Simultaneous Multi-Channel Downlink Operation in Next Generation WLANs

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***Abstract*—The next-generation IEEE 802.11 standard project, IEEE 802.11be, is focused to meet the growing demands of applications including high throughput, low latency and high reliability. With the emergence of dual-radio end user devices (STAs) and tri-band Access Points (APs), efficient operation over multiple channels distributed over multiple bands is a key technology being discussed in IEEE 802.11be task group to achieve the desired objectives. For certain channel combinations with insufficient frequency separation, STAs might not have the ability to simultaneously receive on one channel while transmitting on the other channel. Due to the independent medium access per-channel, there might be severe performance degradation of downlink throughput delivered to such constrained devices. To address this issue, we design and analyze Constraint-aware Aligned Downlink Ending (CADEN) protocol for simultaneous downlink transmissions over multiple channels that adaptively aligns the ending of the simultaneous downlink frames based on medium access conditions and reception capability of constrained STA. Our results show that our proposed mechanism consistently improves the downlink throughput delivered to constrained STAs under various network conditions.**

I. Introduction

The IEEE 802.11 Working Group recently established the IEEE 802.11be project [1] to focus on improved throughput performance in existing Wireless LAN (WLAN) applications and meet growing industry demand for lower latency and high-reliability applications over WLANs. IEEE 802.11be represents the next-generation standard beyond the capabilities of IEEE 802.11ax [2]–[4], now being deployed. Concurrently, there has been an emergence of 802.11 devices with multiple radios, both STAs and APs, capable of operating simultaneously on multiple channels possibly distributed over multiple bands 2.4 GHz, 5 GHz and 6 GHz. Multi-channel operation within the same 802.11 network (BSS) has the potential to *(a)* improve the throughput as frames from a traffic session can be transmitted on multiple channels providing increased bandwidth, *(b)* reduce the latency as devices contend on multiple channels and utilize the first available channel, *(c)* increase reliability as frames can be duplicated over multiple channels and *(d)* enable flexible channel switching without negotiation overhead. For these reasons, multi-channel/multi-band operation is a key candidate technology feature being discussed in the IEEE 802.11be task group [5], [6]. This feature represents a paradigm shift moving from BSS operating on a single channel to BSS operating over multiple channels wherein the STAs can dynamically choose to operate on a subset of channels ranging from a single channel to multiple channels.

To realize the full potential of multi-channel operation, in reference to a pair of channels, an ideal requirement from the participating devices would be having the capability to perform reception on one channel while simultaneously transmitting on the other channel (**STR** capability). The STR capability on a pair of channels is determined by several factors of radio design and BSS operation including channels of operation, bandwidth of each channel, transmit power limit, antenna distribution between the channels, etc. Therefore, a multi-radio device may lack the STR capability for particular channel combinations. If the AP itself lacks STR capability, then the multi-channel operation would be severely restricted leading to negligible gain over legacy single-channel operation. Typically, AP devices are many-antenna systems and the AP establishes the channels of operation in the BSS. Therefore, it is reasonable to assume that the AP shall select the channels of operation such that the AP has STR capability on every pair of channels in its BSS. In contrast, a STA might lack STR capability for particular set of operating channels due to smaller form factor compared to AP. We hereby denote STAs that lack STR capability as *non-STR STAs*.

With medium access being independent on each channel, using the random contention-based mechanisms defined in 802.11 standard, an AP may obtain medium access on each channel in an asynchronous manner. Consequently, if simultaneous downlink transmissions that begin at different times are destined to the same non-STR STA, there might be an overlap in time domain of immediate acknowledgement response in the uplink on one channel and ongoing downlink data transmission on other channel. In the rest of the paper, by overlap, we refer to overlap in time domain unless explicitly stated otherwise. Such overlap would lead to reception failure of downlink data at non-STR STA. In the worst case, if the acknowledgement transmission in the uplink on one channel overlaps with the physical layer preamble at the start of downlink data transmission on other channel, the non-STR STA fails to receive the entire downlink payload.

