RECONN: Receiver-Driven Operating Channel Width Adaptation in IEEE 802.11ac WLANs

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***Abstract*—State-of-the-art IEEE 802.11ac supports wide bandwidth operation, which enables aggregating multiple 20 MHz channels up to 160 MHz bandwidth, as a key feature to achieve high throughput. In this paper, our experiment results reveal various situations where bandwidth adaptation without changing the receiver's baseband bandwidth, called *operating channel width* (OCW), leads to poor reception performance due surprisingly to *time-domain interference* not overlapping with the incoming desired signal in frequency domain. To cope with this problem, we develop *RECONN*, a standard-compliant and receiver-driven OCW adaptation scheme with ease of implementation. Our prototype implementation in commercial 802.11ac devices shows that *RECONN* achieves up to 1.85× higher throughput by completely eliminating time-domain interference. To our best knowledge, this is the first work to discover the time-domain interference problem, and to develop OCW adaptation scheme in 802.11ac system.**

I. Introduction

Over the past few years, thanks to the dramatic increase in mobile data traffic volume and proliferation of mobile applications, IEEE 802.11 wireless local area network (WLAN), often referred to as Wi-Fi, has become an irreplaceable wireless technology, supporting ever increasing high throughput demand [1]. Encouraged by this explosion, state-of-the-art IEEE 802.11ac WLAN provides a physical layer (PHY) data rate of Gb/s to a single user in the 5 GHz unlicensed band [2].

As a key feature to enhance throughput performance, IEEE 802.11ac defines wide bandwidth operation, which enables aggregating multiple 20 MHz channels. Specifically, IEEE 802.11ac supports bandwidth of 20, 40, and 80 MHz as a mandatory feature, and optionally supports 160 MHz bandwidth. To transmit and receive packets using such wide bandwidth, 802.11ac devices need to increase the size of fast Fourier transform (FFT), equivalently, the baseband bandwidth, referred to as *operating channel width* (OCW). Understandingly, it is possible to transmit and receive a packet using the bandwidth less than or equal to OCW. Given that, once OCW is set, it is hardly changed.

The use of wide channel bandwidth has greatly contributed to throughput performance improvement, but there are still many operational issues to be taken care of, such as frequency under-utilization, secondary channel hidden interference problem [3, 4], and coexistence with other technologies such as LTE-LAA [5]. Therefore, there have been many researches that propose new channel access schemes, channel allocation algorithms, and/or bandwidth adaptation methods [6–16]. Moreover, recent 802.11ac chipsets such as Broadcom BCM43602 and Qualcomm QCA9980 provide an internal bandwidth adaptation implemented in the firmware, where the detailed operations are unknown.

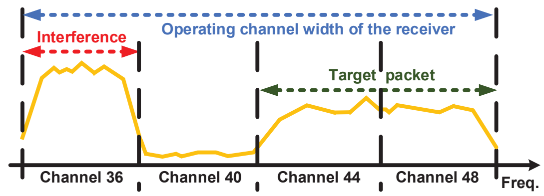

Fig. 1. Spectrum example in which the time-domain interference degrades reception performance. Time-domain interference can be eliminated by reducing OCW to 40 MHz.

However, none of these studies and methods deal with *time-domain interference* when the baseband includes not only the desired signal, but also interference signal that does not overlap with the desired signal on frequency domain. In this paper, our experiment results have revealed strong evidence that using the bandwidth less than OCW causes *time-domain interference problem* such as 1) *packet detection and synchronization failure*, 2) *undesirable receive locking problem*, and 3) *automatic gain control (AGC) failure*, thus leading to poor throughput performance. For example, when the baseband of 802.11ac receiver includes interference signal generated by other WLAN devices or LTE-LAA devices at channel 36 in 5 GHz band, reception performance decreases even if the desired signal transmitted in channels 44 and 48 does not overlap with the interference on frequency domain as shown in Fig. 1. More seriously, changing the baseband bandwidth for every packet is impossible in WLAN system, since the switching delay is known to be several tens of microseconds due to the reconfiguration delay of hardware such as RF front end [17]. This problem might become severer in coexistence with other emerging technologies such as IEEE 802.11ax or LTE-LAA, as well as due to bandwidth heterogeneity of the existing WLAN devices [5, 18].

The main purpose of this paper is to empirically analyze the impact of time-domain interference in 802.11ac WLAN, and to propose a receiver-driven OCW adaptation algorithm with very low overhead, which is amiable to IEEE 802.11ac, to enhance throughput performance. Our major contributions are summarized as follows.

- We first analyze the impact of time-domain interference in IEEE 802.11ac through extensive measurements using commercial off-the-shelf 802.11ac devices and a software

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defined radio (SDR) platform. From this, we reveal that bandwidth adaptation without changing OCW causes packet detection and synchronization failure, undesirable receive locking problem, and AGC failure, when the baseband contains time-domain interference signal, not overlapping with the desired signal on frequency domain.
- We develop *RECONN*, a standard-compliant and ***rec***eiver-driven ***o***perating cha***nn***el width adaptation scheme with ease of implementation. *RECONN* adaptively switches OCW using the frequency domain information obtained by receiver with very low overhead. *RECONN* fully complies with 802.11 medium access control (MAC) and does not require hardware modification.
- We implement *RECONN* on Linux-based open-source device driver (*ath10k* and *mac80211*), and make a prototype using commercial 802.11ac network interface card (NIC).
- Our extensive experiments with prototype under a wide range of scenarios show that *RECONN* enhances throughput performance up to 1.85× by completely eliminating time-domain interference.

To the best of our knowledge, this is the first work that reports time-domain interference problem and develops the OCW adaptation algorithm to handle the time-domain interference problem in 802.11ac WLAN.

The rest of the paper is organized as follows. Section II introduces the summary of related work, and Section III provides the background of IEEE 802.11ac wide bandwidth operation. In Section IV, we empirically study the impact of time-domain interference. The detailed design of *RECONN* is presented in Section V, and its implementation and experimental evaluations are presented in Section VI. Finally, Section VII concludes the paper.

II. Related Work

There have been many studies on wide bandwidth operation over WLAN in the literature. Basically, transmissions using wider bandwidth are more likely to suffer from frequency selective fading, which causes signal-to-noise ratio (SNR) variations across the entire subcarriers. Additionally, fixed total transmission power and bandwidth heterogeneity with legacy devices cause potential hidden interference and frequency under-utilization problem, thus providing lower throughput. To solve these problems, decentralized bandwidth adaptation algorithms based on measurements are proposed in [6–8]. In [3, 9, 10], the authors propose centralized (primary) channel and bandwidth allocation methods to achieve higher throughput by reducing hidden interference.

