$P_{Tx} = a \times ETX + b. \tag{2}$$

Then, OBSS/PD threshold is adjusted according to Equation (1) as usual.

Based on the aforementioned DSC algorithm, an OBSS/PD mechanism compatible method called the RSSI to OBSS threshold (RTOT) algorithm was proposed as one of the initial OBSS/PD algorithms [19]. The idea behind the algorithm is very similar to DSC algorithm. RTOT is also based on beacon RSSI and calculates the OBSS/PD threshold by subtracting a “Margin” level from the RSSI value. In addition to this, with respect to the relationship between OBSS/PD and transmission power in WiFi6 amendment, it adjusts the transmission power as well. In the paper, the simulations were done with constant MCS level and the performance of the algorithm along with rate selection algorithms are not presented.

Similar to RTOT but an extended approach is the control OBSS/PD sensitivity threshold (COST) algorithm also based on RSSI [20]. DSC and RTOT algorithms use the average of the beacon RSSI to calculate OBSS/PD threshold. However, in addition to this, the COST algorithm also uses the average STA RSSIs from the inter BSS signals by using the advantage of color mechanism. A temporary OBSS/PD value, $OBSS/PD_{Tmp}$ is calculated using these RSSI values. Finally, the OBSS/PD threshold is calculated by using this temporary value and the minimum and maximum OBSS/PD values as

$$OBSS/PD = \min(\max(OBSS/PD_{Tmp}, OBSS/PD_{Min}), OBSS/PD_{Max}) \tag{3}$$

where $OBSS/PD_{min}$ and $OBSS/PD_{max}$ are the minimum and maximum limits of the OBSS/PD threshold, and $OBSS/PD_{Tmp}$ is the temporary OBSS/PD threshold value. Similar to the previous work, in the paper, the simulations have also been done via constant MCS.

Another algorithm has been introduced by the same authors that use the OBSS/PD mechanism inside a rate selection algorithm named Damysus algorithm [21]. By evaluating of the transmission statistics, the algorithm tries to select the best data rate and also adjusts the OBSS/PD threshold together.

Kim et al. have proposed a fairness-oriented opportunity-based OBSS/PD algorithm in [22]. In this algorithm, to adjust the OBSS/PD threshold and transmission power, the transmission opportunity (TXOP) of the previous time is used. First, a random OBSS/PD value is initialized and the incoming signals are waited. If the color of the incoming signal is different than the color of the receiver node, and there is a TXOP at the previous time slot, an OBSS/PD value is selected randomly in between the current OBSS/PD value and the maximum OBSS/PD value. Otherwise, If there is no TXOP at the previous time slot, the OBSS/PD threshold is randomly selected in between the minimum and current OBSS/PD values.

In addition to the mentioned mechanisms, a spatial reuse parameter (SRP) based carrier sensing threshold algorithm was proposed in [23]. In SRP, a control parameter named SRP_CCA is sent to STAs within the trigger frame. This mechanism needs additional frame elements to the existing frame format in the protocol.

Finally, in a recent work, Bardou et al. developed a centralized OBSS/PD management solution that gathers all the related observations in a central location, solves a linear programming-based optimization function via a heuristic, and then dictates each device's (STA or AP) OBSS/PD values for a globally optimal threshold selection [24]. Although the mechanism yields higher throughput, its centralized nature limits its flexibility, responsiveness, and ease of deployment.

3.3. Spatial Reuse-based Other MAC-layer Solutions

In addition to pre-IEEE 11ax carrier sensitivity threshold algorithms and OBSS/PD compliant solutions on increasing total throughput, various other spatial reuse-based MAC-layer solutions have also been proposed to achieve the same goal.

Selinis et al. propose an interference-aware MAC queuing algorithm for the downlink traffic to take the BSS color information of incoming frames into account when deciding to send packets to STAs [25]. If the inter-BSS interference is high, it only sends the packets in its queue destined to STAs that are close by; otherwise, it acts like a regular FIFO queue. A variety of parameter tuned versions of their proposed solution has been evaluated in terms of total throughput and it is shown that the proposed queuing algorithm provides improvement over legacy FIFO queues. Although this is not an OBSS/PD selection algorithm it can work hand in hand with an OBSS/PD mechanism but a proper OBSS/PD algorithm may nullify this advantage. Moreover, the proposed work is limited to downlink traffic and cannot be easily adapted to uplink traffic.