In this paper, our objective is to minimize the in-device interference at non-STR STAs during asynchronous simultaneous downlink transmissions due to independent per-channel medium access. In particular, we propose Constraint-aware Aligned Downlink Ending (**CADEN**), the first 802.11 multi-channel operation protocol incorporating the simultaneous transmit and receive operation constraints for simultaneous downlink transmissions and make the following contributions: *(a)* novel signaling information from a non-STR STA to AP during association indicating its capability to receive a downlink data transmission during and beyond an overlapping acknowledgement transmission from the same non-STR STA and *(b)* an adaptive protocol at AP that utilizes the non-

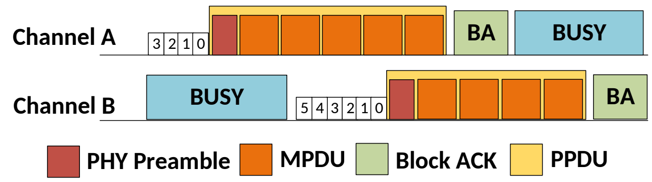

Fig. 1: Asynchronous multi-channel operation with independent medium access per channel from the point of view of a multi-channel device.

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STR STA's reception capability and medium access conditions to adaptively align the ending of the simultaneous downlink transmissions to a non-STR STA. We implement the key components of our proposed design in a custom ns-3 network simulator and evaluate the throughput and latency performance under various network conditions. Our results show that, CADEN significantly improves downlink throughput delivered to non-STR STAs compared to the baseline strategies discussed.

The remainder of the paper is organized as follows. In Section II, we present the multi-channel BSS model, reception failure at non-STR STA due to asynchronous operation and baseline strategies. In Section III, we present our proposed design CADEN. In Section V, we present key results from our performance evaluation. In Section VI, we review related work and we conclude the paper in Section VII.

II. Network Model and Motivation

In this section, we provide the necessary background for the problem addressed in this paper. First, we briefly describe the multi-channel BSS model considered in this paper. Second, we illustrate the problem scenario that occur when AP performs transmissions on multiple channels to the same non-STR STA in an asynchronous manner. Third, we present a baseline conservative approach and illustrate how such an approach can lead to severe under-utilization of the medium.

A. Multi-Channel BSS model

We consider the AP establishes the BSS operation over multiple channels. These channels are possibly located on different bands although a subset of the channels might be on the same band. An example of the multi-channel BSS is 20 MHz operation in 2.4 GHz band, 80 MHz operation in 5 GHz band and 160 MHz operation in 6 GHz band. Due to the diversity in channel conditions across the channels, the data rate used by a device might be different on different channels. The AP advertises the multi-channel operation in broadcast frames including Beacons, Probe Responses, etc. STAs joining the BSS can indicate the channels they want to operate on, during association as well as dynamically in the form of an operating mode change indication after association. For example, a STA might switch temporarily to a single channel operation for power saving when it has no backlogged traffic or for co-existence with other technologies (e.g. Bluetooth). For simplicity, in this paper, we focus on multi-channel operation to be over two channels.

By default, the medium access in each channel is independent of medium state of other channels [7]. In contrast, obtaining medium access on multiple channels at the same time through aggressive means *(a)* might lead to severe unfairness to legacy devices and single channel operating devices and *(b)* have regulatory limitations. Fig. 1 illustrates multi-channel medium access from the perspective of a particular device (AP or STA) operating on channels A and B. In this figure, we highlight the following concepts used in rest of the paper: *(a)* channel state is set to busy following 802.11 busy state determination rules; *(b)* data transmission on a channel begins when the backoff counter value (boxed number) is down to zero; *(c)* a single PHY protocol data unit (PPDU) transmission might consist of multiple MAC protocol data units (MPDUs) and the corresponding immediate block acknowledgement (Block ACK) is comprised of a bitmap where each bit acknowledges (ACK) the successful reception of a particular MPDU, *(d)* asynchronous nature of the medium access wherein the device is receiving Block ACK on channel A and transmitting data on channel B simultaneously. To represent practical implementations of first generation 802.11be devices, we consider the STAs provide acknowledgement on a channel only for the data received on that channel and do not have the integration capability to indicate successful reception of data received on other channels.