Moreover, analytic frameworks to evaluate the performance of wide bandwidth operation are presented in [11–13]. The authors have verified various characteristics and problems of wide bandwidth operation in multiple basic service set (BSS) environment. Besides, several studies have focused on enhancing channel access mechanism or adjusting clear-channel-assessment (CCA) threshold [4, 14–16], because sharing wide bandwidth increases contention level and reduces channel utilization. However, none of the existing studies deals with

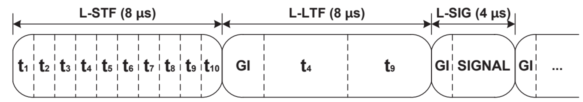


Fig. 2. Structure of the legacy preamble identical to 802.11a preamble.

the time-domain interference problem firstly revealed in this paper, which degrades the reception performance significantly in the 802.11ac WLAN network.

III. Preliminaries

A. Packet Detection and Initial Synchronization

IEEE 802.11 receiver detects the incoming packet by receiving legacy short training field (L-STF) at the beginning of a PHY protocol data unit (PPDU). Fig. 2 shows the legacy preamble structure, identical to 802.11a preamble.[1] L-STF is composed of 10 short repeated symbols from t_1 to t_{10}. Each symbol uses 12 out of 52 subcarriers based on 64-point inverse FFT (IFFT), thus resulting in 0.8 μs periodicity. Because of the repetitive nature of L-STF sequence, the received signal is correlated with a delayed version of itself periodically. Therefore, receiver uses time-domain samples for packet detection in general, i.e., time-domain auto-correlation value exceeding a threshold indicates a detected packet [19]. Thanks to good correlation property of L-STF sequence, incoming packets can be recognized accurately even after signal distortion induced by wireless channel and/or analog RF front end.

Moreover, auto-correlation peaks obtained by time-domain samples can be also used to set AGC parameters and to acquire symbol timing offset (STO). Additionally, receiver calculates initial carrier frequency offset (CFO) by using the difference in phase between two consecutive time-domain samples of L-STF, separated by 0.8 μs.

B. Wide Bandwidth Operation

1) Channelization and contention mechanism: IEEE 802.11ac supports the bandwidth of 20, 40, and 80 MHz as a mandatory feature, and optionally provides 160 MHz channel including non-contiguous 80+80 MHz. The wide bandwidth including 40, 80, and 160 MHz can be divided by the primary 20 MHz channel and one or more secondary channels. Basically, only the primary 20 MHz channel follows IEEE 802.11 distributed coordination function (DCF) contention mechanism, where the channel needs to be idle until an interval of DCF inter frame space (DIFS) plus the backoff counter reaches zero to access the wireless medium. On the other hand, all secondary channels need to be idle for point coordination function (PCF) inter frame space (PIFS) immediately preceding the expiration of primary channel's backoff counter. Specifically, when the backoff counter of primary channel becomes zero, if one or more secondary channels are busy, a station then proceeds either to restart the contention process by randomly selecting a new backoff counter without increasing backoff window (static channel

[1]For backward compatibility, IEEE 802.11n/ac PPDU also contains legacy preamble at the beginning, which is duplicated over each 20 MHz channel.

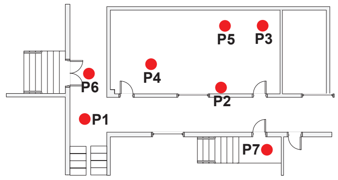


Fig. 3. Floor plan of our experiments (22 m × 12 m). Each point represents locations where devices are deployed.

access), or to transmit a packet using the bandwidth including primary 20 MHz channel plus adjacent PIFS-idle secondary 20, 40, or 80 MHz channel (dynamic channel access) [4].

2) Operating channel width (OCW): OCW denotes twice the baseband bandwidth supported by 802.11ac system, or equivalently analog-to-digital-converter (ADC) sampling rate, which can be 20, 40, 80, or 160 MHz corresponding to 64-point, 128-point, 256-point, and 512-point (I)FFT, respectively. Specifically, OCW determines the amount of the maximum bandwidth actually used for packet transmission, where the AP and its associated station should use the bandwidth less than or equal to the minimum value among them. When a station transmits and receives packets using the bandwidth less than OCW, it does not need to change the baseband bandwidth by adjusting ADC sampling rate, because the station can disregard the unused subcarriers. In this paper, however, we verify that using bandwidth less than OCW might lead to poor reception performance due to time-domain interference not overlapping with the incoming desired signal on frequency domain.

Note that a station can change its OCW without disassociation, using operating mode notification process [2]. However, since it incurs excessive delay due to hardware reconfiguration and protocol overhead, which is known to be several tens of microseconds [17], OCW is rarely changed during run-time.

IV. Case Study

In this section, we present extensive experiment results to verify the cause and effect of the time-domain interference problem, occurring when interference signal is not overlapping with the desired signal on frequency domain. We use two 802.11ac commercial APs, TP-link Archer C3200 (AC3200) equipped with Broadcom BCM43602 chipset and Archer C2600 (AC2600) equipped with Qualcomm QCA9980 chipset. Additionally, for in-depth analysis, we also employ SDR platform, i.e., NI USRP equipped with Xilinx Kintex-7 FPGA, using LabVIEW Communication System Design Suite (CSDS) and 802.11 Application Framework (AF), which is compliant to IEEE 802.11 specification [20].

A. Motivation

We initially conduct an experiment using commercial devices in a controlled office environment, i.e., the basement of our building without neighboring WLAN. Fig. 3 illustrates our floor plan, where circles from P1 to P7 represent different locations where access points (APs) and stations are deployed.

Either AC3200 or AC2600 is installed at P1, and its associated 802.11n station, generating 40 MHz uplink traffic on channel 44 and 48, is placed at P5. For better control of the experiment, we adopt an 802.11n station, which has the baseband of 40 MHz, thus making sure of no contention with the interferer. Interference traffic is generated at P4, using NI USRP, which sends 802.11a packets (occupying 20 MHz) over channel 36. Therefore, transmitters do not share the wireless medium, i.e., no frequency-domain overlapping occurs. Note that the setting corresponds to Fig. 1.

