Two-dimensional Reduction of Beam Training Overhead in Crowded 802.11ad based Networks

Sihua Shao*, Hanbin Zhang†, Dimitrios Koutsonikolas† and Abdallah Khreishah*
*Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey 07102
†Department of Computer Science and Engineering, University at Buffalo, SUNY, Buffalo, NY 14260-2500
Email: *{ss2536, abdallah}@njit.edu, †{hanbinzh, dimitrio}@buffalo.edu

***Abstract*—The millimeter-wave (mm-Wave) or 60 GHz technology emerges as an attractive candidate for indoor wireless access in the 5G architecture. Different from 2.4/5 GHz, high signal attenuation requires mm-Wave antenna utilizing directional transmission to enhance beamforming gain. Consequently, time-consuming beamforming training process between mm-Wave nodes significantly increases communication overhead, especially when the environment is crowded since the nodes perform training process in a contention and backoff manner. In this paper, we propose a novel group beam training scheme that enables simultaneous beam training of all the user devices attempting to associate with the access point. Leveraging the angle-of-arrival sparsity in mm-Wave communications, compressed sensing is adopted to further reduce the beam training overhead. To verify the feasibility of group training and the necessity of compressed sensing under certain conditions, we analyze the signal-to-noise ratio measured on a 60 GHz software defined radio testbed in three typical indoor environments: i) corridor; ii) conference room; and iii) laboratory. Extensive simulations are also performed to evaluate the recovery performance of compressed sensing in mm-Wave WLANs for different sampling capabilities. Simulation results show that compressed sensing reduces the cost of sector sweep by 50%.**

***Index Terms*—60 GHz, mm-Wave, beamforming, group training, compressed sensing.**

I. Introduction

With the concept of 5G coming to reality, the advancement of wireless communication technologies is stimulating the market demands. As a supplementary solution to the limited 2.4/5 GHz spectrum, 60 GHz or millimeter-wave (mm-Wave) is emerging as a wireless access candidate thanks to its wide unlicensed bandwidth. However, the signal propagation in 60 GHz band differs from that in 2.4/5 GHz band, especially in terms of attenuation. To tackle the increased attenuation in 60 GHz band, the IEEE 802.11ad amendment [1] defines a directional communication that leverages the beamforming antenna gain. The beamforming process produces quasi-optical beam patterns with highly concentrated signal propagation. A virtual antenna sector concept is defined in the standard [1] based on the narrow beamwidth signal pattern. The discretized sectors can be implemented by adjusting the weight of each element on a phased antenna array [2]. Since the antenna gain is focused on a certain direction, communication nodes have to coordinate among each other in order to figure out the best pair of sectors that optimizes the signal quality. This coordination, referred to as beamforming training, is divided into two stages [3]. First, during sector-level sweep (SLS), coarse-grained antenna sectors are determined by exhaustive search in the discretized sector space. In the second stage, optional beam refinement phase (BRP) is performed to fine-tune the selected sectors.

Due to the directional connectivity, a network type named personal basic service set (PBSS) is introduced in 802.11ad amendment [1]. One of the participating nodes in PBSS acts as the PBSS control point (PCP) or AP, which announces the schedule and medium access parameters in a sector sweep manner. Other stations associate with the PCP/AP to access beacon intervals (BI). The association process is shown in Fig. 1 [3]. BI header comprises three sub-intervals. First, beacon transmission interval (BTI) consists of multiple beacon frames transmitted by PCP/AP (i.e., initiator) in different directions. Second, association beamforming training (A-BFT) is divided into multiple slots, where each slot can only be used by one station (i.e., responder) for association. The A-BFT implements a contention-based response period. Third, during the announcement transmission interval (ATI), the PCP/AP exchanges management information with associated stations using the selected beams in BTI and A-BFT. Following the BI header, data transmission interval (DTI) is initiated with the coarse-grained antenna sectors obtained in SLS, while multiple BRPs are iteratively performed along with the data transmission. The contention and backoff based mechanism applied in A-BFT severely restricts the number of stations that can successfully associate with the PCP/AP in one BI or results in high overhead especially when short BI duration is set for delay-sensitive applications.