In this paper, we consider the AP has STR capability over the channels operated in its BSS. As described in Section I, STA might lack the STR capability to perform such an operation due to in-device power leakage issues caused by insufficient frequency separation between channel A and channel B. Accordingly, we classify the STAs in the multi-channel BSS as follows: *(a) Single channel STA*: STA operating only on one channel including legacy devices, *(b) STR STA*: STA operating on multiple channels and has STR capability and *(c) Non-STR STA*: STA operating on multiple channels and lacks STR capability. In this paper, we assume the STAs operating over multiple channels indicate their STR capability on each pair of channels to the AP.

Acronym	Description
BSS	basic service set, 802.11 network established by AP
STR STA	multi-channel operating STA with STR capability
Non-STR STA	multi-channel STA lacking STR capability
MPDU	MAC protocol Data Unit
Block ACK (BA)	block acknowledgement with bitmap of ACKs
PHY	physical layer
PPDU	PHY protocol data unit
OBSS	neighboring BSS
TX	transmission
RX	reception

TABLE I: Description of key acronyms [7], [8].

B. In-device Interference at non-STR STAs

In this section, we briefly describe the key scenario focused in this paper. Multi-channel operation is an attractive feature to enable applications that demand high throughput and low latency e.g. augmented reality, virtual reality, etc. To minimize the latency in delivering buffered traffic, AP might perform

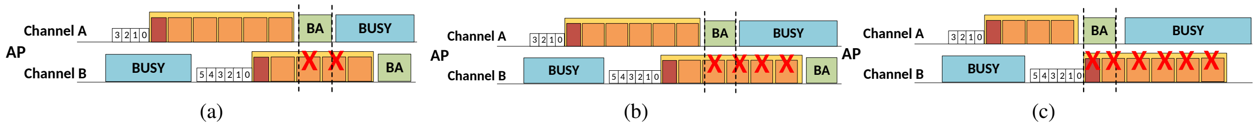

Fig. 2: Illustrations of AP's timeline including AP transmitting or attempting transmission on Channel A and Channel B to the same non-STR STA. X in figures refer to reception failure. (a) Reception failure during Block ACK overlap. (b) Reception failure during and beyond the Block ACK overlap due to non-STR STA's Channel B receiver going out of synchronization. (c) Reception failure due to Block ACK overlap with PHY preamble

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transmission to the same STA on multiple channels. As described in previous section, due to independent medium access, the start and end times of the transmissions on multiple channels are not aligned.

Fig. 2(a) illustrates the simultaneous downlink transmission to a non-STR STA. In this example, the Block ACK transmission by non-STR STA on Channel A interferes with the downlink data transmission to the same non-STR STA on channel B. Depending on the reception capability of non-STR STA for the channels of operation, there are two extreme possibilities. At best, only the MPDU(s) being received on Channel B that overlap with Block ACK transmission on Channel A are lost as shown in Fig.2(a). In contrast, in the worst case, the Block ACK transmission impacts the signal-to-noise-interference ratio on Channel B sufficient to cause the non-STR STA's receiver on Channel B to go out of synchronization with the receiving signal and lead to failure in reception of rest of the MPDUs until the end of the data transmission as illustrated in Fig.2(b). An important point to note here is that as the AP has STR capability, it can receive the Block ACK transmission on Channel B even while transmitting to non-STR STA on Channel B.

Fig. 2(c) illustrates the extreme case of in-device interference case wherein start of downlink transmission including PHY preamble to the non-STR STA on Channel B overlaps with the uplink Block ACK transmission from the same non-STR STA on Channel A. As the non-STR STA fails to decode the physical layer preamble, non-STR STA fails to receive all the MPDUs on Channel B and does not respond with Block ACK. As highlighted in these examples, there might be severe downlink performance degradation if AP simply attempts transmission on each channel without considering the ongoing frame exchange on other channel.

C. Multi-Channel Baseline Strategies

To address the reception failure at non-STR STA due to in-device interference, an AP can prevent overlap in uplink Block ACK transmission from a non-STR STA and AP's downlink transmission to same non-STR STA.

Defer TX strategy. A simplistic approach would be for AP to not transmit to a non-STR STA on other channels when already involved in frame exchange with that non-STR STA as illustrated in Fig. 3(a). In this figure, AP is currently transmitting on Channel A during which its backoff counter on Channel B goes down to zero. As AP is already transmitting to non-STR on Channel A, it does not initiate transmission on Channel B. Accordingly, AP sets an internal wait timer until end of the data-block ACK exchange on Channel A and transmits on Channel B right after the exchange on Channel A ends. However, depending on the channel business, the Channel B medium access might be obtained by another device in the network during the AP's deferral leading to increased delay for AP's medium access on Channel B.

