Characterizing Interference Mitigation Techniques in Dense 60 GHz mmWave WLANs

Ding Zhang*, Panneer Selvam Santhalingam*, Parth Pathak* and Zizhan Zheng†
*Department of Computer Science, George Mason University, Fairfax, VA, USA
†Department of Computer Science, Tulane University, New Orleans, LA, USA
Email: {dzhang13, psanthal, phpathak}@gmu.edu, zzheng3@tulane.edu

***Abstract*—Dense deployment of access points in 60 GHz WLANs can provide always-on gigabit connectivity and robustness against blockages to mobile clients. However, this dense deployment can lead to harmful interference between the links, affecting link data rates. In this paper, we attempt to better understand the interference characteristics and effectiveness of interference mitigation techniques using 802.11ad COTS devices and 60 GHz software radio based measurements. We first find that current 802.11ad COTS devices do not consider interference in sector selection, resulting in high interference and low spatial reuse. We consider three techniques of interference mitigation - channelization, sector selection and receive beamforming. First, our results show that channelization is effective but 60 GHz channels have non-negligible adjacent and non-adjacent channel interference. Second, we show that it is possible to perform interference-aware sector selection to reduce interference but its gains can be limited in indoor environment with reflections, and such sector selection should consider fairness in medium access and avoid asymmetric interference. Third, we characterize the efficacy of receive beamforming in combating interference and quantify the related overhead involved in the search for receive sector, especially in presence of blockages. We elaborate on the insights gained through the characterization and point out important outstanding problems through the study.**

I. Introduction

60 GHz millimeter-wave (mmWave) networks can provide multi-gigabit per second link data rates, making it possible to support applications such as augmented/virtual reality, ultra-high definition videos, sync-and-go, etc. Development of WLAN standards like 802.11ad and 802.11ay, along with availability of Commercial Off-The-Shelf (COTS) devices [1] and software radio platforms [2] is driving the growth of 60 GHz WLANs. A dense deployment of APs in 60 GHz WLANs can provide always-on gigabit connectivity to clients and can potentially enable high spatial reuse with directionality. Recent research on 60 GHz seamless handoff [3], [4], localization [5], [6] and blockage mitigation [7] also motivate the use of multiple APs with significant overlap in their coverage. This is in line with the emergence of dense 5G mmWave wireless networks originally envisioned in [8].

With the dense deployment of APs, harmful interference can occur between links, limiting their ability to provide gigabit data rates. The problem can be aggravated by the fact that today's phased antenna arrays do not provide narrow "pencil-shaped" beams, but instead create non-uniform beams with significant sidelobes [9]. Majority of recent research [9]–[12] has focused on performance of a single link, however, interference in a dense 60 GHz network has received a limited attention from the community. One of the primary challenges of conducting controlled interference experiments has been the inability of controlling beamforming (e.g., set desired sector) on today's COTS devices. For software radio systems which do provide such control, building multi-link testbed to analyze interference has remained a costly endeavor.

In this paper, we attempt to better understand link interference and how to mitigate it in a multi-link 60 GHz WLAN. We use 802.11ad COTS devices and 60 GHz software radio to assess the link performance in indoor environments. To facilitate this study, we first modify the driver (wil6210) of QCA9500 802.11ad chipset to add three critical functionality: (1) set desired transmit and receive sectors; (2) specify the number and the set of sectors to be searched during the beamforming process; (3) implement receive beamforming. Equipped with the modified driver on COTS and software radio platform, we perform indoor measurements (controlled and uncontrolled) to characterize link interference and identify underlying reasons of performance variations. We find that the default sector selection used in COTS devices does not consider interference to/from other links, resulting in non-negligible interference and low spatial reuse even with directionality. The large footprint of the interference can be attributed to indoor reflections and irregular beam patterns with non-trivial sidelobes. We then explore three approaches to reduce interference and investigate their efficacy, benefits, limitations and trade-offs. The findings can be summarized as follows:

(1) Interference alleviation using channelization: 802.11ad uses three channels in 60 GHz spectrum in the United States. Our measurements suggest that using different channels for interfering links in 60GHz WLAN can effectively alleviate interference. However, 60 GHz links observe severe adjacent and non-negligible non-adjacent channel interference upto 10 ft. This interference can be attributed to the use of relaxed channel masks aimed at easing hardware design at high frequencies. Given that 60 GHz links can be densely deployed to achieve Gbps link rates and combat blockages, adjacent and non-adjacent channel interference should be considered when using different channels for interference alleviation.

(2) Interference alleviation using transmit sector coordination: Coordinating the transmit beam sector of multiple interfering links can help in improving spatial reuse. Our experiment results show that it is possible to find combinations of transmit sectors that can be used by links to reduce mutual interference. However, presence of indoor reflections and strong sidelobes make interference-aware sector selection a challenging problem. Furthermore, any such sector selection scheme should take into account fairness. We find that non-uniformity of antenna patterns, relative positioning of link endpoints and reflective objects result in asymmetric interference between the links. The asymmetry leads to unfair medium access with contention-based 802.11ad MAC, resulting in unfair throughput.

(3) Interference alleviation using receive beamforming: Use of receive beamforming can improve spatial reuse and boost network throughput. We implement receive beamforming on the COTS devices and demonstrate its effectiveness in reducing interference, especially when combined with intelligent sector selection. However, receive beamforming can make links more susceptible to blockages and the time overhead of searching the receive sector can be significant, especially in presence of blockages. We elaborate on searching overhead and interference trade-off when using receive beamforming and motivate the need of dynamic, agile schemes that can achieve a balance.

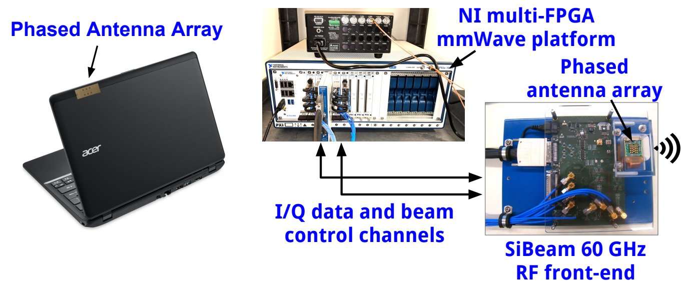
The remaining paper is organized as follows. Sec. II discusses our COTS driver modifications, software radio testbed and experiment methodology. Sec. III provides a detailed look at interference with gigabit links. Then Sec. IV, Sec. V and Sec. VI discuss three interference mitigation techniques. Sec. VII discusses the related work and we conclude in Sec. VIII.