In this paper, we propose a new beamforming training scheme that enables two-dimensional reduction of beam training overhead in 802.11ad based networks with high user density. In one dimension, a group beam training scheme (Sec. III) is proposed to reduce the A-BFT overhead caused by contention and backoff based association process. In particular, instead of each user device occupying one A-BFT slot to perform beam training, all user devices perform receive sector sweep (RXSS) simultaneously while the PCP/AP keeps broadcasting beacon frames in quasi-omni mode. By sweeping N (i.e., the number of phased array antenna elements) different sectors, every user device is capable of generating its own angle-of-arrival (AoA) profile by applying the MUSIC algorithm [4], which infers the direction providing the highest beamforming gain no matter whether it comes from a line-of-sight (LOS) path or non-LOS (NLOS) path. Note that our proposed group beam training scheme can get rid of BRP in DTI and enable multi-gigabit-per-second data rates for all associated users by only performing beam training

978-1-5386-5979-3/18/$31.00 ©2018 IEEE

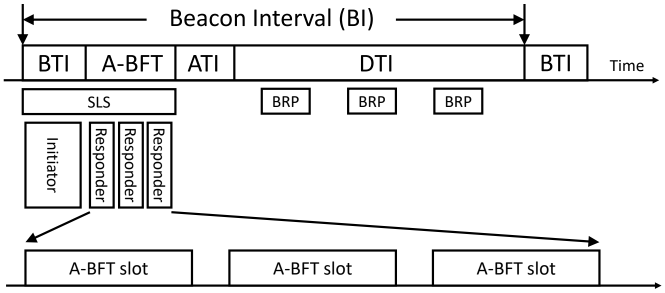


Fig. 1: Association beamforming training structure.

in BI header. In another dimension, compressed sensing [5] (Sec. IV) is adopted to further reduce N by taking advantage of the AoA sparsity. We analyze (Sec. V) an SNR data set collected using X60 [6] – the first SDR-based testbed for 60 GHz WLANs featuring multi-gigabit-per-second data rates and a user-configurable 12-element phased antenna array – to validate the feasibility of our proposed group beam training and the necessity of compressed sensing. Extensive simulations (Sec. V) are also performed to evaluate the accuracy of compressed sensing under realistic mm-Wave system settings.

Our major contributions are summarized as follows:

- We propose a group beam training scheme that allows multiple user devices to associate with the PCP/AP simultaneously without contention. We also theoretically analyze its overhead reduction capability with respect to different number of users.
- The group beam training overhead is further reduced by leveraging AoA sparsity and compressed sensing.
- We analyze the SNR heatmaps collected on a 60 GHz SDR testbed to show the effectiveness of group training and the necessity of compressed sensing.
- Extensive simulations are performed to evaluate the recovery performance of compressed sensing.

II. Related Work

Single link beamforming overhead reduction. Two types of beam training protocols are proposed in [7]. For fixed modulation, a local maximum of the power angular spectrum is determined. For adaptive modulation, iterative multi-level beam training concept is adopted to reduce the complexity of exhaustive searching process. High correlation of spatial channel profile in 60 GHz networks is leveraged in [8] to predict the optimal beams with minimum overhead. This model-driven approach sustains high link performance even when the user is moving. Nevertheless, none of these works investigate their proposed solutions under multi-user settings.

Out-of-band steering beamforming. As an out-of-band access technology, Wi-Fi is utilized in [9] to infer the line-of-sight (LOS) orientation of two stations in mm-Wave system. Experimental results show that the time cost of SLS phase is significantly reduced. Taking energy consumption overhead into account, [10] further improves the Wi-Fi assisted 60 GHz link establishment by fast switching between two access techniques. Although out-of-band steering can simply use angular profile to infer optimal mm-Wave beam direction, the contention in Wi-Fi networks renders the solution difficult to be applied in crowded environment.

Concurrent beamforming of multi-user. The concept of multi-user concurrent beamforming is studied in [11] yet from mitigating the mutual interference perspective. It is also illustrated in a recent survey [12] that taking mutual interference into account for concurrent beamforming of multiple simultaneous links is an emerging research trend in mm-Wave networks. The survey indicates that the group training problem in one PBSS when multiple stations are associating with one PCP/AP has not been investigated.

Enhancing random access in beam training association. In [13], the authors start exploring the reduction of beam training overhead under high user density scenarios. Separated A-BFT, which provides more A-BFT slots for users to compete, and secondary backoff A-BFT, which introduces very small overhead of transmission opportunities, are proposed to reduce collision probability in A-BFT. Even though the A-BFT slot utilization is enhanced, the number of assigned A-BFT slots still limits the maximum number of associated users. Our proposed group training method allows simultaneous beam training without the need to handle contention.