Aligned strategy. Another approach is for the AP to always align the ending [9] of its simultaneous transmissions to a non-STR STA as illustrated in Figure 3(b). As AP aligned the ending of data transmission on both channels, block ACKs are transmitted on both channels at the same time. If the non-STR STA's reception capability is such that only the MPDUs overlapping with short Block ACK are lost, then forced alignment might lead to early ending of data transmission on channel B.

As highlighted above, although this baseline strategies prevent in-device interference at non-STR STA, they might lead to severe under-utilization of the multi-channel operation.

III. CADEN Design

In this section, we present an overview of our design Constraint-aware Aligned Downlink Ending (**CADEN**).

A. CADEN Procedure at non-STR STA

In this section, we briefly describe the procedure followed by non-STR STA in CADEN. As described in Section II-B, depending on the reception capability for the channels of operation, the MPDUs on other channel may be failed to receive even beyond the Block ACK transmission phase and in the worst case all the remaining MPDUs belonging to that transmission. Therefore, in CADEN, for each pair of channels a non-STR STA operates in the multi-channel BSS, the non-STR STA indicates to AP that AP either *(a)* shall always align or *(b)* may not align its simultaneous downlink data transmissions to this non-STR STA. A non-STR STA can provide this information during the initial association with AP as well as in a dynamic manner after association. For example, a non-STR STA may indicate its updated requirement from AP whenever the operating parameters of a channel are updated by AP as the operating parameters determine the STR capability and reception capability at non-STR STA on corresponding pairs of channels.

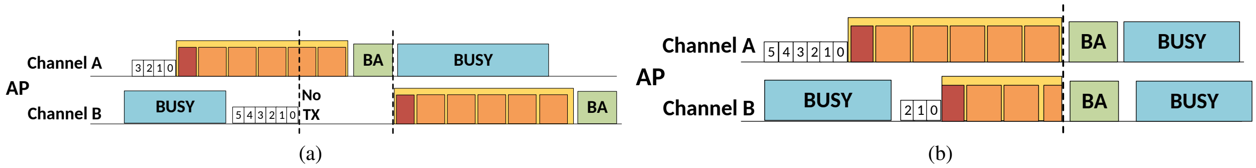

Fig. 3: Multi-channel baseline strategies described in Section II-C

B. CADEN Procedure at AP

In this section, we briefly describe the adaptive behavior at AP in CADEN when transmitting data to a non-STR STA on one channel and upon obtaining medium access for data transmission to same non-STR STA on other channel. In CADEN, the action performed by AP in this scenario varies depending on *(a)* non-STR STA's reception capability indicated as described in Section III-A, *(b)* time domain overlap of downlink data and uplink Block ACK and *(c)* data rate of the channel on which medium access is obtained. Accordingly, in CADEN, AP performs one of the following procedures. For simplicity in explanation, we consider the example of AP currently transmitting to non-STR STA on Channel A and 802.11 backoff counter value reaches zero at AP on Channel B to initiate transmission to same non-STR STA.

a. PHY Preamble Overlap Prevention. If the uplink Block ACK transmission on Channel A overlaps with PHY preamble of data on Channel B, then the entire data transmission on Channel B will be failed to receive at non-STR STA. As AP reserves the Channel A medium for both the data transmission and corresponding acknowledgement reception, AP has precise knowledge of start and end time of the potential Block ACK response from non-STR STA on Channel A. In addition, AP has knowledge of the start and end of PHY preamble corresponding to potential transmission on Channel B. Therefore, after 802.11 backoff counter value reaches zero for AP on Channel B, if AP determines an overlap would occur between Block ACK from a non-STR STA on Channel A and PHY preamble to same non-STR STA on Channel B, AP will not initiate data transmission over-the-air on Channel B and re-attempt transmission after the reserved medium time on Channel A by AP expires. It is important to note that as AP does not perform transmission, the medium can be obtained by neighboring devices operating on Channel B before the reserved medium time on Channel A expires.

