

Efficient Network Level Beamforming Training for IEEE 802.11ad WLANs

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Abstract—Millimeter-wave (mmWave) communication is a promising technology that enables high rate (Giga-bit) multi-media applications. In this paper, we consider the directional multigigabit (DMG) transmission problem in IEEE 802.11ad wireless local area network (WLAN). We propose an amendment to the original MAC design of IEEE 802.11ad to eliminate the need to perform beamforming training during station (STA) to STA communication. During A-BFT access period, all STAs beamform with the Access Point (AP) using different time slots. Our mechanism makes STAs listen to other STAs beamform with the AP. We call this Intelligent Listening during A-BFT (ILA). Using this mechanism, each DMG STA can listen to other DMG STAs sector sweep with the AP and get their approximate beam direction which is later used during STA-STA beamforming to considerably reduce the beamforming overhead. We demonstrate via simulations that ILA mechanism considerably improves the network throughput at higher network size.

Keywords. Beamforming, Sector Sweep (SSW), A-BFT, Directional Communication, mmWave, 60 GHz.

I. INTRODUCTION

The recent emergence of applications such as uncompressed high definition TV (HDTV) and ultra fast file transfer requires very high throughput (VHT) of up to multigigabits of speed in wireless local area networks (WLANs). To cater for such VHT requirements, the IEEE 802.11 working group launched an 802.11ad task group to make modifications to the Media Access Control (MAC) and Physical layer (PHY) of the already established 802.11 standard. The current 802.11ad draft utilizes Directional Multigigabit (DMG) ability, in 60 GHz (Millimeter wave), to achieve a theoretical maximum throughput of up to 7 Gbit/s.

The primary function of the MAC is to control devices so they may access the channel and transmit data. MAC protocol design of mmWave wireless system should additionally consider directional antennas and beamforming techniques to compensate for the high signal path loss due to atmospheric attenuation and absorption of oxygen. For example, the path loss at 4 meters in 60GHz bands is above 80dB. In order to compensate for the high path loss, directional antennas or beamforming techniques, such as phased antenna arrays, are utilized in the 60GHz system [1][2][3]. Progress on antenna array design has demonstrated the feasibility of packing large steerable arrays in small form factors [4][5] which provide enough gain for successful communication at 60GHz even for non-line of sight (NLOS) links.

Even though directional communication improves the communication range, it also complicates communication protocol design. Communication between two devices is only possible if the devices have their beams pointing towards each other. Beamforming training (BF) is used to help choose the best beam direction pair that gives the highest channel gain.

Beamforming at 60 GHz has received a lot of attention in the literature for point to point communication and there has been several methods proposed to achieve this. One method is to exhaustively examine all the beam pairs by sending a single training packet for each beam direction [6]. An alternative method proposed by Wang [7] and the 802.15.3c standard [8] employs a binary search beam training algorithm over a layered multi-resolution beamforming codebook to reduce the training time. However, these schemes focus only on providing efficient beamforming solutions for point to point communication without providing any efficient beamforming algorithm at the network level.

Beamforming is an essential component of directional MAC protocol for ad-hoc networks. Ko, Shankarkuman and Vaidya in [9] propose directional MAC protocol that sends a directional RTS followed by an omni CTS. Omni CTS is sent to let other nodes in the network know about the communication. However, directional MAC protocols like these do not fully exploit the benefits of directional antennas such as high coverage area and spatial reuse since they employ at least one omnidirectional transmission of a control packet. In [10], an opportunistic directional MAC protocol (OPDMAC) where both RTS and CTS are sent directionally is proposed. This MAC tries to eliminate idle waiting time by minimizing idle defer after sensing channel busy and idle backoff after failure. Just like [9], OPDMAC assumes location information which might not always be available in IEEE 802.11ad WLANs.

Fakih et al. propose the BMAC protocol for ad hoc networks with adaptive antenna arrays in [11]. BMAC uses directional RTS followed by Omni-directional CTS. BMAC employs periodic training sequence to learn the beamforming information of the neighbors. The MAC has very low coverage area since the control packets are sent in an omni direction and has a high overhead.