III. Group training for multi-user 802.11ad based networks

A. Group beam training scheme

Compared to the conventional beam training scheme, our proposed group beam training scheme reverses the training order by first training the antenna sector of user device followed by training that of PCP/AP. As an outcome of this reversal, multi-gigabit-per-second data rates are enabled between PCP/AP and associated user devices without iterative BRP. In particular, the scheme consists of three steps:

- First, the PCP/AP broadcasts multiple beacon frames in quasi-omni mode. All the user devices attempting to associate with the PCP/AP perform RXSS and use the AoA profile obtained by applying the MUSIC algorithm [4] to determine the direction with the strongest beamforming gain. The generation of AoA profile will be further described in Sec IV. Note that the strongest signal may arrive via a LOS path or a NLOS path. Based on the observed AoA information, every user device selects from its codebook the fine-tuned beam that is closest to the direction with the strongest beamforming gain for data transmission and reception in the following intervals.
- Second, every user device utilizes the selected fine-tuned beam for receiving signals. The PCP/AP uses narrow beams to perform transmit sector sweep (TXSS). The PCP/AP announces the corresponding sector ID in multiple beacon frames, each transmitted by the PCP/AP on a different sector to cover all possible directions.
- Third, after the PCP/AP sweeps all its sectors, every user device that was listening to the PCP/AP using the fine-tuned beam obtains the best TX/RX sector pair. Each user device then starts sending the feedback including

the best pair and its ID information to the PCP/AP in a contention and backoff based manner, as in the conventional association procedure.

B. Potential issues and solutions

The number of elements on the phased antenna array is not consistent for all associated user devices. In the first step of our proposed group beam training scheme, suppose the PCP/AP broadcasts M beacon frames for all the user devices to train their antenna sectors and the maximum number of elements on a phased antenna array is N, then M should be larger than or equal to N in order to train the user device with the maximum number of elements. However, the value of N is unknown for the PCP/AP before the corresponding user device finishes its association. To overcome the problem, we propose a dynamic M solution. When the PCP/AP is turned on or in the first BI, the value of M is initially set to a large default value that is sufficient to support the RXSS of most commercial user devices. After each round of group beam training, the PCP/AP adjusts the value of M to the maximum N of the associated user devices in the current BI. If a new user device attempting to associate with the PCP/AP in the next BI has a larger value of N than the value of M selected in the previous BI, the new user device might not be able to generate its AoA angular profile. In this case, the new user device uses the best TX beam pattern it found in the group training to send feedback (MCS 0) to the PCP/AP during ATI requesting the adjustment of M in the following BI.

Quasi-omni mode restricts the coverage of PCP/AP. Unlike the conventional PCP/AP performing TXSS in BTI, in the first step of our proposed group beam training scheme, the PCP/AP broadcasts multiple beacon frames in quasi-omni mode, thus one may argue that the quasi-omni mode restricts the beacon announcement range. Regarding this issue, we show by experimental results (Sec. V) that since the user devices are using fine-tuned beam to perform RXSS, the received SNRs will be generally large enough even if the PCP/AP is transmitting in quasi-omni mode.

The number of effective sectors on a user device is less than the number of elements on the phased antenna array. Experimental results based on traces collected in [6] reveal that in typical indoor environments, the number of sectors on user devices that can receive signals with high enough SNR (i.e., sufficient for MCS 0) is not always larger than or equal to the number of antenna elements. Therefore, compressed sensing, even though adopted as an overhead reduction method (Sec. IV), is also applied to handle the situations where the number of effective sectors on user device is limited.

The obtained fine-tuned sector pair might not be the optimal sector pair. Since the user devices are selecting the best TX/RX sector from the codebook that is closest to the direction with the strongest beamforming gain, the selected TX/RX sector might not be the optimal sector that gives the highest SNR. However, we will show in experiments (Sec. V) that a small shift to the optimal fine-tuned sector leads to negligible SNR decrease.