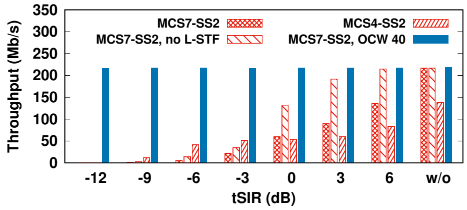
Because there is no transmit signal overlapping on frequency-domain between two transmitters, we cannot adopt conventional signal-to-interference-and-noise ratio (SINR). Therefore, we newly define *time-domain signal-to-interference ratio (tSIR)* as a power ratio of desired and interference signal, both contained in time-domain samples (i.e., baseband of the receiver), but non-overlapping with each other on frequency domain. The interference packets generated by NI USRP have the size of 1,460 B, being transmitted using modulation and coding scheme (MCS) index 0. Note that MCS in IEEE 802.11 denotes a combination of modulation and code rate, where higher MCS index means higher PHY rate. The airtime of interference signal then becomes 2 ms with inter frame space (IFS) of 108 μs.[2] Fig. 4 shows uplink throughput obtained by AC3200 and AC2600 according to tSIR. The 802.11n station uses MCS 7 with double spatial stream over 40 MHz channel width, and OCW of the 802.11ac AP is initially set to 80 MHz (*MCS7-SS2*). We compare throughput by modifying L-STF sequence of interference signal to all zeros (*MCS7-SS2, no L-STF*) using NI USRP, and then we change MCS of the 802.11n station to MCS 4 (*MCS4-SS2*). Finally, OCW of the 802.11ac AP is set to 40 MHz (*MCS7-SS2, OCW 40*).

Throughput result obtained by AC3200 is shown in Fig. 4(a). Without interference, the obtained throughput reaches 219 Mb/s or 137 Mb/s, depending on used MCS. When OCW of AC3200 is set to 80 MHz, throughput is severely deteriorated as tSIR decreases. Interestingly, when interference signal does not include L-STF signal (*MCS7-SS2, no L-STF*), AC3200 achieves higher throughput compared to *MCS7-SS2*. Moreover, when the 802.11n station uses MCS 4, which is more robust to distortion (*MCS4-SS2*), the performance becomes slightly tolerant to time-domain interference. When OCW of AC3200 is set to 40 MHz, however, throughput does not fluctuate depending on tSIR.

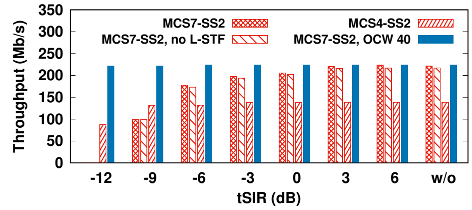
In the meantime, AC2600 shows more stable throughput results compared to AC3200 as shown in Fig. 4(b) because of the unknown implementation specific. AC2600 is not affected by the preamble of interference signal, and throughput of *MCS4-SS2* does not decrease until tSIR reaches -12 dB. Additionally, as expected, throughput does not fluctuate when OCW of AC2600 is set to 40 MHz.

As a result, we observe that throughput decreases depending on tSIR even though interference signal is not overlapping on frequency domain, as long as the receiver's baseband contains the interference. This throughput degradation is not caused by either the contention between two transmitters, or the adjacent

[2] 802.11 AF supports a fixed backoff value rather than the random backoff feature. We set IFS to 12 slots, i.e., 108 μs, which is an approximation of DIFS plus average backoff duration with initial contention window.

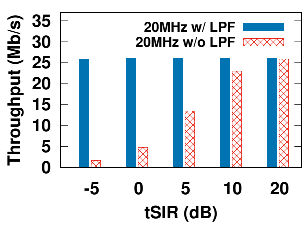


(a) Throughput using AC3200.

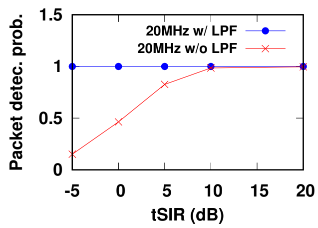


(b) Throughput using AC2600.

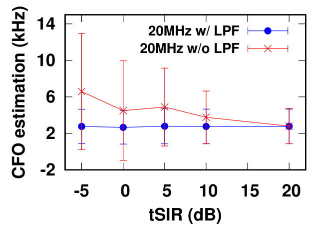
Fig. 4. Uplink throughput according to tSIR. The interference is generated by NI USRP, where no frequency overlapping exists.



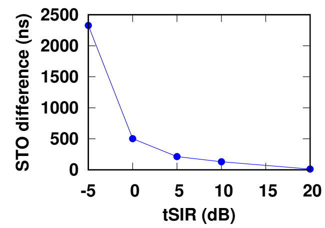
(a) Throughput.



(b) Packet detection probability.



(c) Estimated CFO.



(d) STO difference.

Fig. 5. Average packet detection and time/frequency synchronization measurement results obtained by NI USRP based on Schmidl and Cox algorithm [19].

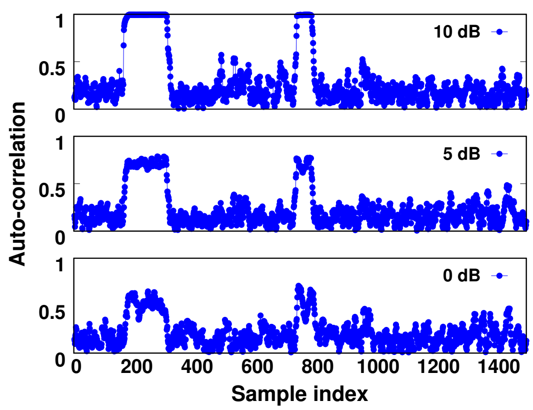


Fig. 6. Normalized auto-correlation magnitude according to time sample index measured by NI USRP.

channel interference, because throughput of *MCS7-SS2, OCW 40* does not fluctuate according to tSIR.

It is worth noting that receiver processes time-domain samples of the identically repeated L-STF signal as explained in Section III-A in WLAN system. In this regard, we have verify that throughput degradation is mainly caused by 1) packet detection and synchronization failure, 2) undesirable receive locking to the interference signal, and 3) AGC failure. The detailed analysis is presented in the following.

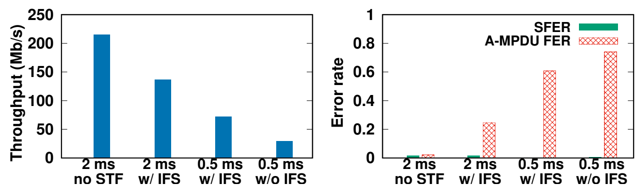
B. Packet Detection and Synchronization Failure

For detailed analysis, we have verified the impact of time-domain interference on the reception performance empirically. We employ 802.11 AF on the top of NI USRP, which provides a ready-to-run, modifiable real-time PHY and MAC reference design [20]. Total three NI USRPs are deployed in proximity as a transmitter, a receiver, and an interferer, respectively. OCW of the receiver is set to 80 MHz based on 256-point FFT, while only 20 MHz bandwidth is used for packet transmission and reception. The transmitter sends packets on channel 48 and the interferer uses channel 40 such that no frequency-domain overlapping exists. In order to change tSIR, we change the transmit power of the interferer from -10 dBm to 15 dBm.