II. Testbed and Measurement Methodology

We use two types of 60 GHz mmWave testbeds in this characterization study.

(1) COTS 802.11ad devices: We use Acer Travelmate TMP446-M/TMP648-MG [1] laptops as COTS 802.11ad devices. Each laptop is equipped with an 802.11ad module containing Qualcomm QCA9500 chipset [13] connected with 32-element phased antenna array (located on top right edge of laptop's LCD screen - Fig. 1a). The laptops run Ubuntu Linux and open-source wil6210 driver for the QCA9500 chipset.

We modify the wil6210 driver to add specific functionality essential in our study. The modifications enable us to perform important operations: (1) set a specific transmit and receive sector; (2) change the number, order and set of sectors used in the transmit sector selection process; (3) achieve receive beamforming compatible with the default transmit beamforming in COTS devices. These operations can be performed in real-time without reloading the driver module. The default codebook of wil6210 provides 36 sectors numbered from 1-31 and 59-63 (as described in [9], [12]). Changing of the transmit sector as desired enables us to perform a wide-range of controlled experiments to understand fine-grained impact of transmit sector selection on interference. Modification of number and set of potential sectors allows us to change the default beamforming procedure. Setting the receive sector from the codebook enables us to fully study the 802.11ad protocol and conduct interference mitigation experiments. Additionally, we extract MAC layer throughput, SNR value of each sector, MCS, transmit and receive sectors of both link endpoints, etc.



(a) (b)

Fig. 1: (a) Acer 802.11ad laptop with phased antenna array and our modified wil6210 driver (b) NI+SiBeam 60 GHz software radio with multiple FPGAs and SiBeam phased antenna array

from the driver every 150 ms. Our modifications are directly usable on 802.11ad compatible laptops.

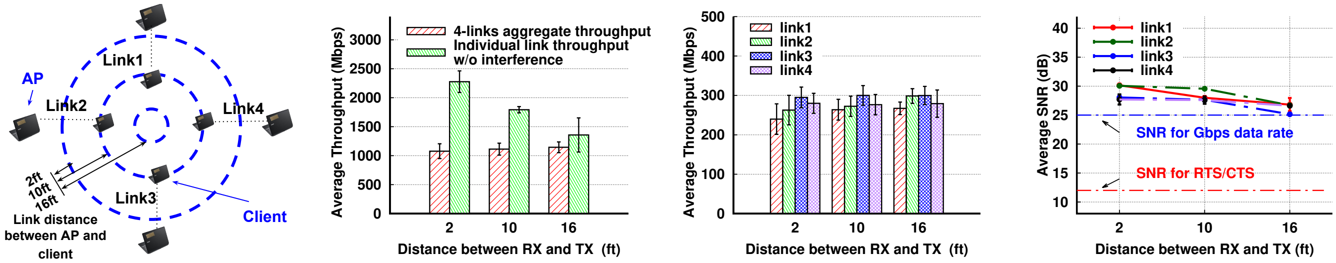
(2) NI+SiBeam reprogrammable software radios: The NI+SiBeam transceiver nodes (shown in Fig. 1b) use National Instrument multi-FPGA millimeter-wave prototyping platform with SiBeam 60 GHz phased antenna array and RF front-end. The baseband processing system contains multiple FPGA modules (NI PXIe 3630, 7902 and 7976) for implementing ADC/DAC, modulation and demodulation, encoding and decoding. This NI backend system is interfaced with a SiBeam V-band transceiver evaluation board as the RF frontend. The SiBeam platform provides 24 antenna elements (12 for transmitting and 12 for receiving) and capability to perform analog beamforming. The transceiver can provide 1.76 GHz of RF bandwidth at two carrier frequencies (60.48 and 62.64 GHz), and up to 16 QAM modulation for over 3 Gbps of data rate. The devices employ time-divided, slotted MAC (10ms super frame with 100 slots of 100μs) with turbo encoding.

SiBeam's default codebook provides 25 antenna sectors (0-24 with Sector 12 being the broadside sector) covering from -60° to +60°. The sectors are separated by approximately 5° and their half-power beamwidth range from 25°-35° [14]. Host can control and switch the sector on per-frame basis. The two-node NI+SiBeam testbed is currently not capable of running UDP/TCP transport layer protocols but can be used to create interference and expand the characterization studies.

Measurement methodology: We operate the Acer laptops in client, AP (Hostapd) or monitor mode. Link throughput is measured by running downlink Iperf3 UDP or TCP flows from AP laptops (Tx) to client laptops (Rx). For each experiment, Iperf3 sessions last for 60-100 seconds, repeated at least 10 times to calculate the mean and 95% confidence intervals.

III. Interference between Gigabit Links

Due to the directionality of 60GHz links and use of phased antenna array, the achievable throughput in 60 GHz links is highly sensitive to device orientation and rotation [12], [14]. This means that a dense deployment of APs would be necessary to guarantee gigabit links. Additionally, recent work shows that dense deployment is necessary for seamless hand-offs of mobile devices, blockage mitigation and localization (for example, 3 APs in a 28ft×22ft room in [3], 4-10 APs in



(a) Setup of 4 interfering links (each client connected to and facing towards the nearest AP)
(b) Aggregate throughput of 4 links vs. individual throughput at different distances
(c) Throughput of each link (downlink) at different distances when 4 links operate concurrently
(d) SNR of each link (downlink) at different distances when 4 links operate concurrently

Fig. 2: High interference and limited spatial reuse are observed with the 4-links setup

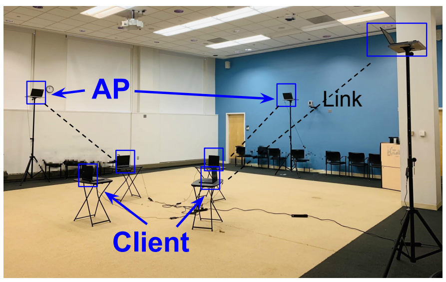


Fig. 3: Setup of 4 links in a 36ft×36ft classroom

a 32ft×22ft room in [4], 8 APs in a 116ft×116ft hall in [7], 14 APs in a 36ft×59ft room [5], and 8APs in a 36ft×68ft room in [6]). However, use of multiple APs within close vicinity of each other can cause non-negligible interference. Given that 60 GHz links are directional, we are interested in measuring link interference with directional communication in a dense deployment.