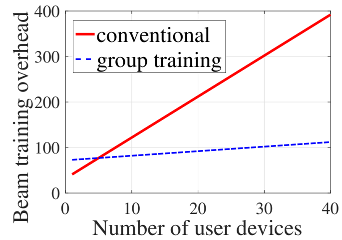
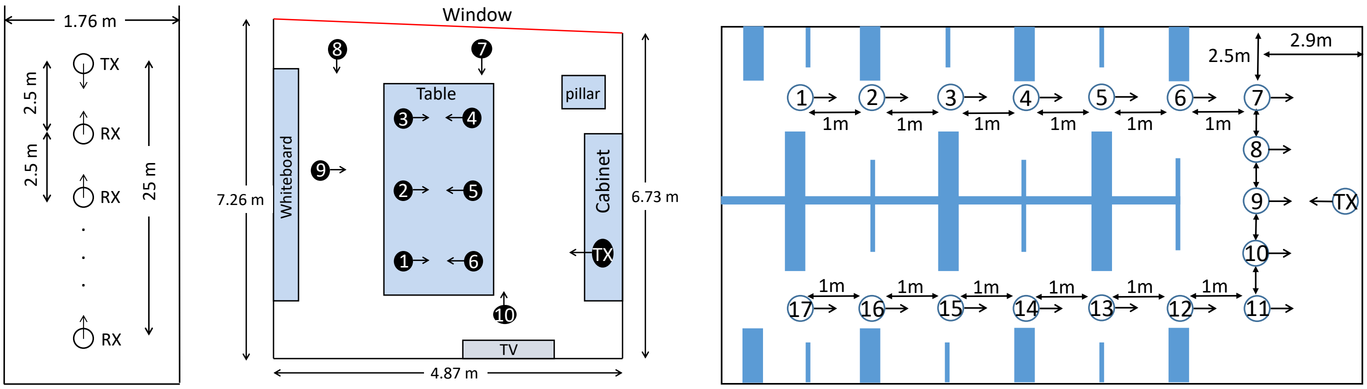


Fig. 2: Beam training overhead vs. number of user devices.

C. Analysis of overhead reduction

In the conventional beamforming training scheme, BRP is generally assigned in DTI. Therefore, it is difficult to quantify the overhead of BRP since it is performed during the data transmission but does not act as appended training process. Also in the 802.11ad standard [1], stations that failed to associate with the PCP/AP in the current BI are supposed to retry in the next BI. To fairly compare the beam training overhead of our proposed group training scheme and the conventional beamforming training scheme, we consider extending A-BFT in order to let all the attempting user devices successfully associate with the PCP/AP in one BI, and we compare the training cost of two schemes before ATI.

Assume we have k user devices, in the conventional beamforming training scheme, denote the number of coarse-grained TX sectors of PCP/AP by P and the number of coarse-grained TX sectors of user devices by Q. Under this setting, the minimum beam training overhead, where the contention is not considered, is $P + kQ + k$. Here the last component k is the overhead of the feedbacks sent from the PCP/AP to associated user devices. The feedbacks sent from user devices to the PCP/AP are piggybacked on the TXSS frames such that the feedbacks are not counted as overhead. For our proposed group beam training scheme, the number of required RX sectors of user devices is denoted by Q', where Q' is normally similar to Q. The number of fine-tuned TX sectors of PCP/AP is denoted by P', where P' is normally larger than P. Under this setting, the minimum beam training overhead (contention is not considered) is $P' + Q' + k$. Here the last component k is the overhead of the feedbacks sent from user devices to the PCP/AP. Note that here we compare the minimum beam training overhead of two schemes without considering contention. Since both the conventional beam training scheme and our proposed group training scheme adopt the same contention and backoff approach for sending the feedbacks from user devices to the PCP/AP, the amount of additional overhead when contention is considered should be similar for both schemes. We leave a detailed analysis of the overhead in the presence of contention for future work. We can observe that, when only one user device is attempting to associate with the PCP/AP, the minimum overhead of the conventional beamforming training scheme is smaller. But as the number of user devices increases, the benefit of our proposed group training scheme is manifested. Nevertheless, it is worth noticing that our proposed group training scheme directly achieves the link performance that the conventional



(a) Corridor (b) Conference room (c) Laboratory

Fig. 3: Plane layouts of three different environments: (a) corridor; (b) conference room; (c) laboratory.

beam training scheme can only achieve after BRP. To provide a clear vision of the comparison of two schemes, we set $P = 32$, $Q = 8$, $P' = 64$ and $Q' = 8$ and plot the overhead vs. number of user devices in Fig. 2.