There has been a lot of work done to increase the efficiency of beamforming. There has not been much work done that study the effect of beamforming on the whole system. We

believe that a lot of beamforming information can be collected by channel listening. To the best of our knowledge, there has been no work done in retrieving beamforming information from data packets even when the receiver is not the intended destination node.

In this paper, we propose an efficient network level beamforming algorithm, which is an amendment to IEEE 802.11ad, to reduce the beamforming overhead for communication among STAs. In IEEE 802.11ad [12] directional MAC protocol, before any communication can take place, each STA needs to beamform with the AP. Furthermore, for two STAs to be able to communicate with each other, they will have to perform beamforming between themselves. We propose a variation of 802.11ad called Intelligent listening during A-BFT (ILA) mechanism. ILA makes each STA listen to other STAs perform beamforming with the AP. The information gathered during the STA-AP beamforming is then used to facilitate the STA-STA beamforming. This reduces the beamforming overhead of the whole WLAN system by providing efficient beamforming among STAs. ILA also exploits directional communication efficiently by not relying on complete omni-directional communication.

This paper is organized as follows. In section II, our network topology is discussed and IEEE 802.11ad MAC protocol with beamforming and discovery is summarized. In section III, ILA is described. In section IV, the performance of our proposed protocol is simulated and compared with 802.11ad. Section V includes a brief summary and conclusion of this paper.

II. SYSTEM MODEL

A. Network Topology

Wireless indoor mmWave networks (e.g. WPANs/WLANs) have centralized network structure. In IEEE 802.11ad draft the personal basic service set (PBSS) consists of one PBSS control point (PCP) or AP and N ($1 \leq N \leq 254$) non-PCP/non-AP DMG STAs. In PBSS, the PCP controls the beacons and schedules the channel access such that every STA knows from where and when to expect the packets so STAs can direct their antennas to the appropriate direction at the right time.

B. IEEE 802.11ad MAC

As specified in IEEE 802.11ad [12], the time is divided into beacon interval (BI) by the PCP/AP. Subdivisions within the beacon interval are called access periods. Different access periods within a beacon interval have different access rules. The access periods are described in a schedule that is communicated by the PCP or AP to the non-PCP and non-AP STAs within the PBSS.

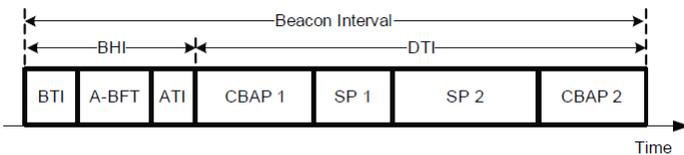


Fig. 1. BI structure in IEEE 802.11ad.

As shown in Fig.1, the schedule communicated by the PCP or AP can include the following access periods:

- BTI: An access period during which the AP performs an initiator sector level sweep (SLS) by sending out DMG beacon frames. The presence of the BTI is optional. A non-AP STA shall not transmit during the BTI of the PBSS of which it is a member.
- A-BFT: An access period during which beamforming training is performed with the AP that transmitted a DMG beacon frame during the preceding BTI. The presence of the A-BFT is optional and signaled in DMG beacon frames.
- ATI: A request-response based management access period between PCP/AP and non-PCP/non-AP STAs. The presence of the ATI is optional and signaled in DMG beacon frames.
- DTI: An access period during which frame exchanges are performed between STAs. There is a single DTI per beacon interval. The DTI, in turn, comprises contention-based access periods (CBAPs) and scheduled service periods (SPs).

C. IEEE 802.11ad Beamforming

BF training is a bidirectional process in which the BF training frames are transmitted to provide the necessary signaling to allow each STA to determine the appropriate antenna system settings for both transmission and reception. A high antenna gain is necessary to compensate for the high propagation loss at 60 GHz. Antenna gain increases as the beamwidth becomes narrower. Since narrow beamwidth is used to achieve the necessary antenna gain, beamforming must be performed to find the best path and possibly avoid obstacles in 60 GHz.