b. Mandatory Ending Alignment. If the non-STR STA indicates that AP shall align the downlink transmissions as described in Section III-A, AP starts transmission to non-STR STA on Channel B immediately after 802.11 backoff counter reaches zero and aligns the end of data transmission on Channel B with the end of ongoing data transmission on Channel A. To achieve this alignment, AP might employ fragmentation and padding mechanisms already defined in existing 802.11 standard.

c. Adaptive Ending Alignment. If the non-STR STA indicates that AP may not always align the downlink transmissions as described in Section III-A, AP adaptively aligns the ending of the data transmission based on the potential data reception failure at non-STR STA if alignment is not performed. Depending on the interference conditions on Channel B and rate adaptation mechanism employed by AP, AP determines the modulation and coding rate for the data transmission on Channel B. Accordingly, AP uses the precise knowledge of the start and end times of potential Block ACK transmission by non-STR STA on Channel A to determine the number of MPDUs that would be failed to receive by non-STR STA if the ending of data transmission on Channel B is not aligned with that on Channel A. An important point to note here is that this MPDU reception failure at non-STR STA can occur on Channel A instead of Channel B if the data transmission on Channel B ends earlier than that of Channel A. Therefore, using a pre-defined MPDU loss threshold, AP will align the ending of data transmission on Channel B with that of Channel A if the estimated number of MPDUs that will suffer reception failure at non-STR STA on Channel A or Channel B is above this pre-defined threshold. Otherwise, AP will perform transmission on Channel B without any alignment with the ongoing transmission on Channel A to the same non-STR STA.

IV. CADEN Implementation and Evaluation Setup

To analyze CADEN's performance under various network conditions, we extend the *ns-3* discrete event network simulator [10]. In this section, we briefly describe our implementation of CADEN and alternative strategies considered for evaluation. Also, we briefly describe the simulation setup.

A. Multi-Channel MAC Architecture

To simulate multi-channel medium access, we extend the ns-3 Wi-Fi module's MAC layer to enable multi-channel operation. In the AP and STAs operating on multiple channels, packets from upper layer arrive to the multi-channel MAC which has the following relevant functional blocks:

Queueing. To maximize the benefit of multi-channel operation, the queues are shared for the multiple channels. In this manner, backlogged data can be transmitted on the first available channel thereby minimizing the access delay.

Channel State. This block tracks 802.11 clear channel assessment states of different channels.

Channel-specific Lower MAC. This sub-layer interfaces with the corresponding physical layer and generates immediate MAC acknowledgement responses following 802.11 standard.

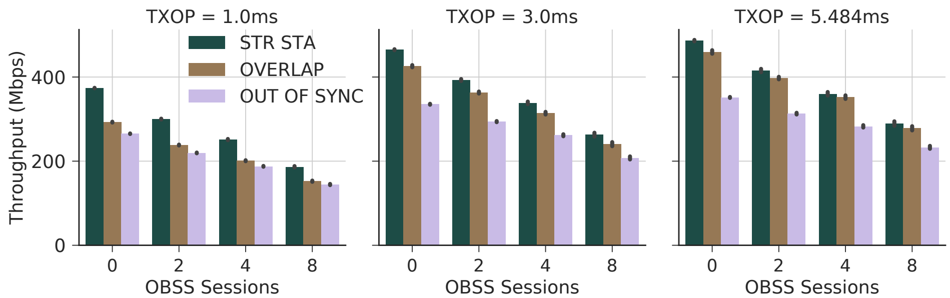

Fig. 4: Performance comparison of asynchronous downlink multi-channel operation to non-STR STA for different reception capabilities. STR STA serves as the baseline.

B. Protocols for Performance Evaluation

Table II provides the list of protocols considered for CADEN's performance evaluation and their brief description. We implement the key components of CADEN and alternative strategies on top of the multi-channel MAC architecture described in the previous section. To compare performance, we consider different reception capability of non-STR STAs including *(a) Overlap loss:* wherein MPDU reception failure at non-STR STA occurs during Block ACK as shown in Figure 2(a) and *(b) Out of Sync loss:* wherein MPDU reception failure occurs at non-STR STA for MPDUs starting from overlap with Block ACK and until end of data frame as non-STR STA receiver goes out of synchronization with the reception as described in Section II-B.