Fig. 5 shows average packet detection probability, throughput, CFO, and STO results. Specifically, using 802.11 AF, receiver detects packets, finds STO index, and estimates CFO based on Schmidl and Cox algorithm (SC) [19]. Moreover, 802.11 AF provides digital low pass filter (DLPF), to extract the primary 20 MHz signal within the entire baseband of 80 MHz, only for the packet detection and synchronization. Accordingly, when DLPF is utilized, time-domain interference signal can be filtered out, thus providing much better packet detection and synchronization performance.[3] Therefore, using DLPF prior to executing SC, throughput is not affected by tSIR as shown in Fig. 5(a), while throughput decreases gradually without using DLPF, as tSIR decreases. This throughput degradation is caused by low packet detection probability as demonstrated in Fig. 5(b). To be more specific, Fig. 6 shows a snapshot of the normalized auto-correlation magnitude according to time sample index at the receiver for a given tSIR, without employing DLPF. Note that NI USRP calculates the normalized auto-correlation magnitude based on moving window of 64 samples. Due to the repeated nature of L-STF sequence, the normalized auto-correlation magnitude is maintained at a value of one during L-STF reception as shown in the case of 10 dB tSIR.[4] However, as tSIR decreases, the normalized peak auto-correlation magnitude decreases. What is worse, when tSIR becomes 0 dB, the peak goes even under 0.5. It is worth noting that although the specific packet detection and synchronization algorithm can vary depending on the implementation, i.e., type of chipset, peak fluctuation negatively affects packet detection and synchronization performance eventually.

[3]As shown in Fig. 4, we believe that DLPF is not used in commercial off-the-shelf devices. More detailed discussion is presented in Section V-A.

[4]Since the transmitter sends packets in the format of 802.11ac, correlation peak can be observed twice in L-STF and very high throughput (VHT) STF.



(a) Throughput results.

(b) Error rate results.

Fig. 7. Uplink throughput and two types of error rate according to the different interference patterns when tSIR is 6 dB. IFS is set to 108 μs.

Additionally, CFO estimation performance is also deteriorated due to time-domain interference. In this setup, CFO should remain around 3 kHz because of the clock difference between the transmitter and the receiver. However, CFO error rapidly increases and widely fluctuates without using DLPF as shown in Fig. 5(c). Fig. 5(d) shows the difference in STO index with and without using DLPF. Note that even a small STO error significantly affects reception performance [21]. Especially, when tSIR is -5 dB, STO error becomes greater than 2 μs, much larger than the guard interval (i.e., 800 ns) used in 802.11 system.

C. Receive Locking to Interference Signal

Going back to Fig. 4(a), when interference signal uses zero sequence instead of the original L-STF sequence, the throughput does not decrease when tSIR is larger than 3 dB. This phenomenon is observed by only using AC3200 equipped with BCM43602 chipset. Here, we further investigate the impact of L-STF by changing the interference pattern. Along with the airtime of interference packet set to 2 ms with IFS of 108 μs as in Section IV-A, we additionally consider the airtime of interference packet set to 0.5 ms with and without IFS for additional comparison.

Fig. 7 shows the throughput of AC3200 and two types of error rate, when tSIR is 6 dB. Aggregate MPDU (A-MPDU) frame error rate (FER) stands for a ratio that the entire A-MPDU is broken such that block acknowledgement (BlockAck) missing event occurs. On the other hand, subframe error rate (SFER) means a subframe error ratio determined by receiving BlockAck. Without L-STF, throughput does not decrease and both A-MPDU FER and SFER remain under 2%. However, if the interference contains L-STF sequence, throughput becomes down to 136 Mb/s with A-MPDU FER of 25%, when the airtime of interference signal is set to 2 ms. Additionally, if L-STF of the interference is transmitted more frequently, throughput decreases even further, and A-MPDU FER also increases rapidly. Interestingly, SFER is not increased for all cases, which means that as long as an A-MPDU is successfully detected, all subframes can be also successfully received. This is not packet detection and synchronization issues dealt with in Section IV-B, because there is no performance degradation when interference signal does not include L-STF. From this experiment, we conclude that some chipsets might receive the preamble of packets not occupying the primary 20 MHz channel, which is undesirable behavior that violates 802.11ac specification. We refer to this phenomenon as *undesirable receive locking*, which results in detection failure of desired packets incoming through the primary channel.

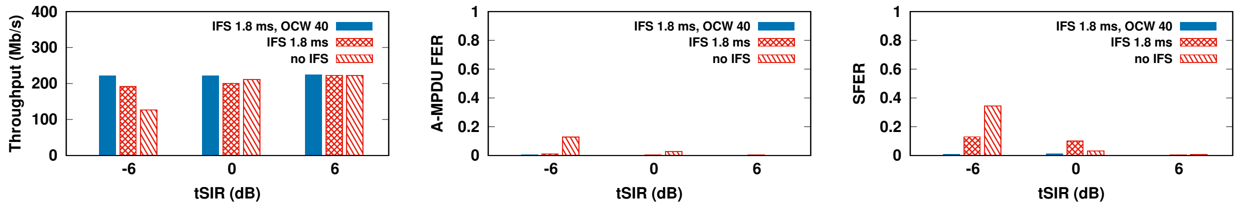
D. AGC Failure

In this section, we verify that AGC failure also deteriorates reception performance due to time-domain interference. Generally, AGC is conducted to provide controlled signal amplitude of the output signal, despite variation of the amplitude in the input signal [22]. WLAN receiver performs AGC using the power measured at L-STF as illustrated in Fig. 2. Unlike packet detection/synchronization failure and undesirable receive locking, AGC failure can occur when an interference packet arrives while the receiver is receiving a desired packet. To be more specific, we have conducted an additional experiment to verify AGC failure actually degrading the reception performance. The experiment setting is described in Section IV-A, while we change interference pattern generated by NI USRP, where the airtime of interference packet becomes 248 μs with and without IFS of around 1.8 ms long. Therefore, interference packet comes in the middle of desired packet reception. In this experiment, we use AC2600 as a receiver, because of undesirable receive locking problem observed only in AC3200.

Fig. 8 shows measurement results for three different tSIR values. When tSIR is 6 dB, time-domain interference does not influence reception performance of AC2600 for all cases. In case of -6 dB tSIR, when interference packets are continuously transmitted without IFS (*no IFS*), throughput of 126.9 Mb/s with 34.5% SFER and 12.8% A-MPDU FER is achieved due to packet detection and synchronization failure. However, when interference packets are transmitted intermittently with IFS of 1.8 ms (*IFS 1.8 ms*), throughput of 191.7 Mb/s, 51% higher than *no IFS* result is achieved because only 10% of the wireless medium is occupied by interference signal. AC2600 is not affected by the interference, as expected, when OCW is set to 40 MHz (*IFS 1.8 ms, OCW 40*).