As specified in 802.11ad [12], BF training of STAs may comprise of a Sector Level Sweep (SLS) and a beam refinement protocol (BRP) phase. In the SLS phase, the initiator of the beamforming sends a training frame from each of its sectors and the responding STA can receive in a quasi-omni mode to find the best transmitting sector for the initiator STA. Similarly, the responder sends out a training frame from each of its sectors and the initiating STA can receive in a quasi-omni mode to find the best transmitting sector for the responder STA. Sector sweep feedback information is then exchanged between the two devices to inform each of them of their best sector IDs. In the BRP phase, the STA trains its antenna arrays and improves its antenna array configuration to fine-tune their beams to achieve the best data rate.

The STA-AP beamforming takes place during the BTI and A-BFT access periods and the STA-STA beamforming takes place during the DTI access period before the STA-STA transmission. Each STA randomly chooses a slot in A-BFT to perform SSW. Only one STA can receive a SSW-Feedback from the AP/PCP per A-BFT slot. The STA that fails to receive a SSW-Feedback waits until the next A-BFT. A STA that has successfully been associated with the AP/PCP upon successful reception of the SSW-Feedback stops contending for the A-BFT, which gives other STAs in the network a better chance

to associate with the AP/PCP.

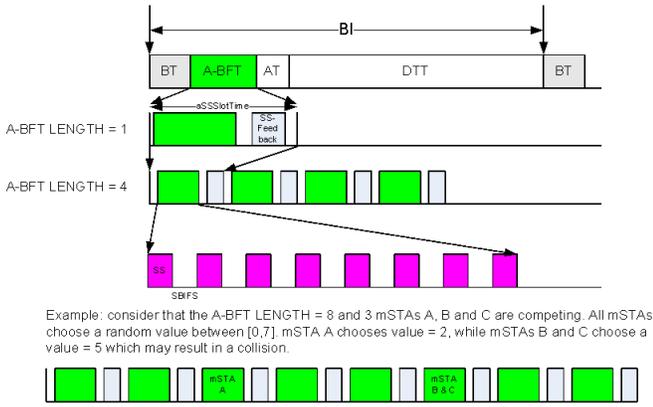


Fig. 2. A-BFT phase in 802.11ad. (This figure is taken from IEEE 802.11ad standard [12])

D. Discovery

During the BTI, the PCP/AP is the initiator and starts the beamforming with the initiator sector sweep. All the non PCP/AP STAs listen in the quasi-omni direction during the BTI while the PCP/AP does an initiator sector sweep. A-BFT phase is slotted as shown in Fig. 2. All the STAs that received the initiator sector sweep (SSW) randomly chooses a time slot in the A-BFT. During this A-BFT time slot, the STA performs responder sector sweep and receives feedback from the PCP/AP confirming the successful SSW phase of beamforming and also informing the responder of its best sector. The BRP phase of the beamforming may be performed during the scheduled DTI access period.

III. INTELLIGENT LISTENING DURING A-BFT (ILA)

The aim of ILA mechanism is to gather information via listening to the channel when STAs beamform with the PCP/AP during A-BFT and to use that information to decrease the overhead of beamforming between STAs. All idle STAs listen in quasi-omni direction during A-BFT. This way, at the end of the A-BFT access period, each STA knows the best sector ID of all the other STAs. In other words, every STA will know in which direction all the other STAs should point to in order to communicate with it. This gathered information can be further used to remove the need to perform SSW beamforming during the STA-STA transmission.

For ease of understanding, the mechanism can be divided into two parts: (1) Listening during A-BFT and (2) Data Communication. To explain the algorithm, we will first explain it through an example and then provide the corresponding algorithm.