IV. Compressed Sensing for Overhead Reduction

In the first step of our proposed group training scheme, one way to generate AoA profile is to isolate the signals on each antenna element using a digital phased array. However, the practical 60 GHz radios use analog phased arrays, which only provide a single scalar output,

$$y = \boldsymbol{W}^H_{R_{1\times n}} \boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S + e,$$

where $\boldsymbol{W}_{R_{1\times n}}$ represents the weight vector of receiving phased array and $(\cdot)^H$ denotes the conjugate transpose, $\boldsymbol{W}_{T_{m\times 1}}$ represents the weight vector of transmitting phased array, $\boldsymbol{H}_{n\times m}$ represents the channel response matrix, S is the data symbol, and e is the additive noise. n and m are the numbers of elements on the receiving phased array and the transmitting phased array, respectively. To tackle the limitation brought by the analog phased array, a general solution is to let the receiving phased array switch across n different weight vectors to receive the same signals by n times, which is equivalent to sweeping n different sectors. Then the received signal vector is

$$\boldsymbol{Y}_{n\times 1} = \boldsymbol{W}^H_{R_{n\times n}} \boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S + \boldsymbol{e}_{n\times 1}. \tag{1}$$

One can simply apply least squares method to solve

$$\boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S = \boldsymbol{W}^{-1}_{R_{n\times n}} \boldsymbol{Y}_{n\times 1},$$

where $\boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S$ represents the signal on each element to realize the isolation of individual antenna's signals. Based on the isolated signals, extended MUSIC algorithm [4] can be applied to obtain AoA profile.

Due to the AoA sparsity in mm-Wave systems, compressed sensing provides us with a better solution, which only requires the receiver to sweep n' ($n' < n$) different sectors in order to produce the AoA profile. Compressed sensing [5] is capable of recovering the signals from limited measurements by solving the underdetermined system if the measurements are incoherent and the signal vector is sparse in certain basis. For our case, the process of RXSS at user device side is viewed as an underdetermined system when the number of sweep sectors is less than n. $\boldsymbol{W}^H_{R_{n'\times n}}$ acts as the sensing matrix. The isolated signal on each element can be represented by

$$\boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S = \boldsymbol{\Psi}_{n\times n} \boldsymbol{\beta}_{n\times 1}, \tag{2}$$

where $\boldsymbol{\Psi}_{n\times n}$ is the sparsity-inducing basis and $\boldsymbol{\beta}_{n\times 1}$ is the sparse vector variable. The signals are generally sparse on popular bases, such as fast Fourier transform (FFT) basis, discrete cosine transform (DCT) basis and Walsh-Hadamard transform (WHT) basis. Therefore, (1) can be rewritten as

$$\begin{aligned}\boldsymbol{Y}_{n'\times 1} &= \boldsymbol{W}^H_{R_{n'\times n}} \boldsymbol{H}_{n\times m} \boldsymbol{W}_{T_{m\times 1}} S + \boldsymbol{e}_{n'\times 1} \\ &= \boldsymbol{\Theta}_{n'\times n} \boldsymbol{\beta}_{n\times 1} + \boldsymbol{e}_{n'\times 1},\end{aligned}$$

where $\boldsymbol{\Theta}_{n'\times n} = \boldsymbol{W}^H_{R_{n'\times n}} \boldsymbol{\Psi}_{n\times n}$. ℓ_1-norm is applied to solve the optimization problem by finding the sparsest solution that

$$\min\{\|\boldsymbol{\beta}_{n\times 1}\|_1 : \|\boldsymbol{Y}_{n'\times 1} - \boldsymbol{\Theta}_{n'\times n}\boldsymbol{\beta}_{n\times 1}\|_2 < \epsilon\}.$$

After obtaining the optimal value of $\boldsymbol{\beta}_{n\times 1}$, we can recover the isolated signals on each element by (2).

V. Experiment and Simulation Results

A. *Experiment settings and results*

Each TX/RX node is built on X60 [6]. All modules involved in the baseband signal generation are assembled inside a NI PXIe-1085 PXI Express chassis. The SiBeam mm-Wave module, on the TX path, takes as input the baseband signal (as differential I/Q), up-converts, and transmits over the air a 2 GHz wide waveform centered around one of the 802.11ad channel center-frequencies. The RX side flow is symmetric to the TX path. The in-built phased array has 24 elements; 12 for TX and 12 for RX. SiBeams reference codebook defines 25 beams spaced roughly 5° apart (in their main lobes direction). The beams cover a sector of 120° (in the azimuthal plane) centered around the antennas broadside direction. The 3 dB beamwidth ranges from 25° to 30° for TX and from 30° to 35° for RX. For more details about the configurations of the testbed, the reader is referred to [6].