Interestingly, when tSIR is 0 dB, even with the weakest intensity of the interference, *IFS 1.8 ms* shows the worst performance, obtaining 10.5 Mb/s lower throughput with 6.9% higher SFER, compared with *no IFS* results. This reduction comes from AGC failure, observing consecutive subframe errors within an A-MPDU. To be more specific, Fig. 9 shows cumulative distribution function (CDF) of duration in which subframe errors occur within an A-MPDU. Note that 802.11n station associated with AC2600 transmits A-MPDUs with airtime of 2 ms each, thus making the maximum duration 2 ms.[5] In case that interference packets are transmitted continuously without IFS, subframe errors within an A-MPDU follow a uniform distribution. However, when interference packet comes in the middle of A-MPDU reception, i.e., after AGC processing, corresponding time-domain samples are clipped off, thus resulting in signal distortion [23], even

[5]Using MCS 7 with double spatial stream and 40 MHz, the total airtime of an A-MPDU is around 2 ms fixed, due to the size limitation of 65,535 B for a single A-MPDU.



(a) Obtained throughput. (b) A-MPDU FER. (c) SFER.

Fig. 8. Uplink throughput and two types of error rate measured by using AC2600, according to three different interference patterns and tSIR of $6, 0, -6$ dB.

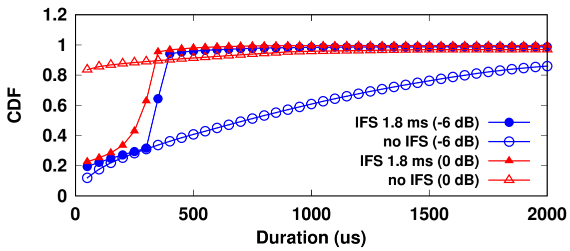


Fig. 9. CDF of duration in which subframe errors occur within an A-MPDU.

though interference signal does not overlap with the desired A-MPDU on frequency domain. Specifically, subframe errors occur consecutively during the interval of interference packet, thus leading to sudden increase in statistical probability near the duration of 350 μs. This phenomenon can be more strictly observed when the interference power increases.

V. *RECONN*: Proposed Algorithm

Motivated by the observation presented above, we first discuss how to overcome time-domain interference. We then propose *RECONN*, a novel receiver-driven OCW adaptation algorithm, designed to eliminate time-domain interference with very low overhead. *RECONN* enables receiver to intelligently adapt OCW based on the frequency-domain information.

A. Possible Solutions

When the interference does not occupy the primary 20 MHz channel of receiver, DLPF can eliminate time-domain interference by filtering out the interference components in time-domain samples as shown in Section IV-B. Note that L-STF is duplicated over each of 20 MHz channels such that the receiver is able to recognize the incoming packet and acquire synchronization, not affected by the interference by using DLPF to extract signal of the primary 20 MHz channel. However, employing DLPF requires a new hardware feature, and causes an additional delay, thus making them costly and impractical for large-scale adoption by commercial products. Moreover, packet detection and synchronization performance might be degraded when the receiver uses L-STF sent over only the primary 20 MHz channel due to frequency selectivity. Additionally, AGC failure still deteriorates the reception performance even with employing DLPF. Further analysis of DLPF will be our future work.

Another way to overcome time-domain interference is to reduce MCS index to be more robust to signal distortion as shown in Section IV-A. However, since lower MCS provides lower throughput, it cannot be generally a desirable solution.

To this end, we develop *RECONN*, a standard-compliant and receiver-driven OCW adaptation scheme, designed to eliminate time-domain interference with very low overhead. *RECONN* fully complies with 802.11 MAC and requires no hardware modification such that it can be applicable to the existing hardware.

B. RECONN

1) OCW adaptation: When a PHY header error event (i.e., checksum failure) occurs, or n subframes are consecutively lost at the receiver, *RECONN* needs to scan frequency spectrum because the loss might have been due to time-domain interference. We refer to this spectrum scanning as *spectral scan*.[6] Spectral scan reports FFT output, i.e., 4 μs long spectral snapshots, and the bandwidth that can be scanned through spectral scan is equal to the current OCW. Moreover, since spectral scan is conducted during *idle state* by reusing hardware block, its output can be used to detect the interference, not overlapping on the primary 20 MHz channel, i.e., time-domain interference, without incurring an additional overhead.

Assuming that current OCW is set to 80 MHz, received signal strength (RSS) of secondary 20 MHz and 40 MHz channels, obtained by processing the spectral scan results, are denoted by P_{s20} and P_{s40}, both in dBm, respectively. *RECONN* then compares RSS of the most recent successfully received A-MPDU, denoted as P_{ampdu} (dBm), with P_{s20} and P_{s40} in sequence. In case that $P_{ampdu} - P_{s20} \leq \alpha_{dB}$, receiver reduces OCW to 20 MHz, to eliminate time-domain interference. If the above condition is not satisfied, but $P_{ampdu} - P_{s40} \leq \alpha_{dB}$, receiver changes OCW to 40 MHz. On the other hand, if current OCW is 40 MHz, receiver obtains only P_{s20}, and changes OCW to 20 MHz if $P_{ampdu} - P_{s20} \leq \alpha_{dB}$.

Note that α_{dB} denotes tSIR threshold to determine whether the interference degrades reception performance or not. An appropriate α_{dB} value varies depending on chipset type, channel condition, interference pattern, and OCW. To reflect this flexibly, *RECONN* initially sets α_{dB} to 0 dB, and intelligently adapts α_{dB} during run-time. Specifically, *RECONN* compares PHY data rate used before and after OCW switching, and then adjusts α_{dB} *in the direction of increasing PHY data rate*. For instance, if reducing OCW results in decreasing (increasing) PHY data rate, α_{dB} is also decreased (increased) by 1 dB such that OCW reduction becomes more difficult (easier).

[6] Linux-based open-source device driver, *ath9k* or *ath10k*, provides *spectral scan* operation. Note that scanning the frequency-domain in idle state can be easily supported by any kinds of chipsets.