A. Listening during A-BFT

Let's consider the scenario shown in Fig. 3, The PCP/AP performs the initiator SSW during the BTI phase. Each STA then randomly chooses a timeslot in A-BFT to perform the responder SSW. During STA A's SSW, all other STAs, including

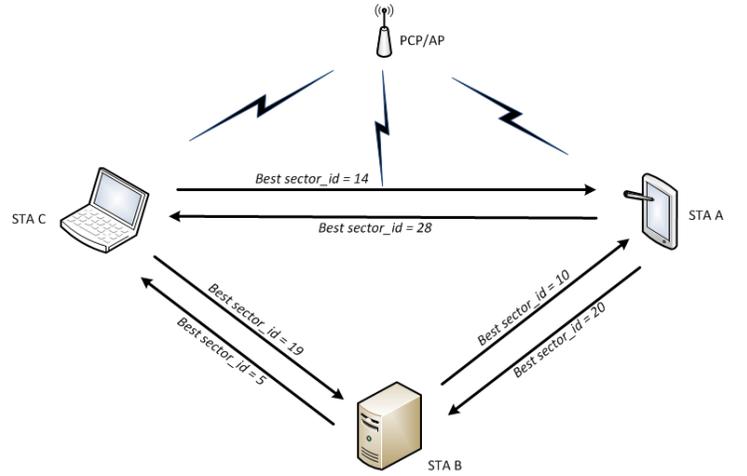


Fig. 3. PBSS.

Algorithm 1 Node's behavior during A-BFT

- 1: Perform SSW in randomly selected A-BFT slot.
- 2: Listen to other nodes perform SSW with the AP.
- 3: Retrieve the sector ID from the received SSW packets.

the PCP/AP, listen in quasi-omni direction. Therefore, STA B gets to know the best sector of STA A (sector_id=20) and STA C gets to know the best sector of STA A (sector_id=28). After the SSW phase, in the same timeslot, PCP/AP sends the sector sweep feedback to STA A. Similarly, STA B performs a SSW in a different timeslot resulting in STA A knowing STA B's best sector (sector_id=10) and STA C knowing STA B's best sector (sector_id=5). Similarly, after STA C's SSW, STA A would know STA C's best sector (sector_id=14) and STA B would know STA C's best sector (sector_id=19). Algorithm 1 describes the behavior of the nodes during A-BFT.

B. Data Communication

When a STA needs to communicate with another STA, during ATI it sends a request to PCP/AP to schedule the communication along with the destination STA's best sector. PCP/AP, while broadcasting the schedule of the communication, adds the best sector of the destination along the schedule. The destination node then uses this best sector information to start the communication with the STA requesting the communication. Let's consider the example in Fig. 3 when STA A wants to communicate with STA B. STA A requests the PCP/AP during the ATI to schedule the communication with STA B including STA B's best sector in the request (sector_id=10). The PCP/AP while broadcasting the schedule informs STA B of its best sector to communicate with STA A. During DTI, STA B using its best sector (sector_id=10) sends an ACK to STA A informing STA A of its best sector (sector_id=20). Now both STAs knowing their best sectors can continue with directional communication.

If two nodes wants to communicate and they don't have each other's best sector ID information then they follow the

Algorithm 2 Communication: Transmitter's behavior

- 1: **if** transmitter has receiver's best sector ID **then**
- 2: Send receiver's best sector ID to AP during the ATI.
- 3: **else**
- 4: Ask AP to schedule beamforming before transmission.
- 5: **end if**
- 6: Receive the schedule from AP.
- 7: During the scheduled transmission slot, wait to receive a packet from receiver.
- 8: **if** received packet has transmitter's best sector ID **then**
- 9: Start transmitting data using the sector ID received.
- 10: **else**
- 11: Perform a SSW.
- 12: Receive SSW-feedback from the receiver.
- 13: Retrieve sector ID from SSW-feedback.
- 14: Start transmitting data using the sector ID.
- 15: **end if**

Algorithm 3 Communication: Receiver's behavior

- 1: Receive the schedule from AP during the ATI.
- 2: **if** received schedule has receiver's best sector ID **then**
- 3: Send a packet to the transmitter.
- 4: **else**
- 5: Perform SSW.
- 6: **end if**
- 7: Receive either data packets or SSW packets from transmitter.
- 8: **if** data packet received **then**
- 9: Send ACK.
- 10: **else**
- 11: Send SSW-feedback.
- 12: **end if**

standard procedure of beamforming before transmission. ILA mechanism is better explained in Algorithms 2 and 3 which shows both the transmitter as well as receiver's behavior. With the use of this mechanism we have at best removed the need to perform two extra sector sweep during STA-STA communication.