To explore the performance of multiple links in an indoor space, we set up 4 links as shown in Fig. 2a and Fig. 3 in a 36ft×36ft classroom. 4 laptops configured as APs are mounted on tripods with 10ft height and placed next to the center of four room walls. 4 clients are placed in the room as shown in Fig. 2a where distance between each client and and its corresponding AP remains the same. We vary this AP-client distance from 2ft to 16ft. Note that each client always connects to the nearest AP. This scenario is similar to the practical case where multiple users in a large hall connect to multiple APs on the ceiling. Each link's achievable throughput is measured by downlink UDP Iperf individually first and then with all four links operating concurrently. We use UDP in order to generate mostly one-way (downlink) traffic as opposed to TCP which can create bidirectional traffic.

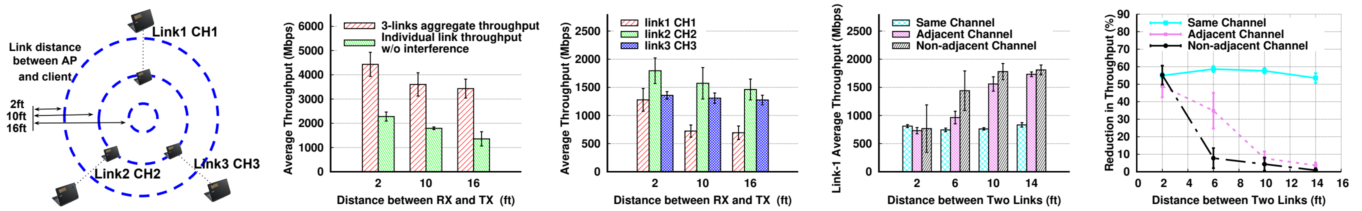
It is expected that the directionality of 60GHz networks allows multiple links to operate concurrently (spatial reuse). However, we observe that the achievable spatial reuse is limited. When each link is operating individually without interference, the throughput reduces from 2.27 Gbps at 2ft to 1.35 Gbps at 16ft as shown in Fig. 2b. On the other hand, when all 4 links are operating at the same time, the throughput of each link reduces to 205-320 Mbps (Fig. 2c) and average aggregate throughput is 1.1 Gbps as shown in Fig. 2b. The SNR value of each link is shown in Fig. 2d. We find that all links can achieve high enough SNR that could adequately support Gbps data rate. However, in presence of interference, the SINR value decreases significantly, reducing the overall throughput. The current COTS devices use contention-based access period (CBAP) scheme instead of using scheduled service period (SP) based time divided access. With CBAP, virtual carrier sensing (RTS/CTS) is used to coordinate medium access between the interfering links. Similar to 2.4/5 GHz networks [15], RTS/CTS can yield a conservative estimation of interference, further limiting the spatial reuse in 60 GHz links. We also repeat the experiment in an indoor lab, and observe similar results of limited aggregate throughput and spatial reuse.

In case of the 60 GHz links, high interference and limited spatial reuse can be attributed to the following reasons: (1) Irregular beam patterns: The consumer-grade phased antenna arrays used by 60 GHz COTS devices provide wide and irregular beam patterns with non-trivial sidelobes (also shown in [9]). Such irregularities reduces the directionality and increases interference. (2) Indoor reflections: Many of the indoor objects (e.g., walls, whiteboard, metal cabinets, etc.) are good reflectors of 60 GHz signals. Such ambient reflectors can further increase the interference footprint by reflecting the signal radiated from sidelobes and even mainlobes. Given the interference characteristics of 802.11ad COTS WLAN, we now investigate the three different interference mitigation strategies (channelization, transmit sector selection and receive beamforming) and evaluate pros and cons of each of them.

IV. Interference Mitigation Using Channelization

Scheduling transmissions on different channels has the potential to effectively mitigate interference between links. Channel assignment has been studied [16] in 2.4/5 GHz 802.11 networks. However, because of the higher frequency and wider channels used by 802.11ad networks, we now explore how effective channelization can be in mitigating interference. We first look at the feasibility of using different channels to reduce interference, and then study adjacent and non-adjacent channel interference in 802.11ad networks. To best of our knowledge, our work is the first to explore the use of different channels in 802.11ad to reduce interference.

802.11ad uses the ITU-R recommended channelization comprising of three 2.16 GHz wide channels in U.S. (Fig. 5) centered at 58.32 GHz, 60.48 GHz and 62.64 GHz, respectively. According to [17], the channel mask has maximum signal level within 1.88 GHz around the center frequency, and



(a) Setup of 3 links with separated channels and different distances (each client facing towards the nearest AP)

(b) Aggregate throughput of 3 links with separated channels vs. individual throughput at different distances

(c) Throughput of each individual link operating on different channel when all 3 links operate concurrently

(d) Average throughput of Link-1 with Link-2 at varying distances

(e) Percentage reduction in throughput with different type of channel interference

Fig. 4: Channelization can effectively reduce the interference between links but adjacent and non-adjacent channel interference cannot be neglected when clients are close to each other.

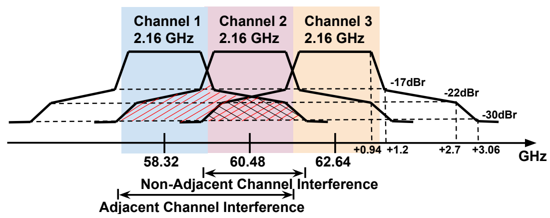


Fig. 5: Channelization and mask used by 802.11ad

-17 dBr (dB relative to the maximum signal level) within 2.4 GHz. Given that each channel is 2.16 GHz wide, -17 dBr breakpoint extends to adjacent channels. Furthermore, the mask has -22 dBr signal upto 5.4 GHz, extending even to non-adjacent channels (e.g., Channels 1 and 3). Table I shows a comparison between channel mask breakpoints of 802.11ac 80 MHz and 802.11ad channels. As it can be observed, the channel mask requirements in 802.11ad have been substantially relaxed, primarily to reduce circuit design complexity and support both OFDM and single carrier modulations [17].