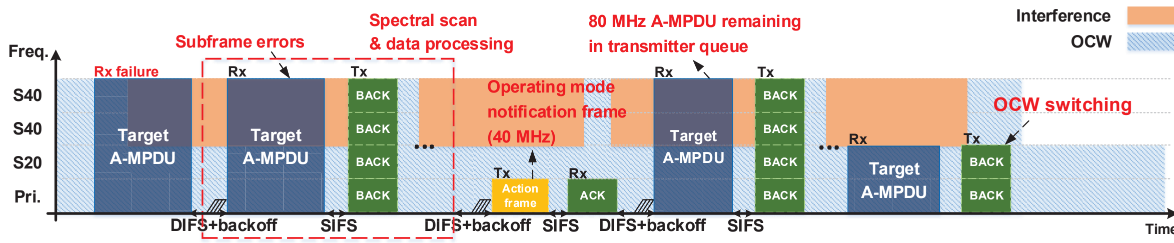


Fig. 10. Example of decreasing OCW due to time-domain interference: A-MPDU loss triggers spectral scan, while A-MPDU reception continues. If the receiver detects the interference, in this case, at the secondary 40 MHz channel, it sends an operating mode notification frame to the transmitter prior to reducing OCW to 40 MHz. After receiving 40 MHz A-MPDU, the receiver finally reduces OCW in order to receive A-MPDUs scheduled to be transmitted over 80 MHz channels.

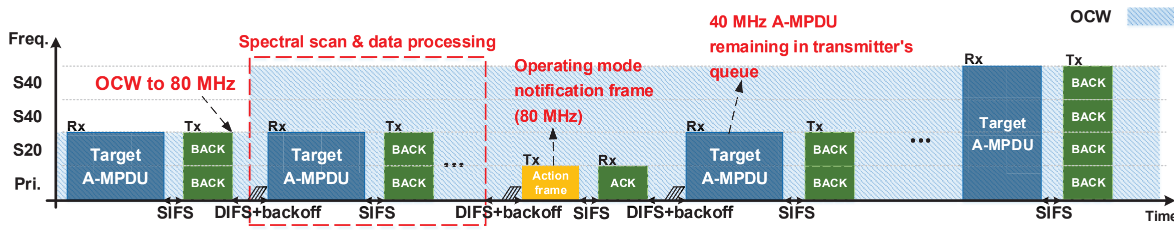


Fig. 11. Example of increasing OCW: Expiration of N_{wnd} triggers probing, where the receiver increases OCW to 80 MHz, and conducts spectral scan. Because time-domain interference does not exist, the receiver decides to remain on 80 MHz OCW, and hence, sends a operating mode notification frame to the transmitter.

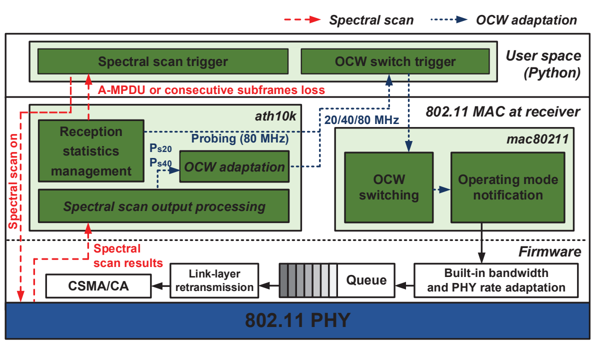


Fig. 12. Implementation structure of *RECONN*.

In this manner, *RECONN* tries to find the optimum OCW consistently according to the pattern and magnitude of time-domain interference to improve the throughput performance eventually.

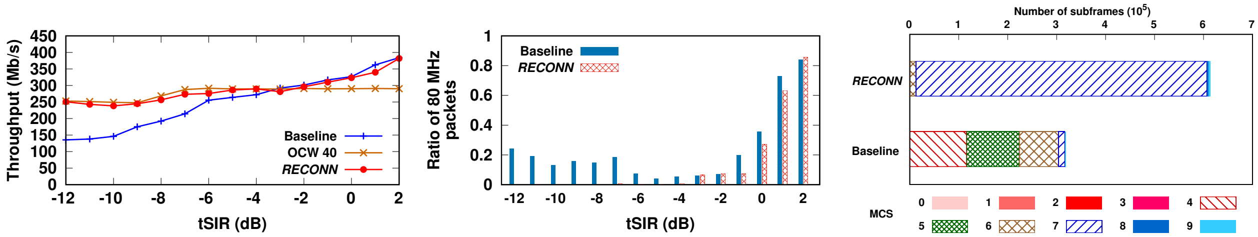
In the meantime, if the current OCW is 20 MHz or 40 MHz, receiver needs to verify whether time-domain interference still deteriorates reception performance in order to check the possibility to widen OCW. Accordingly, receiver periodically performs probing, i.e., spectral scan on the entire 80 MHz. Specifically, *RECONN* employs probing window, N_{wnd}, i.e., the number of A-MPDUs required to trigger probing. Therefore, if the number of received A-MPDUs reaches N_{wnd}, receiver performs spectral scan on the entire 80 MHz channel after increasing OCW to 80 MHz. If time-domain interference is still expected to negatively affect reception performance, that is, $P_{ampdu} - P_{s20} \leq \alpha_{dB}$ or $P_{ampdu} - P_{s40} \leq \alpha_{dB}$, *RECONN* then reduces OCW back to 20 MHz or 40 MHz and doubles N_{wnd}. On the other hand, if none of the above two conditions is satisfied, receiver remains on OCW of 80 MHz, because it is expected that time-domain interference does not exist anymore.

2) Notification of the change: OCW switching is triggered by receiver, which is actually interfered. Therefore, whenever OCW is newly selected, receiver should notify transmitter of the changed OCW in order to be able to update the available bandwidth.[7]

When a station changes its OCW, it needs to transmit an *operating mode notification frame* to its AP. Operating mode notification frame is an action frame used to notify other stations of changing OCW or the maximum number of spatial streams [2]. On the other hand, when AP changes OCW, it should announce the changed width to all associated stations. AP can notify associated stations of the change, using individually addressed operating mode notification frames, but it takes too much overhead in practice. Instead, the AP is able to broadcast *channel switch announcement action frame* without performing a backoff after PIFS-long idle time.

3) Discussion: As mentioned in Section III-B, switching OCW incurs delay which is known to be several tens of microseconds such that OCW cannot be changed for each packet in the current 802.11ac system. Indeed, depending on the random backoff value selected by transmitter, receiver might not be able to receive A-MPDU during switching period, thus resulting in frame loss. Therefore, when receiver cannot tolerate frame loss, it can utilize *power management operation* alternatively, as if it enters power saving mode during switching period. After completing OCW switching, receiver then sends a frame to AP to indicate that it has exited power saving mode. However, since an exchange of power management frame causes an additional overhead, a careful consideration is required to effectively use the power saving feature with OCW adaptation, which will be included

[7]The increase in OCW to 80 MHz for probing does not need to be notified.



(a) Throughput according to tSIR. (b) Ratio of 80 MHz subframes. (c) MCS distribution with tSIR of -12 dB.