Kim et al. propose an alternative, nonstandard mechanism to OBSS/PD where each STA derives the location of each other STA in the vicinity (i.e. STAs belong to the same BSSID and other BSSIDs) and decide on when to transmit accordingly [26]. This mechanism relies on APs sending RSSI information on neighboring APs in their beacon frames as well as STAs sending RSSI information about their APs within their PHY preambles. Then, each STA derives the location of each other STA using this RSSI information. Although the mechanism improves the overall throughput, it is a nonstandardized solution that cannot be deployed in a practical WiFi setting. Moreover, it is limited to uplink traffic and cannot be easily adapted to downlink traffic.

Lastly, in a different study, Wilhelmi et al. develop a federated learning model to predict the performance of WiFi networks utilizing OBSS/PD mechanisms to improve their total throughputs [27]. Although no OBSS/PD mechanism has been proposed in this work, and the federated learning model requires a considerable amount of data to work with; such machine learning-based models can be utilized in evaluating the benefits of OBSS/PD in a given topology without actually running a simulation in that topology.

4. RACEBOT: Rate adaptive inter-bss carrier elimination-based OBSS/PD threshold

As explained in the previous section, most of the dynamic OBSS/PD threshold selection algorithms proposed in the literature only work with either fixed MCS levels, are joint algorithms that also set the MCS level or centralized solutions. In a practical WiFi network, the MCS levels will vary with time so a fixed MCS selection is far from being a realistic assumption. Moreover, most WiFi devices already have a rate selection algorithm, and a centralized solution may have unacceptable responsiveness issues. Therefore we can summarize that, considering a realistic environment a distributed dynamic OBSS/PD threshold selection algorithm should work on its own, should assume that there is a rate selection algorithm, and should be agnostic to the rate selection algorithm being used in the device.

With these considerations in mind, we propose a distributed dynamic OBSS/PD threshold selection algorithm named RACEBOT, which is designed to increase spectral efficiency with smooth transitions by using transmission statistics and channel conditions. Since RACEBOT algorithm is compatible with the OBSS/PD mechanism, besides the carrier sensitivity threshold, it also adjusts the transmission power according to the rules of the IEEE 802.11ax standard, hence it affects the selection of MCS level indirectly.

RACEBOT algorithm consists of three main stages: collecting statistics of received WiFi signals, calculating a goal OBSS/PD, and adjusting the OBSS/PD level according to the goal OBSS/PD. Note that RACEBOT works on a distributed fashion on each WiFi device independently. The first two stages run once every t_1 units of time while the third stage runs once every t_2 units of time where t_1 is an integer multiple of t_2. The algorithm continuously collects RSSI values from its own AP's beacons (i.e. BSS RSSI) as well as frames belonging to other WiFi networks (i.e. OBSS RSSI). While collecting frames from other WiFi networks, it also keeps track of the frame count belonging to other WiFi networks. Then, a threshold-based outlier elimination is applied to OBSS frames to filter out frames with very low occurrence counts, i.e. RSSI levels observed only a couple of times. After trimming the outliers, the algorithm uses the remaining OBSS RSSI values as well as its BSS RSSI values to calculate a new goal OBSS/PD. Finally, the actual OBSS/PD threshold is adjusted step by step according to the changes in the channel conditions and transmission statistics. The high-level representation of these steps of the RACEBOT algorithm is as shown in Figure 4.

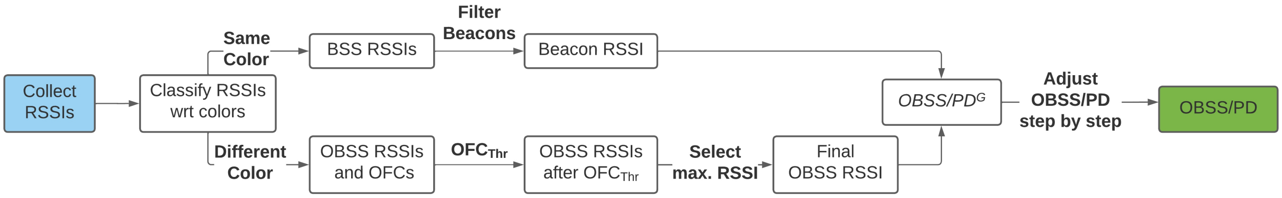

Figure 4. RACEBOT flowchart.