The A-BFT's primary purpose is to facilitate beamforming between the AP/PCP and a STA that may want to associate with it. Keeping this in mind not all STAs are able to receive another STA's SSW packet during an A-BFT slot. This can happen because of two reasons. First, if two STAs performing a SSW in the same A-BFT slot, they would not be able to receive each other's SSW packet. Second, if a STA receives two SSW packets at the same time, there might be a collision resulting in the STA not able to receive one or both of the SSW packets. For clarification purposes we would be calling the first case packet loss as 'Loss due to Non-Listening' and the second case packet loss as 'Loss due to Collision'.

IV. PERFORMANCE EVALUATION

In this section, we quantify the performance of the ILA mechanism in networks of different sizes for different network

TABLE I
SIMULATION PARAMETERS

Number of sectors	32
Mainlobe Gain	20 dB
Sidelobe Gain	-5.5 dB
Transmission Power	10 dBm
Background Noise	-158 dBm
SINR threshold	5.5 dBm
SSW duration	286 us
BI duration	30720 us

TABLE II
MCS AND SINR THRESHOLD

MCS mode	MCS1	MCS2	MCS3
Modulation	QPSK	QPSK	16QAM
Code rate	1/2	2/3	2/3
Data rate	0.952Gbps	1.904Gbps	3.807Gbps
SINR threshold	5.5 dB	13 dB	18 dB

parameters.

A. Simulation Scenario

We used MATLAB to simulate our scenario. We randomly deploy different number of nodes in a 10x10 meters square room. Each STA in the network is either transmitting or receiving. Each transmitting station randomly chooses a receiver STA and communicates with it. Half of the STAs in the network are transmitting whereas the other half receiving concurrently. Table I shows the simulation parameters we used in our simulations.

Additionally, the IEEE 802.11ad draft uses different modulation and coding schemes (MCSs) to provide multiple data rates support. Thus, if two or more stations (STAs) have large distances between themselves, they must communicate at a smaller data rate to guarantee the accuracy of decoding the signals. Table II shows the different modulation and coding schemes we used in our simulations.

We use two-dimensional cone plus circle model as a directional antenna model assuming all STAs are in the same plane. As can be seen in Table I, the antenna gain of the mainlobe and the sidelobe are different with the gain of the mainlobe being considerably higher than the gain of the sidelobe. The number of beams depends on the number of antenna elements and the amount of coverage [13] required. For example, for Uniform Linear Array (ULA) with 16 antenna elements, 32 beams are suggested.

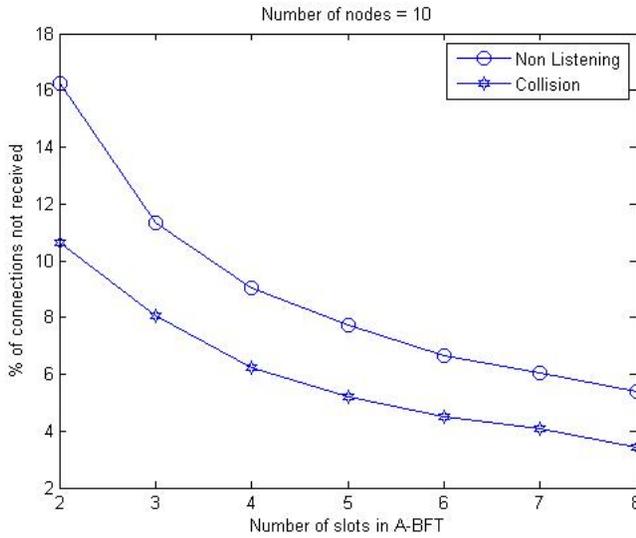


Fig. 4. Percentage of connections not received successfully during A-BFT in a 10 STA WLAN.