Fig. 13. Measurement results obtained by the receiver according to tSIR. The transmitter is AC2600 and the interference is generated by NI USRP.

in our future work. Instead, *RECONN* sets the initial value of N_{wnd} to 1,000 A-MPDUs, and exponentially increases N_{wnd} up to 16,000 A-MPDUs, to prevent excessive OCW changes, and hence, the overhead incurred by changing OCW can be effectively reduced.

One thing to note is that the notification of OCW change should occur prior to a decrease and following an increase in OCW [2]. Transmission bandwidth of a packet is determined when the packet is enqueued in transmitter's queue, and it cannot be easily changed once the packet is enqueued. Accordingly, if receiver suddenly reduces its OCW, it will not be able to receive packets, which are scheduled to be transmitted over wider bandwidth. Therefore, receiver should give a transmitter enough time to update the bandwidth. When OCW increases, receiver has no problem to receive packets transmitted by using smaller bandwidth. Accordingly, receiver informs transmitter of its change, after completing OCW switching. Figs. 10 and 11 show examples of switching OCW with notification action frames, where the y-axis denotes channel including the primary 20 MHz (*Pri.*) and secondary channels (*S20* and *S40*). Note that BlockAck (*BACK*) is transmitted after Short IFS (SIFS) from the end of A-MDPU reception, which is duplicated in each 20 MHz channel.

VI. Performance Evaluation

To verify the feasibility and excellence, we implement *RECONN* on the Linux-based open-source device driver, *ath10k* and *mac80211*, and make a prototype using commercial 802.11ac NIC with QCA9880.[8] Detailed implementation of *RECONN* is best explained with a blueprint in Fig. 12. *RECONN* is composed of 1) spectral scan module implemented in *ath10k*, 2) OCW switching and notification module managed by *mac80211*, and 3) triggering module in python-based user space program. Specifically, the need for spectral scan is determined in *ath10k* by detecting A-MPDU or three consecutive subframe losses [24], and the actual triggering is conducted via a python-based triggering program, not disturbing on-going packet reception. An appropriate OCW is then calculated in *ath10k* by processing the spectral scan results. Finally, OCW switching and notification are triggered in user space, and then, actually performed in *mac80211*.

[8]Because QCA9880 does not suffer from undesirable receive locking problem, performance of *RECONN* might be underestimated using QCA9880. Nevertheless, we implement *RECONN* on *ath10k* and *mac80211*, due to accessibility and ease of playing with the open-source device driver.

A. One-to-One Scenario

We firstly conduct an experiment of an one-to-one scenario in the same topology shown in Fig. 3, where AC2600 sends saturated downlink traffic at P1 to an associated 802.11ac station located at P3, using channel 48 as the primary 20 MHz channel. Interference is generated by NI USRP at P5, using channel 36 and 20 MHz bandwidth. All measurement results are averaged over five runs, where each run lasts for 20 s.

Fig. 13(a) shows throughput obtained by the 802.11ac station according to tSIR. We compare performance of *RECONN* with baseline 802.11ac (*baseline*), which uses 80 MHz fixed OCW. For a comparison, we also consider the case of receiver's OCW equal to 40 MHz (*OCW 40 MHz*). When tSIR is higher than -3 dB, *Baseline* achieves the highest throughput, because the interference does not significantly influence on the reception performance of the 802.11ac station. However, when tSIR is lower than -3 dB, *OCW 40 MHz* shows the best performance. As expected, *RECONN* adapts OCW depending on the degree of interference to effectively eliminate time-domain interference, thus following the upper most curves and achieving 1.85$\times$ higher throughput than that of *Baseline* when tSIR is -12 dB, and 1.32$\times$ higher throughput than that of *OCW 40* when tSIR is 2 dB.

Furthermore, Fig. 13(b) shows a ratio of successfully received 80 MHz subframes. Since *RECONN* uses 40 MHz OCW when tSIR is lower than -3 dB, no 80 MHz subframe is observed. Interestingly, even though *Baseline* employs autonomous bandwidth adaptation implemented in AC2600 firmware, more than 10% of subframes are received by sharing the wireless medium with the interferer, when tSIR is lower than -6 dB, thus resulting in low channel utilization [4, 12]. Furthermore, more than 80% of subframes are received, by using 40 MHz bandwidth, but lowering MCS index unnecessarily due to time-domain interference. In particular, as shown in Fig. 13(c), *Baseline* uses MCS 3, 4, and 5, while *RECONN* dominantly uses MCS 7 when tSIR is -12 dB.

In order to check the adaptability of *RECONN*, we obtain instantaneous downlink throughput results as shown in Fig. 14. Interference traffic making -12 dB tSIR begins at 9 s and stops at 19 s. As soon as interference traffic is generated, *RECONN* reduces OCW to 40 MHz, by immediately detecting time-domain interference. On the other hand, after interference traffic disappears, *RECONN* waits until probing window expires, and then increases OCW to 80 MHz.

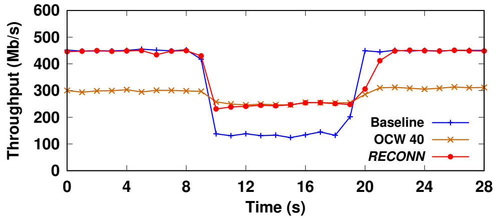


Fig. 14. Snapshot of instantaneous throughput when tSIR is -12 dB. Interference is turned on at 9 s and turned off between 18 s and 19 s.

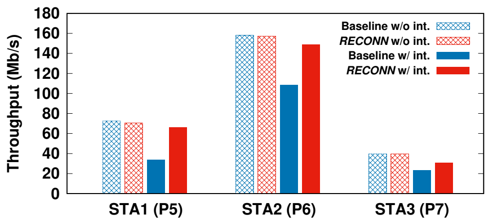


Fig. 15. Multi-station environment. *RECONN* achieves 1.49× higher network throughput than that of *Baseline*, when the interference exists.

B. Multi-station Scenario

We deploy three stations at P5 (STA1), P6 (STA2), and P7 (STA3), where AC2600 transmits saturated downlink traffic to each station. Different from other experiments, interference traffic is generated by commercial 802.11n devices equipped with QCA9380, where an 802.11n AP located at P3 sends saturated downlink traffic to its associated 802.11n station deployed at P2. Accordingly, only STA1 at P5 is severely interfered by the interferer at P3.