4.1. Stage 1: RSSI statistics collection

This stage runs once every t_1 units of time and generates a reference RSSI value for the BSS traffic (i.e. $RSSI_r^{BSS}$) and a reference RSSI value for the OBSS traffic (i.e. $RSSI_r^{OBSS}$) to be used in the second stage.

In calculating the $RSSI_r^{BSS}$ value, first, the RSSI level of the last beacon frame received within the last t_1 period of time, $RSSI^{BSS}(t)$, has been determined. Then, to smooth out variations in beacon RSSI values in previous time slots an EWMA is conducted to calculate the $RSSI_r^{BSS}$ value as

$$RSSI_r^{BSS}(t) = \alpha \times RSSI^{BSS}(t) + (1-\alpha) \times RSSI_r^{BSS}(t-t_1) \tag{4}$$

where α coefficient determines the importance of the last t_1 period's representative RSSI level.

As for calculating the $RSSI_r^{OBSS}$ value, all OBSS frames received within the last t_1 period are investigated and a set of RSSI values, RV, has been created with each unique RSSI values of these OBSS frames.

Then, the number of OBSS frames received with each RSSI level j where $j \in RV$ has been noted as OFC_j. Next, these OFC_j values have been smoothed out via EWMA similar to the BSS RSSI levels as

$$\overline{OFC_j}(t) = \alpha \times OFC_j(t) + (1 - \alpha) \times \overline{OFC_j}(t - t_1). \tag{5}$$

where α coefficient determines the importance of the last t_1 period's OFC_j value.

Then, as shown in (6), the maximum RSSI value over the set of RV is selected where its $\overline{OFC_j}(t)$ value is greater than a certain threshold, OFC_{Thr}. This threshold check is conducted to eliminate less frequently seen outlier frames with very low RSSI values. Such frames can occur due to the irregularities of the wireless medium such as small scale fading effects.

$$RSSI_r^{OBSS}(t) = \max_{j \in RV}\{j \,|\, \overline{OFC_j}(t) \geq OFC_{Thr}\} \tag{6}$$

4.2. Stage 2: Calculation of the goal OBSS/PD

After determining the reference RSSI values for both BSS and OBSS traffic, the algorithm selects an appropriate OBSS/PD goal value, $OBSS/PD^G$, by using these reference values. This stage comes directly after the first stage and is conducted once every t_1 units of time. Here the $OBSS/PD^G$ value is evaluated as

$$OBSS/PD^G = min(RSSI_r^{OBSS}, RSSI_r^{BSS}) + M \tag{7}$$

where M determines a margin whose value is evaluated as

$$M = \begin{cases} M\ , \text{ if } \min(RSSI_r^{OBSS}, RSSI_r^{BSS}) = RSSI_r^{OBSS} \\ -M, \text{ if } \min(RSSI_r^{OBSS}, RSSI_r^{BSS}) = RSSI_r^{BSS} \end{cases}. \tag{8}$$

As seen in Equation 8, if the minimum value is attained by $RSSI_r^{BSS}$, M value is subtracted from the minimum value to preserve communication with AP, otherwise, M is added to the minimum value to set an interval for not hearing the OBSS signals. By taking the minimum of $RSSI_r^{OBSS}$ and $RSSI_r^{BSS}$, RACEBOT avoids disconnection with the STAs associated AP if the STA has a weak connection to its associated AP while trying to reduce the carrier sensitivity as much as possible according to the strongest OBSS signal.

4.3. Stage 3: Adjusting the OBSS/PD threshold

After setting an appropriate $OBSS/PD^G$ value in the second stage, in this third and final stage, the algorithm adapts its OBSS/PD value to this goal value. This stage is conducted once every t_2 units of time and works independently from the first two steps.

The main motivation for not directly setting the OBSS/PD value to the calculated $OBSS/PD^G$ value is the fact that changing the OBSS/PD values (and consequently the transmission power) will affect the rate selection algorithm which may lead to reduced MCS levels hence reduced throughput. Since RACEBOT is designed to be agnostic to the selected rate selection algorithm, it does not directly communicate with the rate selection logic but instead, it gets feedback from the output of the rate selection algorithm by checking the MCS levels of the frames sent by this device and decides if the set $OBSS/PD^G$ is a good choice or not. If the MCS levels are not degraded by the previous change in the OBSS/PD value, the algorithm will try to get closer to the $OBSS/PD^G$. Otherwise, the OBSS/PD level will be changed accordingly and the $OBSS/PD^G$ is decreased.