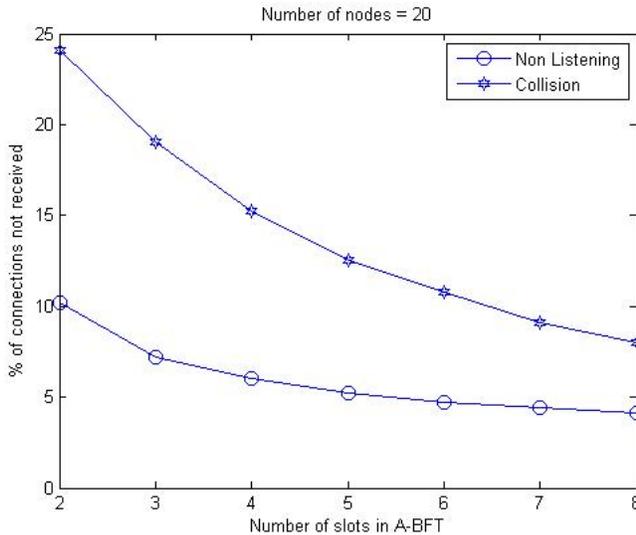


Fig. 5. Percentage of connections not received successfully during A-BFT in a 20 STA WLAN.

B. Simulation Results

Figs. 4 and 5 show the percentage of connections that the STAs were not successfully able to receive during the A-BFT in a 10 and 20 STA WLAN respectively. As the A-BFT size increases, the percentage of connections not received decreases. This is understandable since more slots mean less collisions and less chances of two nodes transmitting at the same time. We observe that with the increase in the number of nodes, the percentage of connections not successfully received due to collision increases since the number of nodes contending for the same time slot increases. On the other hand, the percentage of connections not received due to non-listening decreases as the number of nodes increases. This is because since the nodes

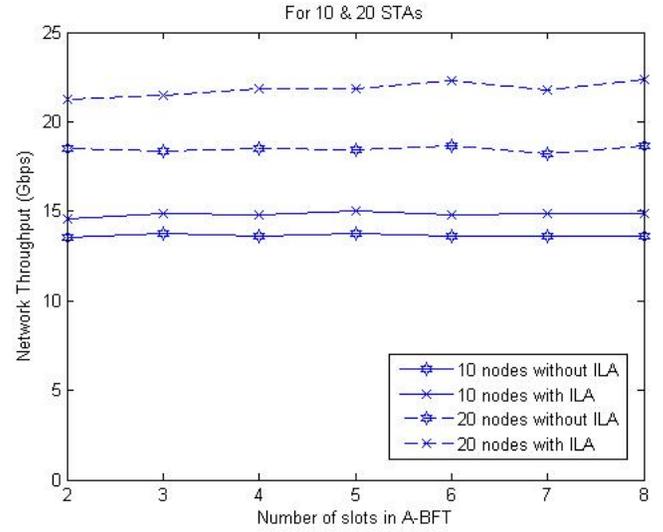


Fig. 6. Network throughput in 10 and 20 STA WLAN.

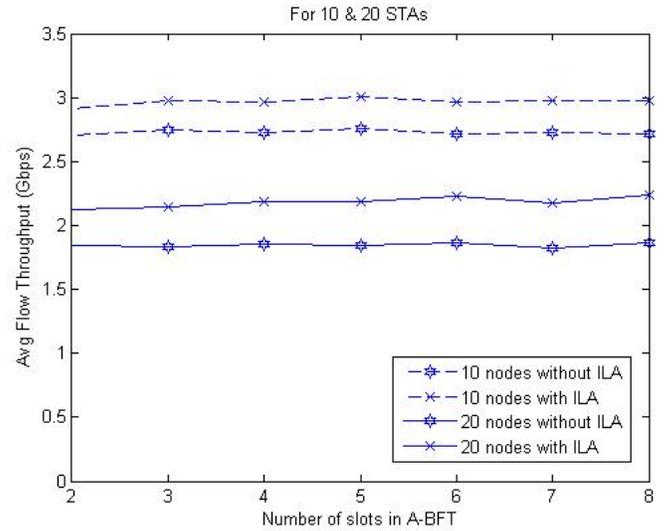


Fig. 7. Average flow throughput in 10 and 20 STA WLAN.

keep trying until successful SSW, the nodes listening would have more chances to listen to a STA's transmission.