Fig. 15 shows downlink throughput obtained by three stations. When the interference does not exist (*w/o int.*), *Baseline* and *RECONN* provide almost the same throughput, using 80 MHz bandwidth. On the other hand, when the interference is generated (*w/ int.*), *Baseline* achieves throughput of 33.6 Mb/s, 108 Mb/s, and 23 Mb/s for STA1, STA2, and STA3, respectively. Even though only STA1 is intensively affected by the interference with tSIR $= -10$ dB, both STA2 and STA3 also suffer from throughput degradation, due to the airtime waste and heavy retransmission attempts to STA1. However, *RECONN* reduces STA1's OCW to 40 MHz, and hence, it is not affected by time-domain interference, thus resulting in 96.5% throughput enhancement. Interestingly, although packets to STA1 consume longer airtime due to the reduced bandwidth, network throughput of *RECONN w/ int.* is slightly decreased (only 8% reduction) compared to *RECONN w/o int.* because 1) STA2 and STA3 are independent from the interference, and 2) STA1 obtains higher power spectral density thanks to fixed transmit power and less impact of frequency selectivity. Finally, we find that *RECONN w/ int.* achieves 48.9% higher aggregate throughput, compared to *Baseline w/ int.*.

VII. Conclusion

In this paper, we have verified that using bandwidth less than OCW might cause packet detection and synchronization failure, undesirable receive locking problem, and AGC failure due to time-domain interference not overlapping with the incoming desired signal on frequency domain. To solve this problem, we develop *RECONN*, which intelligently adapts OCW using the frequency-domain information at receiver side. *RECONN* fully complies with 802.11 MAC and requires no hardware modification. Our prototype implementation in commercial 802.11ac devices demonstrates that *RECONN* achieves up to 1.85× higher throughput compared to baseline 802.11ac, by completely eliminating time-domain interference. We expect that *RECONN* will highly benefit the future large-scale and heterogeneous 5 GHz network, where the time-domain interference problem might be severer in the future.

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References

[1] IEEE 802.11, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, IEEE Std., Mar. 2012.
[2] IEEE 802.11ac, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Enhancements for Very High Throughput for Operation in Bands below 6 GHz*, IEEE Std., Dec. 2013.
[3] S. Jang and S. Bahk, "A Channel Allocation Algorithm for Reducing the Channel Sensing/Reserving Asymmetry in 802.11ac Networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 3, pp. 458–472, Jun. 2014.
[4] S. Byeon, C. Yang, O. Lee, K. Yoon, and S. Choi, "Enhancement of Wide Bandwidth Operation in IEEE 802.11ac Networks," in *Proc. IEEE ICC*, Jun. 2015.
[5] *Evolved Universal Terrestrial Radio Access (E-UTRA), Physical Layer Procedures (Release 13), document 3GPP TS36.213 V13.2.0*, 3GPP, Jun. 2016.
[6] L. Deek *et al.*, "Joint Rate and Channel Width Adaptation for 802.11 MIMO Wireless Networks," in *Proc. IEEE SECON*, Jun. 2013.
[7] J. Herzen, R. Merz, and P. Thiran, "Distributed Spectrum Assignment for Home WLANs," in *Proc. IEEE INFOCOM*, May 2013.
[8] S. Jang, K. G. Shin, and S. Bahk, "Post-CCA and Reinforcement Learning based Bandwidth Adaptation in 802.11ac Networks," *IEEE Trans. Mobile Comput.*, vol. PP, no. 99, pp. 1–14, May 2017.
[9] L. Deek *et al.*, "Intelligent Channel Bonding in 802.11n WLANs," *IEEE Trans. Mobile Comput.*, vol. 13, no. 6, pp. 1242–1255, Jun. 2014.
[10] B. A. H. S. Abeysekera, M. Matsui, Y. Asai, and M. Mizoguchi, "Network Controlled Frequency Channel and Bandwidth Allocation Scheme for IEEE 802.11a/n/ac Wireless LANs: RATOP," in *Proc. IEEE PIMRC*, May 2014.
[11] B. Bellalta *et al.*, "On the Interactions Between Multiple Overlapping WLANs Using Channel Bonding," *IEEE Trans. Veh. Technol.*, vol. 65, pp. 796–812, 2016.
[12] A. Faridi, B. Bellalta, and A. Checco, "Analysis of Dynamic Channel Bonding in Dense Networks of WLANs," *IEEE Trans. Mobile Comput.*, vol. 16, no. 8, pp. 2118–2131, Aug. 2017.
[13] C. Kai, Y. Liang, T. Huang, and X. Chen, "To Bond or not to Bond: An Optimal Channel Allocation Algorithm For Flexible Dynamic Channel Bonding in WLANs," in *arXiv:1703.03909v2*, Mar. 2017.
[14] J. Fang and I. T. Lu, "Efficient channel access scheme for multiuser parallel transmission under channel bonding in IEEE 802.11ac," *IET Communications*, vol. 9, no. 13, pp. 1591–1597, 2015.
[15] W. Wang, F. Zhang, and Q. Zhang, "Managing Channel Bonding with Clear Channel Assessment in 802.11 Networks," in *Proc. IEEE ICC*, May 2016.
[16] R. Karmakar *et al.*, "Channel Access Fairness in IEEE 802.11ac: A Retrospective Analysis and Protocol Enhancement," in *Proc. ACM MobiWac*, Nov. 2016.
[17] O. Lee, J. Kim, and S. Choi, "WiZizz: Energy Efficient Bandwidth Management in IEEE 802.11ac Wireless Networks," in *Proc. IEEE SECON*, Jun. 2015.
[18] IEEE 802.11ax-2016, *IEEE Proposed TGax draft specification, IEEE P802.11ax/D0.4*, IEEE Std., Aug. 2016.
[19] T. M. Schmidl and D. C. Cox, "Robust Frequency and Timing Synchronization for OFDM," *IEEE Trans. Commun.*, vol. 45, pp. 1613–1621, 1997.
[20] National Instrument, "LabVIEW Communications 802.11 Application Framework White Paper," NI, Technical Report, 2015.
[21] M. Morelli, C. C. J. Kuo, and M. O. Pun, "Synchronization Techniques for Orthogonal Frequency Division Multiple Access (OFDMA): A Tutorial Review," *Proceedings of the IEEE*, vol. 95, no. 7, pp. 1394–1427, 2007.
[22] V. P. G. Jimenez, M. J. F.-G. Garcia, F. J. G. Serrano, and A. G. Armada, "Design and Implementation of Synchronization and AGC for OFDM-based WLAN Receivers," *IEEE Trans. Consumer Electron.*, vol. 50, pp. 1016–1025, 2004.
[23] R. Gummadi *et al.*, "Understanding and Mitigating the Impact of RF Interference on 802.11 Networks," in *Proc. ACM SIGCOMM*, Aug. 2007.
[24] R. Anwar *et al.*, "Loss Differentiation: Moving onto High-Speed Wireless LANs," in *Proc. IEEE INFOCOM*, May 2014.