The SNR measurements were performed in three typical indoor environments: (a) corridor; (b) conference room; and

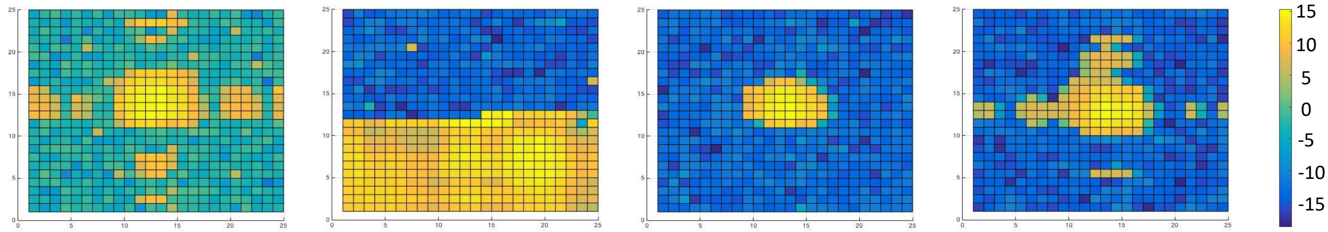


Fig. 4: Heatmaps of the four lowest average SNR in corridor

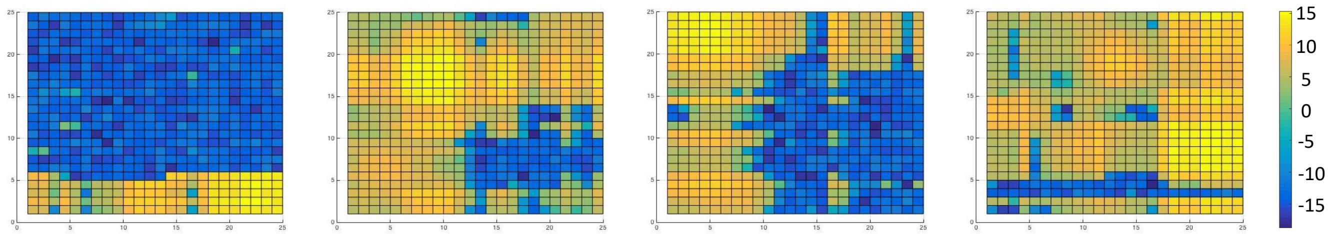


Fig. 5: Heatmaps of the four lowest average SNR in conference room

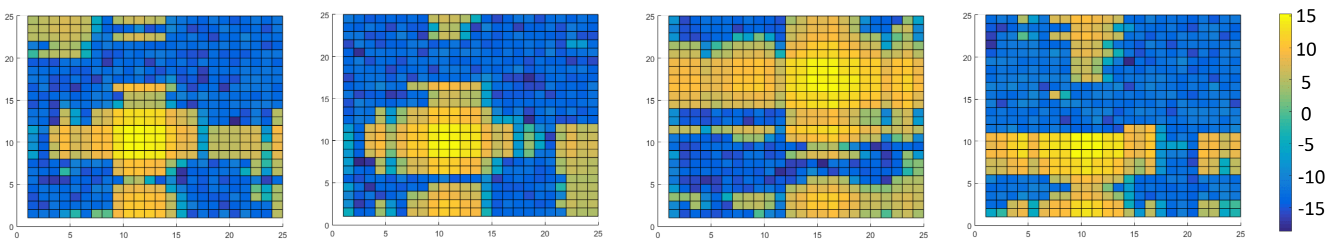


Fig. 6: Heatmaps of the four lowest average SNR in laboratory

(c) laboratory. The layouts, the candidate locations of RX, the fixed positions of TX and their orientations are replicated from [6] in Fig. 3. Due to the limited space, for each environment, we only show the four heatmaps with the lowest average SNR in Fig. 4 to Fig. 6. In the SNR heatmaps, Y-axis represents the RX beam index and X-axis represents the TX beam index. Based on the heatmaps, we can observe that a small shift to the optimal fine-tuned sector (the highest SNR) will not lead to large SNR variation.