	802.11ac 80MHz Channel	**802.11ad 2.16GHz Channel**
0 dBr	39MHz	0.94GHz
-20 dBr	41MHz	1.96GHz
-28 dBr	80MHz	3GHz

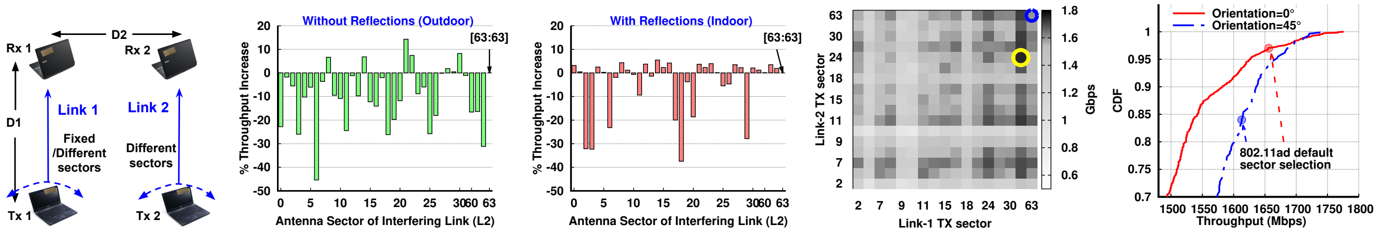
TABLE I: Comparison of channel mask between 802.11ac 80 MHz channel and 802.11ad 2.16 GHz channel

In the same room (36ft×36ft) used in previous experiments, we create 3 links operating on different channels with different distances as shown in Fig. 4a. Link-1, Link-2 and Link-3 operate on channel 1, 2 and 3 respectively. Downlink Iperf flows are created simultaneously on all three links and default sector selection algorithm is used to determine the transmit sectors. We can observe from Figs. 4b and 4c that using different channels increases the aggregate throughput significantly by reducing the inter-link interference. For example, in Fig. 4b, the total throughput is approximately 2.2 times higher than the throughput of independent link at all distances. From Fig. 4c, we can observe that link operating at Ch-2 achieves higher throughput compared to the other two channels. It can be conjectured that this is a result of Ch-2 overlapping with both Ch-1 and Ch-3, affecting both other links.

We now evaluate the Adjacent Channel Interference (ACI) and Non-adjacent Channel Interference (NACI) in 802.11ad networks. Here, two links perpendicular to each other are created in the classroom (Link-1$\uparrow$ and Link-2 $\rightarrow$). We create Iperf flows on both links which also use default sector selection algorithm to determine their transmit sectors. Distance between the Tx and Rx of each link is fixed to 5 ft which can support high SNR and data rate. Then the distance between the two links is varied from 2ft to 14ft in increments of 4ft. We consider three cases where both links operate on same channel (Ch3), adjacent channels (Ch1-Ch2, Ch2-Ch3) or non-adjacent channels (Ch1-Ch3). Fig. 4d shows the throughput of Link-1 as distance separation between the two links increases for the three cases. We observe that when both links operate on the same channel, the throughput of Link-1 reduces by more than 50% (Fig. 4e). For the same channel interference, the reduction remains consistent even when the distance between the two links increases. When the links operate on adjacent channels, we find that Link-1 throughput reduces by 48.9%, 34.9%, 7.7% on average for 2, 6 and 10 ft distance separation, respectively. This means that two 802.11ad links operating on adjacent channels have to be separated by as much as 10 ft in order to eliminate ACI. When the links are densely deployed (within 10ft), adjacent channel links operate more or less like links operating on the same channel. For non-adjacent channels, the interference decreases faster with increase in distance separation. However, NACI is still severe (50% throughput reduction - similar to same channel) at 2ft distance, and non-negligible even at a distance upto 10ft.

This higher ACI and NACI in 802.11ad links can be attributed to relaxed channel masks. Fig.5 shows that based on -17dBr and -22dBr breakpoints, the channels can have significant overlap with adjacent and even non-adjacent channels. This overlap reduces the link SINR at closer distance, making links with weaker signal quality especially vulnerable to ACI and NACI. ACI is observed and studied in previous research for 802.11 g/n. For example, [18] showed that when the distance between 802.11n radios operating at adjacent channels is within 3-4 ft, non-negligible ACI occurs. Compared to this, 802.11ad ACI and NACI are more severe (higher throughput reduction) and for longer distances (upto 10ft).

Findings: Even though the use of different channels in 802.11ad networks can mitigate interference, due to relaxed channel masks, 802.11ad 60 GHz channels exhibit severe adjacent channel interference and non-negligible non-adjacent channel interference. Given that 802.11ad APs can be deployed in a dense manner due to blockages and limited gigabit communication range, this high adjacent and non-adjacent



(a) Interference-aware sector selection measurement setup
(b) Aggregate throughput in outdoor scenario
(c) Aggregate throughput in indoor scenario
(d) Aggregate throughput of two links with different Tx sectors on each link
(e) CDF of aggregate throughput of two scenarios with different Tx orientations

Fig. 6: (a,b) Interference-aware sector combination can increase the aggregate throughput in outdoor scenario, however, in indoor case (c), reflections and sidelobes make such combinations less effective. (d) 802.11ad default sector selection is not interference-aware and many other sector combinations with higher throughput can be found in different scenarios (e) with different Tx Orientations.

channel interference should be considered in network deployment, performance analysis of dense network operations, channel assignment and design of multi-radio 802.11ad APs. The interference should also be considered while developing channel aggregation and bonding schemes proposed in upcoming 802.11ay which uses the same channelization.

V. Interference Mitigation by Sector Selection

Selecting an alternate sector has been shown to be effective for blockage mitigation and mobility [10], [11], [19], [20]. However, the impact of sector selection on interference has not been thoroughly measured and characterized for 802.11ad COTS devices. In this section, we explore how judiciously selecting Tx sector of the APs help mitigate interference and what are the associated challenges and trade-offs.