As the device keeps track of the beacon frame and OBSS frame RSSI values, it also records the MCS level of each frame it had sent in the last t_2 unit of time. Then, the average MCS level for this unit of time, $\overline{MCS}(t)$, is calculated by taking the simple mean value among all frames it had sent. Next, $\overline{MCS}(t)$ is compared against the weighted average MCS level of the previous time step: $\gamma \times \overline{MCS}(t - t_2))$ where γ is a unitless system parameter.

- if $\overline{MCS}(t - t_2) \times \gamma \leq \overline{MCS}(t)$

  $OBSS/PD(t) = \min(\frac{(OBSS/PD(t-t_2)+OBSS/PD^G(t-t_2))}{2}, OBSS/PD_{max})$

  $OBSS/PD^G(t) = OBSS/PD^G(t - t_2)$

- if $\overline{MCS}(t - t_2) \times \gamma > \overline{MCS}(t)$

  $OBSS/PD(t) = \max(\frac{(OBSS/PD(t)+RSSI_r^{BSS}-M)}{2}, OBSS/PD_{min})$

  $OBSS/PD^G(t) = \frac{(OBSS/PD(t)+OBSS/PD^G(t-t_2))}{2}$

In the first case, the new MCS average is at least as good as the weighted previous MCS average. Therefore, the algorithm sets the OBSS/PD value closer to the $OBSS/PD^G$ value and the goal does not change. In the second case, the new MCS average is lower than the weighted previous MCS average. In that case, the algorithm should modify the $OBSS/PD^G$ since the current value caused a drop in the MCS levels. Hence, it modifies the $OBSS/PD^G$ to a more conservative value and change the OBSS/PD threshold accordingly.

5. Performance evaluation

We present the performance evaluation of our proposed algorithm compared against several other carrier sensing threshold mechanisms namely the DSC and RTOT algorithms. All the evaluations are conducted via simulations using the NS-3 simulator. The NS-3 simulator is an open source discrete network simulation tool that is quite modular and has extensive capabilities [28]. We also evaluate the performance of a scenario (named NO-OBSSPD) which does not use any carrier sensing threshold mechanism as reference algorithms [13][19].

We utilized several topologies in our simulations. First, we use the "Box5 Scenario" among the outdoor scenarios of TGax (Figure 5 [29]). "Box5 Topology" is used by various of WiFi AP vendors as well as researchers to calibrate their devices and algorithms while performing simulations with the IEEE 802.11ax protocol. This topology is composed of three APs with different BSS values. BSS-A has 15 associated STAs whereas each BSS-B and BSS-C has 5 associated STAs respectively. Additionally, we also use a set of topologies based on the "Box5 topology" called the "Custom Box5" topologies. These "Custom Box5" topologies have the same three APs as given in the "Box5 topology" with varying numbers of STAs per AP, $nSTA_{AP}$, and the location of each STA is determined via a random position generator. The position generator places $nSTA_{AP}$ number of STAs per each AP whose locations are randomly generated based on three parameters: minimum distance from its AP, R^{Min}, the maximum distance from its AP, R^{Max}, and the $Seed$ value.

In the simulations, to observe the performance of our proposed mechanism for both sparse and dense environments. We start with scenarios with small number of STAs, then the number of STAs for each AP is increased. While the STA count increases, the existent STA locations are kept, only locations for the additional

STAs are created on top of the existing topology. Simulations have been repeated 3 times for each generated topology with different *Seed* values and the average of each results were taken for the corresponding node density. We use two performance metrics: the total transmitted data rate over the whole simulation (in Mbits) as well as the aggregated throughput of all STAs at a given time (in Mbps).

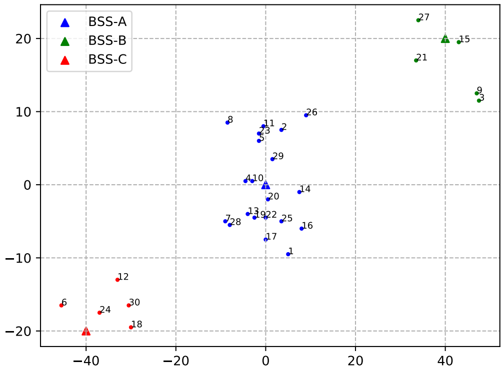

Figure 5. TGax Box5 outdoor topology.