To evaluate the required SNR for MCS 0 in 802.11ad based communication, we perform the following calculations. Based on the X60 testbed, achieving Gbps data rate needs 10 dB SNR. According to [14] and [15], in 802.11ad based communication, MCS 0 (27.5 Mbps) requires 15 dB less than MCS 4 (1155 Mbps) that is closest to Gbps data rate. Hence we conclude that MCS 0 defined in 802.11ad, which is used in the first step of our proposed group beam training, needs at least -5 dB SNR. According to [16], the beamforming gain loss of quasi-omni mode compared to 3 dB beamwidth at 30° is -10 to -15 dB. We reduce the measured SNR values in Fig. 4 - Fig. 6 by 15 dB to emulate the scenarios where the TX operates at quasi-omni mode. Then we compare the SNR values after subtraction to -5 dB SNR (i.e., the minimum requirement of MCS 0) to evaluate the number of effective sectors when the user devices perform RXSS in the first step of our proposed group beam training. Based on the comparison, we found that the number of effective sectors for corridor is (12, 5, 3, 6), for conference room is (5, 20, 14, 23), and for laboratory is (20, 20, 7, 12). For most cases, the number of effective sectors is larger than or equal to the number of elements (i.e, 12) on receiving phased array. For the cases where the number of effective sectors is not enough to generate the AoA profile based on MUSIC algorithm, compressed sensing will be applied. The accuracy performance of compressed sensing will be evaluated by simulations in Sec. V-B.

B. Simulation settings and results

We consider a 2D model that matches the settings of the X60 testbed. Moreover, we consider a conference room environment that contains one LOS path and two NLOS clusters. Since there is no depository giving the AoA distribution of 802.11ad based indoor networks, we adopt Gaussian distribution to emulate the distribution of AoA. Simulations are run with different configurations of the devices equipped with 16 elements and 32 elements, respectively. The value of SNR is set to 0 dB for all simulations.

As shown in Figs. 7 and 8, the curves marked by star sign indicate the probability that the MUSIC algorithm successfully computes the correct AoA distribution, and the curves marked by circle sign indicate the probability that the MUSIC algorithm successfully computes the direction with the strongest beamforming gain. We observe that successful rate of computing the direction with the strongest beamforming gain increases first as the number of effective sectors increases but decreases after reaching to a maximum percentage around 75%. The reason for the decreasing trend is that restricted isometry property (RIP) conditions cannot be satisfied anymore [5], as we use the specified sensing matrix $\boldsymbol{W}^H_{R_{n'\times n}}$ instead of

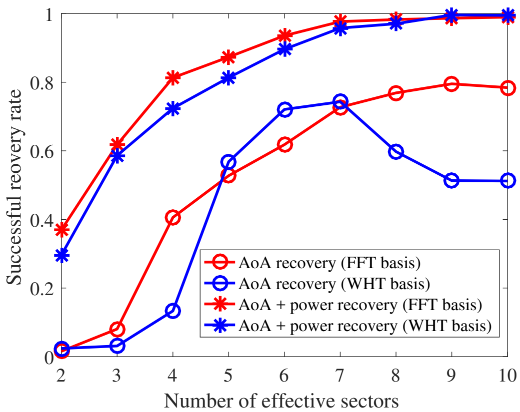


Fig. 7: Successful recovery rate vs. number of effective sectors for user devices with 16 antenna elements

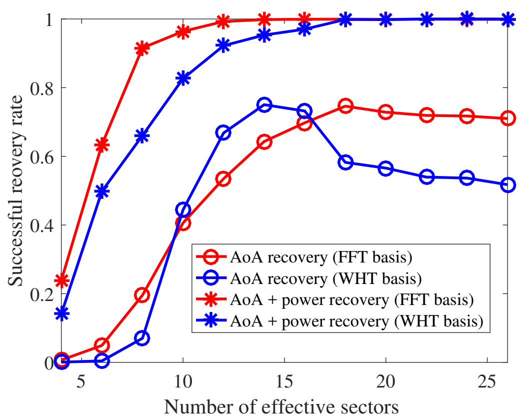


Fig. 8: Successful recovery rate vs. number of effective sectors for user devices with 32 antenna elements

the one conforming to Gaussian distribution or Bernoulli distribution. The maximum successful rate of computing the direction with the strongest beamforming gain does not exceed 75%. This is because for some cases only the side lobes have the opportunities to receive the strongest signal given limited number of effective sectors. In such circumstances, the strength of the signal from the strongest path is being suppressed and the MUSIC algorithm will classify the channel gain of different paths by mistakes. However, we can perform minimal additional sweeps (i.e, depends on the number of arrival paths) based on the observed AoA distribution, which achieves nearly 100% successful recovery rate after sweeping 9 effective sectors for 16 elements setting and 14 effective sectors for 32 elements setting, respectively. As a result, with x times additional switching weight vector at user devices, the successful recovery rate for the direction offering the strongest beamforming gain increases to almost 100%, and generally the value of x will be no more than 4 due to the AoA sparsity in mm-Wave system. In summary, compressed sensing solution achieves nearly 100% and over 80% success in AoA+power recovery when the number of effective sectors is half and 1/4 of the number of antenna elements, respectively.