Protocol	**Brief description**
SINGLE CHANNEL	legacy 802.11 single channel operation
DEFER TX	Conservative strategy described in Section II-C
ASYNC	asynchronous operation with no alignment
ALIGNED	Baseline strategy described in Section II-C
CADEN	Adaptive ending alignment presented in Section III

TABLE II: Protocols for performance evaluation.

C. Simulation Setup

We focus on a single AP multi-channel BSS operating on two channels. To isolate the analysis of downlink performance to non-STR STAs, we consider multi-channel operating STAs in the network to be non-STR STAs. To analyze a dense, congested BSS environment, we consider fully backlogged traffic generated at AP in the BSS for the non-STR STAs. We consider the AP randomly selects the non-STR STA to transmit data to upon gaining medium access. To analyze simultaneous downlink transmissions, if AP is already transmitting to a non-STR STA on one channel, we focus on the scenario where AP selects the same non-STR STA for downlink transmission on second channel. To represent typical data rate achieved by 802.11 technologies, we utilize the PHY data rate on each channel to be 480 Mbps. For throughput computation, we incorporate the overheads in PHY preamble, 802.11 RTS-CTS protection mechanism, inter-frame spacings, Block ACK, etc. To isolate the downlink performance analysis, we consider a single non-STR STA in the BSS to which the AP has full-buffered traffic unless stated otherwise. To represent interference in the network, we consider varying number of neighboring BSS (OBSS) traffic flows on each channel with channel occupancy per access opportunity following a random distribution. For each combination of network conditions, we perform over 100 runs of 10 seconds each separately for CADEN and alternative strategies.

V. Performance Evaluation

In this section, we present the key results of our performance evaluation.

A. Asynchronous Multi-Channel Operation

In Fig. 4, we analyze the performance degradation suffered by a non-STR STA due to asynchronous operation. In this figure, the x-axis represents the number of OBSS sessions on both channels in the BSS and the y-axis represents the downlink throughput delivered by AP to non-STR STA. The OBSS sessions are equally distributed over the two channels. To replicate varying traffic applications of different packet sizes and aggregation limit, we vary the PPDU transmission time used by AP on obtaining medium access on a channel. TXOP denotes 802.11 transmission opportunity including the data transmission and corresponding block ACK. First, expectedly, as STR STA does not suffer in-device interference, it consistently provides the highest throughput across different traffic and network conditions. Second, there is significant performance degradation for non-STR STA due to asynchronous operation as it suffers in-device interference. Third, the performance degradation is worst for non-STR STA that suffers out-of-sync loss as all the MPDUs starting from overlap with Block ACK transmission are lost. In comparison, non-STR STA that suffers overlap loss fails to receive only the MPDU(s) that overlap with the short Block ACK transmission. Fourth, an important point to note here is that due to the asynchronous operation, non-STR STA with either overlap loss or out-of-sync loss might experience complete PPDU reception failure due to overlap of PHY preamble reception with Block ACK transmission (Fig. 2(c)). Lastly, for shorter TXOP durations, we observe higher degradation compared to STA STA scenario as the probability of in-device interference increases leading to preamble reception failure as well as MPDU reception failure.

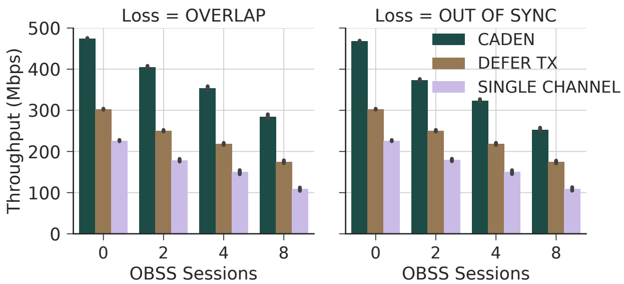

Fig. 5: Throughput performance comparison of CADEN with legacy single channel operation and a conservative baseline strategy that does not perform simultaneous transmissions.