The system parameters used in the simulations shown in Table are used. The simulations have been done with the 5 GHz band of IEEE 802.11ax standard with 20 MHz channel bandwidth with 0.8 µs guard interval. For each STA, a constant bit rate (CBR) UDP uplink traffic of 1024 byte packets where the interarrival of the generated packets follows an exponential distribution. Each STA has a single antenna (i.e. no MIMO), RTS/CTS is disabled, and as the rate selection algorithm, both Minstrel and Thompson rate selection algorithms have been used. The decay rate in Thompson is selected as $decay = 0.1$. In 20 MHz bandwidth, minimum and maximum OBSS/PD values are -82 dBm and -62 dBm respectively. In NS-3, RxSensitivity and preamble detection thresholds are -82 by default and CCA/ED threshold is -62 dBm. The initial transmission powers of APs and STAs are 21 dBm. As a path loss model, Friis loss model has been used. Since RACEBOT works hand in hand with rate selection algorithms which run once every 100ms in general, t_1 and t_2 should be selected as integer multiples of 100ms. Moreover, WiFi nodes generally follow a nomadic movement pattern and are unlikely to move a lot in a few seconds. Consequently, the simulations are done for 50 s simulation time with $t_1 = 2s$ and $t_2 = 1s$ values. The RACEBOT parameters OFC_{Thr}, α, M, and γ are set as 10, 0.8, 0.5, and 0.7 respectively.

Table. System parameters.

Parameter	**Value**	**Parameter**	**Value**
Frequency, Channel bandwidth	5 GHz - 20 MHz	**Loss Model**	Friis Loss Model
Guard Interval, # of Antennas	Short (0.8 µs), 1	**CCA/ED**	-62 dBm
Traffic rate, **Payload size**	300 Mbps, 1024 Bytes	$OBSS/PD(min, max)$	-62 dBm, -82 dBm
Scenario	Box5 and Custom Box5	t_1, t_2	2 s, 1 s
PD threshold, RxSensitivity	-82 dBm, -82 dBm	OFC_{Thr}	10
Traffic type	Uplink - UDP CBR OnOFF	**TxPower AP/STA**	21 dBm / 21 dBm
Traffic duration	ON: 5 s, OFF: Exp (1 s)	**Simulation time**	50 s
Rate selection	(Minstrel, Thompson)	**RTS/CTS**	Disabled

5.1. Box5 scenario

In Figure 6, the performance results of the RACEBOT, RTOT, DSC, and NO-OBSSPD algorithms are shown along with the Minstrel and Thompson rate selection algorithm in the Box5 Scenario. For Minstrel rate selection algorithm, none of the carrier sensing threshold mechanisms can outperform the NO-OBSSPD results. The pre-11ax mechanism, DSC, performs even worse than NO-OBSSPD. RACEBOT and RTOT results are very close to the RTOT algorithm performing poorly. When we switch to the more recent, efficient rate adaptation algorithm, the Thompson algorithm, the benefit of the carrier sensing threshold mechanisms starts to emerge. Here RTOT gives a slight improvement over the NO-OBSSPD case whereas our proposed RACEBOT algorithm outperforms both methods. Similar to the Minstrel results, the DSC algorithm shows worse performance than the NO-OBSS case. Note that with Thompson, all methods yield a higher (i.e. 20%-25%) total transmitted data rate than with Minstrel.