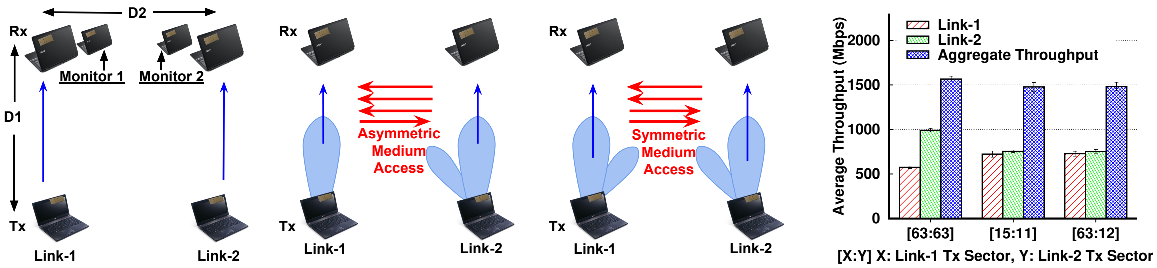
A. Interference-aware Sector Selection

We first attempt at understanding if the default sector selection algorithm used by the COTS 802.11ad devices considers interference or not. Given that reflections (NLOS path) can affect interference (especially with strong sidelobes), we first perform outdoor measurements in an open parking lot with minimal/no reflections. In the indoor and outdoor comparison experiment, we set up two links (Fig. 6a) and change one or both Tx sectors using our modified wil6210 driver. Two Iperf flows are created from Tx to Rx simultaneously and the network throughput is evaluated. We set the distance in Fig. 6a as D_1=28ft and D_2=22ft. We first allow the link endpoints to run their default sector selection process and find that the Tx of both links (APs in downlink Iperf flows) choose Sector 63 (high gain at broad side) for over 95% of the time. The total average throughput of two links is observed to be 1,309 Mbps. We then set transmit sector of Link-1 Tx to 63 and vary the transmit sector of Link-2 Tx to all 36 sectors (1-31, 59-63) one by one. Fig. 6b shows the percentage increase in aggregation throughput (L1+L2) compared to the sector combination found by default sector selection [63:63]. We find that, in fact, there exists 7 sector combinations that achieve higher throughput compared to the default combination. For example, sector combination [63:21] achieves 14.3% increase in aggregate throughput.

We repeat the same experiment in an indoor environment (classroom) with reflections with the same setup. Fig. 6c shows the percentage increase in aggregate throughput compared to what is observed with the default sector combination (also [63:63]). Here, we find that even though more sector combinations can provide higher throughput but their throughput increase is actually lower (2.3% on average) compared to the outdoor case. A closer examination reveals that indoor reflections and presence of strong sidelobes in sector patterns make the interference worse. Even if there exists a sector combination that can achieve a higher aggregate throughput and lower mutual link interference, presence of sidelobes and reflections render them less effective in indoor scenarios.

To find the optimal Tx sector combination for the above mentioned two links, we now exhaustively search all possible Tx sector combinations (36×36) and determine how many of them yield aggregate throughput higher han the default Tx sector combination used by the COTS driver. We use the topology shown in Fig. 6a with D_1=22 ft and D_2=10 ft in the classroom environment. Here, each link creates a downlink Iperf flow when the two Tx use different sectors and Rx fixed to the quasi-omni sector. Two different Tx orientations are considered. In the first one, the Tx and Rx of both links align with each other. In the second case, the Tx is set at $45°$ orientation from its Rx with both Tx facing away from each other to reduce interference.

Figs. 6d and 6e show the observed aggregate throughput. Fig. 6d shows the aggregate throughput of two links with different Tx sector combinations for two links in the $45°$ orientation scenario. The default sector selection algorithm uses the Tx sector combination of [63:63] (blue circle in Fig. 6d) which achieves throughput of 1594 Mbps. However, upon exhaustively searching, we find that other sector combinations can achieve higher aggregate throughput. For example, sector combination [61:24] (yellow circle in Fig. 6d) achieves an aggregate throughput of 1748 Mbps. Fig. 6e shows the CDF of aggregate throughput for two orientations. When the Tx orientation is $0°$, 4.1% of combinations can achieve higher throughput than the default combination, and when the orientation is $45°$, 16.2% combinations can achieve higher aggregate throughput. This shows that it is possible to achieve



(a) (b) (c) (d)

Fig. 7: (a) RTS/CTS/DTS monitoring setup with D_1=22 ft and D_2=10 ft (b) Asymmetric interference where Link-1 receives more RTS/CTS from Link-2, but Link-2 has more deafness to Link-1, (c) Link-1 and Link-2 have relatively more symmetric interference to each other, (d) Default transmit sector combination [63:63] results in unfair throughput compared to [15:11].

interference-aware sector selection. However, searching within all possible sector combinations can incur very high overhead (N^k where N is the number of sectors for each link and k is the number of links).

B. Asymmetric Medium Access

Although careful selection of sectors can help alleviate interference, fairness is also an important challenge to consider in sector selection. Depending on the selected sectors, it is possible that the links observe significant unfairness between their achievable throughput. In this section, we characterize this unfairness using controlled experiments and find that asymmetric medium access is the underlying reason of the unfairness in directional transmissions of 60 GHz WLANs.

Current wil6210 driver only supports contention based medium access (verified through sniffing Beacons where DMG parameter Contention-based Access Period "CBAP only = True"). In 802.11ad DCF CSMA/CA, a Directional Multi-gigabit (DMG) transmitter sends a Request-To-Send (RTS) frame to its intended receiver using the transmit antenna sector found during sector selection process. The receiver responds with a DMG Clear-To-Send (CTS) if it senses the medium to be idle, or with a DMG Denial-To-Send (DTS) otherwise. The DTS frames are used to reduce excessive RTS transmissions when the transmitter finds the medium idle but the receiver does not (common with directional communication).

To better understand the unfairness, we deploy two additional laptops working in monitor mode as sniffers close to the receivers (Fig. 7a). Tables II and III show the average number of RTS, CTS and DTS frames received by both monitors. The experiments are repeated many times to calculate averages, and monitoring sessions with too few frames are removed from the analysis. The average capture sessions were approximately 40 seconds long. We show control frames captured by Monitor-1 and Monitor-2 belonging to Link-2 and Link-1, respectively. This indicates how many RTS, CTS and DTS a receiver receives from the other link.

In case of the throughput, Fig. 7d shows the individual and aggregate throughput of two links. With default sector selection (both links's Tx use Sector 63), Link-2 achieves 41.9% higher average throughput compared to Link-1. Now, we use our modified wil6210 driver to set different transmit sectors on both links' Tx and evaluate throughput fairness. It can be observed that other transmit sector combinations (such as [15:11], [63:12]) can achieve a much higher fairness while ensuring a comparable aggregate throughput.

The unfairness can be attributed to asymmetric interference and medium access as shown in Figs. 7b and 7c. Due to the non-uniform antenna patterns, it is possible that one link interferes with the other, but not vice versa. To confirm this, we analyze the number of RTS/CTS packets captured by the monitors. In case of default sector selection with [63:63] (Table II), Link-1 Rx receives substantially more number of RTS/CTS from Link-2, compared to the number of RTS/CTS received by Link-2 Rx from Link-1. It explains why Link-1 achieves lower throughput because the higher number of RTS from Link-2 will increase the backoffs on Link-1. In case of sector combination [15:11] (Table III), the number of RTS is similar, resulting in similar throughput.