VI. Conclusion

Contention and backoff based association process in the conventional beamforming training scheme introduces large overhead in crowded 802.11ad networks. To overcome this limitation, we propose a group beam training scheme that allows multiple user devices to train their sectors with the PCP/AP at the same time. Thanks to the AoA sparsity in mm-Wave system, compressed sensing is adopted to further reduce the beamforming training overhead. We analyze the measured SNRs from a 60 GHz SDR testbed to validate the feasibility of our proposed group beam training and the necessity of compressed sensing under certain conditions. Also simulations are performed to evaluate the recovery performance of compressed sensing, which reduces the cost of sector sweep by 50% when applied in mm-Wave system.

Acknowledgment

This work is supported in parts by NSF grants CNS-1629929, CNS-1553447, CNS-1617924 and EEC-1560131.

References

[1] IEEE 802.11 WG, "IEEE 802.11 ad, Amendment 3: Enhancements for very high throughput in the 60 GHz band," Dec, 2012.

[2] A. Valdes-Garcia, S. Reynolds, A. Natarajan, D. Kam, D. Liu, J.-W. Lai, Y.-L. O. Huang, P.-Y. Chen, M.-D. Tsai, J.-H. C. Zhan *et al.*, "Single-element and phased-array transceiver chipsets for 60-ghz gb/s communications," *IEEE Communications Magazine*, 2011.

[3] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and J. C. Widmer, "IEEE 802.11 ad: directional 60 GHz communication for multi-Gigabit-per-second Wi-Fi," *IEEE Communications Magazine*, 2014.

[4] M. H. Hayes, *Statistical digital signal processing and modeling*. John Wiley & Sons, 2009.

[5] D. L. Donoho, "Compressed sensing," *IEEE Transactions on Information Theory*, 2006.

[6] S. K. Saha, Y. Ghasempour, M. K. Haider, T. Siddiqui, P. De Melo, N. Somanchi, L. Zakrajsek, A. Singh, O. Torres, D. Uvaydov *et al.*, "X60: A programmable testbed for wideband 60 ghz wlans with phased arrays," in *IEEE WiNTECH*, 2017.

[7] J. Kim and A. F. Molisch, "Fast millimeter-wave beam training with receive beamforming," *IEEE Journal of Communications and Networks*, vol. 16, no. 5, pp. 512–522, 2014.

[8] A. Zhou, X. Zhang, and H. Ma, "Beam-forecast: Facilitating mobile 60 GHz networks via model-driven beam steering," in *IEEE INFOCOM*, 2017.

[9] T. Nitsche, A. B. Flores, E. W. Knightly, and J. Widmer, "Steering with eyes closed: mm-wave beam steering without in-band measurement," in *IEEE INFOCOM*, 2015.

[10] S. Sur, I. Pefkianakis, X. Zhang, and K.-H. Kim, "WiFi-assisted 60 GHz networks," in *ACM MobiCom*, 2017.

[11] J. Qiao, X. Shen, J. W. Mark, and Y. He, "MAC-layer concurrent beamforming protocol for indoor millimeter-wave networks," *IEEE Transactions on Vehicular Technology*, 2015.

[12] S. Kutty and D. Sen, "Beamforming for millimeter wave communications: An inclusive survey," *IEEE Communications Surveys & Tutorials*, 2016.

[13] P. Zhou, X. Fang, Y. Fang, Y. Long, R. He, and X. Han, "Enhanced random access and beam training for mmwave wireless local networks with high user density," *IEEE Transactions on Wireless Communications*, 2017.

[14] J. Kim, S.-C. Kwon, and G. Choi, "Performance of video streaming in infrastructure-to-vehicle telematic platforms with 60-ghz radiation and ieee 802.11 ad baseband," *IEEE Transactions on Vehicular Technology*, 2016.

[15] ITU-R, "Report ITU-R M.2227," https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2227-2011-PDF-E.pdf, [Online].

[16] E. Perahia, "TGad Evaluation Methodology," http://www.ieee802.org/11/Reports/tgad_update.htm, [Online].