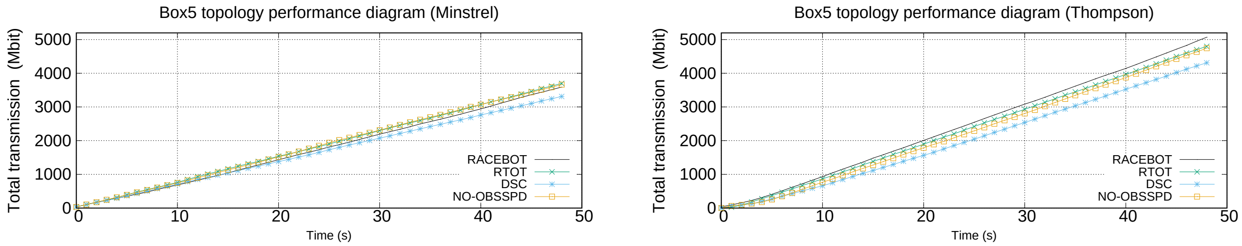

Figure 6. Scenario Box5 - Minstrel and Thompson

Based on these results it can be seen that the effect of using an OBSS/PD algorithm with the Minstrel rate selection algorithm on the performance is negligible. This can be attained to the well-known limitations of the Minstrel algorithm in scenarios with varying channel conditions. On the other hand, the OBSS/PD algorithms show their benefit when coupled with the newer, more capable Thompson rate selection algorithm.

5.2. Custom Box5 scenarios

For these scenarios, we consider five different cases in three different categories: sparse scenarios (3 and 6 STAs), medium density scenarios (9 STAs), and dense scenarios (15 and 27 STAs). For each scenario three different topology configurations have been generated via different *Seed* values and the average of each result has been calculated to get more consistent performance results. In all five cases, the performances of the investigated methods give similar results when Minstrel rate adaptation algorithm is used. Therefore, we only give the performance values when the methods are used in conjunction with Thompson algorithm.

In Figure 7, the simulation results of the cases that have 3 and 6 STAs are shown. For the 3 STAs, our RACEBOT algorithm shows slightly better performance than the other OBSS/PD algorithms while RTOT algorithm gives a poor performance similar to the Box5 scenario. In the case with 6 STAs, the performance enhancement of the RACEBOT algorithm becomes much more evident than in the previous case. In this scenario, the other OBSS/PD algorithms again show a similar but worse performance than the RACEBOT algorithm.

In Figure 8, the case that has 9 STAs is shown. The RACEBOT algorithm and the DSC algorithm show similar results in the NO-OBSSPD case. However, the RTOT algorithm decreases the performance of the system that even does not work with any OBSS/PD mechanism. From this result, it is inferred that, even if there is no performance enhancement, the RACEBOT algorithm preserves stability and the existing performance of the system.

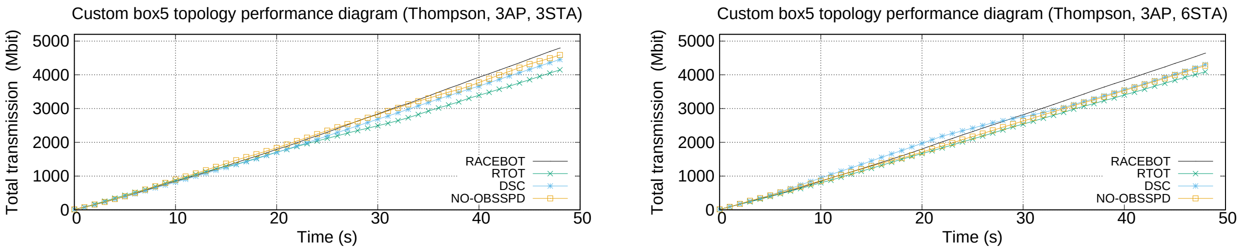

Figure 7. Low Density Custom Box5 Scenarios with Thompson rate selection algorithm.

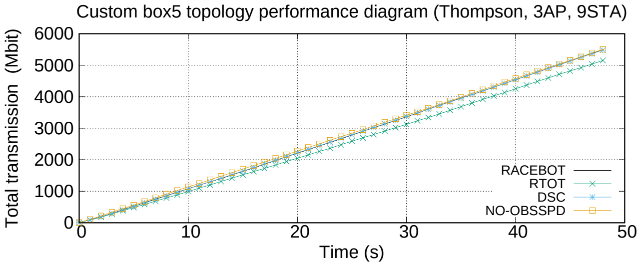

Figure 8. Medium density custom Box5 scenario with Thompson rate selection algorithm.

In Figure 9, the high-density scenarios with 15 and 27 STAs are simulated. According to the case with 15 STAs, the performance enhancement of the RACEBOT algorithm can be clearly seen where it outperforms all other methods. The lowest performance belongs to the case that does not use any OBSS/PD algorithm. In dense environments, all methods start to show improvement over the NO-OBSSPD scenario albeit in varying improvement levels. DSC algorithm has shown slightly better performance than the NO-OBSSPD case whereas the performance of the RTOT algorithm is similar but again slightly better than DSC algorithm.