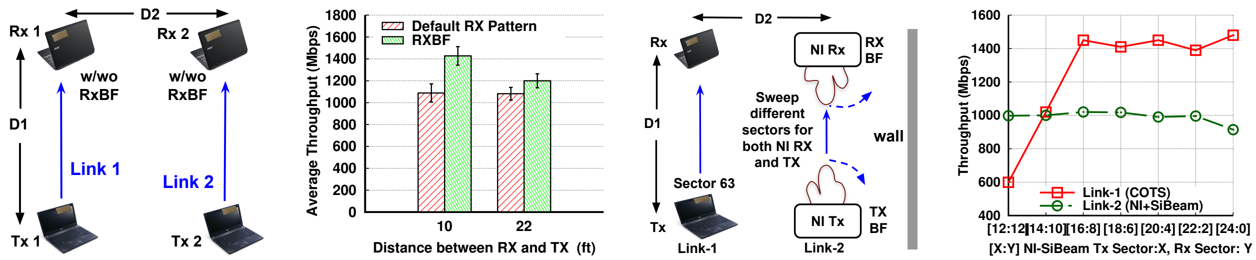
L1 Sector 63 L2 Sector 63	Control Frame of Link 2 Received by *Monitor 1*	Control Frame of Link 1 Received by *Monitor 2*
RTS	17,358	11,432
DMG CTS	10,745	6,147
DMG DTS	514	685

TABLE II: Link-1 (557 Mbps) and Link-2 (990 Mbps) get unfair medium access which is evident in number of RTS, CTS and DTS frames exchanged

L1 Sector 15 L2 Sector 11	Control Frame of Link 2 Received by *Monitor 1*	Control Frame of Link 1 Received by *Monitor 2*
RTS	16,531	16,460
DMG CTS	10,350	7,470
DMG DTS	229	2,003

TABLE III: Link-1 (723 Mbps) and Link-2 (754 Mbps) get a more fair medium access as evident in number of RTS, CTS and DTS frames exchanged

Findings: The default sector selection algorithm used in today's 802.11ad devices does not consider interference between links as it primarily aims at improving individual link's SNR. It is possible to find combinations of transmit sectors that can reduce interference between links, but with the presence of reflections and large sidelobes, the gains of such interference-aware sector selection remains limited in indoor environments. However, the performance of such interference-aware sector selection should be better when narrower beams with smaller sidelobes are provided by the antenna array. Also, exhaustive search of an interference-aware sector combination requires searching within all links and sectors combinations, incurring a prohibitive overhead even for a small-sized network. There



(a) 2 links setup with and without RxBF

(b) Aggregate throughput of 2 links with and without RxBF

(c) Setup for interference-aware sector selection with RxBF

(d) Throughput using interference-aware sector selection with RxBF

Fig. 8: (a,b) RxBF reduces interference and improves throughput; (c,d) The effectiveness of interference-aware sector selection increases when combined with RxBF

is a need of designing intelligent schemes that can balance this overhead with gains.

Even though interference-aware sector selection is an effective way to reduce interference, it should be used carefully as it can result in severe unfairness in link throughput due to the asymmetric medium access. The asymmetry of interference depends on antenna sector patterns, relative positions of link endpoints and reflective objects in an indoor environment. In presence of client mobility and dynamic blockages, a measurement/probing based approach can be used to determine sector combinations that can not only achieve higher throughput but also better fairness.

VI. Interference mitigation using RxBF

802.11ad standard includes both transmit beamforming as well as receive beamforming (RxBF). However, today's 802.11ad devices do not employ RxBF but instead use a quasi-omni receive pattern to provide more robust connection. It is expected that the quasi-omni receive pattern increases the interference at a receiver, but it is not clear how significant this impact is compared to RxBF. In this section, we first show the effectiveness of receive beamforming to reduce the interference on both COTS and NI+Sibeam SDR devices. We then demonstrate how RxBF can be used in conjunction with sector selection for better interference mitigation. Lastly, we quantify the overhead of RxBF and discuss the tradeoffs involved in its usage.

A. *Effectiveness of Receive Beamforming*

To understand the impact of RxBF on interference, we measure the aggregate throughput of the network with and without RxBF respectively. We create the same setup as shown in Fig. 6a with D_1=22ft or 10ft and D_2= 10ft. We implement RxBF procedure at receivers for both links. The current COTS devices use quasi-omni pattern as receive sector to receive all TX sectors. Instead, we take use of the tool [21] to use existing patterns for receiving and implement the receive beamforming procedure in the user space on the COTS laptops. To this end, the Rx sets receive sector one by one, and for each Rx sector, the Tx performs (inbuilt) transmit beamforming. Then the Rx collects the SNR values for all combinations, and uses the pattern with the highest SNR as its receive sector. The Rx also feeds back the corresponding Tx sector to the transmitter for it use as its Tx sector.

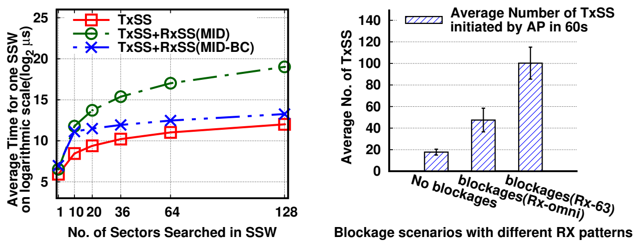
Figs. 8b shows the aggregate throughput with and without RxBF when both links use COTS device. The RxBF increases the aggregate throughput by 11% at 22ft distance in our settings. When both the Rx move closer to the Tx (at 10ft), the aggregate throughput gain reach to 31%. We also observe similar gains in terms of throughput and SNR with the SDR systems. Note that the gains could be higher with narrower beams and reduced sidelobes.

We now show that interference-aware sector selection can be more effective when combined with RxBF. To demonstrate this, we use the experiment setup shown in Fig. 8c with D_1=22ft and D_2=10ft. As seen in the figure, the communication on Link-1 (COTS devices, transmit sector 63) is interfered by Link-2 (NI+SiBeam link with RxBF). With NI SDR system, we can precisely control the beam direction for each sector with reduced sidelobes. In this experiment, the NI SDR system's (Link-2) Tx and Rx sectors are intentionally varied such that their respective gain is concentrated in direction moving away from Link-1. After such diversification, Link-2 utilizes a reflected path from a wall. Fig. 8d shows that as Link-2 sectors move away from Link-1, Link-2's throughput slowly decreases while Link-1's throughput increases substantially. In this case, the total throughput significantly rises by judicially selecting Tx and Rx sectors to alleviate the interference. The throughput of Link-2 decreased slowly as it switches to a reflected path using the wall. In conclusion, RxBF and interference-aware sector selection (coordinating both Tx and Rx sectors on multiple links) can jointly mitigate the interference in 60GHz networks but its benefits are highly dependent on factors such as sector beamwidths and sidelobes, indoor reflections, etc.