B. CADEN Comparison with Non-Simultaneous Transmission Strategies

In Fig. 5, we compare CADEN's performance with strategies that do not perform simultaneous downlink transmissions. To analyze peak throughput performance, we consider AP utilizes PPDU transmission time of 5.484 ms (802.11 PPDU maximum duration) on the first channel it obtains medium access at any time. First, despite no performing simultaneous transmissions, as the AP still performs medium access on two channels compared to single channel operation, Defer TX strategy consistently betters the legacy operation. Second, however, Defer TX suffers from not utilizing the obtained medium access as OBSS traffic flows can acquire the medium instead during the deferral period. CADEN's adaptive alignment strategy consistently provides the highest gains independent of non-STR STA's reception capability and network conditions.

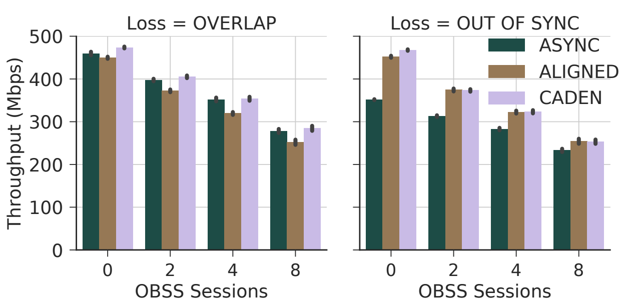

Fig. 6: Throughput performance comparison of CADEN with asynchronous operation and always aligned baseline strategy.

C. CADEN Comparison with Simultaneous Transmission Strategies

In Fig. 5, we compare CADEN's performance with strategies that do not perform simultaneous downlink transmissions. Similar to previous section, we consider AP utilizes PPDU transmission time of 5.484 ms on the first channel it obtains medium access at any time. First, when non-STR STA suffers overlap loss, we observe that Aligned strategy consistently has the worst performance. This is because of the shorter transmission on second channel leading to increased overhead attempting channel access, PHY preamble and MAC overhead. In this scenario, CADEN provides better performance than asynchronous operation as it does not suffer from reception failure highlighted in Fig. 2. Second, when non-STR STA suffers out-of-sync loss, performing ending alignment prevents MPDU reception failure at non-STR case for CADEN and Aligned strategies. Third, when non-STR STA suffers out-of-sync loss, CADEN provides better performance than Aligned strategy due to its preamble overlap prevention mechanism. Preamble reception failure can occur in Aligned strategy when the AP obtains medium access on second channel right after its transmission ends on the other channel but the Block ACK transmission from non-STR STA has not concluded.

VI. Related Work

To the best of our knowledge, this paper presents the first 802.11 multi-channel operation protocol that addresses the downlink performance degradation at non-STR STAs due to in-device interference caused by independent medium access. Several works have studied the optimization of channel assignment and bandwidth selection in 2.4/5 GHz multi-channel operation for ad-hoc networks [11]–[13] and enterprise deployments of IEEE 802.11n/802.11ac WLANs [14], [15]. Few works have studied joint operation of 2.4/5 GHz band and higher frequency bands including 60 GHz [16] and visible light communication [17]. In such joint operation, the STR constraint does not exist. Authors in [18]–[20] presented the throughput and latency gains provided by performing 802.11 medium access backoff on multiple channels compared to single channel operation. In these works, the multi-channel operating devices were assumed to have STR capability. In [7], authors proposed mechanisms for improving the uplink medium access of non-STR STAs participating in asynchronous multi-channel operation. Authors in [21] analyzed the downlink performance of non-STR STAs in completely asynchronous multi-channel operation with no alignment. In contrast to existing works, we propose novel protocol that includes signaling from non-STR STA about its reception capability and adaptive alignment by AP of simultaneous transmissions to improve the multi-channel downlink service to non-STR STAs. Nonetheless, mechanisms proposed in existing works can be used in conjunction with CADEN to meet the growing demands of applications requiring high throughput, low-latency and high reliability.

VII. Conclusion and Future Work

In this paper, we addressed the challenges introduced by asynchronous multi-channel operation, a key feature of next-generation IEEE 802.11be standard, to downlink throughput delivered to client devices lacking simultaneous transmission and reception capability. We presented CADEN, a novel design in which the non-STR STAs indicate their reception capability for simultaneous downlink transmissions and accordingly the AP adaptively constructs its data transmissions with ending alignment. Our results show that CADEN's adaptive ending alignment mechanism consistently provides better performance across various network conditions compared to alternative strategies.

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