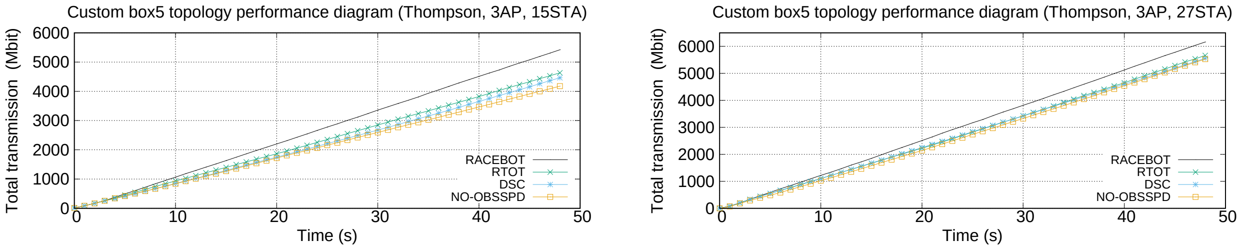

Figure 9. High density custom Box5 scenarios with Thompson rate selection algorithms.

In the case of 27 STAs, again the RACEBOT algorithm has the best performance. The remaining ones showed similar performance with respect to each other but their performances are worse than the RACEBOT algorithm. From these high-density scenarios, it can be inferred that as the node density increases, the effect of using OBSS/PD is much more evident. Our RACEBOT

In Figure 10, the aggregated throughput of all STAs in the topology at a given simulation time is depicted for the two high-density scenarios. This metric is also important to show the stability of different algorithms which will become highly important for jitter sensitive applications. The improvement of our proposed RACEBOT mechanism is also prevalent in this performance metric and the order of the methods is the same as in the total transmitted data rate metric.

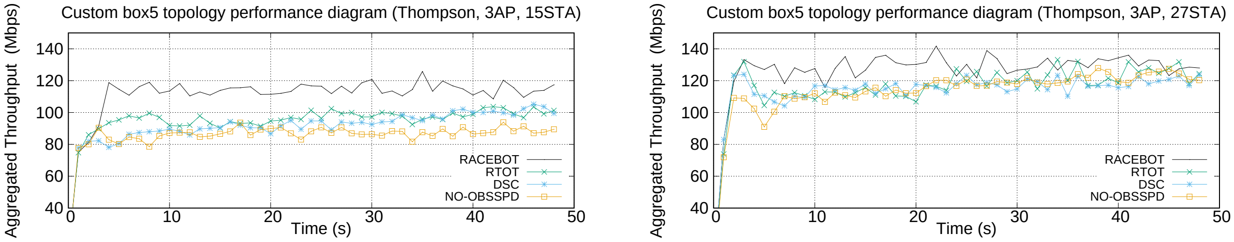

Figure 10. Aggregate throughput in high density custom Box5 scenarios with Thompson rate selection algorithms.

6. Future work and conclusion

In this paper, we present a novel adaptive OBSS/PD threshold selection mechanism, RACEBOT, for WiFi6 devices. The main goal of the RACEBOT algorithm is controlling OBSS/PD thresholds of each WiFi node, while preserving the maximum available MCS level satisfying the given channel conditions and transmission power, to maximize the overall total throughput of the WiFi networks in the environment. Using the RACEBOT algorithm coupled with the Thompson rate selection algorithm, the overall total throughput of the WiFi networks in the environment increases significantly over a NO-OBSS scenario as well as other legacies OBSS/PD threshold selection algorithms in both sparse and dense topologies. In future work, we plan to expand our algorithm to work in a centralized fashion and optimize the OBSS/PD threshold values of all individual WiFi nodes in the vicinity in a coordinated manner. Such a centralized approach shall reduce the instabilities of RACEBOT's distributed approach and increase its benefit even more. A second avenue for investigation is the interaction between the OBSS/PD threshold selection and rate selection. RACEBOT works completely agnostic to the selected rate selection algorithm. It can be argued that instead of two separate algorithms, a joint OBSS/PD threshold and rate selection algorithm can yield much better performances. Coupled with a centralized approach, a joint threshold and rate selection algorithm is envisioned to have much higher impact than methods focusing on either of these aspects.

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