B. *Tradeoffs of Receive Beamforming*

RxBF can be helpful in reducing interference but makes the links more susceptible to blockage-related outages. Especially, in case of indoor environments where blockages can occur frequently, use of RxBF triggers frequent searching for a usable Rx sector, substantially increasing the beam searching time overhead. In this section, we first quantify the overhead of using RxBF with 802.11ad protocol.

802.11ad protocol performs Sector Level Sweep (SLS) procedure to train the transmit sectors (TxSS) and receive sectors (RxSS) beams in both directions. The SLS process includes initiator sector sweep (ISS), responder sector sweep



(a) Overhead of RxBF with different number of sectors

(b) Average number of TxSS by AP in 60s with/without blockages

Fig. 9: (a) Use of RxBF increases the average time for one SSW and (b) presence of blockages will increase the average number of TxSS per minute.

(RSS), sector sweep feedback (SSW-FB), and sector sweep acknowledgement (SSW-ACK). In current COTS devices [1], only TxSS is employed and no RxSS is used in the default setting as we mentioned before. In this case, SLS is accomplished using Sector Sweep (SSW) frames as follows. First, initiator transmits N frames (one from each of the N sectors), while responder receives them using quasi-omni pattern. The responder then transmits N frames which are received by the initiator using quasi-omni pattern. In these frames, the responder includes ID and SNR of the best sector (e.g., highest SNR) for the initiator's frames. After responder's N frames, the initiator replies with SSW-FB informing the responder about the best observed sector and its SNR, which is acknowledged using an SSW-ACK by the responder. Altogether, this involves exchange of $(2 \times N) + 2$ frames. We use monitoring nodes to sniff the SSW frames and find that the SLS process with $N = 36$ sectors takes on an average 1203 μs (16 μs for each SSW frame, while both SSW Feedback and ACK together take on average 51 μs).

As per the 802.11ad standard [17], RxBF can be implemented using two methods: MID (multiple sector ID capture) and MID-BC (Beam Combining). MID is an optional subphase following the SLS phase. In this process, the initiator fixes the same transmit sector and the responder changes the receive sectors in sequence and records the corresponding SNR. Then the initiator changes to the next transmit sector and repeats the process. After this exhaustive search, the responder will find the best sector pair or the first k optimal pair to transmit data frame. The overhead of MID could be estimated as the sum of the overhead of SLS phase and $2 \times N^2$ which is the searching overhead for all combinations for both directions. In the MID-BC process, instead of searching all combinations, the initiator fixes the transmit sector as quasi-omni direction and the responder goes over all receive sectors. After that, a Beam Combining(BC) phase is performed. Up to 7 sectors from Tx and Rx side are selected to perform another round of search among 49 combinations. In this case, the best one or first k pairs are selected as a result of the MID-BC subphase. The overhead of MID-BC subphase could be estimated as the sum of SLS phase and $2 \times (N + 49)$.

Fig. 9a shows the estimated average searching overhead for the three schemes (MID, MID-BC and no RxBF) based on our measured frame length. In the estimation of the overhead, the constant time of exchanging control frames is ignored. The vertical axis of Fig. 9a is in logarithmic scale. We can observe from Fig. 9a that with the default TxSS in 802.11ad protocol, the average searching overhead of just using 36 sectors is $\approx 1.18ms$. However, with RxBF, the searching overhead of using 36 sectors would be $\approx 3.9ms$ for MID-BC, and $\approx 42.6ms$ for MID which exponentially increases with the number of sectors. To put it in context, the overhead of using RxBF (MIDC-BC) with 128 sectors (which is the maximum sector allowed in 802.11ad so far) is $\approx 9.7ms$ which occupies nearly 10% of the Beacon Interval $(100ms)$, substantially reducing the time for useful data transmission.

Additionally, the sector sweeps will be triggered more frequently in presence of blockages in indoor environments. To verify this, we measure the average number of TxSS triggered by human blockages with COTS devices. An AP is configured to create a downlink Iperf flow to a client at 30ft distance. A human walks back and forth (same mobility pattern in every measurement instance) closer to the client device, imitating a typical scenario of a user being closer to her mobile device. Two monitors are deployed to collect the SSW-FB, which we then use to count the number of TxSS. Fig. 9b shows that the number of TxSS increases from 17.8 ss/min (sector sweep per minute) to 47.5 ss/min in presence of blockages. When the client uses sector 63 as its receive sector (instead of quasi-omni), the number of TxSS further increases to 100.3 ss/min. This is because SNR varies and degrades more frequently when using a narrower beam (sector 63) compared to quasi-omni, triggering more TxSS. Similarly, when using RxBF, presence of blockages will also trigger more RxSS. This increasing number of TxSS and RxSS, combined with the time taken by them (Fig. 9a) will incur very high overhead negatively affecting the achievable throughput. Many efficient searching algorithms [4], [22], [23] have been proposed to reduce the overhead, but they need to be adapted to include RxBF.

Findings: Our observations show that receive beamforming can be an important technique in combating link interference and improving effectiveness of interference-aware sector selection. Given that receive beamforming has received only a little attention in 60 GHz studies, there is a need of designing adaptive and agile schemes that can opportunistically exploit receive beamforming while ensuring robust connectivity. Such a scheme should not only take into account the robustness but also the time overhead of search when using RxBF. Novel algorithms that can achieve a balance between searching overhead, interference gains and link reliability are needed.

VII. Related Work

60GHz link profiling and measurement: 60 GHz physical channel profiling was studied decades ago in [24] which profiled reflections, power delay and angular profiles in indoor environment. Recently, a detailed indoor link-layer characterization [10] was performed using a software radio platform with horn antenna. Authors in [14] studied the performance of phased antenna array-based NI+SiBeam system and its impact on beamforming in indoor environments. Availability of 802.11ad 60 GHz COTS devices has sparked further research in design and development of 60 GHz WLANs. Indoor coverage, link performance and deployment were studied recently in [12]. 60 GHz WLANs with multiple clients and a single AP was studied in [25] with primary focus on the impact of TCP buffer size, CSMA/CA and aggregation on throughput and fairness. In comparison, our research builds on these works of single link profiling and extends to *multi-links/AP* 60GHz WLANs. In addition, our focus in this paper is to understand the link interference in terms of throughput and fairness at link level with multiple APs, and most importantly how to mitigate the interference by different techniques.