Figs. 6 and 7 show the network throughput and average flow throughput for 10 and 20 STA WLAN respectively. We observe that the change in the number of slots during A-BFT does not affect the network throughput considerably, even though the percentage connections that STAs were not successfully able to listen to during the A-BFT changes a lot with the change in A-BFT length. This is because the probability that a STA communicates with another STA that it was not able to listen in the A-BFT is still low and hence the difference in the throughput with respect to A-BFT length is small.

Fig. 8 shows the network throughput for different number of data flows in a WLAN. ILA mechanism considerably

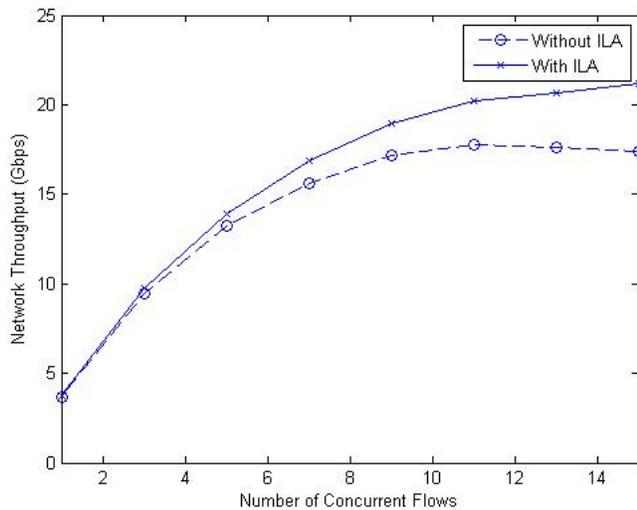


Fig. 8. Network throughput for different number of concurrent transmissions.

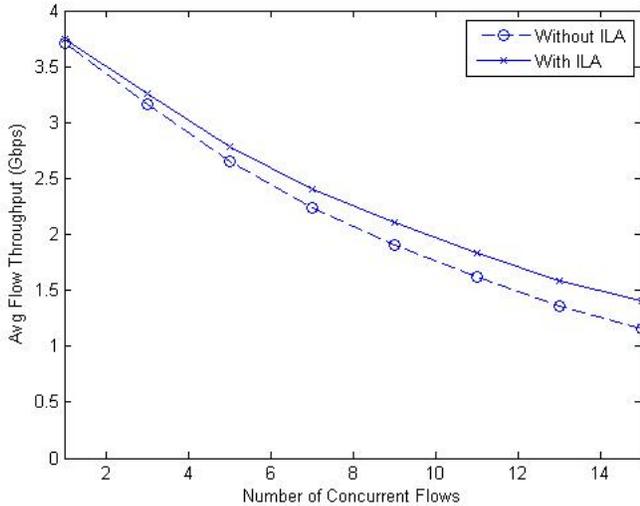


Fig. 9. Average flow throughput for different number of concurrent transmissions.

improves network performance especially as the number of concurrent flows in the network increases. Fig. 9 shows the avg. network throughput per flow in a WLAN with and without ILA mechanism. We again observe that ILA mechanism works better as the number of STAs communicating or the number of flows in the WLAN increases. This is quite understandable since ILA mechanism decreases the number of SSW required. Since the number of SSW increases as the number of STAs increases, there are more SSW that can be decreased by ILA mechanism.

V. CONCLUSION

In this paper, we propose an intelligent listening during A-BFT (ILA) mechanism to help reduce the beamforming

overhead. ILA makes each STA listen to other STAs perform beamforming with the AP. The information gathered during the STA-AP beamforming is then used to facilitate the STA-STA beamforming. We simulated how much beamforming information can be collected through channel listening during A-BFT. Then we used this beamforming information to find out how it increased the overall network throughput. Simulation results show that the beamforming overhead plays a fundamental role in the IEEE 802.11ad WLAN systems, and the proposed ILA scheme achieves remarkable throughput enhancement and solves the problem of high beamforming overhead for a large number of STAs in a WLAN.

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