Blockage and mobility being challenging problems in directional mmWave networks, a variety of approaches have been proposed including probing-based beam switching or dilation [11], sensor-based detection [3], joint transmissions [7], and out-of-band (2.4/5 GHz) session transfer [26]. Efficient sector searching has been studied recently using compressive sensing in [9]. In [27], an effective 3D scanning scheme is proposed to accelerate the beam seraching. In comparison, our work focuses on measuring and studying the impact of multiple links interference problem in 802.11ad WLANs.

60GHz WLAN interference: Authors in [28] studied interference and medium access with highly directional links for 60GHz outdoor mesh networks through modeling and simulation. In [19], communication range, effect of blockage and mobility, and interference were studied in outdoor picocell through measurements with COTS 60GHz dock and customized radio. In comparison, our study focuses on indoor environment with reflections and richer multi-path which can affect the interference footprint. In [20], authors first studied the impact of sidelobes and reflection on interference using WiGig and WiHD devices. Our research advances this understanding with 802.11ad devices, software radios and controlled experiments not only to better understand interference in terms of throughput and medium access but also to explore ways to reduce the interference in 60GHz WLAN by using receive beamforming and channel assignment. In [29], authors proposed a technique to select receive sector to reduce interference with low probing overhead. As we discuss, receive beamforming is an important mitigation technique and our work also elaborated on how it can be combined with transmit sector selection. Authors in [30] proposed a centralized transmit sector selection scheme in a very dense network to boost spatial reuse and mitigate interference. Our results are in line with the proposed protocol, and we additionally study the effectiveness and trade-offs of other mitigation techniques such as channelization and receive beamforming.

VIII. Conclusions

In this paper, we systematically studied the impact of interference and three interference mitigation methods in 60GHz WLAN. We first showed the limited spatial reuse and non-negligible interference in dense 60GHz WLANs. Then three interference mitigation methods including channelization, interference-aware sector selection and receive beamforming are studied. We find that the three techniques can be effective in combating interference, but each of them have some limitations that need to be addressed to realize their full potential. The insights gained in the measurement study can be used to design novel interference mitigation protocols which is also a part of our ongoing work.

References

[1] *Acer TravelMate P446 and P648*, 2016. [Online]. Available: https://www.acer.com/ac/en/IN/content/professional-model/UN.VAJSI.044

[2] "NI mmwave transceiver system," http://www.ni.com/sdr/mmwave/.

[3] T. Wei and X. Zhang, "Pose information assisted 60 ghz networks: Towards seamless coverage and mobility support," in *MobiCom '17*.

[4] S. Sur and et al., "Towards scalable and ubiquitous millimeter-wave wireless networks," in *MobiCom '18*.

[5] J. Palacios and et al., "Jade: Zero-knowledge device localization and environment mapping for millimeter wave systems," in *INFOCOM 2017*.

[6] G. Bielsa and et al., "Indoor localization using commercial off-the-shelf 60 ghz access points," in *INFOCOM 2018*.

[7] D. Zhang, M. Garude, and P. H. Pathak, "mmchoir: Exploiting joint transmissions for reliable 60ghz mmwave wlans," in *Mobihoc '18*.

[8] T. S. Rappaport and et al., "Millimeter wave mobile communications for 5g cellular: It will work!" *IEEE access*, vol. 1, pp. 335–349, 2013.

[9] D. Steinmetzer and et al., "Compressive millimeter-wave sector selection in off-the-shelf ieee 802.11ad devices," in *CoNEXT '17*.

[10] S. Sur, V. Venkateswaran, X. Zhang, and P. Ramanathan, "60 ghz indoor networking through flexible beams: A link-level profiling," in *SIGMETRICS '15*.

[11] M. K. Haider and E. W. Knightly, "Mobility resilience and overhead constrained adaptation in directional 60 ghz wlans: Protocol design and system implementation," in *MobiHoc '16*.

[12] S. K. Saha and et al., "Fast and infuriating: Performance and pitfalls of 60 ghz wlans based on consumer-grade hardware," in *SECON '18*.

[13] *Qualcomm QCA9500*, 2017. [Online]. Available: https://www.qualcomm.com/products/qca9500

[14] S. K. Saha and et al., "X60: A programmable testbed for wideband 60 ghz wlans with phased arrays," in *WiNTECH '17*.

[15] M. G. Kaixin Xu and S. Bae, "How effective is the ieee 802.11 rts/cts handshake in ad hoc networks," in *GLOBECOM 2002*.

[16] A. Raniwala and T. cker Chiueh, "Architecture and algorithms for an ieee 802.11 multi-channel wireless mesh network," in *INFOCOM 2005*.

[17] IEEE P802.11adTM/D4.0, "Part 11: Wlan mac/phy enhancements for very high throughput in the 60 ghz band," 2012.

[18] A. Zubow and R. Sombrutzki, "Adjacent channel interference in ieee 802.11n," in *WCNC '12*.

[19] Y. Zhu, Z. Zhang, Z. Marzi, C. Nelson, U. Madhow, B. Y. Zhao, and H. Zheng, "Demystifying 60ghz outdoor picocells," in *MobiCom '14*.

[20] T. Nitsche, G. Bielsa, I. Tejado, A. Loch, and J. Widmer, "Boon and bane of 60 ghz networks: Practical insights into beamforming, interference, and frame level operation," in *CoNEXT '15*.

[21] J. Palacios and et al., "Adaptive codebook optimization for beam training on off-the-shelf ieee 802.11ad devices," in *MobiCom '18*.

[22] H. Hassanieh and et al., "Fast millimeter wave beam alignment," in *SIGCOMM '18*.

[23] M. E. Rasekh and et al., "Noncoherent mmwave path tracking," in *HotMobile '17*.

[24] H. Xu, V. Kukshya, and T. S. Rappaport, "Spatial and temporal characteristics of 60-ghz indoor channels," *IEEE JSAC '02*.

[25] H. Assasa and et al., "Medium access and transport protocol aspects in practical 802.11ad networks," in *WOWMOM '18*.

[26] S. Sur, I. Pefkianakis, X. Zhang, and K.-H. Kim, "Wifi-assisted 60 ghz wireless networks," in *MobiCom '17*.

[27] A. Zhou and et al., "Following the shadow: Agile 3-d beam-steering for 60 ghz wireless networks," in *INFOCOM 2018*.

[28] R. Mudumbai and et al., "Medium access control for 60 ghz outdoor mesh networks with highly directional links," in *IEEE INFOCOM 2009*.

[29] D. Steinmetzer and et al., "Mitigating lateral interference: Adaptive beam switching for robust millimeter-wave networks," in *mmNets '17*.

[30] S. Jog and et al., "Many-to-many beam alignment in millimeter wave networks," in *NSDI 2019*.